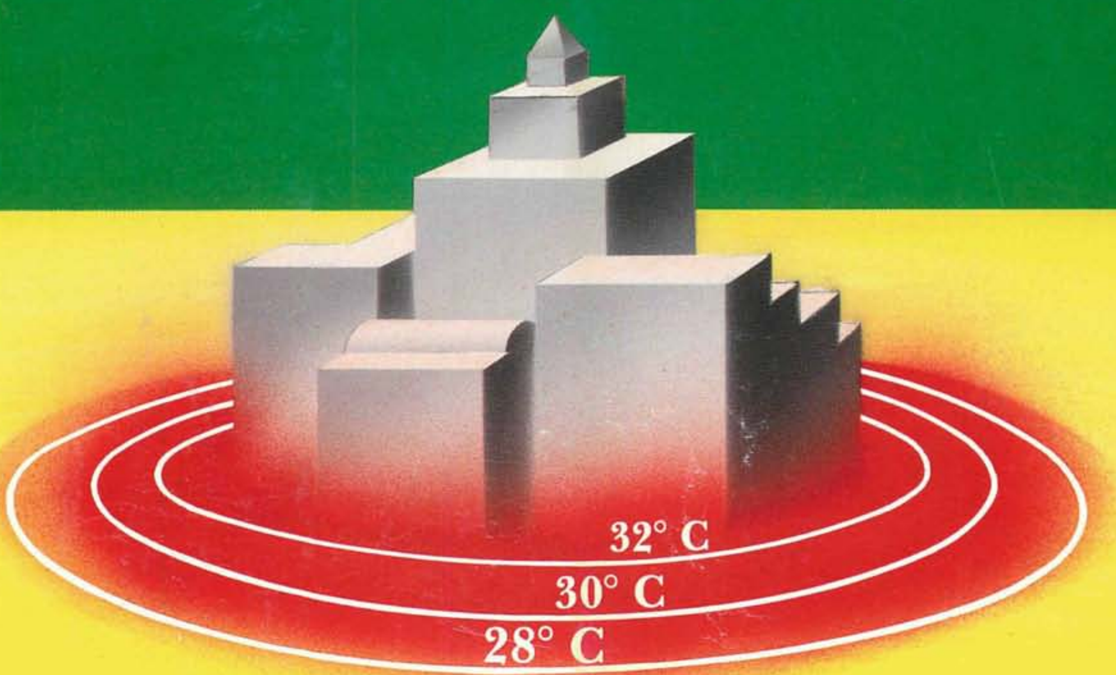
World Climate Programme

URBAN CLIMATOLOGY AND ITS APPLICATIONS WITH SPECIAL REGARD TO TROPICAL AREAS

PROCEEDINGS OF THE TECHNICAL CONFERENCE

organized by the World Meteorological Organization and co-sponsored by the World Health Organization

(Mexico D. F., 26-30 November 1984)



WMO — No. 652

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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Scientific editor: T.R. Oke

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NOTE

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Dedicated to
Helmut E. Landsberg
by his friends

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FOREWORD

The unplanned growth of cities, especially in tropical and sub-tropical countries, can have disastrous effects on the urban environment and economy. The proper application of climate in land-use, urbanization and building can contribute to improved human health, environment, energy usage and other social and economic benefits. Acting on recommendation stemming from its Commission for Climatology, the World Meteorological Organization organized with co-sponsorship of the World Health Organization the Technical Conference on Urban Climatology and it Applications with Special Regard to Tropical Areas which, at the kind invitation of the Mexican Government, was hosted by the National Meteorological Service in Mexico D. F., from 26 to 30 November 1984. The National Meteorological Service of Mexico, UNEP, HABITAT and other international organizations, were also actively involved in the organization of the Conference. Mr. Silvino Aguilar Anguiano, Director-General of the Meteorological Service of Mexico, was the President of the Conference and Dr. Tim R. Oke, Professor of Urban and Boundary Layer Climatology at the University of British Columbia, Vancouver, was the Scientific Director.

There were 114 participants from 31 Member countries and five international organizations. During the Conference, presentation of twenty invited lectures and 44 short papers was followed by discussions through which ideas and experiences were exchanged among professionals involved in urban related activities in different parts of the world. Abstracts of all these papers were published in separate English and Spanish versions (WMO/TD-No.7). Great interest was expressed from many institutions and individuals in the publication of the proceedings of the Conference. Professor T.R. Oke kindly accepted to act as scientific editor of the invited lectures which are published in this book. The outcome of the discussions is reflected in conclusions and recommendations of the Conference which are printed in the proceedings and which will serve as a basis for new WMO actions additional to those already listed in the WMO Plan of Action in Urban and Building Climatology approved in June 1984.

I am pleased to have this opportunity of expressing the appreciation of WMO to all who have contributed to this very successful project.

G.O.P. Obasi

Secretary-General

TECHNICAL CONFERENCE ON URBAN CLIMATOLOGY AND ITS APPLICATIONS
WITH SPECIAL REGARD TO TROPICAL AREAS
MEXICO D.F. (MEXICO), 26-30 NOVEMBER 1984

CONCLUSIONS AND RECOMMENDATIONS OF THE CONFERENCE

General

1. One of the most important achievements of the Conference has been the diffusion of ideas, in contrast with the fact that, otherwise, many research findings are not known beyond a very small circle of experts.

2. Much research in Urban Climatology has been too descriptive. The number of descriptive studies for mid-latitude cities is now large enough; for tropical cities more studies are required and they need to be identified. Cost/benefit studies may facilitate obtaining of funds for research. But the emphasis of research should be changed - the study of physical mechanisms should lead to a better appreciation of problems and to simple predictive models based on elementary data, such as can be collected in most tropical cities without great costs of equipment or personnel. It is realized that a long list of sophisticated data would have a negative effect on the co-operative spirit of national Meteorological Services. At the same time, researchers should be encouraged to concentrate on the basic understanding of urban impacts, rather than on the proliferation of heat island statistics and site specific studies that do little to show the practical importance of such phenomena and their role in human health comfort. Very little research has been interested in the informal sector and living conditions of the poorest sections of the urban population in the tropics.

3. To increase their usefulness to research and planning as well as to meteorological forecasting, urban climate models should be validated with observational data. The ability to model should not affect the ability to measure. There is a need for better understanding of the role of aerosols in the urban atmosphere.

4. Many of data needed for Urban Climate Activities are not readily available in tropical countries and their collection and analysis should be promoted without delay.

5. The Conference recommended the holding of an International Year of Urban Climate to act as a focus for public information and international cooperation in the field. Activities might include the issuance of a postal stamp and/or a logo; the holding of an international competition to encourage urban design plans which incorporate climatic concerns; the development and dissemination of attractive and informative literature, films and other media. Member countries would be invited to participate in a world-wide observation programme centered on simple measurements in one or more of their urban areas and contributing to a unified set of scientific objectives. WMO may seek ways and means to help developing countries in the acquisition, installation and operation of such a network. The Year may be feasible by 1992.

6. It is recommended to investigate the possibility of holding an international meteorological experiment targetted upon a better understanding of the atmospheres of tropical cities. The experiment would be modelled on the pattern set by previous WMO initiatives such as ALPEX, MONEX or HAPEX etc, and will require support from other organizations such as ICSU and UNEP. The selection of appropriate cities should include criteria regarding the climate, geographic setting and physical structure of the location. The experiment(s) will be designed to speed up the acquisition of scientific knowledge on tropical urban climatology to a level approaching that for mid-latitude cities and to assess the transferability of knowledge between the two. Such a project could include aspects of all components in the World Climate Programme (Research, Impacts, Applications and Data).

7. The physical complexity of the urban climate and the need to improve the knowledge and information (e.g. climatological statistics related to city centre and residential sites as well as to the urban-rural comparisons, temporary/mobile stations, topography) require careful programming of climatological measurements.

8. The data needs of urban climatologists should be expressed in order of urgency, and preference should be attached to data obtainable with simple, cheap and reliable instruments and methods, easy to use. The same refers to the analysis procedures.

9. To enable data comparability between different cities and countries, standards for detailed calibration of instruments and for measurement methods and techniques should be developed and applied accordingly.

10. In large tropical urban areas where some studies already exist, implementing more sophisticated measurements, such as vertical extent of mixing height and temperature wind structure in the vertical, could be envisaged.

11. There is a need for guidance with respect to urban meteorological practices. Although much of this information is scattered throughout the available literature, there is no clear synthesis in a form that can be made readily available internationally, in particular as regards tropical countries. This should cover programme and methods of measurements (including elements, siting, time), description of instrumentation (including calibration and maintenance), techniques for air quality measurements, presentation of data and their analysis.

12. In discussing the use of urban climatological models in tropical countries, the essential constraints lie in the available resources of those countries, the sophistication of available models compared to their data requirements and the type of information that is appropriate. The limitation on available resources implies that techniques must be simple and effective and not require sophisticated technology for their support. Model sophistication on the other hand should not outstrip the available data and there is little value in transferring highly sophisticated numerical models that require large data bases and/or extensive computational facilities. In both tropics and temperate latitudes, the emphasis should be put on the relevance of data required throughout the urban boundary layer and the urban canopy layer, as well as on data highlighting urban features in general, rather than on data that are site specific. The advancement of the science and its application will be enhanced if the transfer of information emphasizes an understanding of the physics and chemistry of the urban atmosphere rather than the unique features of individual cities.

13. It would be useful to publish an overview of urban climate models indicating for each class of model its goal, limitation (including whether validated) as well as data and computational requirements and costs of running the models. It would be useful if description of models includes the pattern of urban features such as urban geometry.

Applications

14. To promote the use of urban climatology and of its applications, it would be useful to translate climatological information into planning guidelines.

15. Climatological data supplied to architects and planners should show direct links to the design elements in order to indicate their purpose and objective, i.e. the human comfort requirements from building.

16. For the impact of urbanization on humans, detailed data need to be collected and, for the purpose, health statistics should be a basic set. It is particularly important to stress how some problems could be improved or avoided on a government level (e.g. pollution controls) and on an individual level (e.g. change of behaviour to better cope with heat stress).

17. The cost effectiveness of utilizing climate information is essential in convincing policy makers of the need of such information in the planning process.

18. The needs and requirements of planners and architects are not always known to urban climatologists and their professional organizations should be contacted to get a better formulation. It is realized that these needs differ from area to area, according to climatic, social, economic and political conditions.

19. There is need to exchange technical and scientific information on Urban Climatology in tropical areas among professional and scientific community in those countries. For the purpose, workshops in selected tropical countries would be useful. This should be geared to the needs, resources and aspirations of the tropical countries rather than the uncritical transplanting of approaches from mid and high latitudes.

Research

20. The Conference recognized that research in urban climatology (both basic and applied) is in need of continued support and advancement. General areas requiring special attention include the need to change the emphasis of basic research from the descriptive to a more physical and ultimately predictive approach, to place greater stress on applied aspects, and to intensify efforts to advance work in tropical areas.

The following topics of special interest were identified:

Basic Research

(a) urban energy budget;
(b) urban water balance;
(c) influence of topography on urban climates;
(d) validation of urban climate models using field observations;
(e) role of aerosol in the urban atmosphere;
(f) relation between conditions in the urban canopy and boundary layers;
(g) development of urban diffusion models for use in urban areas;

Applied Research

(a) relationship between elements of urban structure (e.g. street and building geometry, arrangement of greenspace) and climate;

(b) climatic input to impact assessment when considering the siting of industry and potentially hazardous or noxious facilities;

(c) climatic considerations relevant to the design of urban transport systems to best preserve or enhance human health and urban ecology;

(d) relationship between urban climate and energy (sources, demand, etc);

(e) impact of urban weather and climate on human health (comfort, aero-allergens, morbidity, mortality, etc);

(f) impact of weather and climate on urban water resources, surface water availability and flood hazard with special regard to the design of urban systems of water supply and drainage;

(g) impact of extreme climatic forces on urban design;

(h) impact of weather and climate on urban air quality;

(i) quantification of urban climate impacts on economic and other urban activities via cost-benefit or other appropriate analyses;

(j) design of urban observation networks and specification of instrument exposure requirements in harmony with urban climate characteristics at both the urban canopy and boundary layer scales;

(k) role of surface cover and wind field upon dust generation and impact of dust on health and public nuisance.

21. Special efforts should be made to help alleviate problems associated with slums and squatter settlements. To improve their environmental conditions, information should be disseminated to national authorities with regard to the benefits, in terms of human comfort, safety and productivity that accrue from rational use of local climate and employment of very inexpensive building techniques. The goal is to recommend techniques that will improve thermal comfort and air quality whilst minimizing risks due to natural hazards without additional expenditure of financial resources.

Education and Training

22. The Conference supported the key role of education and training in urban climatology, conceived in the widest sense. Education and training should not only be directed towards professional meteorologists, but should also aim to:

(a) Educate the public and officials about the considerable economic, social and health benefits which result from utilizing climatology in urban planning;

(b) Forge effective communications between meteorologists and the various other professional groups and authorities involved in urban related activities;

(c) Aim to reduce the risks of disasters, especially in the poorest sections of towns, which are the most vulnerable to such risks;

(d) Create awareness of the value of suitably drafted laws and regulations incorporating urban climatological principles in ensuring the planning process takes proper account of climate at the detailed level of development;

(e) Preparing, using suitable courses in their university education, meteorologists and planning specialists of various disciplines to effectively contribute and collaborate in the process of applying climatology in urban planning;

(f) Develop suitable publicity activities including public meetings, press conferences, personal contacts, popular articles, posters and films with a view to influencing both politicians, government officials and general public, to create a favorable climate of public opinion, in which to make progress in the field.

23. The Conference gave special importance to the development of short intensive courses and workshops on urban climatology with emphasis on creating successful applications (illustrated by suitable examples) rather than simply on theoretical considerations.

LIST OF PARTICIPANTS

ARGENTINA

Nicolás Antonio Mazzeo
Departamento de Meteorología
Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires
Ciudad Universitaria
1428 Buenos Aires

AUSTRALIA

T.J. Lyons
School of Environmental and Life Sciences
Murdoch University
Murdoch
Western Australia 6154

AUSTRIA

Konrad Cehak
Institute for Meteorology and Geophysics
University of Vienna
Hohe Warte 38
A-1190 Vienna

BRAZIL/BRASIL

Carlos Augusto Figueiredo Monteiro
Department of Geography
Rua Sao Carlos do Pinhal
485 Ap. 96 (Bela Vista)
01333 Sao Paulo

Ademilde de Seixas Valenca (Mrs.)
Instituto Nacional de Meteorologia
Praça 15 de Novembro No. 2 - Sala 506
Centro-Rio de Janeiro

CANADA

Mr. Peter Nicholas Georgiou
Boundary Layer Wind Tunnel Laboratory
University of Western Ontario
London, Ontario, N6a 5B9

Susan Grimmond (Miss)
Department of Geography
University of British Columbia
No. 217-1984 West Mall
Vancouver, B.C. V6T 1W5

T. Oke
Urban and Boundary Layer Climatology
Department of Geography
1984 West Mall
University of British Columbia
Vancouver, B.C. V6T 1W5

Guenter Zeuner
Department of Geography
No. 217-1984 West Mall
University of British Columbia
Vancouver, B.C. V6T 1W5

CHINA

Chow Shu Djen (Mrs.)
Department of Geography
East China Normal University
Shangai 200062

COSTA RICA

Gerardo Lizano V.
Instituto Meteorológico Nacional
Apartado postal 5583
San Jose

Hugo Alfaro Alfaro
1 Km. Este Iglesia de Samparados
Alajuela

CUBA

Carlos Manuel Lopez Cabrera
Instituto de Meteorología
Loma de Casablanca
Municipio Regla
La Habana

Luis Raul Paz Castro
Instituto de Meteorología
Loma de Casablanca
Municipio Regla
La Habana

ECUADOR

Gustavo Franco Cortes
Instituto Nacional de Meteorologia e Hidrologia
Diego Mendez 255 y Ulloa
Quito

EGYPT/EGIPTO

Elsabban Ahmed Fouad
Meteorological Authority
Koubry el-Quobba
Cairo

EL SALVADOR

Guillermo Navarrete Lopez
Servicio Meteorologico
Apto Ministerio de Agricultura y
Ganaderia
San Salvador

FINLAND/FINLANDIA

Bengt Olavi Tammelin
Finnish Meteorological Institute
Hiirenkuja 5
04230 Kerava

GERMANY, FEDERAL REPUBLIC OF/ALEMANIA, REPUBLICA FEDERAL DE

Jurgen Baumüller
Landeshauptstadt Stuttgart
Chemisches Untersuchungsamt
Stafflenbergestr. 81
7000 Stuttgart 1

Erich F. Meffert
Laurentiusstr. 18,
D-56 Wuppertal 1

INDIA

B. Padmanabhamurty
Meteorological Office
Lodi Road
New Delhi 110003

ISRAEL

Arieh Bitan
Department of Geography
Tel Aviv University
P.O.B. 39040
Ramat Aviv 69 987
Tel Aviv, Israel

Baruch Givoni
Jacob Blaustein Institute for Desert
Research
Ben-Gurion University of the Negev
Sede Boqer Campus, 84990

Yair Goldreich
Department of Geography
Bal-Ilan University
Ramat Gan 52100

Michael Poreh
Tecnion
Haifa 3200
Israel

JAPAN

Takeshi Kawamura
Institute of Geoscience
The University of Tsukuba
Sakura-mura
Ibaraki 305

Ilva Ruri Imamura
Institute of Geoscience
The University of Tsukuba
Sakuramura Niihari Gun

MALAWI

H.E. Dandaula
Meteorological Department
P.O. Box 2
Chileka

MEXICO

Silvino Aguilar Anguiano
Director-general
Direccion General del Servicio
Meteorologico Nacional
Avenida del Observatorio 192
Tacubaya, D.F.
Mexico

Ing. Dario Barrios Sánchez
Sub-Director General
Servicio Meteorologico Nacional
Avenida del Observatorio 192
Tacubaya, D.F.
Mexico

Alfonso Greenham A.
Comision de Aguas del Valle de Mexico
OHIO 72 col.
Coyoacan, D.F.

Leonor Alvarez de Mulia
Secretaria de Desarrollo Urbano y
Ecologia, Direccion General de
Equipamiento Urbano y Edificios,
Circuito Juristas No. 11
Cd. Satelite
Edo de Mexico

Humberto Bravo Alvarez
UNAM
Centro de Ciencias de la Atmosfera
Dpto. Contaminacion Ambiental
Circuito Exterior, Ciudad Universitaria
Mexico 20 D.F.

Armando P. Báez
UNAM
Centro de Ciencias de la Atmosfera
Ciudad Universitaria
Circuito Exterior
Mexico 20 D.F.

Enrique Camarillo Cruz	Direccion General del Servicio Meteorologico Nacional Av. Observatorio 192 11830, Mexico D.F.
Maximo Javier Castillo Flores	Escuela Nacional de Estudios Profesion- ales Iztacala UNAM Av. de los Barrios S/N Los Reyes Iztacala Tlalnepantla Estado de Mexico
Jorge J. Castro	Teotihuacan No. 18 Col. Hipodromo Condesa 06110 Mexico D.F.
Maria de Lourdes de la I. de Bauer	Centro de Fitopatologia, C.P. Apdo. 85 Chapingo Mexico
Ignacio Galindo	Instituto de Geofisica, UNAM Ciudad Universitaria Circuito Exterior 04510 Mexico D.F.
Marco Antonio García Blanco	Dirección General para Organismos Especializados de la ONU Secretaría de Relaciones Exteriores Av. Ricardo Flores Magón No. 1, Pisa 12 Tlatelolco, Cuahutémoc Mexico D.F. C.P. 06995
Alberto Carlos H.	Glorieta Parque San Andres No. 20 Col. Parque San Andres Col. Coyoacan CP 04040
Jose Ramon Herrera Velarde	Apoyo a la Meteorologia/SARH Teotihuacan No. 18 Col. H. Condesa 06110 MEXICO D.F.
Ernesto Jauregui O.	Instituto de Geografia UNAM Mexico 20, D.F. 04510
K. K. Kanuga	16/407 Lodi Colony New Delhi 110003 India
Guadalupe López Aguado	Retorno de Girasoles No. 15 Izcalli Ecatepec Ecatepec de Morelos Estado de México

Abdias Yañez Marín	Comision de Aguas del Valle de Mexico Col. Del Mar Calle Pinguino Lote No. 20 Mza 146 Tlahuac, Mexico, D.F.
Irma Rosas Perez	UNAM Ciudad Universitaria Circuito Exterior Mexico 04510, D.F.
Maria Isabel Saavedra Rosado	UNAM Depto. Contaminacion Ambiental Centro de la Atmosfera Circuito Exterior, Ciudad Universitaria Mexico, D.F. 04510
Ricardo Torres Jardon	UNAM Depto. Contaminacion Ambiental Centro de la Atmosfera Circuito Exterior, Ciudad Universitaria Mèxico, D.F. 04510
Mayor F.A.M. Hector Nava Gil	Servicio Meteorologico Militar Calle Antonio Garcia Cubas No. 719 Int. 4 Col. Obrera C.P. 06800 Lomas de Sotelo, D.F.
Antonio Cruz Sanchez	Servicio Metereologico Militar Fuerza Aerea Mexicana, 7 Piso Lomas de Sotelo, D.F.
Francisco Cruz Navarro	Tecnico Academico Instituto de Geografia Multifamiliar Libertad C-3-320 Colonia Peralvillo Mexico, D.F.
Alejandro Ramirez Alcazar	Facultad Ingeneria Civil Universidad Autonoma de Nuevo Leon Apartado Postal 722 San Nicolas de los Garza, N.L. Mèxico
Benjamin Limon Rodriguez	19 de Marzo 309, Col. Roble San Nicolas de los Garza Nuevo Leon Mexico
Ruben Medina Gonzalez	Calle Emiliano Zapata No. 86 Santiago Tepalcatlalpan Xochimilco, D.F. Mexico

Teodora Juana Diaz Soberanes	Comision de Ecologia del D.D.F. Glorieta de Colon 250 Col. Amp. J. Villada, CP 57710 Cd. Netzahualcoyotl Mexcio
Ma. Emma Rubi Sandoval	Av. Guadalupe I, Ramirez 166 San Marcos, Xochimilco C.P. 16050 México
Leticia Rivera Guzman	Centro de Ciencias de la Atmosfera UNAM Calle 7, No. 169 Colonia Porvenir, C.P. 02940 Mexico, D.F.
Ma. de Lourdes Godinez Calderon	Tecnica Academico Instituto de Geografia Fernando Ramirez No. 54 Col. Obrera Mexico D.F. 06800
Gabriel Haro Aguilar	Cord. de Agrometeorologia, Chapingo Olmillos 15 Frac. El Tejocote Tex. Mexico
Everardo Hernandez	Coordinacion Arquitectura Aplicada, UNAM A.P. 69-738 Mexico D.F. C.P. 04460
Eduardo Perez Fuentes	Heriberto Frias 342-D Col. del Valle Mexico D.F.
Alma Luz Yela Miranda	Centro de Ciencias de la Atmosfera, UNAM Ciudad Universitaria, Circuito Exterior Mexico D.F. C.P. 04510
Ma. Guadalupe Roy-Ocotla Romero	Xochicalco 51-301 C.P. 03020 México, D.F. Mexico
Sara D. Gutierrez Arriola	Centro de Ciencias de la Atmosfera, UNAM Agricultura 11-B Col. Escandon México 18, D.F. CP 11800
Mr. Agustin Muhlia V.	Rinconada Diligencias No. 37 Naucalpan, Lomas Verdes Edo. de México
Mr. Héctor Mendez Garcia	Bosques de Japon 15 Fraccionamiento, Bosques de Aragon México, D.F.

Mr. Luis Enrique Hernandez Ruiz	2a. Cerrada del Olivar No. 11 Col. Olivar de los Padres Alvaro Obregon, D.F. CP 01780
Sylvie Turpin	Univ. Autonoma Metropolitana - Azc. Boston No. 21 int. 9 Colonia Napoles 03810 Mexico D.F.
David Baz Contreras	Oficina de Monitoreo y Analisis de la Calidad del Aire Comision de Ecologia D.D.F. Canada No. 74, Plazas de la Colina Tlalnepantla, Edo. de México
Jeronimo Morales Olivares	U. Hab. Ex-Hacienda de Enmedio Depto. 402-Edificio 37 Col. Prado Vallejo Tlalnepantla, Edo. de México
Maurilio Sota Estrada	SARH Membrillo No. 306-5 Colonia Nueva, Santa Maria México, CP 16
Ma. Luisa Maya Martinez	Instituto Nacional de Inv. Forestales Progreso No. 5 Coyoacan, D.F.
Jose Maria Reyes Chavarria	Direccion de Proteccion y Fomento Forestal Netzahualcoyotl 109, 6o Piso Mexico 1, D.F.
Jose Antonio Pena Lezama	Depto. de Analisis Atmosferico Subdireccion de Prevision Atmosferica Gomez Farias No. 2, Piso 3 Col. Revolucion Centro Mexico, D.F.
Macario Alvarez Zavala	Direccion del Servicio Meteorologico Militar Secretaris de la Defensa Nacional Fuerza Aerea Mexico, 7o Piso Lomes de Sotelo, D.F.
Susana Reyes Trestrail	UNAM Guerrero 46, Col. Heroes de Padierna Mexico CP 10700
Walter Ritter Ortiz	UNAM, Centro de Ciencias de la Atmosfera Jose Moran 53, Edif. 13-206 San Miguel Chapultepec Mexico, D.F.

Eduardo Salazar Rosales	Dept. de Meteorologia Marina Direccion General de Oceanografia Secretaria de Marina Medellin No. 10, 4°Piso Colonia Roma, Mexico, D.F. CP 06700
Carlos Sanchez Rivas	SEDUE Mecanografos No. 91, Col. Sifon 09400 D.F. Mexico
Leonardo Zeevaert	Cerro dos Conejo No. 10-A Romero de Terreros Coyoacan 04320 Mexico, D.F.
Amando Leyva	Apartado Postal 103-126 04800 Mexico D.F.

NETHERLANDS/PAISES BAJOS

S. Nieuwolt	Neerstraat 26 6004 KC WEERT The Netherlands

NIGERIA

Julius S. Oguntoyinbo	Department of Geography Faculty of the Social Sciences University of Ibadan Ibadan
Simon Oyeduran Ojo	Department of Geography University of Lagos Lagos

NORWAY/NORUEGA

Ivar Dugstad	Geophysical Institute Avd B University of Bergen 5000 Bergen
Yngvar Gjessing	Director Division for meteorology Geophysical Institute University of Bergen Bergen

PAPUA NEW GUINEA/PAPUA NUEVA GUINEA

Samuel Geno	National Weather Service Box 1240 Boroko

PERU

Tito Pesce Schreier	Universidad Nacional Ingenieria Av. Diagonal 380 - 63 Lima 18 (Miraflores)

POLAND/POLONIA

Janina Lewinska (Mrs.)
Research Institute on Environmental Development
Krakow Branch
Ul. Salwatorska 14
30109 Krakow

SPAIN/ESPANA

Juan Ignacio Jiménez Jiménez
Departamento de Física Fundamental
Facultad de Ciencias
University of Granada
Granada

SWEDEN/SUECIA

Roger Taesler
Swedish Meteorological and Hydrological Institute
Box 923
S-601 76 Norrkoping

SWITZERLAND/SUIZA

W. H. Weihe
Biological Central Laboratory
University Hospital
University of Zurich
Rämistrasse 100
CH-8091 Zurich

THAILAND/TAILANDIA

Oranut Paisarnuchapong (Miss)
Meteorological Department
612 Sukhumvit Road
Bangkok 10110

UNITED KINGDOM/REINO UNIDO DE GRAN BRETANA E IRLANDA DEL NORTE

Ian Davis
Department of Architecture
Disaster and Settlements Unit
Oxford Polytechnic
Headington, Oxford

Derek Lee
Department of Geography
Birkbeck College
7-15 Gresse St.
London W. 1

J.K. Page
c/o Division of Economic Studies
The University of Sheffield
Western Bank
Sheffield S10 2TN

UNITED STATES OF AMERICA/ESTADOS UNIDOS DE AMERICA

R.D. Bornstein	Department of Meteorology San José State University San Jose, California 95192
Loren Crow	3064 S. Monroe St. Denver, CO 80210
T. Dunne	Department of Geological Sciences, AJ-20 University of Washington Seattle, Washington 98195
H.E. Landsberg	Department of Meteorology University of Maryland College Park, Maryland 20742
Glen E. Long	National Center for Atmospheric Research P.O. Box 3000 Boulder, Colorado 80307-3000
Paulette Middleton	Environmental and Societal Impacts Group National Center for Atmospheric Research P.O. Box 3000 Boulder, Colorado 80307-3000
Everett C. Nickerson	NOAA/GMCC, R/E/AR4 325 Broadway Boulder, Colorado 80303
F.T. Quinlan	National Climatic Data Center Federal Building Asheville, NC 28801-2696
Herbert Riehl	1200 Humboldt Denver Colorado 80210

INTERNATIONAL ORGANIZATIONS/ORGANIZACIONES INTERNACIONALES

UNITED NATIONS ENVIRONMENT PROGRAMME/PROGRAMA DE LAS NACIONES UNIDAS PARA EL MEDIO AMBIENTE (UNEP)

Naigzy Gebremedhine	P.O. Box 47074 Nairobi Kenya

WORLD HEALTH ORGANIZATION/ORGANISACION MUNDIAL DE LA SALUD (WHO)

Thomas S. Schorr	Panamerican Centre for Human Ecology and Health Rancho Guadelupe Metepec Mexico

WORLD METEOROLOGICAL ORGANIZATION/ORGANIZACION METEOROLOGICA MUNDIAL (WMO)

G.O.P. Obasi	Secretary-General World Meteorological Organization C.p. No. 5 CH-1211 Geneva 20
Luiz Gylvan Meira Filho	WMO Regional Director for the Americas P.O. Box 401 Asuncion Paraguay
S. Jovicic	World Climate Programme Department WMO Secretariat C.p. No. 5 CH-1211 Geneva 20

INTERNATIONAL COUNCIL FOR BUILDING RESEARCH STUDIES AND DOCUMENTATION/CONSEJO INTERNACIONAL DE ESTUDIOS DE INVESTIGACION Y DE DOCUMENTACION EN EL SECTOR DE LA CONSTRUCCION (CIB)

Richard D. Marshall	Center for Building Technology National Engineering Laboratory National Bureau of Standards Washington, D.C. 20234 USA

INTERNATIONAL FEDERATION FOR HOUSING AND PLANNING (IFHP)

Arieh Bitan	(see address under Israel)

PART A: URBAN CLIMATE

URBAN CLIMATOLOGY AND THE TROPICAL CITY : AN INTRODUCTION

T. R. Oke
Department of Geography
University of British Columbia,
Vancouver, B. C., Canada, V6T 1W5

1. INTRODUCTION

The central aim of the WMO Technical Conference on Urban Climatology and its Applications with Special Regard to Tropical Areas was clear. It was a working meeting to assess the ability of the urban climatological community to meet a pressing challenge. Namely, to ensure that the rapidly expanding cities of the Developing World incorporate climatological concerns in their design. The adoption of only a few simple and inexpensive principles may help provide a better living and working environment for a large segment of the World's inhabitants. Benefits may include healthier conditions; greater personal safety; improved efficiency; less wastage of energy and water; reduced property damage, etc. These are humane, sensible and profitable goals that may be attainable without great cost, and are therefore very deserving of our attention.

2. THE PROBLEM

The statistical dimensions of the problem are much publicized but nonetheless mind-boggling (see also Weihe, this volume). Using the most recent United Nations estimates the total World population will climb from about 4.4 billion in 1980, to 6.1 billion in 2000, to 8.2 billion in 2025 before levelling out at about 10.2 billion in 2100 (Peterson, 1984). Of greater concern here is the fact that this population is increasingly tending to congregate in urban areas (Figure 1), so that by the year 2000 almost 50%, and by 2025 more than 60% will live in cities. Within these data lies an even more dramatic shift of urbanization activity to the Less Developed, often tropical parts of the World. In Developed areas both the rate of total population growth and of urbanization is slowing, indeed in the largest cities there are signs of real decline (counterurbanization). By contrast the Less Developed portions of the World are projected to grow rapidly in both total population and in the proportion who are urban dwellers. This is especially true in Africa and South Asia. As a result urban populations are exploding around the tropical world (Figure 1). Today there are 34 urban areas with greater than 5 million inhabitants, of which 21 are in the Less Developed areas. Further, it seems likely that 11 of those city regions will have populations in the 20-30 million range (Mexico City, São Paulo, Lagos, Cairo, Karachi, Delhi, Bombay, Calcutta, Dacca, Shanghai and Jakarta). In Developed regions only Tokyo and perhaps New York are anticipated to exceed 20 million in the same period.

Another major difference between the two regions is the historical fact that urbanization in Developed areas occurred in conjunction with industrialization. In the Less Developed regions urbanization occurs before industrialization as a result of migration from largely agricultural areas. Without an attendant growth in urban wealth cities find it almost impossible to supply the needs of their inhabitants (i.e. housing, jobs, food, energy, water, sanitation, security, education, transportation, etc.). Hence the growth threatens the ability of the city to function, leading to urban chaos and gloom with massive unemployment, poverty, slums, social breakdown, inadequate resources, utilities and services and a degraded physical environment. Example cities already abound (see for example Hardoy and Satterthwaite 1984).

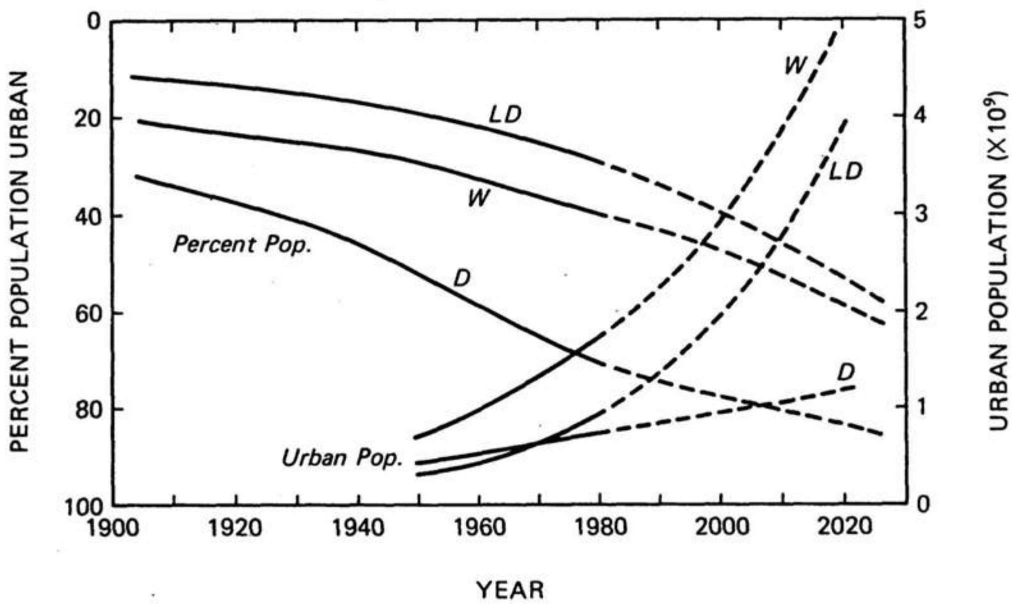

Figure 1. Percentage of the population living in urban areas in the Less Developed (LD), Developed (D) and total World (W) communities, and the number of urban inhabitants according to the same groupings. Data and projections using United Nations sources according to Sassin (1980) and Peterson (1984). [LD - Africa, Asia, Latin America and Oceania; D - Europe, North America, Australia, Japan and USSR].

3. THE CHALLENGE TO URBAN CLIMATOLOGY

In the face of such massive social economic and political problems the role of urban climatology in improving conditions is faint indeed. Our input can only be of significance if it is part of a larger movement to increase the role of urban planning and design in the Less Developed World. Within that we must press for the inclusion of climate-sensitive concerns in the physical arrangement, design, construction and operation of urban areas.

Assuming that such a movement occurs, and is embraced by Developing countries, what is the state of readiness of the urban climatological community to meet the challenge? At the present moment the answer is unknown but first impressions are not promising. Every review of the field since the World Meteorological Organization (WMO) Symposium on Urban Climates and

Building Climatology of 1968 has concluded that whilst the general state of urban climatology is fairly healthy there are two obvious weaknesses. First, there is very little work on cities outside of the mid-latitude zone. The need for information on tropical urban climates in particular has been stressed (e.g. Chandler 1970, Sham 1979a, Oke 1982, Lee 1984). Second, applied science aspects of the subject have been relatively neglected so that little use is made of urban climate information (Givoni 1972, Chandler 1976, Oke 1976, 1984a, Landsberg 1982). The challenge therefore is to devise a plan whereby we can maximize the utility of our knowledge in the two weakest parts of our subject, and bring it to bear on the environmental problems of urbanization in the Less Developed World.

4. A PLAN TO MEET THE CHALLENGE

If the preceding assessment is approximately correct the following skeletal framework of a general plan of action is offered to promote discussion. It represents a personal view but bears some general resemblance to the suggested WMO programme (WMO, 1982). The plan is conveniently divided into three time frames: immediate, short- and long-term.

4.1 Immediate

It is necessary to take stock of the field, especially with regard to tropical and applied aspects. The theoretical, observational, methodological and practical base must be considered in such a review. It should identify both areas of knowledge and agreement as well as those where gaps exist. The likelihood of transferability of knowledge from one climatic region to others should also be assessed, including the value of climatic models. The stock-taking should involve as wide a group of urban climatologists and users as possible. The results should be summarized and disseminated.

The foregoing represent the objectives and underlie the format of the Technical Conference and this volume.

4.2 Short-term (∿ 5 years)

Assuming that sufficient information of value is deemed to exist it should be carefully considered and prepared for dissemination. This will require close liaison with user agencies. The output should consist of very basic guidelines concerning the benefits of including climate concerns in planning: simple means of judging the relevance of climate to any given urban area; very general recommendations concerning solutions to existing or potential climatic concerns couched in terms of fundamental principles rather than rigid answers; suggestions regarding sources of data and expertise; etc. The distribution of this information to planners, engineers, architects, meteorologists, development agencies, educational institutions, etc. will only be effective if it is done in a co-ordinated and imaginative manner and if the material is relevant, comprehensible and applicable (Page 1970, Oke 1984a). Repeated information campaigns will probably be necessary together with a system of user feed-back services.

4.3 Long-term (continuing)

In the longer view it will clearly be necessary to foster development of all aspects of the field including research into tropical and applied urban climates; co-operation and exchange of expertise between the low and mid-latitude areas and between climatology and urban planning; development of educational materials; training of personnel; publicizing the role of the atmosphere in urban affairs, etc.

The remainder of this paper seeks to make a general contribution toward the immediate and short-term needs outlined in Sections 4.1 and 4.2. In doing so it may serve to provide a context for the more specialized papers of the invited technical experts in this volume. It addresses two pivotal themes: the transferability of urban climate information between different climate zones, and the adoption of design procedures suitable for use by planners in the Less Developed World.

5. TRANSFERABILITY OF URBAN CLIMATE INFORMATION

The great imbalance between mid- and low latitude knowledge of urban climate and its applications has already been noted. It therefore naturally arises to ask if the findings of one zone can be utilized in the other, i.e. is there a basis for transferability?

Given the unfortunate coincidence, stated earlier, that the challenge of tropical urbanization combines the need for two of our weakest areas of expertise, it probably comes as little surprise to know that in this author's judgement our other poorly developed area is that of methods. That includes methods of assessing transferability, in fact we have yet to establish objective means of extrapolating results from one city to another in the same general climate zone, let alone from one zone to another (Oke, 1984b).

In the absence of any agreed means of assessing transferability the following approaches are suggested on an interim basis, and to enable us to feel our way forwards with the task in hand:
(a) simple a priori reasoning considering the special characteristics of surface and atmospheric controls on urban climates in the two zones;
(b) consideration of the results of numerical and other urban climate models. These should be capable of simulating the impacts of the above controls;
(c) review and assessment of available urban climate studies in the two zones.

5.1 *A priori* Reasoning

In this section we will consider urban climate controls in tropical and mid-latitude cities. These will be arranged under the following convenient headings: the physical nature of cities in the two zones, their environs, and their large-scale climate contexts. Emphasis will obviously be placed on anticipated differences in controls known to produce strong climate responses. These should not overshadow the fact that in many respects (of importance to their climates) they are strikingly similar. This is especially true of modern central city and multi-storey residential areas. Indeed their essential sameness is a common lament of travellers.

URBAN CLIMATOLOGY AND THE TROPICAL CITY

5.1.1 Physical nature of temperate and tropical city systems

Structure - in many tropical cities the buildings are arranged in a more compact configuration than in temperate areas. The higher density may be a traditional response to the need to minimize solar penetration to street-level, or a more basic expression of the transportation modes, the land-holding system, lack of land, or poverty. It is also common to find a preponderance of low (single-storey) dwellings. Such geometric features, in combination with the prevalence of high solar elevations, make building roofs relatively more important than their walls in terms of surface energy and mass exchange. This has implications for the urban surface albedo, surface emissivity, shade and diffuse lighting, day length, screening of out-going long-wave radiation, aerodynamic roughness and the interaction between streets and the air above roof level. Unfortunately it is not possible to make simple assessments of these features. For example the albedo depends on the reflectivity of the materials as well as the geometry, and the roughness length is related to geometric descriptors in a non-linear manner. Nevertheless in general terms there seems little reason to anticipate any new effects due to structural differences between cities in the two zones, but one can anticipate some changes in the magnitude of some surface properties.

Fabric - the building materials of tropical cities are often very different from their temperate counterparts. The thermal properties (e.g. thermal capacity, conductivity, diffusivity and admittance) of the materials may have been chosen expressly to serve a building climate role. In hot, dry areas with a large daily temperature range materials with high thermal mass are often adopted (e.g. stone, brick, adobe) so as to delay the penetration of the temperature wave, whereas in hot, humid areas light construction is favoured so as to promote ventilation. These two extremes may be expected to result in very different patterns of energy storage.

Radiative properties - the surface albedo and emissivity are also expected to be altered by the choice of materials. Light-coloured or painted surfaces are a prominent feature of tropical cities, on the other hand the importance of roof surfaces (mentioned earlier) brings the role of tiles and metal sheeting to the fore. The off-setting impacts of these features will have to be combined with the geometric influence before the net result is known. The meagre amount of tropical urban albedo data do not suggest dramatic tropical-temperate differences (Oguntoyinbo 1970, Aida 1982; Table 1) but certain cities may confound this view. Little is known about surface emissivities of any cities. Differences between the two zones are probably small but it might be noted that the value for corrugated iron sheets is abnormally low, and this is a common roofing material in tropical cities.

TABLE 1. *Generalized differences of surface thermal, radiative, moisture and aerodynamic properties likely to exist between typical temperate climate cities, and those in either tropical dry or tropical humid climates.*

Climate zone comparison	Thermal admittance	Albedo	Emissivity	Moisture Availability	Roughness
Temperate vs tropical (dry)	$\leqslant$	$<$	$\geqslant$	$>$	$\geqslant$
Temperate vs tropical (humid)	$\geqslant$	$\leqslant$	$\geqslant$	$<$	$\geqslant$

Sign convention: > means temperate greater than corresponding tropical value, etc.

Moisture availability - this property is a powerful determinant of energy sharing at surfaces, including cities (Oke 1982, 1985). Since in tropical settlements this property is likely to cover the complete range, from almost totally dry to almost continually wet (or at least moist) there is little to say that can have general applicability. It would seem that this surface control could overshadow almost all others.

Anthropogenic influences - in comparison with temperate and cold winter climates the amount of heat released to the atmosphere due to combustion of fuels in tropical cities is usually safely regarded to be small. It is possible to find larger values in the vicinity of industrial areas and in some way very densely settled parts of cities where electrically-powered air-conditioning is employed (e.g. Hong Kong, see Kalma and Newcombe 1976). Similarly there is no reason to expect the flux of water vapour associated with fuel burning to be more significant either. Nevertheless in both cases the extra heat or vapour added to an already hot and/or humid atmosphere may have important comfort implications.

Air pollution - there is little reason to expect that the pollutant emissions from tropical cities are fundamentally different to those in temperate climates in terms of their role in effecting climatic modification. Two possible exceptions to this statement should be mentioned. First, in hot, dry cities, especially those where the roads are unpaved, the levels of dust are likely to be much higher than in temperate cities. Second, in many Less Developed countries the role of the internal combustion engine is not as dominant as in more Developed economies, and industrial/domestic uses may still favour fuels such as coal and wood. Together these factors suggest that the average tropical city may exhibit a higher preponderance of particulate-type rather than gaseous pollutants. If this is correct there are likely to be impacts. For example short-wave radiation attentuation is sensitive to such pollutant differences in respect of both the magnitude of the reduction and the wavelengths preferentially filtered. The size and chemical composition of condensation nuclei are also critical in haze and cloud droplet formation.

The reality of the suggested differences listed in Table 1 needs to be verified. Probably the greatest importance is attached to knowledge of the thermal admittance and moisture availability properties.

5.1.2 Physical nature of temperate and tropical city environs

Implicit or explicit in virtually all urban climate research is the aim to gauge the urban effect. The most commonly used surrogate for this is the use of urban-rural differences. (For an evaluation of this and other measures of urban effects, see Lowry 1977.) In some respects the physical characteristics of cities have more in common than those of their 'rural' surroundings. Therefore when comparing urban effects, evaluated in this manner, from cities in widely different geographic areas, the question of similarity of 'rural' characteristics needs to be addressed.

It is very difficult to make clear generalizations because the range of 'rural' surfaces is large. Nevertheless, if we ignore the case of snow-covered conditions for temperate cities, it seems possible that the range is larger for the environs of tropical cities. Most temperate cities are surrounded by farmland including bare soils, pasture, crops, scattered trees and buildings and in some cases copse and forest. The resulting tendency of typical urban-rural differences in the temperate snow-free city is given in Table 2. (The snow-covered case shows an accentuation of these differences.)

TABLE 2. *Generalized urban-'rural' differences of surface thermal, radiative, moisture and aerodynamic properties. Temperate differences are based on observation whereas tropical values are largely anticipated.*

Climate zone	Thermal admittance	Albedo	Emissivity	Moisture availability	Roughness length
Temperate (snow-free)	⩾[1]	<[2]	⩽[3]	<[4]	>[5]
Temperate (snow)	≫[1]	≪[2]	⩽[3]	?*	>[5]
Tropical (dry)	>	⩽	⩽	?[+]	≫
Tropical (humid)	⩽	⩾	⩽	<	≫

Sign convention: > means urban greater than 'rural' value, etc.

Temperate city references: [1]Oke (1981), [2]Oke (1985), [3]Arnfield (1982), [4]Carlson <u>et al.</u> (1981), [5]Counihan (1975).

*Unknown but probably small.

[+]Depends on water supply and irrigation.

The environs of hot, dry cities are likely to consist of bare or sparsely vegetated soil, sand or rock areas, scattered trees and shrubs and some farms and orchards where local or imported water is available. The anticipated urban-'rural' differences (Table 2) suggest larger thermal admittance contrasts than the temperate case because 'rural' soil moisture is very low and the urban area may be characterized by buildings with large thermal mass (heat capacity). The relatively high albedo of dry and desert landscapes, and the low emissivity of some urban roofing materials should keep the radiative differences with the same sign as the temperate case. Potentially the most significant difference from the temperate case is that of moisture availability. If the city is an oasis, or the water supply is otherwise assured it is possible that the moisture availability is higher in the city; where agricultural irrigation is practised or rainfall is moderate the opposite may hold.

The surroundings of the hot, humid city may well include tall lush vegetation, intensive agriculture including paddy fields, swamp or forest. The 'rural' wetness, including standing water, could well result in thermal admittances being larger than in the city. Similarly, the albedo may be lower than for the light-coloured city (e.g. Aida 1982). Both effects are the reverse of the temperate snow-free case.

Again it is worthwhile to note that the suggestions in Table 2 require validation. Greatest interest centres on the thermal admittance and albedo differences for the tropical humid case, and moisture availability for the tropical dry case.

5.1.3 Meteorological and Other Modulation of Urban Climate

The magnitude and operation of all atmospheric exchange processes, and any resulting climatic features, are dependent upon the meteorological conditions at any geographic location. Day-to-day variations depend on the synoptic and meso-scale meteorology and seasonal variations upon the macro-scale climate. Urban effects are clearly subject to such controls (e.g. Unwin 1980) and any comparison of the climatic features of different cities must take this into account (Lowry 1977). In the context of temperate vs tropical comparison this may be of great concern. For example, in an attempt to standardize synoptic effects and to maximize urban effects many temperate climate studies give results for calm, clear conditions. Whilst this may be an equally good base for comparison in some tropical areas it is of little relevance to work in cities of the Trade Wind Belts where winds are almost unceasing, or in the Equatorial zone where although winds are very light, cloudiness is an ever present feature. If urban climate effects based on unstrafied, standard climate data are compared between such areas the results are biased by the differing synoptic régimes. Similarly at coastal locations in many tropical climates there is a persistent diurnal cycle of local breezes, convective activity, cloud and precipitation. This must be expected to impose modulation upon the diurnal cycle of urban effects such as the heat island. For example late afternoon and evening convective showers with their attendant interruption of radiation exchanges, surface wetting and evaporation, humidity and local winds will probably greatly complicate the development of the nocturnal urban heat island. Therefore comparisons of the temporal dynamics of heat islands in different climate zones are in danger of working from different bases.

Another general difference between the two zones is the higher humidity in wet climates. In combination with pollutants this leads readily to haze (smaze) with radiative effects in both the short- and long-wavelengths, and to cloud droplets. The instability of many tropical air-masses together with their large latent heat content and warmth lead to deep convection. It also follows that collision and coalescence processes are usually more important than Bergeron ice-crystal growth.

Finally, we should mention some features which are restricted to one of the two zones. The most obvious include frozen precipitation in the temperate case and duststorms and hurricanes in the tropical one. All involve hazards or nuisance requiring planning or operational responses.

5.2 Urban Climate Models

Models potentially provide extremely powerful tools for the urban climatologist and planner. In the present context of establishing transferability they hold the promise of combining all of the temperate/tropical similarities and differences outlined in Section 5.1, and generating realistic climate simulations therefrom. They can also be used to indicate the sensitivity of urban climate systems to variations in input, or to test suggested solutions to urban climate problems. These capabilities are beyond those of the unaided human mind.

A few attempts to compare aspects of temperate and tropical urban climates using models are available. Terjung and Louie (1973) devised a model of solar radiation exchange and urban geometry, and examined the role of latitude. The conclusions included a recommendation to avoid east-west aligned streets in low latitude cities where heat loads need to be minimized. Later this urban canopy model was expanded to include other canyon energy budget components and surface temperatures and latitudinal variations were again studied (Terjung and O'Rourke 1980, 1981a, 1981b). Given the possible combinations of geometry, latitude, season, etc. the output soon becomes somewhat unwieldy and difficult to generalize or digest. If this model were to be applied to a specific set of conditions and then validated it would become an even more valuable resource.

Miller et al. (1972) used a simple one-dimensional model of the surface energy balance, involving iterative solution of the surface temperature, to investigate urban-rural energy and thermal differences. It was applied to an hypothetical mid- and a low-latitude city (45^{o} and 20^{o} respectively) surrounded by either vegetation or desert, and used to simulate either summer or winter conditions. Unlike the previous urban canopy model this is a boundary layer model using areally-averaged urban 'surface' properties. The input values of these properties used by Miller et al. (1972) conformed in large measure with those given in Tables 1 and 2. The general conclusions regarding heat islands in the different environments are summarized in Table 3. (Note: these are not necessarily canopy layer heat islands, they are those pertaining to some urban 'surface' whose definition is not clear.) A similar set of simulations were conducted by Atwater (1977) using a more complex two-dimensional model. Again the urban-rural, temperate-tropical input data are in agreement with the relative tendencies given in Tables 1 and 2, and the results are given in Table 4.

Comparison of Tables 3 and 4 reveal complete agreement between the two sets of results except for the daytime desert (this appears to be related to the moisture and roughness values chosen) and the temperate, daytime, winter cases. Drawing attention to this convergence of results is not necessarily to promulgate the veracity of the specific outcomes. The results are only as good as the models and their input values, both are imperfect. The results do however suggest a reasonable set of régimes which can be matched with carefully gathered field observations. In this way models can be of considerable diagnostic value.

TABLE 3. *Summary of heat island findings based on the numerical-model of Miller et al. (1972).*

1. Nocturnal urban heat islands will be relatively easy to detect in low-latitude, vegetated environments as many observations have already shown them to be in mid-latitude vegetated environments.

2. Nocturnal urban heat islands will be relatively difficult to detect in low-latitude and mid-latitude desert environments.

3. Midday urban heat islands will be difficult to detect during high-Sun periods in low-latitude, vegetated environments in all seasons.

4. Midday urban heat islands will be easy to detect in low-latitude and mid-latitude desert environments, but they will probably be 'negative islands' in which the city is a cool oasis.

TABLE 4. *Summary of heat island findings based on the numerical model of Atwater (1977). Table lists the warmest environment (urban or 'rural').*

Climate zone	Winter (Low-Sun season)		Summer (High-Sun season)	
	Day	Night	Day	Night
Temperate[1]	Urban	Urban	Rural	Urban
Tropical (dry)[2]	Urban	Rural	Urban	Rural
Tropical (humid)[3]	Rural	Urban	Rural	Urban

Rural environs: [1]Agricultural area, latitude 40°
[2]Desert, latitude 25°
[3]Agricultural, latitude 15°

Atwater notes that all tropical heat island effects are relatively weak.

Simulation of urban boundary layer wind effects for tropical cities should be relatively straightforward, especially for strong wind effects where roughness rather than thermal influences are dominant. Modelling of air pollution on radiation exchange in the two zones presents no special problems as demonstrated by Lal (1975) and Atwater (1977). The ability to model humidity and precipitation effects is less well developed at present.

It would be wise, however, to sound a few cautionary notes. The full potential of models of the type mentioned here has yet to be realized. They have several limitations (see the paper by Bornstein in this volume), of special relevance here are the problems associated with satisfactory specification of 'surface' properties, and with the identification of the 'surface' to which the output applies. Together these difficulties mean that it is not a straightforward task to apply such models to real cities, and thereby to validate their capabilities. Thus it seems important to urge that we seek performance tests using temperate city characteristics (that are reasonably well known) before applying models to tropical cities.

5.3 Comparison of Published Observations

Comparing the emerging tropical city climate results with the relatively abundant information from temperate ones is an obvious approach to establishing transferability.

The total number of tropical urban climate studies is both small, and biased towards descriptive rather than process work. Combined with the wide range of possible macroclimates involved this makes it difficult, indeed unscientific, to seek too much in the way of generalization. On the more positive side we do have some reasonably well-formed conceptual models of urban climates (derived from mid-latitude work) within which to evaluate the tropical observations. If future tropical work is designed to test these models, or to formulate more relevant ones, the field will advance most rapidly. Another positive point is the fact that in the past 10 years we have been given remarkably full accounts of the urban climates of a few key cities: notably Kuala Lumpur (Sham 1973, 1977, 1978, 1979a, b, 1980), Johannesburg (Goldreich 1971, 1974, Goldreich et al. 1981, Tyson et al. 1972, Von Gogh and

Tyson 1977), Mexico City (Jauregui 1973a, b, 1974, 1981, 1983, Jauregui and Klaus 1982, Galindo and Muhlia 1970), and Shanghai (Chow 1983, 1984, Chow and Chang 1982, 1984). It is perhaps helpful to note that these cities cover a large proportion of the major tropical and sub-tropical climate types, viz:

Wet equatorial - Kuala Lumpur
Tropical wet-dry - Delhi
Tropical steppe - Johannesburg
Sub-tropical highland - Mexico City
Humid sub-tropical - Shanghai

That leaves only Tropical and Sub-tropical desert climates largely unrepresented. These cities are not 'ideal', but in terms of establishing a consistent picture of tropical urban climate responses it is helpful to have a reasonably full understanding of conditions in a few locations, rather than case studies from a large number.

In reviewing the studies from these five cities one is impressed more by similarities than differences from the mid-latitude consensus.

Heat island - all of the cities exhibit heat islands whose morphological characteristics resemble those of temperate communities including sensitivity to building density and land-use (e.g. parks). The intensity of the heat island also seems to react to wind and cloud in accordance with temperate climate norms. In some cases the intensity of the maximum heat islands appears somewhat smaller than for a similar sized temperate city and the timing of the maximum may be different.

Humidity - little information is available on humidity effects in either zone. Whilst it is to be expected that relative humidities are lower in the city purely because of the heat island, and the dependence of the saturation vapour value on temperature, very few studies make comparison of urban-rural vapour pressure or density values. This is unfortunate because whilst relative humidity values may be of interest in human comfort studies they are of little value in climate process work.

Wind - the temperate climate result, that cities retard airflow above a certain speed but accelerate it below that threshold, seems to have been borne out in tropical cities.

Precipitation - rainfall modification is a notoriously difficult weather effect to establish. Most of the available information seems to support the temperate consensus of urban enhancement but no generalization is recommended before much careful work is undertaken.

These terse remarks do not constitute a proper analysis, they reflect a general impression gathered whilst reading the results of work in the five cities cited, and the remainder of the tropical urban climate literature. It suggests that tropical urban climates bear strong resemblances to their temperate counterparts. In most respects any differences are those of degree (magnitude) or timing which may be traced to different values of surface properties or macro-climatic controls. Exceptions to these remarks can no doubt be found, but most often they can be traced back to special features, such as the local topography (Hannell 1976, Goldreich 1985) or water availability (urban or 'rural' irrigation patterns) which would cause similar deviations from the temperate city model as well.

It is a much hackneyed phrase in modern science to 'call for more research'. Nevertheless, in the case of tropical urban climates, the call can be issued with genuine support for its scientific need, urgency and value. Given the philosophy mentioned earlier a case could be made for an international field experiment (a TROPCIMEX or similar) concentrating upon a dry and a wet tropical city with a mandate to fully describe all aspects of their urban climate (effects and processes), to draw comparisons with temperate experience as a basis for establishing transferability, and to construct and validate models to simulate urban climate and/or be applied in urban design. This is a tall order but, given realistic terms of reference, a soluble one which explicitly makes use of existing expertise and technology and provides a focus for study.

6. DESIGN PROCEDURE GUIDELINES FOR TROPICAL CITIES

A nagging question underlying this conference must be: 'If climate-based design solutions and recommendations for tropical cities are formulated and made available *will they be used*? In the Less Developed World most national meteorological services cannot afford the 'luxury' of devoting one or more personnel positions to a specialist subject like urban climate and urban design, urban planners are few and their priorities understandably are elsewhere trying to handle massive problems of housing, transportation, utility services, social services, etc. Our provisional answer to the question must be 'Only if the costs and benefits are clearly enunciated and if procedures to do so are strikingly appropriate and simple.' Papers which demonstrate the relevance of climate to safety, health, air quality, energy and water in cities are to be found elsewhere in this volume. In the following section we will consider some suggestions for a simple operating procedure for the planner (or better, the planner and a meteorologist) to incorporate climate into the design process.

The design procedure for a single building has been systematized by Page (1976). It consists of three stages. Stage A is an evaluation of the climate of the site (often an urban climate) together with a statement of activities to be carried out in and around the proposed structure. Stage B is centred on the choice of the three-dimensional built form that meets the internal climate and activity needs. Stage C is an assessment of the impact of the structure on the climate of the site and a decision as to whether it changes the site climate, whereupon Stage A is re-evaluated, and so on until an optimal solution is achieved.

These and other ideas were synthesized by Chandler (1976) to produce a sequence of decisions to be taken by planners when incorporating climatic data into urban design (Figure 2). The sequence involves two parallel lines of analysis. That on the right starts with regional climate input and assesses the modifications to it produced by local topography and land uses (presumably including the proposed as well as the existing urban development) thereby arriving at a final *anticipated* climate after the construction is complete. The line on the left considers all urban activities to be incorporated and what the *required* urban climate should be. The anticipated and required climates are compared and a decision made to proceed or to return to the left line and repeat the sequence with a revised urban development scheme.

It is not known to what extent the detailed scheme of Figure 2 is used by individual planning authorities in the cities of temperate climates, but it is probably small. Given the competing concerns and weak technical back-up of planners in most tropical cities it would seem certain that it will receive even shorter shrift there. Until more is known about tropical urban climates, and the environmental consciousness of urban planners is raised by education and publicity, a much simpler approach may be more effective. The following is forwarded for discussion purposes.

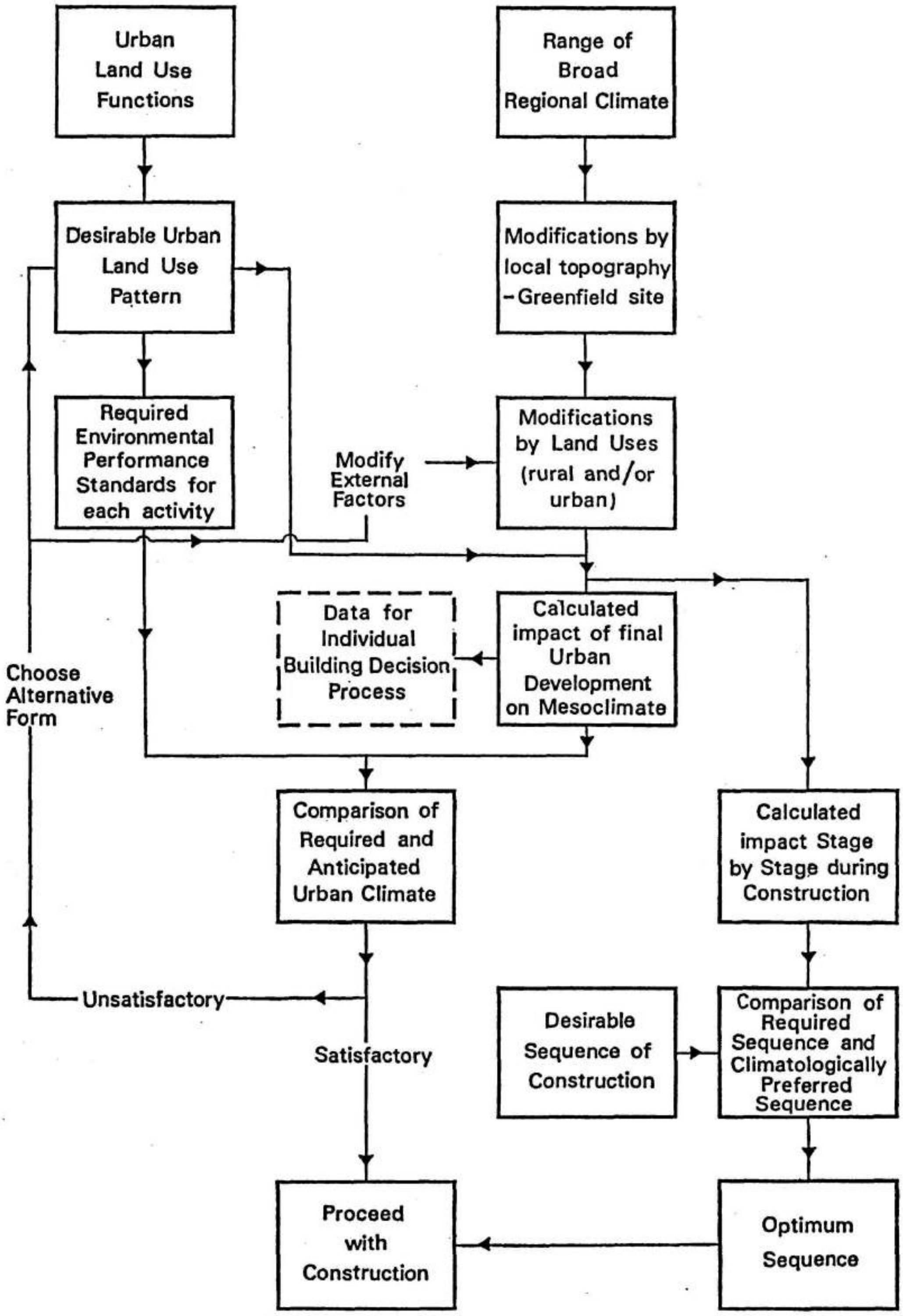

Figure 2. Sequence of decisions to be made by an urban planner when incorporating climatic information into a design (after Chandler 1976).

Following the WMO Technical Conference, and further digestion of its papers and recommendations, it may be deemed possible to issue guidelines to aid tropical city planners, engineers and the like. The guidelines would apply to already established settlements (say > 50,000 inhabitants). Separate guidelines might be issued for locating new towns or special facilities such as industrial complexes and airports. The person involved would enter the scheme armed only with information on the geographical characteristics of the site (location, landforms, surrounding land-uses), the nature of the proposed development, and the monthly climatological statistics of a nearby station (often an airport).

Step 1 - identify the broad climatic class of the area (Wet Equatorial, Tropical Desert, etc.) from a standard climatic map supplied.

Step 2 - compare the monthly data against a standard set for the climatic class. Note any anomalously low or high values along with suggestions as to the importance of such features in urban development considerations (i.e. are they favourable and should be enhanced or are they unfavourable and need amelioration).

Step 3 - qualitatively allow for climatic differences between the climate station and the development site due to local effects such as orography, water bodies, urbanization, and other land-use contrasts.

Step 4 - indicate any special climatic problems gleaned from local knowledge (e.g. shifting sand, blowing dust, noise or pollution hazard, etc.).

Step 5 - obtain identifying codes of suggested solutions to negative climatic features from a table of climate planning principles. The table might be organized according to the climate classes determined in Step 1, and refined in Steps 2, 3, and 4, and by the scale of the development at the city or sub-division scale.

Step 6 - using the relevant codes identified in Step 5 consult the rest of the publication which is a directory of climate-sensitive planning principles related to urban elements in the control of the planner or engineer. For example, at the city scale there would be recommendations regarding spatial layout, street orientation, street geometry, amount of greenspace, building heights, storm-water routing, shelterbelts, etc. At smaller scales recommendations would concern use of trees and parks, colour and materials of buildings, building orientation, siting of pollutant sources, hints regarding maximizing or minimizing airflow, shading, etc.

Thus with the help of the initial screening steps the planner has been guided to amass a battery of planning tools which will be of climatic benefit to the community.

There is the obvious danger that such a 'cook book' type of procedure will lead to improper design because of unintelligent, unsupervised application in certain cases. We have only to refer back to the slavish use of the prevailing wind principle in the improper siting of pollution sources in the cities of the mid-latitude Westerlies belt to see the potential for problems. Some of this can be overcome by including advice as to where, when and how specialized meteorological advice should be sought. In many cases such advice will not even be available and it seems preferable to accept some problems in return for getting climatically-sensitive design into rapidly growing cities before their rigid structure is indelibly laid down. Most of the decisions we would like to see taken occur at the earliest stages of urban design and cannot be 'tacked on' later. We should also press home the point that the cost of infusing climate into urban plans at the beginning is minor, whereas the benefits are large and enduring. Unfortunately, given the rate of tropical urbanization, we cannot wait for more sophisticated solutions; we must seek ways of getting our message across now. To do this we must gain closer ties with the planning, engineering and architectural communities and their international organizations.

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TROPICAL URBAN CLIMATES:
REVIEW AND ASSESSMENT

Ernesto Jauregui
Instituto de Geografia
National University of Mexico, Mexico 20, D. F., Mexico

1. INTRODUCTION

It is not fortuitous that urban-rural thermal anomalies were first observed in fast-growing European capitals during the 19th century. It must have been quite an evident phenomenon on calm autumn nights. Today a large body of information relating to heat islands is available for mid-latitude urban areas, large and small.

With few exceptions, accelerated urban growth is a relatively new phenomenon in low-latitude countries. Only after the Second World War has an uncontrolled and continuous flow of immigrants to the cities led to proliferation of metropolitan areas with more than a million inhabitants in the Developing World. In 1940 there were only 6 such cities, but 20 years later the number had increased by 6 times and by 1970 by more than 8 fold (Table 1). From 1970 to the present this trend has not appreciably changed, particularly in Latin America, where by the year 2000 AD, 45% of the total population will be concentrated in cities of 500,000 inhabitants or more (Lubell, 1984).

Therefore it is not surprising that only recently (in the last decade or so) local climatologists have begun to investigate the urban climate of large cities in the tropics, especially with regard to meteorological aspects of air pollution (Sham, 1979a, 1979b; Padmanabhamurty and Mandal, 1981; Galindo and Muhlia, 1970; Klaus, 1974; Jauregui, 1958, 1969, 1974b).

TROPICAL URBAN CLIMATES

Since most large urban areas in the tropics are located in Developing Countries, few meteorological services or centres of learning are motivated enough, or economically able, to afford the instrumentation and specialized personnel required for sophisticated urban climate studies. At present this research area lies quite low in the scale of priorities in Developing Countries. Therefore, it is only natural that most studies of urban climate in the tropics have had to make use of routine meteorological observations, just as was done in the early studies of urban climate in mid-latitude countries.

TABLE 1. *Tropical Cities with more than one million inhabitants.*

REGION	1940	1960	1970
Tropical Latin America	3	12	16
Tropical Africa	1	6	7
South Asia (India Paquistan)	2	10	29
South East Asia	0	9	
Total	6	37	52

The rapid growth in urbanization in large tropical cities has brought about varied degrees of industrialization. Not infrequently this has led to a deterioration of air quality and air pollution problems have started to plague some large urban conglomerations in the tropics. At this point local climatologists have been asked to look into the relationships between air pollution and some atmospheric variables (mainly temperature and wind) in order to have a better understanding of transport of pollutants within such urban areas (Raman and Kelkar, 1972; Jauregui et al., 1981).

The tools used by local climatologists have been basically limited to standard climatological records from stations established primarily for synoptic purposes and, in some cases, to mobile surveys of temperature and humidity (Sham, 1979a, b, 1980a, b, c).

The financial difficulties and scarcity of technicians for making boundary layer surveys in tropical urban areas with expensive instrumentation (captive minisonde, instrumented tower or aircraft, sodar, etc.) explains in part the present slow progress in this field. However, it is possible that urban studies in the tropics based on climatological records could become more numerous in the future and thus serve as a starting point for more elaborate urban studies.

2. URBAN CLIMATE STUDIES IN THE TROPICS

As has been stated previously, the effects of urbanization on the climate of low-latitude urban areas has been the object of very few investigations. Most studies refer to urban-rural thermal contrasts sometimes in association with precipitation (Khemani and Murty, 1973; Jauregui, 1973a, 1974a). These have been reviewed by Oke (1974, 1979, 1982a) and Chandler (1976).

The appallingly slow progress made during the last decade in low-latitude urban climate studies may be appreciated via Table 2. Only 26 investigations related to urban climate in the tropics (published mainly in English) have been produced in about 12 years. In comparison to the corresponding mid-latitude production this is insignificant (only 1 or 2%). One hopes that this disproportionality might be somewhat lessened when one considers that some of the urban climate studies in the tropics have remained unnoticed by mid-latitude reviewers since they have been published in other languages.

TABLE 2. *Urban Climate Studies for Tropical Areas during the period 1968-1980, in comparison with the number of mid-latitude investigations listed by Oke (1974, 1979, 1982b).*

PERIOD	URBAN CLIMATE STUDIES		% TROPICAL
	LOW-LATITUDE	MID-LATITUDE	
1968-73	8	368	2
1974-76	5	475	1
1977-80	13	554	2

TROPICAL URBAN CLIMATES

From the limited sources available, it seems that most of the low-latitude urban climate literature has been produced in a small number of countries possessing medium/large urban areas, such as India, Ecuador, South Africa, Malaysia and Mexico. From this rather meagre body of information it is not yet possible to draw any firm generalizations on heat islands or wind or humidity/precipitation modification in tropical urban areas. However, some differences in behaviour with regard to mid-latitude experience are apparent.

These differences are tied to contrasts in the seasonality of the weather controls in low latitudes:

- relatively small annual variation in radiation climate,
- for the sub-tropics: large variation in the wet/dry season air mass stability, which in turn is related to the seasonal variation of wind and cloud,
- small or negligible seasonal variation in air mass stability and radiation climate for cities near the Equator.

Other characteristics of urban effects in tropical areas probably originate from physical features common to low-latitude cities such as the type and colour of construction materials, downtown building density and geometry, and type of land-use in surrounding suburban areas.

3. METHODOLOGY

The study of the physical and chemical processes leading to changes in the mean state of the atmosphere in cities is called urban climatology (Oke, 1984). The study of urban climatology in mid-latitudes has developed around the notion that the climate in cities has been modified by Man who has also altered the original rural landscape (by clearance, drainage, cultivation) around the city. Therefore, the traditional approach (since the time of Howard, founder of this science) has been to compare urban vs. rural climatological variables with the purpose of isolating the effects of urbanization.

If we follow the suggestion of Lowry (1977), the climate of an urban location is the integrated sum of the various weather elements (temperature, humidity, etc.) and each weather variable is the linear sum of contributions attributable to macroclimate (C), local topography (L) and urban effects (U), that is:

$$M_{itu} = C_{itu} + L_{itu} + U_{itu} \qquad (1)$$

where the subscripts refer to the weather types (i) during the period (t) at urban station (u). However, in order to estimate the urban effect upon one element of climate one would have to obtain data just before the settlement was established, (at t = 0), at a rural (r) site i.e. when there was no urban effect:

$$M_{ior} = C_{ior} + L_{ior} + 0 \qquad (2)$$

If the general climate has not changed:

$$C_{ior} = C_{itu} \text{ and } L_{ior} = L_{itu} \text{ so substituting:}$$

$$U_{itu} = M_{itu} - M_{ior}$$

which means that in order to evaluate the urban effect upon one weather element we would have to have started to take observations before urbanization began. In practice this requirement is difficult to meet anywhere, as pointed out by Oke (1984). This is especially true in the tropics. It is only by chance that a settlement begins to grow around a rural climatological station, let alone that this station be especially established for the specific purpose to record pre-urban conditions for a planned future settlement.

It follows from the above that the methodology currently used to illustrate urbanization effects on climate in low-latitude cities, such as urban-rural temperature differences is both somewhat inexact and therefore not completely valid, and difficult to employ.

4. MID-LATITUDE VS LOW-LATITUDE URBANIZATION EFFECTS ON CLIMATE

If the climate in a city is the linear sum of macro-local-urban effects, Lowry's equation may prove useful for the purpose of examining the question "In what respect (if any) are the urban climates of tropical cities different as compared to those of the middle latitudes?"

Going back to eqn. (1), for a given landscape and assuming no anthropogenic heat (so $\Delta L = 0$):

$$L_{itrop} = L_{imid\text{-}lat}$$

and mid-latitude/tropical urban climates might differ mainly as a result of contrasts in their macroclimate regimes (ΔC) and in their urban structures or morphologies (ΔU).

4.1 Heat-island related contrasts in macroclimate

Let us examine first some tropical/mid-latitude differences in macroclimate which may lead to radiation/humidity contrasts:

In contrast with mid-latitude climates a less marked cycle of seasons (temperature) is observed in the tropics, and the growing season (with warm temperatures) may last the whole year. Instead, seasonal changes in humidity become more important. One may distinguish the following temperature-humidity régimes which may affect seasonal changes in nocturnal cooling rates and therefore heat island development:

(a) Wet (warm) and dry (cool) season subtropical (humid/sub-humid) climate (Mexico City, Addis Ababa, Guadalajara) with seasonal changes of air mass inducing a marked seasonal variation in radiation climate.

(b) Tropical/subtropical dry climates (Karachi, Monterrey) with short (cold or warm) wet season, and large (continental) or small (coastal) seasonal thermal variation, and with seasonal air mass changes. High-radiation climate prevails most of the year.

(c) Equatorial humid climate with all-year wet (Singapore) or alternate dry/wet season (Jakarta, Entebbe) and prevailing trades throughout the year. High-radiation climate is limited to short periods (dry) during the year.

4.2 Mid-latitude/tropical heat-island contrasts in regard to thermal inertia and the configuration of urban canyons

There is at present observational evidence to support the view that the structure and composition of the urban canopy, as well as the thermal properties of urban construction materials are the main factors in determining urban-rural thermal contrasts (Goward, 1981; Oke, 1981).

In terms of thermal behaviour urban canopies consist of buildings, pavements and green areas. Although tropical cities are made up of the same elements as their mid-latitude counterparts, some differences may be pointed out; for tropical cities:

- the vertical extent of the urban canopy may be generally shallow.
- A proportion of the streets are unpaved (especially in slum areas)
- there is a relatively small proportion of green spaces and large slum areas.

5. HEAT ISLAND INTENSITY - SEASONAL VARIATION AND TROPICAL TYPE

Canopy heat islands in an urban area with a wet/dry season tropical climate are mainly observed at night during the dry season (Tyson et al., 1972; Bahl and Padmanabhamurty, 1979; Philip et al., 1973; Mukherjee and Daniel, 1976; Jauregui, 1973a,1985). This is probably because the urban/rural nocturnal cooling differential is very much related to changes in the humidity content in the lower layers of the atmosphere (Gall and Herman, 1980). This explains the high frequency of intense surface inversions observed during the dry season in this tropical climate type, when specific humidity observed in the layer above (in the case of Mexico City) is only half the amount prevailing in the rainy months (Riehl, 1979). Seasonal variation of heat island intensity at sunrise for this type of tropical climate is illustrated in Figure 1. It shows values for two inland mid-size cities: Monterrey (24^{o}N) and Guadalajara (20^{o}N), and a seaport, Veracruz (19^{o}N). Although less marked in the coastal city, the three urban areas exhibit similar seasonal variations in urban-rural thermal contrasts at the end of the cooling period. Maximum mean heat island intensities are between 3 to 4^{o}C for these Mexican cities, while mobile surveys for Indian cities with a similar climate show maximum temperature differences of 5 to 7^{o}C (Bahl and Padmanabhamurty, 1979).

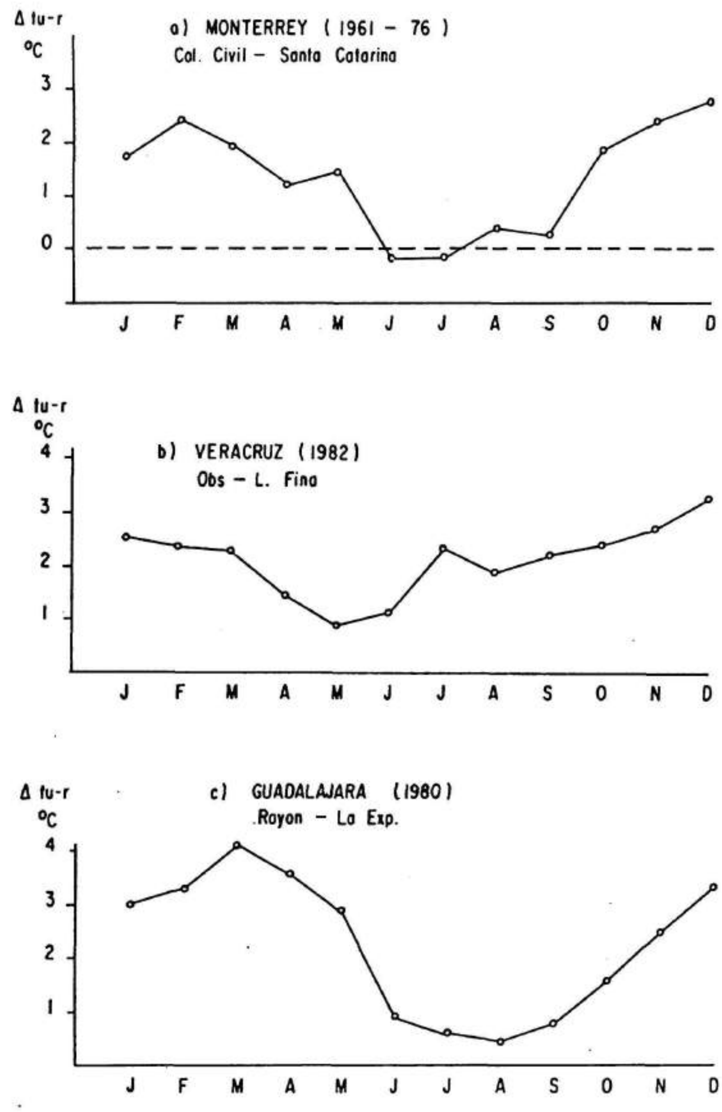

Figure 1. Seasonal variation of heat island intensity at the time of the daily minimum temperature, (T min), for three cities in Mexico.

Although day-time city surface radiant temperatures observed for mid-latitude cities (Carlson et al., 1977) are 10 to 15°C warmer than adjacent rural areas, turbulent mixing of the atmosphere and other factors such as shadow effects tend to reduce thermal contrasts in the air during the day (Figure 2a). The effect of the cool afternoon sea breeze is evident in the case of Vera Cruz because the urban station is located near the coastline (Figure 2b). On the other hand, oceanic régime thundershowers, that typically occur at the end of the night in Vera Cruz, are probably enhanced by heat island development.

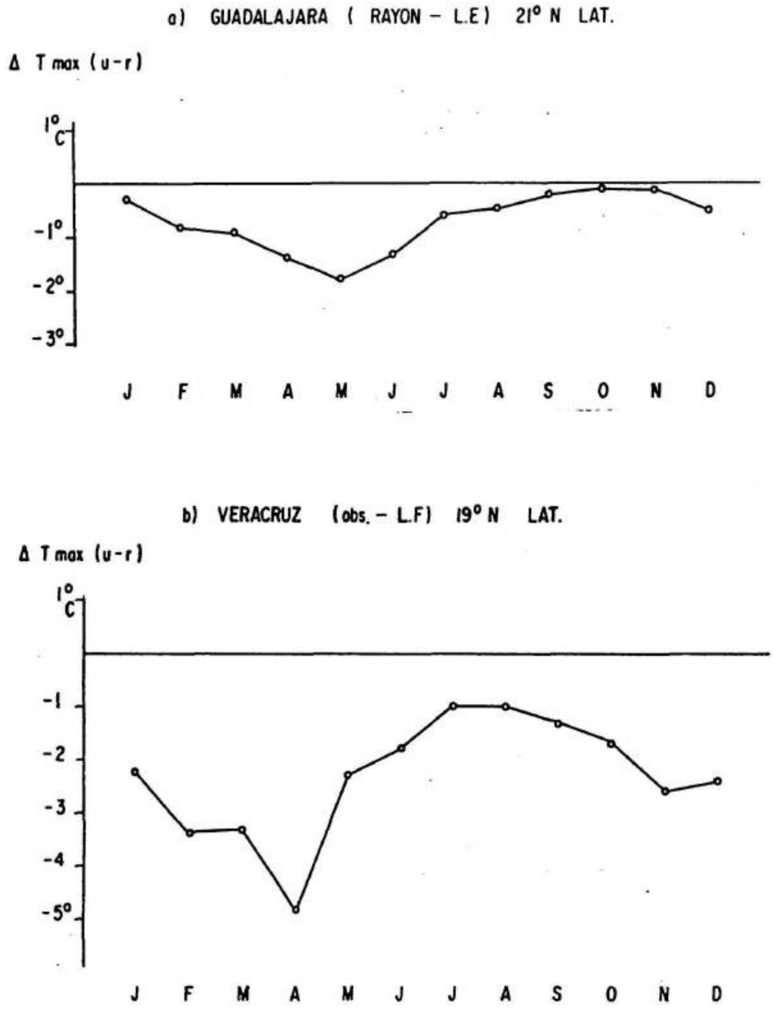

Figure 2. Seasonal variation of heat island intensity at noon (ΔT max (u-r)) for (a) an inland (Guadalajara) and (b) a coastal (Veracruz) tropical urban area, 1980.

Less marked urban-rural thermal seasonal changes are displayed in urban areas near the Equator (Bogota, La Paz), where the dry/wet seasonal rhythm is less well differentiated (Figure 3).

Coastal urban areas located in the arid tropics also show a small seasonal variation of the heat island (Lima), as illustrated in Figure 3.

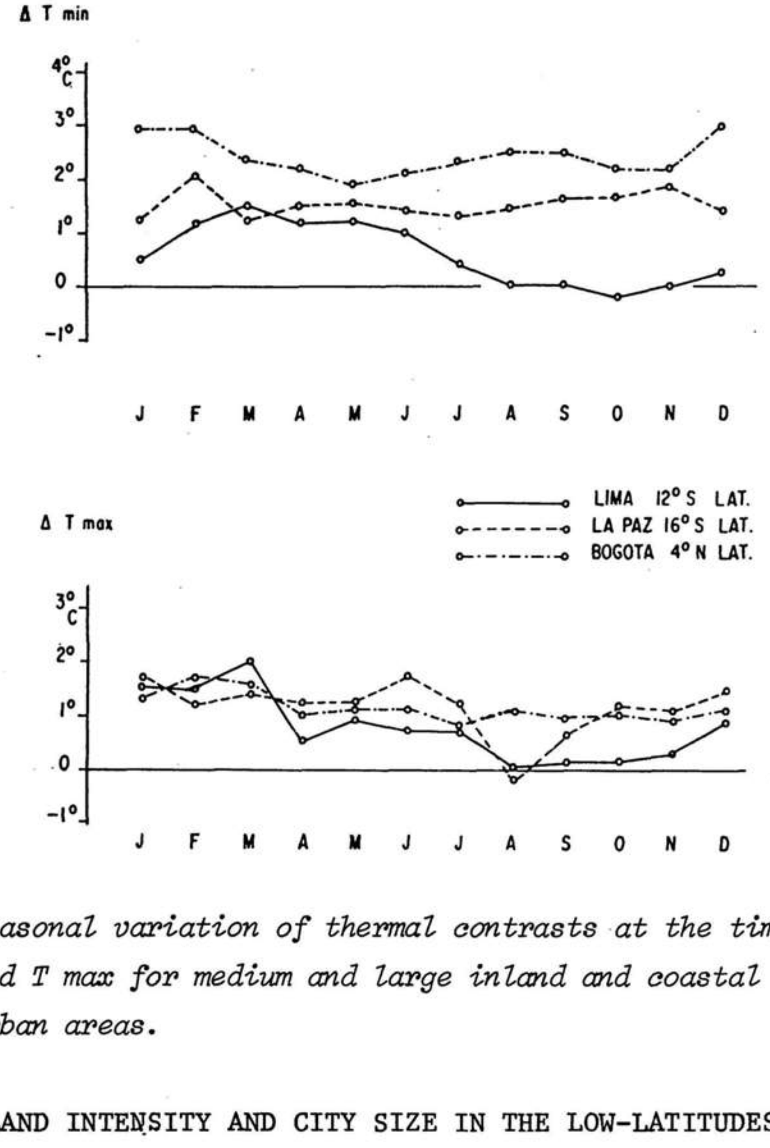

Figure 3. Seasonal variation of thermal contrasts at the times of T min and T max for medium and large inland and coastal low-latitude urban areas.

6. HEAT ISLAND INTENSITY AND CITY SIZE IN THE LOW-LATITUDES

6.1 ΔT_{u-r} vs population relationships

For mid-latitude cities a relationship has been established between heat island intensity (ΔT_{u-r}) and city size as measured by population (P) (Oke, 1973). Even though population has been used by this author to approximate some measure of the city's physical size, the points plotted on a chart seem to be well aligned along a regression line. The slope of the regression line is different for North American and European cities. The reason for this difference in slope has been explained by Oke in terms of differences in the urban morphology between European (with less tall buildings) and North American cities (Figure 4). For comparison we have plotted in the same figure the mean seasonal maximum ΔT_{u-r} values for the time of minimum temperature for some tropical cities obtained from urban-rural climatological stations. Although the two groups are not strictly comparable, the resulting points are grouped along a line showing even less slope than the corresponding European cities. This is explained in part by the averaging process of ΔT_{u-r} done for the tropical cities, while the maximum mid-latitude ΔT_{u-r} values have been obtained mostly from individual automobile traverses at night. However, one cannot discard the possibility that part of the differences observed could be attributed to differences in urban morphology existing between mid-latitude and tropical cities. Another source of discrepancies may lie in the nature of the "rural" stations selected.

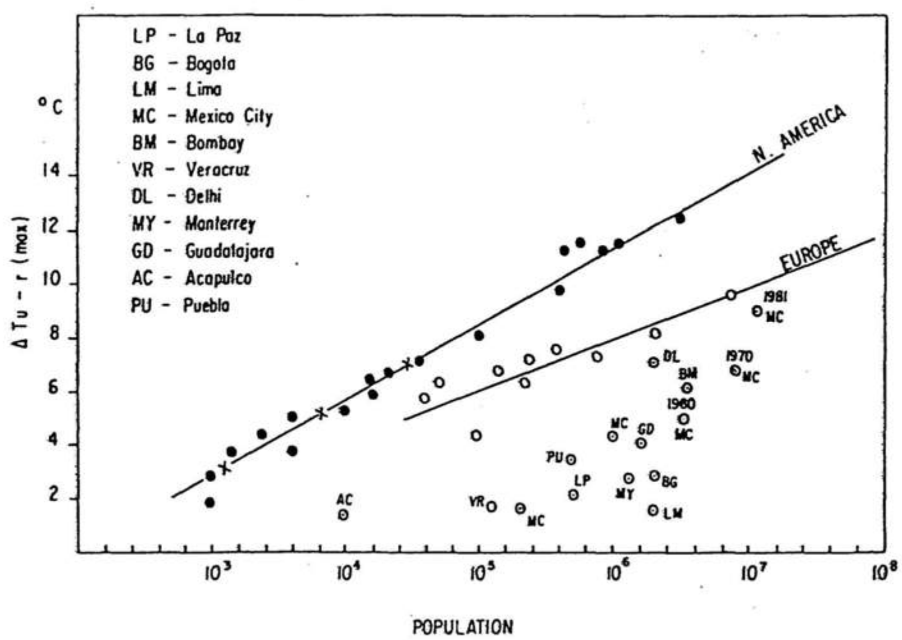

Figure 4. Maximum heat island intensity (ΔT_{u-r}(max)) vs. population for tropical and mid-latitude cities (mid-latitude data, from Oke, 1982).

It has been suggested to the present author (T. Kawamura and T. Oke, personal communication), that the ΔT_{u-r} vs P points on the plot in Figure 4 for tropical cities seem to display a change of slope for cities larger than about 10^6 inhabitants. This change in slope could imply that some tropical cities in Developing Countries appear to experience a marked change in their morphology (larger slum areas, reduced proportion of green areas, taller central city buildings, etc.) once they reach a certain size. Beyond this threshold their thermal response with respect to population is modified.

Perhaps when a larger data set for tropical cities (with similar synoptic/topographic controls) is available, a relationship between population and $\Delta T_{u-r\ (max)}$ of the form proposed by Oke (1973) may be arrived at for tropical cities.

6.2 Time-trend of maximum mean monthly urban heat island vs urbanization

Trend analysis of minimum temperature has been used by Pradhan et al. (1976) in order to assess the effect of urbanization and industrialization on the suburbs of Bombay (near the airport at Santa Cruz). These authors eliminate the synoptic effects by taking urban-suburban temperature differences at sunrise, assuming that synoptic effects are of the same order of magnitude at both sites (an airport and a downtown station near the coast). They conclude that a change in the trend of minimum temperature observed for two periods (1952-58 and 1964-72) could be attributed to an accelerated process of urbanization during those periods.

The existence of climatological records of urban/rural minimum temperatures for Mexico City since the beginning of the century (however, only continuous for the urban station) presents an opportunity to study the effect of urbanization for another metropolitan urban area in the tropics. As Mexico City's urban area expanded it exerted an increasing influence upon the local climate. The accelerated rate of growth began in the 1840s and in the following 30 years the capital of Mexico experienced one of the largest growths of population in the World. Urban growth in this vast tropical city has contributed to significant changes in the thermal climate, as illustrated in Table 3.

A large urban-rural temperature difference rate of increase has taken place during the period 1960-81 when the mean increase in ΔT reached $0.22^{o}C$ per year, which is about double that for the overall period. Between 1940-70 the city grew from 1 million to 9 million inhabitants, and by the early 1980s there were around 14 million. This tremendous increase in population during the 1970s corresponds to the highest rate of increase in ΔT_{u-r} for the whole period.

TABLE 3. *Increase of maximum mean monthly minimum urban-rural temperature difference in Mexico City for the period 1900-1981.*

YEAR	$\Delta T_{u-r(max)}$ (^oC)	DIFFERENCE from period to period (^oC)	PERIOD	$\Delta T_{u-r}/y$ ($^oC\ y^{-1}$)
1900	1.2		1900-1941	0.07
1941	4.0	+ 2.8	1941-1981	0.14
1960	4.7	+ 0.7	1960-1981	0.22
1970	6.3	+ 1.6	1970-1981	0.28
1981	9.4	+ 1.4	1900-1981	0.10

The previous results suggest that the urbanization process exerts an influence on the observed urban minimum screen-level air temperatures and therefore, on the nocturnal rate of cooling in the city as compared with the surrounding rural area which should remain relatively unaffected, as long as it is not engulfed by the city.

7. TROPICAL/MID-LATITUDE CONTRASTS IN URBAN MORPHOLOGY

In section 4.2 we listed some characteristics common to tropical cities as regards to their structure. In what follows we shall examine in more detail these traits.

Structurally, fast-growing cities in low latitudes differ considerably in one important respect from their corresponding mid-latitude counterparts, and that is in the morphology of the canyons of their suburbs. While mid-latitude suburbs are typically represented by low-density housing and a considerable proportion of the area covered with green space, peripheral suburbs in tropical urban areas are predominantly occupied by squatter settlements with scant (if any) green areas. In addition, materials used in low-latitude slum areas differ between different climates. Thus, in inland high-altitude tropical cities (e.g. La Paz, Quito, Bogota, Mexico City) squatter housing is predominantly more solid (to protect against cold) than in coastal or low-land tropical urban areas (e.g. Rio de Janeiro, Bombay, Salvador, Singapore), where light materials like cardboard, bamboo, metal sheets, are more prevalent.

From the foregoing it would appear that since suburban composition and structure in low-latitude cities differs considerably from that of mid-latitude cities, thermal behaviour may also be expected to differ to an extent not yet determined. Table 4 illustrates the importance of slum areas (mainly in suburbs, but also in inner-city areas) in some low-latitude medium/large urban areas.

TABLE 4. *Proportion of urban dwellers living in slums in some medium/ large low-latitude urban areas in 1970 (Habitat, 1976).*

CITY	%	CITY	%	CITY	%
Addis Ababa	90	Guayaquil	50	Delhi	40
Calcutta	70	Mexico City	50	Kuala Lumpur	40
Casa Blanca	70	Recife	50	Jakarta	30
Abidjan	70	Brasilia	40	Rio	30
Bogota	70	Bombay	40	Cali	30

8. OTHER CLIMATIC FACTORS AFFECTED BY URBANIZATION

In the previous sections we have examined some aspects of the effect of urbanization upon air temperature in some tropical cities; but as mid-latitude experience shows urban development affects other elements of the urban climate as well like precipitation, wind, humidity and solar radiation. For low-latitude cities very little is known about these urban-induced changes.

(a) Precipitation. As already mentioned, descriptive accounts of urban-related precipitation enhancement have been made for tropical environments (Klaus et al., 1983; Khemani and Murty, 1973; Jauregui, 1974a, 1982). While intensification of showers may give rise to more frequent street flooding, the additional rainfall amounts may be important for the recharge of the aquifer. However, the quality of this rain water may be degraded by urban air pollutants and thus affect crops or other vegetation downwind. For low-latitude urban areas in the humid tropics urban precipitation anomalies may become more important since, in contrast with mid-latitudes where rainfall anomalies are limited mainly to summer convective activity, precipitation anomalies may extend to a larger portion of the year.

(b) Wind. The increase in surface roughness within cities causes a reduction of strong wind speeds, mainly during the day. However, faster nocturnal wind speeds in the city have been found to occur in mid-latitude cities (Lee, 1979; Chandler, 1965). As would be expected, preliminary results show that this pattern is also observed in a tropical urban area such as Mexico City (Jauregui, 1984). Higher afternoon wind speeds observed in tropical urban areas would tend to ameliorate human comfort. Therefore, more research is needed in examining the relationship between urban air flow and urban/rural stability contrasts.

(c) Humidity. Urban/rural humidity contrasts are important in determining comfort conditions in the tropics. Relative humidity surveys for tropical cities have been made by Nieuwolt (1966), Padmanabhamurty (1979), and Jauregui (1973b). Although relative humidities as reported by these authors may have been lower in the urban area, it is probable that the moisture content of air in the cities studied was high with respect to the rural surroundings due to the low rate of diffusion of air in the urban canyons at certain times, as documented by Chandler (1965), for a mid-latitude city. Just as with other elements, considerable further research is required to determine effects of urbanization on humidity in the tropics.

(d) Solar radiation. Since large low-latitude urban areas are now in the process of increasing their industrial production, little control has been exerted to reduce emissions of gases and particulates. Consequently, the increasing amount of pollutants in tropical urban areas leads to greater absorption, scattering and reflection of incoming solar radiation, which in turn reduces the amount of energy reaching the urban surface. This attenuation can be at least 10% as compared with rural surroundings, as documented by Galindo (1962) for Mexico City. Padmanabhamurty and Mandal (1981) have also detected significant urban/rural solar radiation differences for Delhi. The reflected part of global radiation has been measured for an urban area in the tropics by Oguntoyinbo (1970). This author found that reflection coefficients over built-up areas in Nigeria are about 22% lower than for extratropical urban settlements.

9. CONCLUSIONS

Tropical urban climatology is a relatively new area of research. This is evidenced by the fact that one of the pioneering studies in this field was written in 1966 by Nieuwolt. The first attempt made by local climatologists has been to search for similarities (or contrasts) of urban climate in tropical cities as compared with mid-latitude experience.

Since the heat-island effect has been central to research in urban climatology in mid-latitudes, most of the existing literature on urban climate in the tropics also refers to near-surface thermal and humidity modifications by cities. In some cases these changes have been examined in relation to air pollution and/or enhancement of showers over tropical cities. The literature on these and other aspects of urban-induced changes remains very scant.

Given the topographic/geographic diversity of the few low-latitude cities where urban climate studies have been made, it is not possible at this stage of knowledge to draw any generalizations regarding the effects of urbanization in tropical environments. To illustrate this point, one need only to compare the results of surveys in two cities with similar topographic setting (inland valley) but displaying contrasting heat-island development (e.g. Quito (Hannell, 1976) and Mexico City (Jauregui, 1973 a)).

Consequently, at the present stage of development, urban climate studies based on routine climatological data and/or near-surface (temperature, humidity, wind, etc.) surveys leading to description of features will be necessary for some time in tropical areas until sufficient knowledge is available for generalization.

With one notable exception (Tyson et al., 1972), studies of urban-induced climate modifications in the vertical (i.e. in the urban boundary layer as defined by Oke (1984)),for the tropical region are, to our knowledge, non-existent.

TROPICAL URBAN CLIMATES

Urban problems in low-latitude countries are so numerous that only some climate-related hazards like street-flooding, dust-storms or air pollution receive any level of attention from city authorities.

Effects of urbanization on human health/thermal comfort in low-latitude cities should be the object of more attention from local climatologists. For example, there is need for work to mitigate the adverse effects of heat stress and air pollution through the use of ventilation, vegetation and appropriate choice of building materials.

As suggested by Zeuner (1983), when favourable economic conditions permit, more sophisticated surveys like energy-balance studies of typical urban locations (inner-city, suburbs, parks) that are at present current practice in mid-latitude cities should be pursued for tropical urban areas.

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AIR QUALITY IN TROPICAL CITIES

T. Kawamura
Institute of Geoscience
University of Tsukuba, Ibaraki 305, Japan

1. INTRODUCTION

Kratzer (1956) pointed out in his well-known textbook *Das Stadtklima (Urban Climate)* that air pollution is one of the most prominent phenomena of urban climate, the location of the city can be perceived as the cap of dust "Dunsthaube" when viewed from afar, e.g. by airplane. Various kinds of emission sources are concentrated in urban areas. The pollutants emitted from them, mix with the ambient air so that a polluted airmass covers the urban area and disperses into suburban and rural regions in its lee. Simple models, which show the urban air circulation régime and the related behaviour of the polluted air, have been presented (for example, Bach, 1970; Oke, 1976; Landsberg, 1981), however, there are few detailed field experiments to verify them. Of course air quality is not the only important atmospheric element to be modified in the urban environment. There are other effects such as the heat island. Oke (1976) describes the significance of the atmosphere in planning human settlements and Chandler (1976) considers the role of air pollution on urban climate, and its relevance to urban design.

Air pollution problems have been studied intensively since the 1950's in Developed countries located in the temperate or cool regions of the World. Recently, however, rapid urbanization and industrialization have given rise to severe air pollution in the cities of sub-tropical and tropical countries. Though the data on air quality are extremely limited, the author has attempted to prepare an outline of the air pollution climatology and air quality in tropical and sub-tropical cities.

2. AIR POLLUTION CLIMATOLOGY IN TROPICAL CITIES

The air pollution ecosystem comprises the following chain going from the sources to the receptors. Pollutants emitted from the source are affected by atmospheric turbulence and diffusion, transport by the wind, chemical reactions and finally by sink (depletion) mechanisms in the atmosphere. These mechanisms are common everywhere. Briefly speaking, in the case of primary pollutants, such as suspended dust and sulphur dioxide, air quality is governed by the amount of pollutant emitted and the ventilation of the atmosphere. On the other hand, secondary pollutants, such as photochemical oxidants, include the influence of chemical reactions.

Urban air pollution is affected by meteorological and climatological conditions not only at the macro- (synoptic) scale, but also at the local and micro-scales. Especially urban areas with complex terrain, local meteorological conditions affect the wind distribution and the thermal stratification of the atmospheric boundary layer.

A summary outline of climatological and meteorological conditions surrounding the incidence of air pollution in temperate and tropical regions is given in Table 1. Of course it should be mentioned that there exist slight regional differences in these conditions.

A tropical or subtropical climate is characterized by high temperature and very little temperature variation during the year. Since pollution sources operate all year, and with an approximately constant rate of emission, any seasonality in the incidence of air pollution depends on the wet and dry seasons, which are caused by the north/south shift of the semi-permanent sub-tropical anticyclone and the Intertropical Convergence Zone. In tropical regions where there are no strong winds, rain plays an important role. The diurnal range of temperature may become large and nocturnal inversions frequently occur in the dry season (Setzer _et al._, 1980).

TABLE 1. *Climatic and meteorological conditions related to the incidence of air pollution in temperate and tropical (sub-tropical) regions. Pollutants included are: total suspended particulate matter (SPM), oxides of sulphur (SO_x), and oxidants.*

	Temperate region (examples of Japan)	Tropical and sub-tropical region
Period of highest incidence	SPM & SO_x: December-February (scattered incidence in other months) Oxidants: June-August	Especially winter or dry season
Distribution	SPM & SO_x: In the rear of an anticyclone, or weakening of the winter monsoon (winter) High pressure belt near a stationary front (other seasons) Oxidants: Weakening of baiu front, sub-tropical anticyclone	Sub-tropical anticyclone (before a cold front) Stable pressure pattern in a tropical region
Temperature inversion	SPM & SO_x: Ground inversion on clear days, frontal inversion on cloudy days Oxidants: Frontal inversion associated with a stationary front, subsidence inversion of a sub-tropical anti-cyclone	SPM & SO_x: Ground inversion during clear night. Topographically-induced inversion in a valley and basin. Strong subsidence inversion associated with sub-tropical anticyclone Oxidants: Subsidence inversion and topo-graphically-induced inversion. Low mixing depth is important
Temperature	SPM & SO_x: No relation (but seasonal change of emissions) Oxidants: Daily max. temp. > $24^{\circ}C$	Tropical climate with little temperature change during the year, but diurnal change is important (for example Sao Paulo > $10^{\circ}C$)
Wind velocity	SPM & SO_x: < 3 m s^{-1} Oxidants: < 4 m s^{-1} (mean in daytime)	Light wind < 3 or 4 m s^{-1} (Dust from desert may be brought by strong wind)
Visibility	SPM & SO_x: < 3 km (frequently < 2 km) Oxidants: < 5 km	Same as left column
Wind direction	SPM & SO_x: Leeward from sources. Oxidants: Local winds can be important (sea breeze and valley winds)	Leeward from sources
Precipitation	No precipitation or slight rainfall	Same as left column

If the city is situated in the bottom of a valley or basin, ground inversions develop during the night. Subsidence inversions are also important in sub-tropical anticyclones. The height of the subsidence inversion is only a few hundred metres above the ground. The combination of weak winds and a low mixing height result in poor ventilation and leads to a deterioration in air quality. Moreover, strong insolation results in high concentrations of photochemical oxidants under subtropical anticyclonic conditions. The cases of Los Angeles, Venice and Sydney are good examples. The summer monsoon usually brings the wet season. Rainfall washes out many of the pollutants, however breaks in the long spells of rain produce high concentrations of sulphur oxides (e.g. in Bombay).

Sea breezes or lake breezes frequently transport photochemical oxidants to inland areas, as far as 100 km or more from coastal urban areas. Weak winds are usually considered to be unfavourable and associated with pollution problems. However, strong winds can transport fine sand or dust from desert to urban or industrial areas. Satellite photographs reveal strong clouding of the background as a result of continental dust- and sandstorms. The finest particles of loose material can be carried from the Sahara Desert as far as the Red Sea, a few thousand kilometres away. Cairo, as with all cities of the Middle East, is subjected to a turbulent atmosphere during storms, particularly in the Khamsin season (February-July) when the air humidity is low and the lands and deserts are very dry (Salam et al., 1967; Sowelim, 1983). The amounts deposited are approximately proportional to the duration of the storms and inversely proportional to their mean wind speed.

When a city is located on the coast or surrounded by mountains with hills, separating the districts, the geographical characteristics give an inverse relationship between the concentration of suspended particulate matter and a "dispersion factor" (defined as the product of mixing depth and the surface wind speed). Since human activities in Rio de Janeiro are constant over the year, the seasonal variation of total suspended particle concentrations can be explained by changes in the meteorological parameters alone, since they affect the transport, dispersion and removal of atmospheric particulates. Landsberg (1970) has pointed out that wind speeds are reduced by 25% and the frequency of calms is increased by 5-20%, in large industrial cities. Goldreich (1984) has discussed the role of topography on urban climate. It seems that urban climate assists the deterioration of urban air quality in tropical cities.

In winter months, the air reaching Hong Kong is often heavily polluted in the low-level cold monsoon layer beneath the upper warm westerlies. The dense haze is usually less than 1 km deep and can be seen clearly from above. It is considered that the pollutants originate from the Gobi Desert and other arid areas of China, where they are stirred up by fresh outbreaks of the monsoon and carried southwards. The air is much cleaner in the summer because most dust particles and pollutants are dispersed upwards by strong thermal convection near the ground due to the large lapse rate in the lower levels (Bell et al., 1970).

Recently, acid rain has been observed in tropical regions. High temperature and humidity increases the oxidation rate of sulphur dioxide, so tropical climates are probably favourable for the formation of acid rain.

On the other hand, there have been few studies of the effect of air pollution on the urban climate of tropical cities. Visibility is closely correlated to the concentration of suspended particle matter. A steep, shallow inversion helps to cause poor visibility and poor dispersion. Thus visibility was inversely proportional to the concentration of pollutants at Bombay airport (Chandiramani et al., 1975). Urban-suburban depletion of the direct solar radiation caused by particulate contamination approaches 25% in the case of the Helwan atmosphere of Egypt.

It has been shown that diffusion models can be applied to the calculation of air pollution concentrations in tropical regions (Raghavan et al., 1983).

3. AIR QUALITY IN TROPICAL CITIES

Most Developing countries devote considerable efforts towards industrialization and economic development. Simultaneously, there is a movement leading to the concentration of population in urban areas. Air pollution observation networks have been set up in Developing countries since the latter half of 1970's, but the collection of air quality data remains difficult in many tropical cities. Nevertheless it is clear that the air quality of urban areas, especially large cities, has deteriorated drastically in tropical regions.

An example is the rapid increase of automobiles, buses, motor cycles and trucks in Asian countries (Middleton and Middleton, 1983). The nature, extent and severity of air pollution created by motor vehicles varies not only with terrain and weather conditions, but also with the kinds of automobiles, engine age and maintenance, urban design, the roadway system and so on. In Malaysia, in 1980, there were 2,357,000 automobiles, an increase of 86% over 1975. Air pollution in the Philippines is a problem in the major cities, principally Manila where 60% of the country's industries, and 45% of its motor vehicles, are found. Visibility is frequently restricted due to a brown haze associated with oxidant pollution. Pollution generated by the rapidly growing motor vehicle population is responsible for about 75% of the total air pollution in Metro Manila. Sri Lanka has no systematic ambient air quality measurement system. As in other countries in Asia, the motor vehicle population is increasing rapidly.

Although a marked deterioration of urban air quality is known to have been experienced by large cities in the tropics (such as Rio de Janeiro, São Paulo, Mexico City etc.) it is very difficult to obtain the appropriate air quality data with which to judge the state of their atmospheric environment. Table 2 indicates only two examples, (a) São Paulo (Barros and Guimaraes, 1977; Nefussi et al., 1977) and (b) Taiwan (Chow et al., 1983). Greater São Paulo (Table 2a), including the City of São Paulo, is a highly developed industrialized area, employing around 48% of the total labour force in the country. It is therefore a densely populated area where close to 10 million people live. The main sources of air pollution in this area have been recognized to be industrial processes (there are about 50,000 industries), the use of fuel oil with a high sulphur content, solid waste incineration, fugitive dust sources and automobile emissions. The 1.2 million automobiles in circulation are responsible for the daily emission of about 3,500 tons of carbon monoxide. Reduction of carbon monoxide emissions will be necessary to meet the federal air quality standards (9 ppm).

Chow et al. (1983) summarized the air pollution in the Republic of China (Taiwan) (Table 2b). Over the past 20 years, efforts have been directed towards industrialization and economic development, and air pollution concentrations have drastically increased over the last two decades as a result. The main factors for the deterioration of the atmospheric environment are as follows:

- the substantial increase in the number of industries;
- the combustion of fuel, oil, coal and wood;
- automobile exhaust emissions; and
- high population density.

The effects of environmental pollution upon health have been perceived to be a major problem in recent years.

Suzuki (1981) mentions that the concentration of carbon monoxide and lead in the ambient air of Djakarta City has reached levels which Japanese cities have never experienced. It seems that similar problems exist in many tropical cities, such as Caracas (Escalona and Sanhueza, 1981), Bombay (Khandekar et al., 1980), Mexico City (Barfoot et al., 1984), Santiago (Prendez et al., 1984) and Brazzaville, Congo (Cros, 1967).

Of course, other kinds of particulate matter are also important. For instance, the Helwan industrial area about 24 km south-east of Cairo has a construction-cement industry as its major source which is responsible for polluting the atmosphere of this region. The highest values of 3,310.95 tons km^{-2} $month^{-1}$ and 2,787.92 tons km^{-2} $month^{-1}$ averaged over the two years of record (Ghandour et al., 1983a, b).

UNEP considers sulphur oxides as the most important pollutant. They rank it No. 1 on their list of priority environmental monitoring items. As an example, São Paulo shows that the daily average concentration of sulphur dioxide reaches 0.081-0.42 ppm. Various problems are included in air quality impacts of sulphur oxides. The main source of pollution in Jerusalem is vehicular traffic, so distribution of motor vehicles is a very important factor in analysing pollutant concentrations. The average daytime SO_2 concentration was 238 $\mu g\ m^{-3}$ while during the night it was 91 $\mu g\ m^{-3}$

TABLE 2 (a). *Ambient air quality data in Great São Paulo area - 1976 (Nefussi et al., 1977).*

Parameter	Pollutant	Sulfur dioxide ug/m³	Particulates ug/m³	Carbon monoxide ppm	Nitrogen dioxide ug/m³	Ozone ug/m³	Noise dB (f)
Air quality standard		80 (a) 365 (e)	80 (b) 240 (e)	9 (c)	n.e.	200 (d)	n.e.
Annual average	Industrial area	125	63	–	–	–	–
	Commercial area	109	79	–	–	–	
	Residential area	64	60	–	–	–	–
	Downtown	105	92		73		–
24 hours average (maximum and second of the year)	Industrial area	342/329	666/562	–	–	–	62 dB (A)
	Commercial area	340/321	448/427	–	–	–	69 dB (A)
	Residential area	152/151	412/408	–	–	–	57 dB (A)
	Downtown	284/264	465/445	–	150/144	25.6/24.1	71 dB (A)
8 hours average (downtown) (maximum and second of the year)		–	–	29.8/28.9	–	–	73 dB (A)
One hour average (downtown) (maximum and second of the year)		–	–	43.5/42.5	–	180.3/125.4	–
Number of times the air quality, standards were surpassed		40	179	164	–	0	–
Seasonal average (downtown)	Winter	115	103	11.6	80	5.2	
	Spring	99	61	9.8	66	–	
	Summer	91	78	3.5	64	–	
	Fall	117	118	7.9	79	–	
Alert levels		800 (e)	375 (e)	15 (c)	–	200 (d)	
Number of times the alert levels were surpassed		6	35	98	–	0	

(a) Annual aritmethic mean
(b) Annual geometric mean
(c) Maxi daily 8 hours average
(d) Max. daily 1 hour average
(e) Daily average
(f) Level equivalent

TABLE 2 (b). *Ambient air quality data in Taiwan (Chow et al., 1983).*

Measurements	Averaging Time	Sampling Frequency	Measurement Method	Typical Average Concentrations: Monthly	Typical Average Concentrations: Annual	Average Concentration Ranges: Monthly	Average Concentration Ranges: Annual	National Ambient Standard: Monthly	National Ambient Standard: Annual
Dustfall (tons/km²)	30-day	1/month	Dustfall Jar	[a]	15	3–30	6–20	No standard	15
TSP <40 μm (μg/m³)	24-h	2/month	HIVOL	210	170	85–400	140–330	260[b], 290[c]	170[b], 190[c]
Small Particles (μg/m³)	1-h	24/day, sporadic	Dust Analyzer (Light Scattering Method)	180	140	100–230	[a]	210[b], 240[c]	140[b], 160[c]
COH (COHS/ 1000 ft)	2-h	12/day, sporadic	AISI Automatic Smoke Tape Sampler	2.5	1.5	0.5–5	1–3	No standard	3[e]
				Hourly	Daily	Hourly	Daily	Daily	Annual
SO_2 (ppm)	1-h	24/day, daily	Ambient SO_2 Analyzer (Conductometric Method and Colorimetric Method)	0.1	0.05	0.05–0.25	0.02–1.4	0.1, 0.15[f]	0.05, 0.075
H_2S (ppm)	1-h	24/day, sporadic	Ambient H_2S Analyzer	0.05	0.005	0.008–0.13	0.0025–0.06	0.1, 0.2	No standard
NO_2 (ppm)	1-h	24/day, sporadic	Chemiluminescence (mobile van)	0.021	0.016	0.007–0.046	0.014–0.028	0.05, 0.1[g]	10% of sampling days exceed 0.05, 0.1
CO (ppm)	1-h	Various	Non-Dispersive Infrared Spectroscopy (mobile van)	1.6	1.2	0.8–3.1	1.1–1.5	1	No standard
HC (ppm)	1-h	Various	Flame Ionization (mobile van)	2	1.1	0.4–3.8	1–1.2	No standard	No standard
O_3 (ppm)	1-h	Various	Chemiluminescence (mobile van)	0.005	0.012	0.003–0.034	0.008–0.016	No standard	No standard

[a] Insufficient data.
[b] Light industry, commercial, and residential areas.
[c] Heavy industrial area.
[d] Data average was taken from air monitoring mobile vans at 11 different cities only.
[e] No Taiwan standard exists, this is a standard in the U.S.
[f] Standard for SO_x which includes SO_2 and SO_3.
[g] Standard for NO_x.

(Steinberger et al., 1975). In India, Bombay, Calcutta, Delhi and a few other industrial areas have been found to have fairly high levels of SO_2 in the atmosphere. The SO_2 concentration shows a relatively close correlation with the concentration of suspended particulate matter in most tropical cities. In a sub-tropical climate, the diurnal temperature range, mixing depth and rain in winter seem to exert a dominant influence on SO_2 concentrations in cities.

As mentioned previously, topography around a city affects the concentration of sulphur dioxide. Atmospheric pollution in Hong Kong has become a significant problem. Measurements indicate that in some areas the atmosphere is already polluted to a degree well above the limits tolerated in many countries. However, consideration of the meteorological factors involved, and the geographical setting of the city, suggest that the potential for pollution is no greater in Hong Kong than in some other large industrial cities (Bell et al., 1970).

High temperature exerts an active photochemical role when nitrogen oxides and hydrocarbons are mixed. This explains the high concentrations of oxidants produced in the polluted urban atmospheres of sub-tropical and tropical regions, as demonstrated by Los Angeles. Scattered information from monitoring systems support this view. Unfortunately published research on photochemical oxidants in subtropical regions is mainly limited to cities such as Sydney (Post and Bilger, 1978; Post, 1979), Los Angeles (Elkus and Wilson, 1977; Nieboer et al., 1976) and so on. Although these cities are located in temperate climate regions, the sub-tropical anticyclone covers them in their summer season.

One of the characteristic features of photochemical air pollution is the long range transport of oxidants. The winds of local circulation systems play an especially important role in urban photochemical air pollution (Lyons and Cole, 1976), as shown by the example of Tokyo and its adjacent region (Kawamura, 1984). A schematic representation of the local wind systems around Tokyo Bay and its adjacent areas is shown in Figure 1. In this example an anticyclone covers the area with an extremely weak gradient flow during the warm season. Land-breezes prevail over the entire area in the morning (Stage 1). At this stage the concentration of oxidants has not started to increase. At about 9-10 h sea-breezes start from Tokyo Bay (A) and Sagami Bay (B) and the sea-breeze front is established between the sea- and land-breezes (Stage 2). The area covered by sea-breezes gradually extends inland until noon. However, the advance of the sea-breeze front is temporarily stopped by the land-breeze (C), and easterly winds from the Kashimanada area (D) (Stage 3). Large amounts of primary pollutants, such as nitrogen oxides and hydrocarbons, emitted from sources in the urban area, accumulate in the lower atmosphere and are transformed into oxidants by photochemical reactions. High concentrations of oxidants are observed in urban areas influenced by the sea-breeze at this stage. Thereafter strong southerly winds promptly expand to cover the entire area of the Kanto plain, as a result of the development of a low pressure area in the inland area caused by solar heating (Stage 4). Polluted air, which accumulated in the area affected by the sea-breeze, is transported from south to north by this southerly wind. An example of the stream-lines of surface winds at 15 h is shown in Figure 2. The thick lines in the right-hand panel of Figure 2b indicate when and where the maximum concentration of oxidants was observed. The concentration of oxidants rose immediately after the arrival of the polluted air at the inland area of the Kanto Plain. Alternation from sea-breeze to land-breeze occurs at midnight (Stage 5). Naturally, the concentration of oxidants gradually declines after sunset. Winds weaken in the urban area in the early morning (Stage 6), the cycle is complete, and is succeeded by Stage 1 again.

4. FUTURE CONSIDERATIONS

(a) More detailed knowledge of the air pollution climatology of tropical regions is necessary if there is to be an input to the design of tropical cities. Monitoring networks of ambient air quality have developed only very recently in tropical cities. As the available data increases it is to be hoped that the climatic and meteorological conditions related to urban air quality in tropical <u>and</u> temperate regions will become known more precisely.

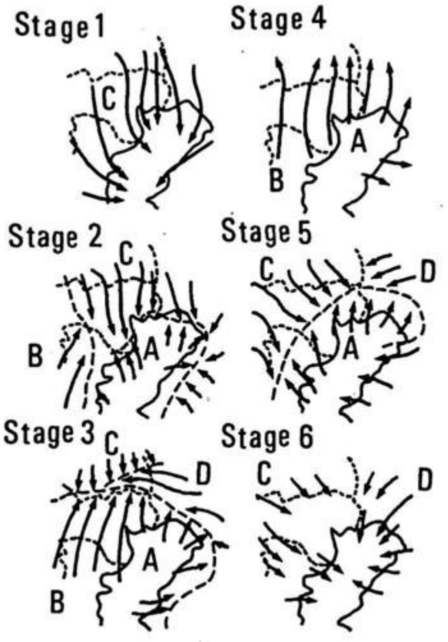

Figure 1. Schematic representation of the diurnal change of the local wind systems around Tokyo Bay and its adjacent area, under conditions of a very weak pressure gradient. Stage 1: morning, Stage 2: 9-10h, Stage 3: 12-13h, Stage 4: afternoon, Stage 5: night (after 21h), Stage 6: from midnight to early morning.
Notes: A: sea-breeze from Tokyo Bay, B: sea-breeze from Sagami Bay, C: land-breeze, D: local easterly wind.

(b) The structure of urban pollution distributions and their time variations must be analysed in relation to the urban heat islands of tropical cities, and must also include consideration of the topographical setting of the urban location.

(c) Since pollution tends to expand outside of the urban area then the role of urban climate on this dispersion of air pollutants should be studied.

(d) Photochemical air pollution and acid rain are important problems in tropical regions requiring close attention.

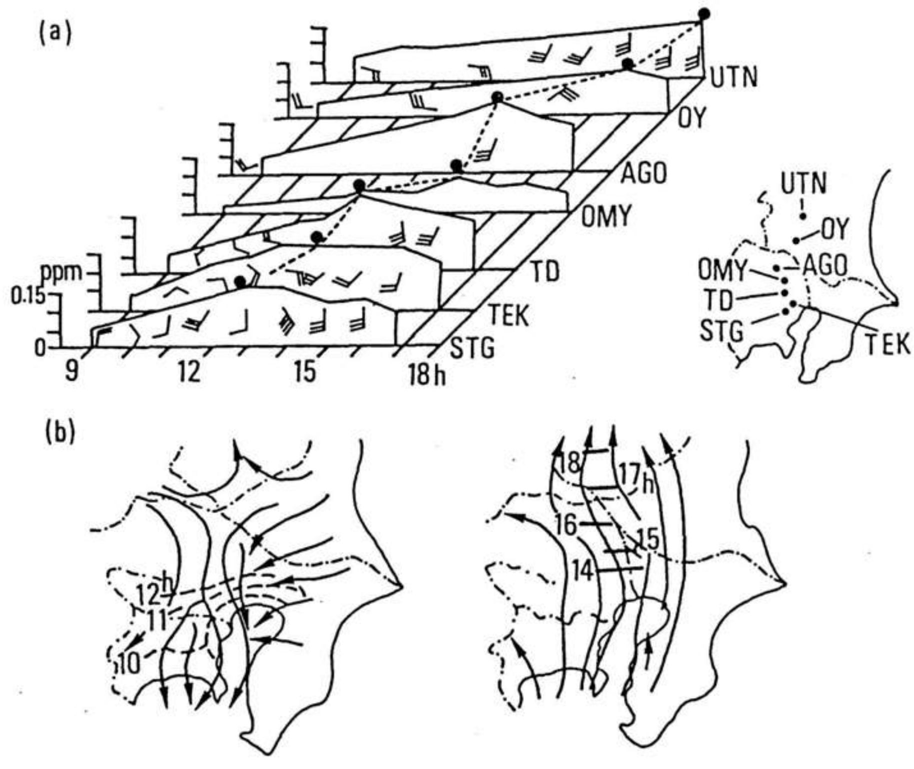

Figure 2. (a) Temporal changes in the concentration of oxidants and winds on June 11, 1972. Station symbols - UTN: Utsunomiya, OY: Oyama, AGO: Ageo, OMY: Omiya, TD: Toda, TEK: Toeiken, STG: Setagaya. (b) Left: Streamlines of the surface winds at 9h and the locations of the sea-breeze front (broken-line). Right: Streamlines of the surface wind at 15h and the locations of the maximum concentration of oxidants at each hour in the afternoon (solid heavy line).

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THE URBAN CLIMATE OF MEXICO CITY

Ernesto Jauregui
Instituto de Geografia
National University of Mexico, Mexico 20, D. F., Mexico

1. INTRODUCTION

In this paper recent empirical evidence is presented concerning urban effects of Mexico City on the local climate of the valley where the city lies, and some physical examinations are offered to account for the Capital City's climatic regime peculiarities in comparison with those of mid-latitude cities.

Even though Mexico City lies in the tropics, the regional (synoptic) and local (topographic) controls in addition to its location in the interior of a high plateau, make it a rather unique case, and therefore the peculiarities of its urban climate can only be representative of those low-latitude urban areas with similar climatic and geographic setting. It would be desirable that more attention be given to studies of urban climate in cities where the prevailing regional and local controls are more general for the tropics.

2. SYNOPTIC CONTROLS

During the cool half of the year (November-April) the valley of Mexico is subject to a high frequency of anticyclonic conditions that give rise to almost cloudless night skies (and therefore radiation surface inversions) and abundant sunshine during the day. The rest of the year the Westerlies retreat northwards giving way to the moist, frequently unstable

Trade-wind current. During this period cloudy skies predominate from about noon to midnight and convective thundershowers often occur from about 1600 to 1900h.

The 'summer' (warmest) season for Mexico City takes place at the end of the dry season (March to mid-May) when maximum temperatures reach around 30°C. The sensation of sultriness is then somewhat reduced by the associated low relative humidity prevailing in the afternoon.

3. LOCAL CONTROLS

During the dry season the NE limits of Mexico City have a semi-arid character; the dried lake-bed clay soils are then easily eroded by wind, especially during the first four months of the year. The dried soil surface with scant vegetation being a good absorber of solar energy on sunny days becomes very hot. Soil heat convergence and negligible latent heat losses bring about higher air temperatures in the rural area near the airport in comparison with the urban area. At night, as a result of heat flux divergence, the dry land becomes cold and a strong surface inversion develops.

The sparse vegetation and low diffusivity of the soils characteristic of the central area of the valley of Mexico enhance the extreme nature of the thermal climate there as compared with the more conservative one in the urban area. Also, compared with the urban area, radiation input over the denudated soils is perhaps larger due to less attenuation by air pollution. The abundant radiant energy during the second half of the dry season must be dissipated as sensible heat. The day-time radiative surplus is transported into the atmosphere by turbulent eddies which not infrequently lead to the development of dust devils and dust storms. The unrestricted radiative cooling at night causes the temperature to drop markedly. The result is a larger diurnal range of temperature as compared with the urban thermal climate. In the other more humid and vegetated city suburbs to the South and West, urban-rural thermal amplitudes are less differentiated (see Figure 1).

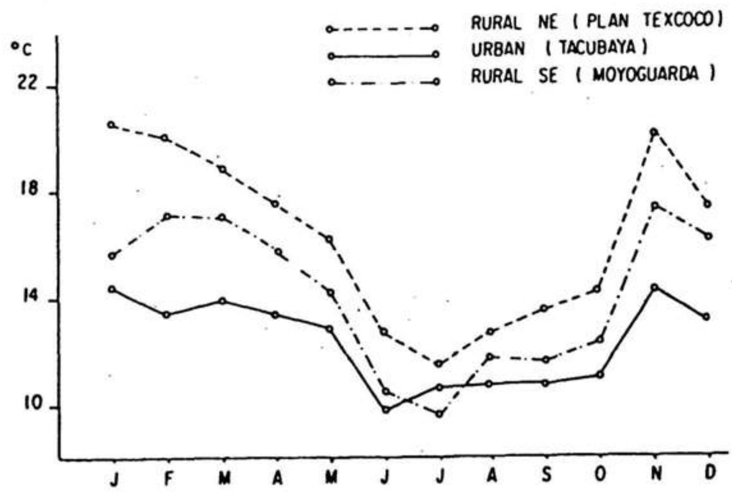

Figure 1. Amplitude of mean monthly temperatures for urban, suburban, and rural stations in Mexico City for 1981.

4. URBAN MORPHOLOGY, STATION LOCATIONS AND DATA SOURCES

4.1 Urban climatological stations

The downtown area of Mexico City has numerous buildings of less than 4 storeys dating from colonial times. After the Second World War an increasing re-building took place in the city centre with tower blocks lining a few wide boulevards. Two climatological stations are located in this area (Figure 2). Heavily industrialized areas developed to the North with the heaviest concentration to the NW in the Vallejo-Tlalnepantla-Naucalpan area with few green spaces. Three stations are located in this area. Toward the West and South where rainfall is more abundant, the urban area has many streets lined with trees as well as some medium and large parks and playground areas. Three stations are located in this area: Tacubaya Observatory, University and Viveros.

The Eastern sector of the city (including the International Airport station*) is characterized by a high density of one or two-storey, low cost

* The Airport site has gradually changed from its rural character to a more suburban one.

dwellings for the working class where green areas are scanty and few trees survive in the semi-arid climate. Urban development in this crowded sector of the Capital, often unplanned and uncontrolled, has served in the beginning as a catchment district for migrants. Beyond the Eastern fringes of the city and along the main roads, lie various kinds of squatter settlements erected mainly from waste building materials and where sanitary installations are minimal. Extensive shopping centres have been built lately at important nodal points of communications within the upper-class residential quarters to the West and South where the climate is more humid.

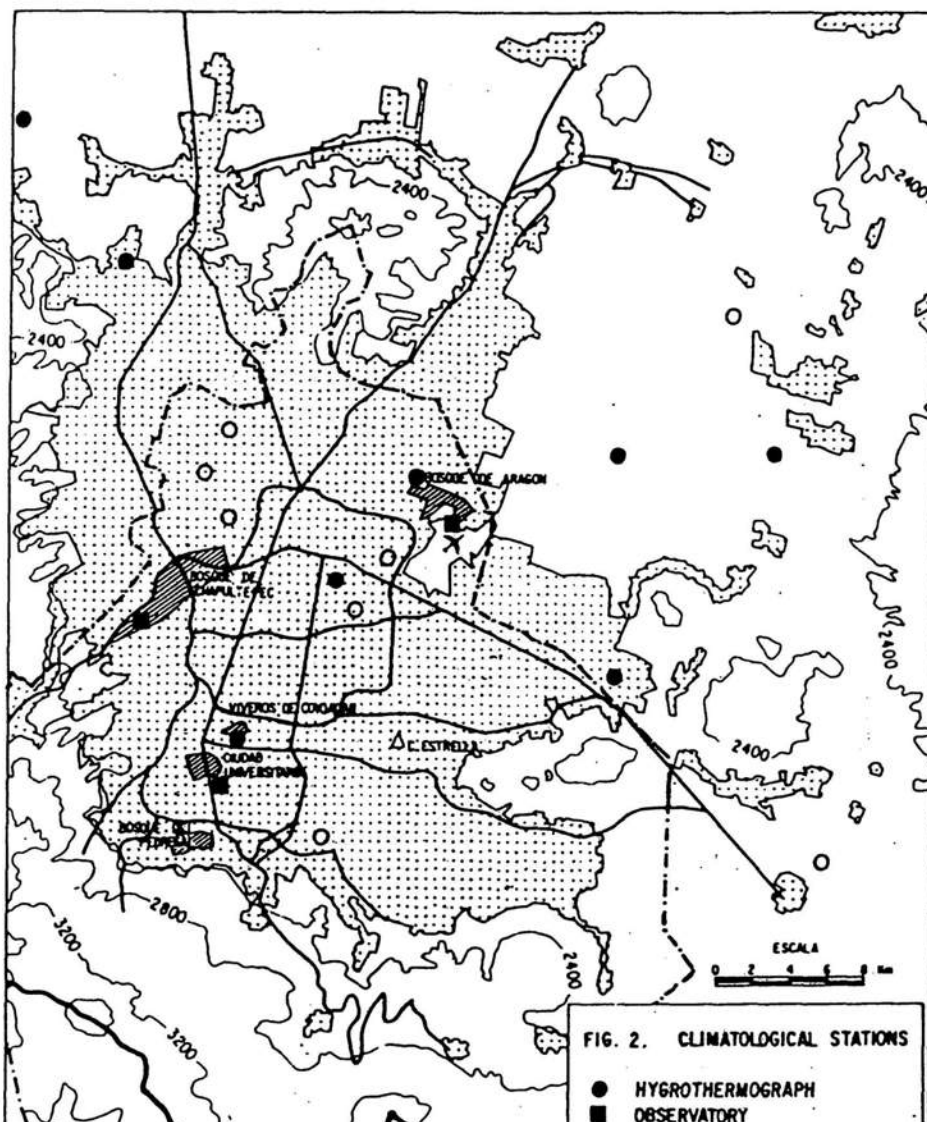

FIG. 2. CLIMATOLOGICAL STATIONS

A recent development of urban growth is the arrangement of upper-middle class residential quarters mingled with squatter settlements. These have been expanding rapidly outwards over the hills to the West and South of the city. Overlooking the valley, and frequently above the top of the surface inversion, these outermost settlements enjoy perhaps the best climate in the capital city.

4.2 Rural climatological stations

Plan Texcoco site is located about 3 km East of the International Airport (Figure 2) on the dried-up bed of Lake Texcoco. The soil is salty clay susceptible to wind erosion. The land surrounding the station is flat and treeless with patches of salt-resistant grass and shrubs that grow during the rainy period (May-October). There is a shallow brine-water artificial pond covering about 200 hectares upwind to the North. The other rural site is Chalco about 15 km SE of the Airport. The climatological station is surrounded by cultivated flat land within a radius of 5 km or more. The climate here is somewhat more humid and native shrubs and trees line the crop fields (mostly corn and alfalfa).

4.3 Data sources

Climatological records from the National Meteorological Service for a period of the last 5 to 12 years are used, as well as those from the SENEAM (Airport Authority).

5. HEAT ISLAND CLIMATOLOGY OF MEXICO CITY

5.1 Spatial morphology

Spatial and seasonal features of screen-level air temperatures for Mexico City have been documented by Jauregui (1970, 1971, 1973). Figure 3 illustrates the typical heat island morphology for a dry (mostly cloudless skies and light winds at night) month in Mexico City for a recent year (1981). Two island cores protrude markedly. They are located slightly to the West of the geometric N-S axis of the urban area and are separated by the cool island induced by the extensive green area of Chapultepec Park (450 Ha). The Northern island core is somewhat downwind of the industrial zone, while the Southern one approximately follows the outline of the most densely built-up area. Cool air advected from the slopes of the mountains to the West, South and North gives rise to a 'cliff' on those sides of the urban area. Over the NE sector, characterized by open flat terrain, a slacker horizontal temperature gradient is displayed.

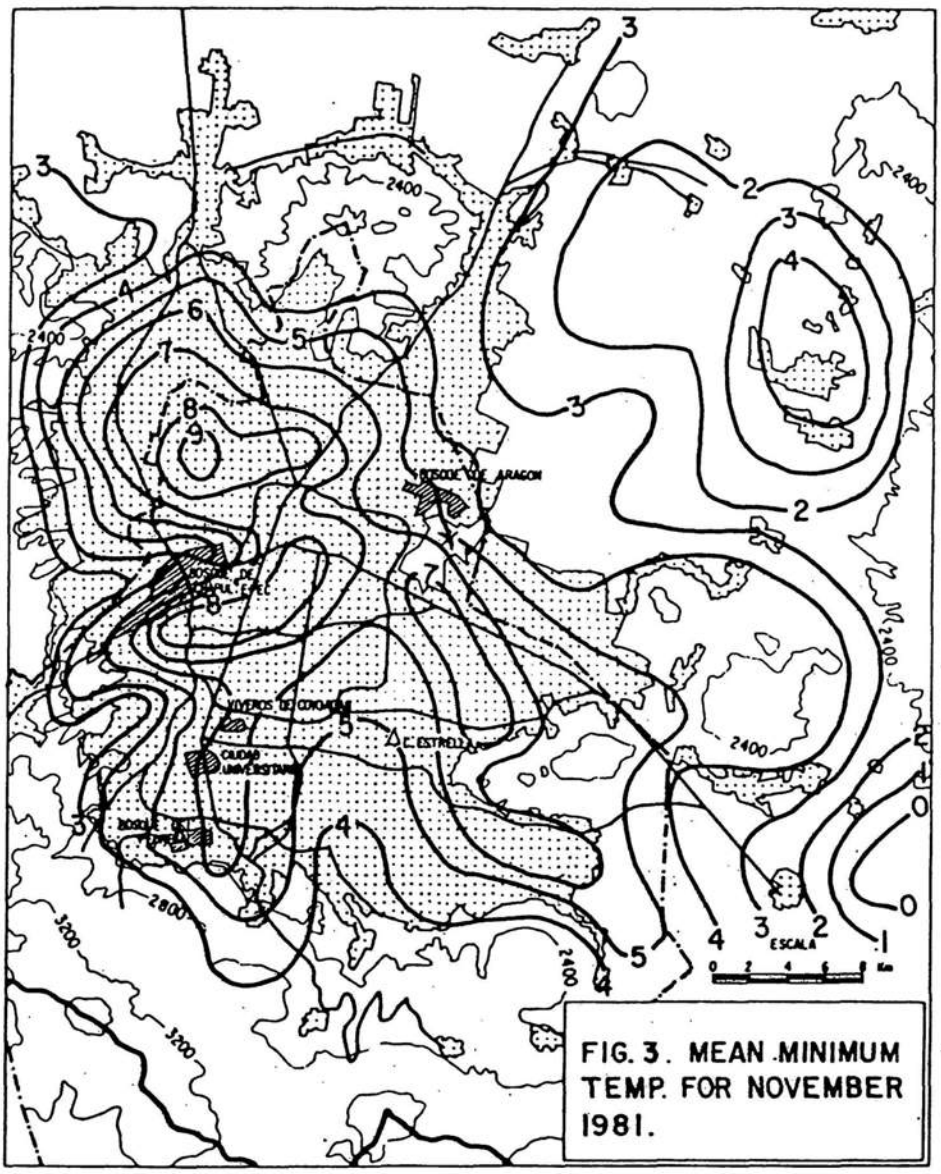

FIG. 3. MEAN MINIMUM TEMP. FOR NOVEMBER 1981.

5.2 Urban/rural cooling rates

It is now well established that heat island phenomena are the result of urban/rural energy balance and stability differences, which in turn produce different rates of near-surface cooling and warming (Lee, 1979; Oke and Maxwell, 1975; Unwin, 1980). Figure 4 illustrates cooling rates for urban/suburban sites in Mexico City. During winter, and after sunset, air temperatures in and outside Mexico City begin to diverge, first somewhat slowly and after about midnight more rapidly, so that by about sunrise the urban/rural temperature contrast reaches its peak. This is better illustrated in Figure 5 which, following Oke and Maxwell (1975), shows the relation between urban/rural cooling rates and the heat island intensity for Mexico City. Strongest cooling for both areas occurs at about sunset declining thereafter until about midnight. After this time the urban cooling rate decreases steadily, while the suburban curve maintains a steady rate until dawn.

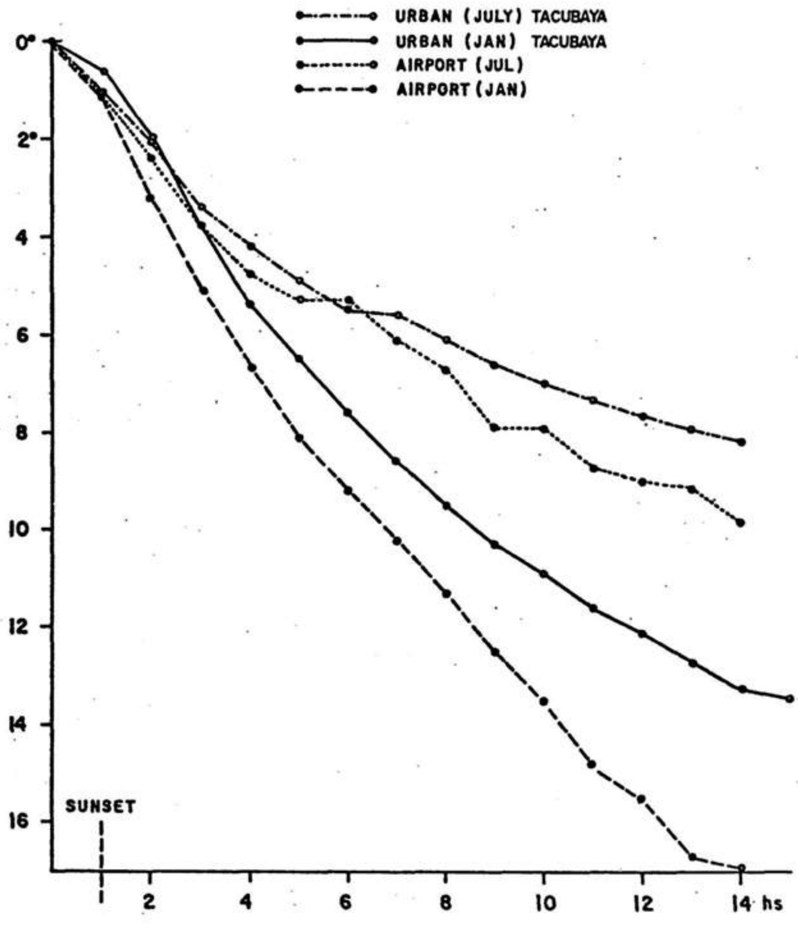

Figure 4. Cumulative nocturnal cooling curves for urban/suburban sites in Mexico City for January and July, 1979.

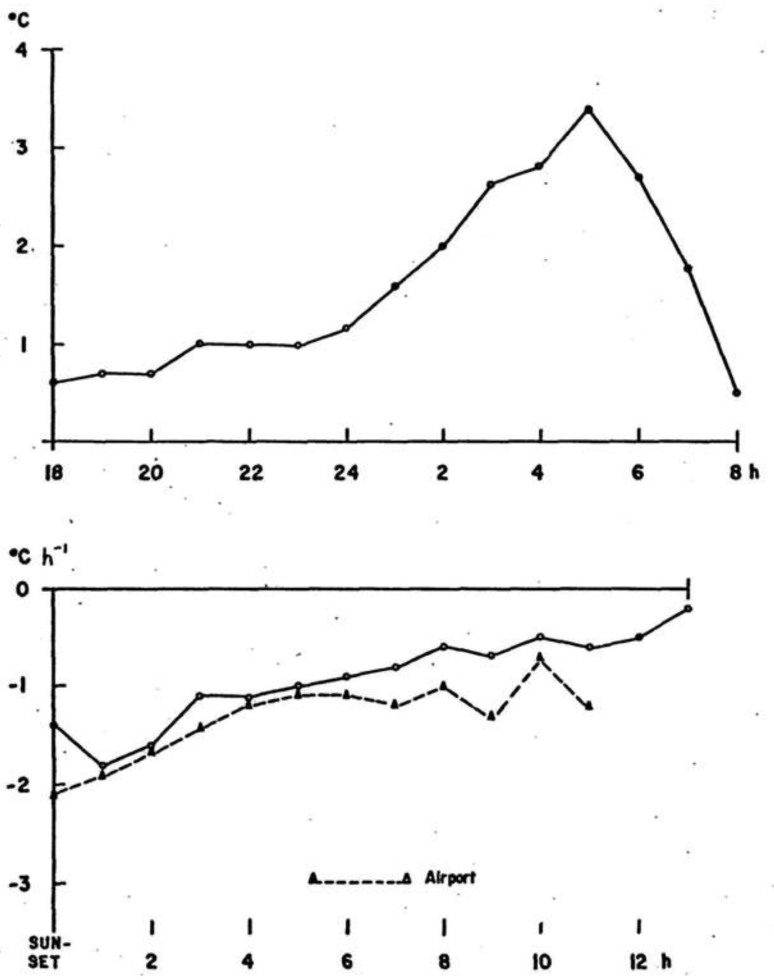

Figure 5. Nocturnal urban heat island intensity (top), and urban and suburban cooling rates (below) for January 1979 in Mexico City.

This cooling behaviour differs somewhat from that observed in some mid-latitude cities in summer (Chandler, 1976; Landsberg, 1969; Oke and Maxwell, 1975) where the largest thermal difference occurs about 3 to 5 hours after sunset. This difference in behaviour might be attributed to the fact that nights are relatively longer in winter in Mexico City (and therefore there is a longer cooling process) than summer nights in mid-latitudes, when maximum heat-island intensities are observed (Chandler, 1976). Another factor that could contribute in the same direction is the high frequency of calm or light winds in the period from midnight until dawn that prevails in Mexico City (Figure 6). But perhaps other factors, such as differences in canopy structure (green areas and urban development densities) might have to be invoked in order to explain the observed contrasts.

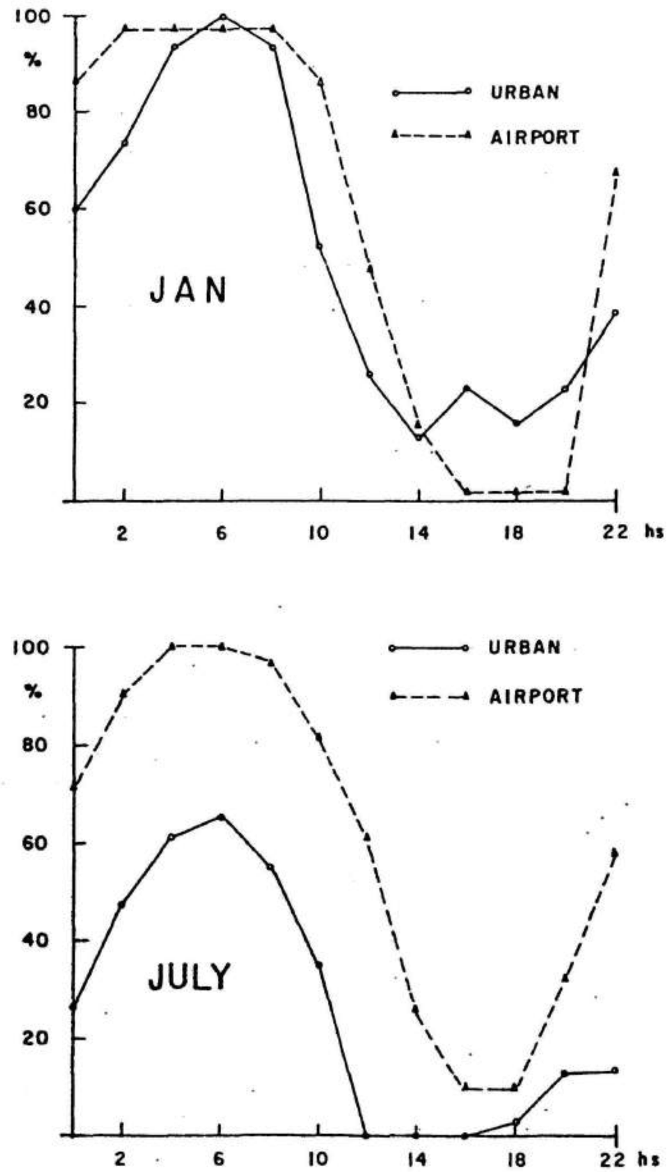

Figure 6. Frequency of calms at urban and suburban sites in Mexico City, 1980.

5.3 Diurnal variation of heat island intensity

The observed differences in the urban/rural thermal regime for Mexico City lead to the diurnal variation of heat island intensity seen in Figure 7.*

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* Here the Airport site has been used as the "rural" station, since the other "rural" sites do not report hourly values of temperature.

The diurnal variation of the heat island for London, U.K. is also shown for comparison.

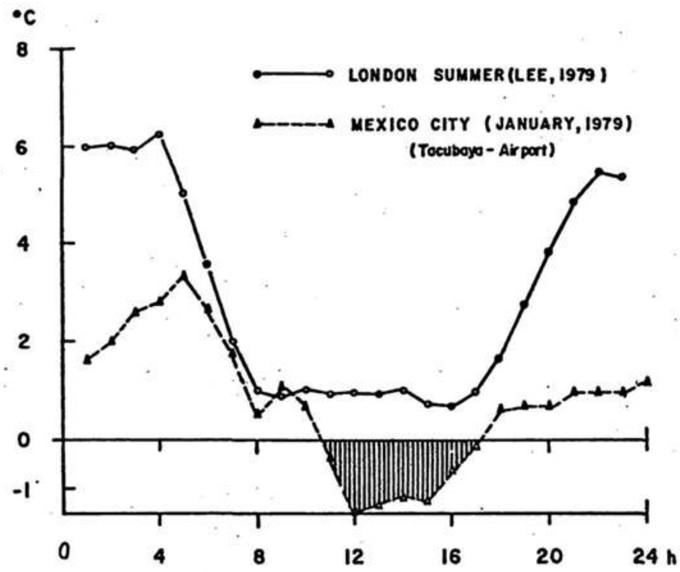

Figure 7. Diurnal variation of heat island intensity for Mexico City and London.

Although somewhat similar in shape, the variation of heat island intensity for both cities differs in:

(a) The heat island intensity for the mid-latitude city increases rapidly after sunset thereby attaining by midnight a value several times as large as that for a corresponding tropical city. If anthropogenic heat is negligible, this suggests that for this period the urban long-wave radiation losses in the mid-latitude city, which depend on the geometry (sky view) and heat storage capacity of its buildings, are smaller than those for Mexico City.

(b) After midnight, and perhaps favoured by the high frequency of calm conditions, the heat island intensity increases rapidly for the tropical city reaching its peak at 0500 h, when London's heat island intensity has started to decline.

(c) During the afternoon hours (from 1200 to 1600 h) temperatures in the tropical city are about $1^{\circ}C$ lower than the suburbs, whereas for London the heat island reaches its minimum value (less than $1^{\circ}C$) without becoming negative. The differences observed in the cool island intensity of both cities is probably due to differences in the thermal admittance and shading, but this explanation would have to be further substantiated. As has been pointed out by others (Ludwig, 1970; Chandler, 1976) differences in heat capacity between urban and rural areas is not a sufficient explanation for the observed day-time temperature patterns.

5.4 Seasonal variation of heat island intensity

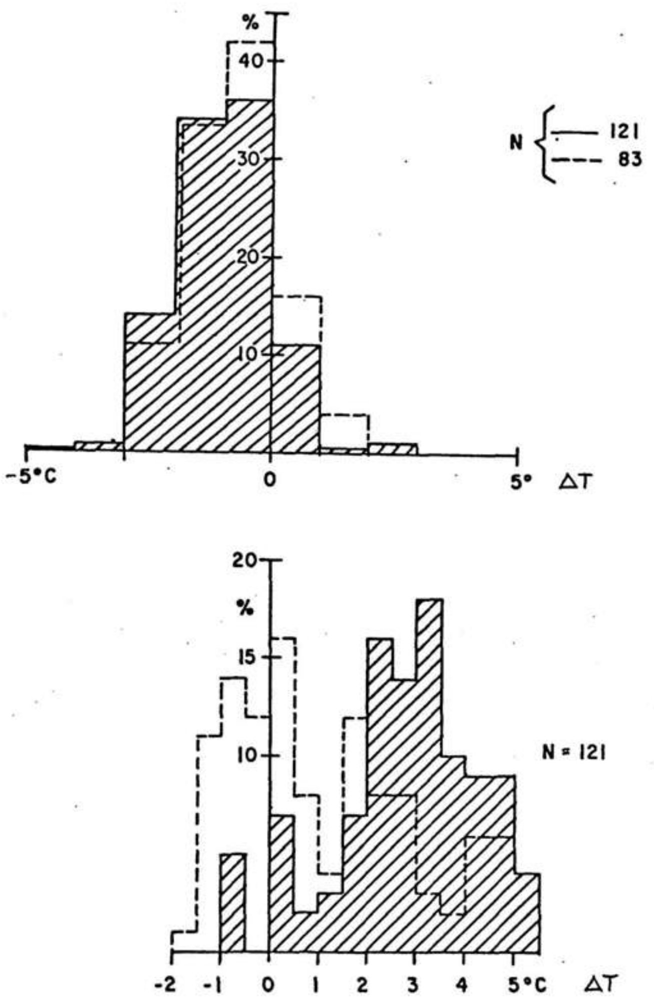

Figure 8. Frequency distribution of urban heat island intensity (ΔT = T at Tacubaya - T at Airport) for dry-cool months (December to March 1979, solid line) and humid months (August to October 1979, dashed line). Top results at 1400 h; below at 0600 h.

Figure 8 illustrates the frequency distribution of the heat island at the hours of maximum and minimum intensity and for the wet and dry seasons. At noon more than 70% of the time the city is 1 or $2^{o}C$ cooler than the suburbs throughout the year, while at sunrise and during the dry season more than 60% of the time urban/suburban thermal contrasts are between 2 and 4°C. A schematic representation of heat island variation for Mexico City throughout the year is given in Figure 9. Again, it is clear from this figure that the canopy heat island in Mexico City is a nocturnal phenomenon restricted mainly to the cool season. During the rest of the year (and during the day), the city is either cooler or maintains the same temperature as the surrounding suburbs.

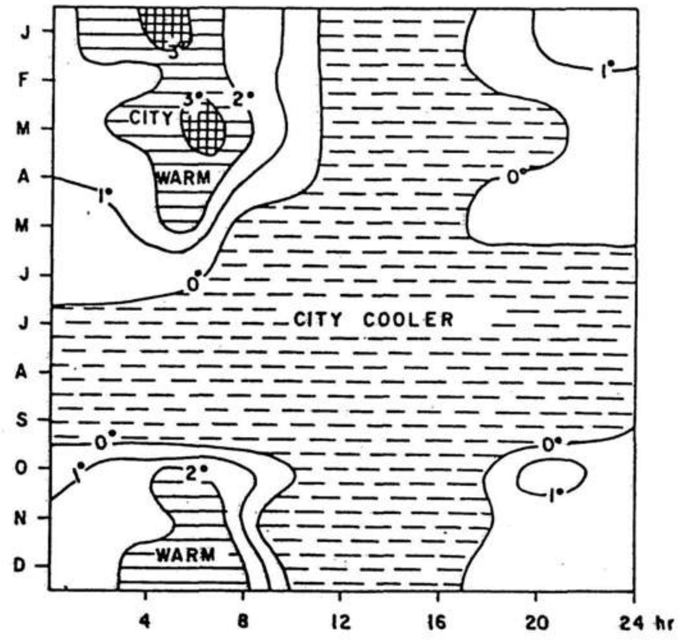

Figure 9. Variation of daily and monthly heat (cool) island intensity in Mexico City for 1979. ΔT(°C) - T at Tacubaya (urban) - T at Airport (suburban).

5.5 Surface temperature inversions and urban/rural temperature differences

As has been pointed out, heat island intensity is dependent on diverging urban/rural cooling rates, which in turn are caused by contrasts in radiation geometry and surface thermal properties, as has been suggested by Oke (1982). Therefore, differences in heat island strength depend most strongly on differences in rural cooling. We have seen that nocturnal radiation loss is strongest on calm clear nights that prevail during the dry season; as a result surface radiation inversions are then most frequent. Figures 10 and 11 illustrate the similarity of the frequency curve of surface inversions with the corresponding one of the average intensity of screen-level heat island. During the wet months of June to September urban/rural temperature contrasts are either null or negative (city cooler) while the frequency of surface inversions is very small.

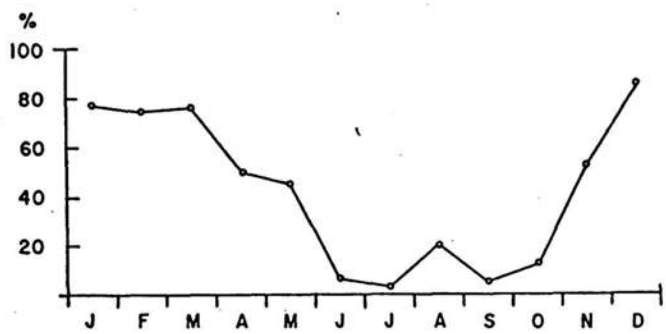

Figure 10. Frequency of surface inversions in Mexico City in 1981. Units are percent of observations at the Airport having surface inversions.

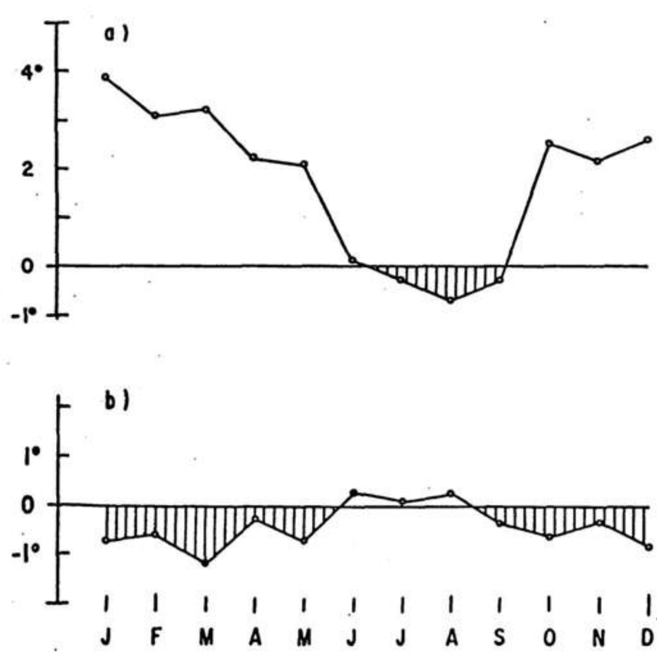

Figure 11. Average monthly variation of urban-suburban temperature difference (ΔT = T at Tacubaya - T at Airport) in Mexico City, (a) at 0700 h and (b) at 1400 h.

Since rural cooling rates seem to be relevant in determining heat island intensity, a relationship similar to that found by Ludwig and Kealoha (1968) for a mid-latitude city may be established for Mexico City. For some months in the dry season this relationship is very clear (Figure 12).

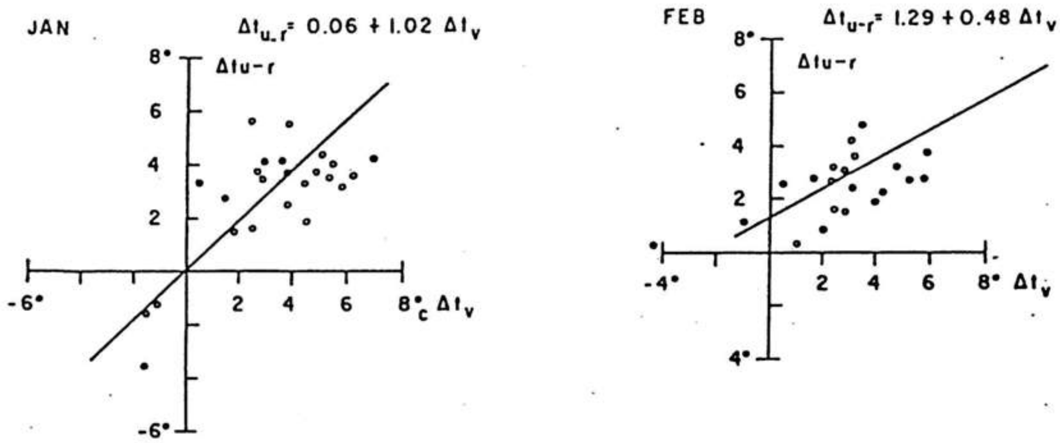

Figure 12. Urban/rural temperature differences vs. surface inversion strength in Mexico City for two dry months in 1981.

6. HUMIDITY

The spatial distribution of the near-surface relative humidity for Mexico City, as estimated from psychrometer readings taken from a vehicle, have been reported by Jauregui (1971). Differences of up to 25% in relative humidity were found between the centre of the urban area and the airport at the time of maximum heat island intensity (0400 to 0600 h) as illustrated in Figure 13. The relative humidity pattern closely follows the heat island morphology on the same morning. During the dry season (except for the month of March) relative humidities are higher in the suburbs (Airport) than in the centre of town at the time of maximum heat island intensity. They are very similar during the wet months for both sites, as illustrated in Figure 14. This is to be expected given the inverse relationship between relative humidities and air temperature. However, urban/rural specific humidity (q) differences exhibit a marked diurnal variation, as seen in Figure 15. At night, and during the dry season, the city is more humid, whereas by day no appreciable differences are observed. These results are in agreement with those of cities in the mid-latitudes (Hage, 1975; Ackerman, 1971). During the wet season however, urban/rural humidity contrasts are negative (city drier) during the whole day. This is probably due to enhancement of evaporation from pavement and roof surfaces and more rural evapotranspiration, but the exact reasons for this situation are not yet clear.

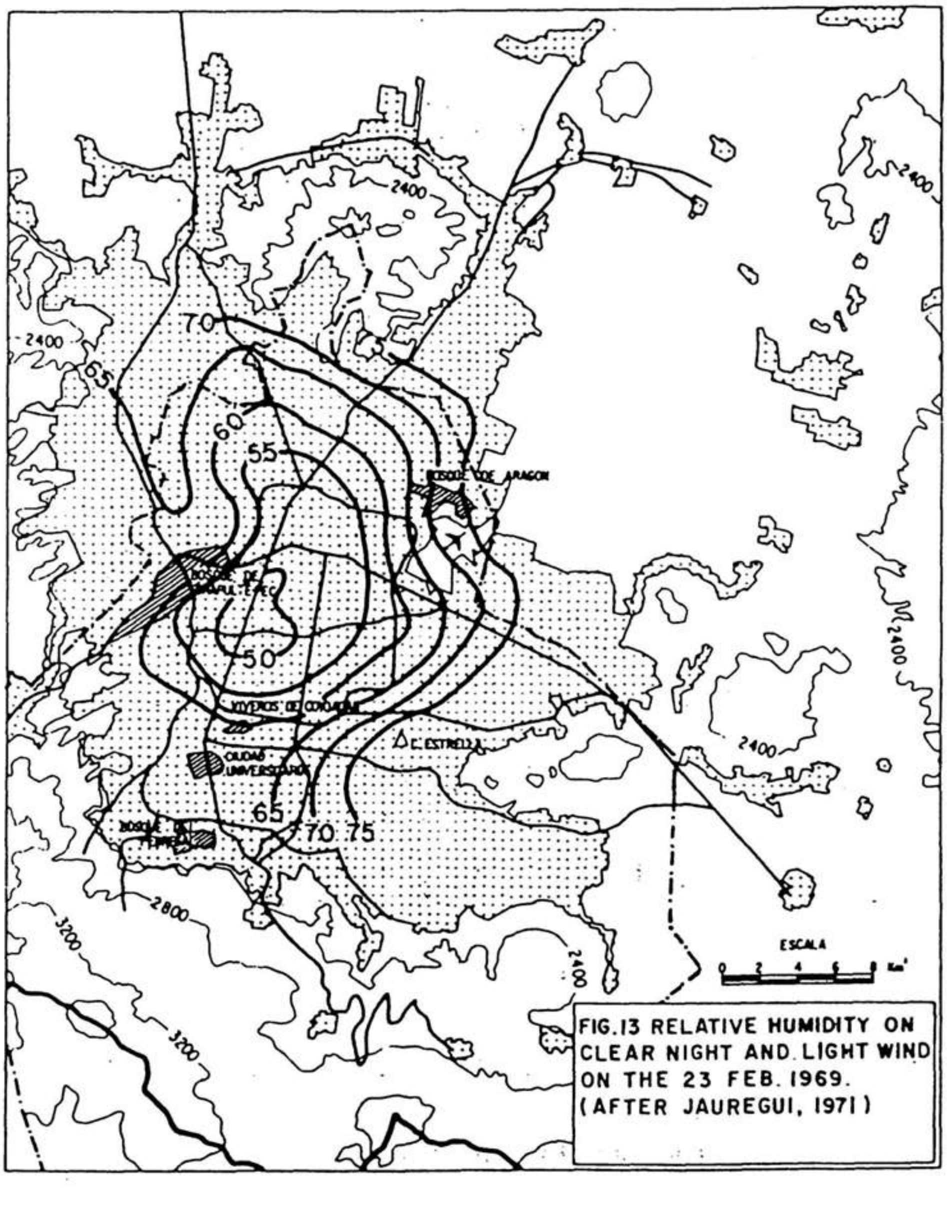

FIG.13 RELATIVE HUMIDITY ON CLEAR NIGHT AND LIGHT WIND ON THE 23 FEB. 1969. (AFTER JAUREGUI, 1971)

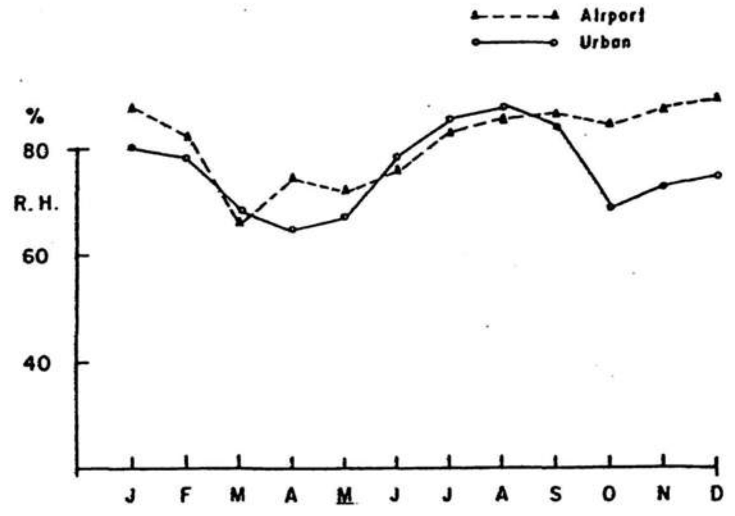

Figure 14. Seasonal variation of urban/suburban relative humidity differences at 0500 h for Mexico City, 1979.

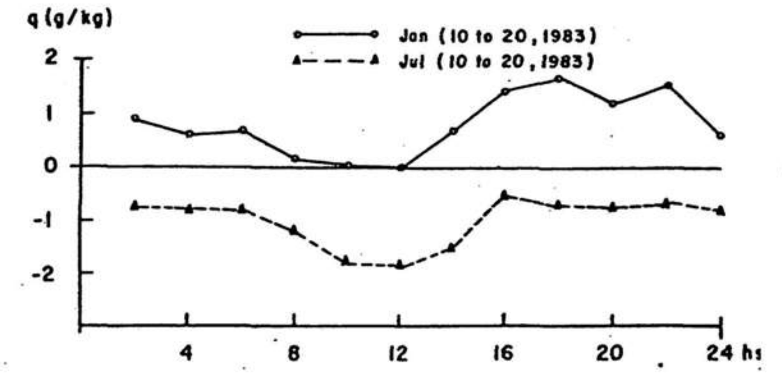

Figure 15. Diurnal variation of average urban/suburban specific humidity differences for 10 days in Mexico City.

7. URBAN-RELATED PRECIPITATION ANOMALIES

Urban effects on precipitation for Mexico City have been documented by Jauregui (1974), Jauregui and Klaus (1982) and Klaus et al. (1983). The so-called 'rain island' is frequently observed, somewhat downwind from the industrial area of the capital city. Urban/suburban differences may be as high as 300% for individual days. The increase in precipitation in the city has been accompanied by a rise in the frequency of heavy thundershowers. A steady increase in rainfall amounts since the 1940s is apparent from urban/rural precipitation ratio analysis. The observed precipitation enhancement occurs in typical tropical air masses, however much research remains to be done in order to determine the nature of the processes contributing to the anomaly.

8. VENTILATION

According to mid-latitude experience (Chandler, 1965), wind-speeds are generally lower in built-up areas than in their surrounding country. For light winds however, wind speeds have been observed to increase in urban areas when nocturnal rural cooling leads to the formation of a surface inversion (Lee, 1979). Table 1 shows preliminary results of urban/rural wind-speed differences for Mexico City.

TABLE 1. *Urban/rural wind-speed differences for several periods of the day in Mexico City, 1980.*

PERIOD OF DAY (h)	JANUARY					JULY				
	CITY WIND STRONGER (%)	MEAN DIFF. (m s^{-1})	CITY WIND WEAKER (%)	MEAN DIFF. (m s^{-1})	CALM (%)	CITY WIND STRONGER (%)	MEAN DIFF. (m s^{-1})	CITY WIND WEAKER (%)	MEAN DIFF. (m s^{-1})	CALM (%)
0-12	18	0.7	9	1.2	73	49	0.7	5	0.4	45
13-19	19	0.8	74	1.8	6	61	1.0	35	0.8	1
20-23	36	1.1	30	1.4	32	58	0.7	23	0.9	11

In the cool season, and during the day, mean urban wind speeds are lower than those on the fringes of the city as a result of the prevailing regional turbulence and greater surface roughness of the city. At night however, the development of the rural surface inversion reduces near-surface rural wind speeds. When the air is not calm at both the urban and the rural sites (which very frequently occurs as seen in Table 1), a centripetal circulation develops reinforced by the strong heat island formation so characteristic of the dry season. During the wet season there is a high frequency of positive urban/rural wind-speed differences, as may be seen for July in Table 1. These cannot be attributed to temperature contrasts, since urban heat island and rural stability are then seldom observed.

Although these differences are somewhat small, and might be in part attributed to instrumental error or poor exposure of anemometers, another mechanism would have to be invoked in order to explain the acceleration of night-time urban winds during the wet season in Mexico City.

The high frequency of positive urban/rural wind speed differences observed in the afternoon during the wet season (Table 1) is a condition that tends to ameliorate human comfort during those hours. Higher wind speeds in the urban area in the afternoon could be attributed to the intensification of rain clouds induced by the city and their associated turbulent winds. However these winds are on the average less strong (by about 1 m s^{-1}) than those during the dry season, as may be seen in Figure 16.

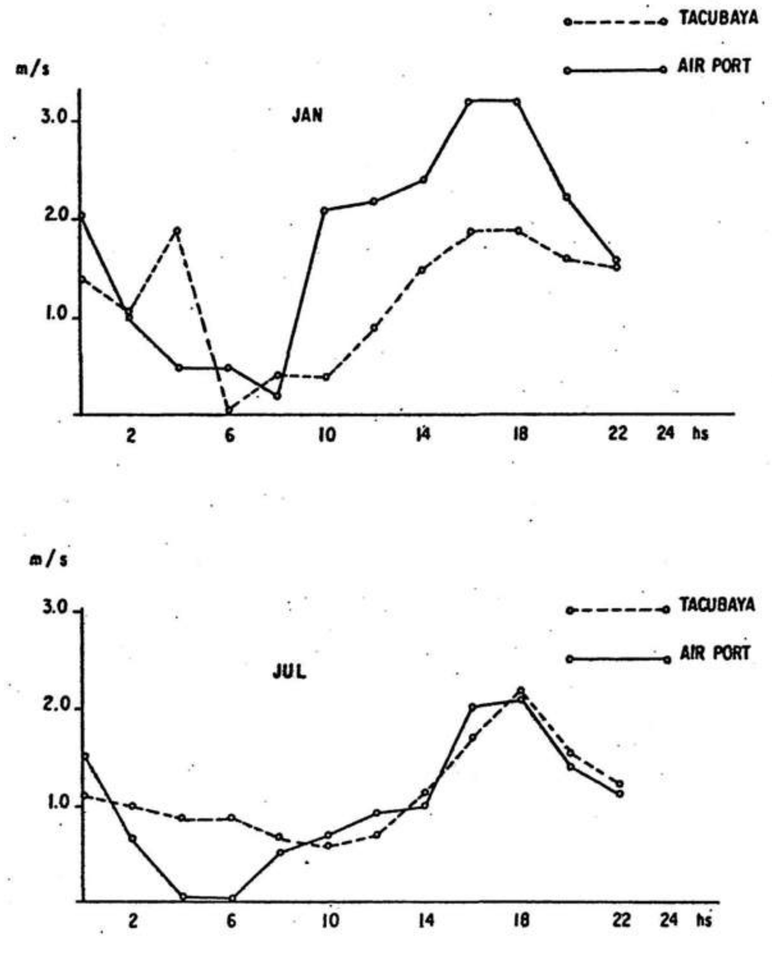

Figure 16. Wind strength in Mexico City (m s^{-1}) in 1980.

9. BIOCLIMATIC ASPECTS

Mexico City's urban area is so extensive that strong contrasts in several climatic elements are observed within its boundaries. Thus, such bioclimatic variables as temperature, humidity, insolation and wind show marked gradients across the city. We have already shown some of these distributions in previous sections. In what follows we shall briefly examine variations of some of the human comfort-related factors.

9.1 Insolation

The hours of sunshine show a seasonal as well as spatial variation across the Capital City, as illustrated in Figure 17. Insolation is least in the Southern portion of the City (University Station) that has a more humid climate, whereas the dry Eastern part of the urban area (Airport) receives higher insolation. As would be expected, high insolation is registered during the dry season, when clear skies predominate and therefore less contrast across the city is evident for this variable. These variations in the radiation climate within the city could provide useful information for architects and planners.

9.2 Assessment of human comfort

In order to distinguish zonal differences in bioclimate within the city, one may wish to make use of monthly pairs of the maximum (T max), and minimum (T min) temperatures and the corresponding relative humidities plotted on a psychrometric diagram, as illustrated in Figure 18 for urban (Tacubaya) and suburban (Airport) stations. Comfort conditions differ slightly (less comfort at Airport) from one place to the other according to these criteria. The relative importance of the incidence of high temperatures, or discomfort conditions for different areas in the city, and during the warm or hot season (March-May) may be evaluated by use of afternoon temperature-humidity histograms (Figure 19). According to such a criterion conditions of high values of temperature-humidity reaching the limits of comfort are only seldom experienced (one quarter of the time or less) in Mexico City's urban area. It should be noted however that even though during the warm season in the city midday air temperatures are slightly cooler than over the suburbs, we have also seen that wind speeds are frequently lower in the urban area at those hours and therefore, the beneficial effects of the cool island might be offset by the reduced ventilation and also by the reflection of radiation from downtown buildings.

In short, assessment of human comfort by use of bioclimatic indices should be supplemented with information on radiation and ventilation in such large tropical urban areas as Mexico City.

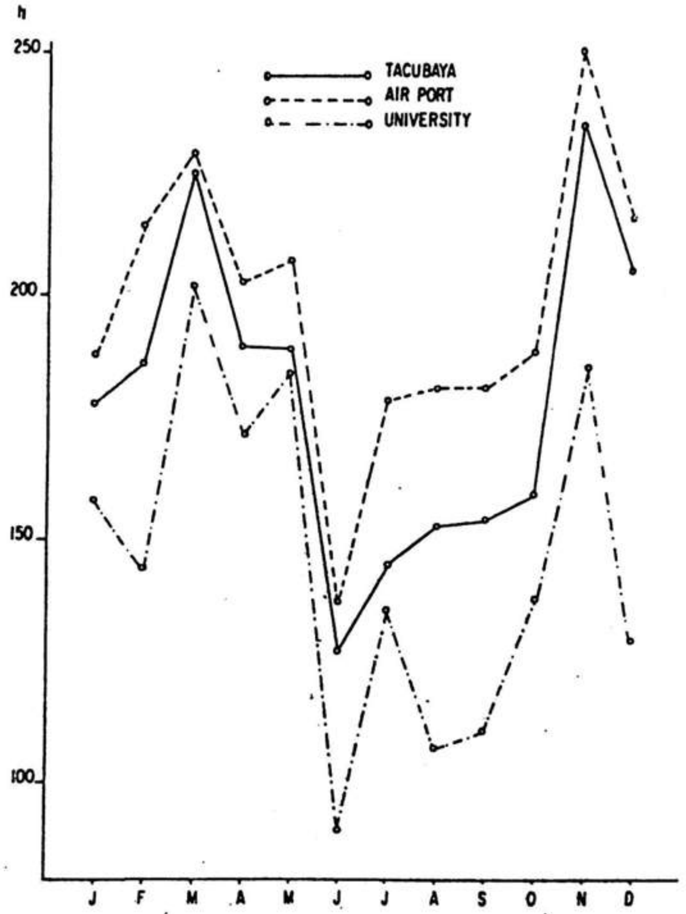

Figure 17. Hours of sunshine/month for 3 sites in Mexico City in 1981.

10. CONCLUSIONS

In this paper we have attempted to illustrate the effects of urbanization on climate in a large city in the Tropics. These effects have been determined by using routine observations from a metropolitan network of climatological (and radiosonde) stations established for other purposes (synoptic or hydrologic stations). It should be admitted however that not all medium or large urban areas in low latitudes have a reasonably good (if any) network of climatological stations. Even when they do, the location of stations is not always ideal, as is the case of Mexico City.

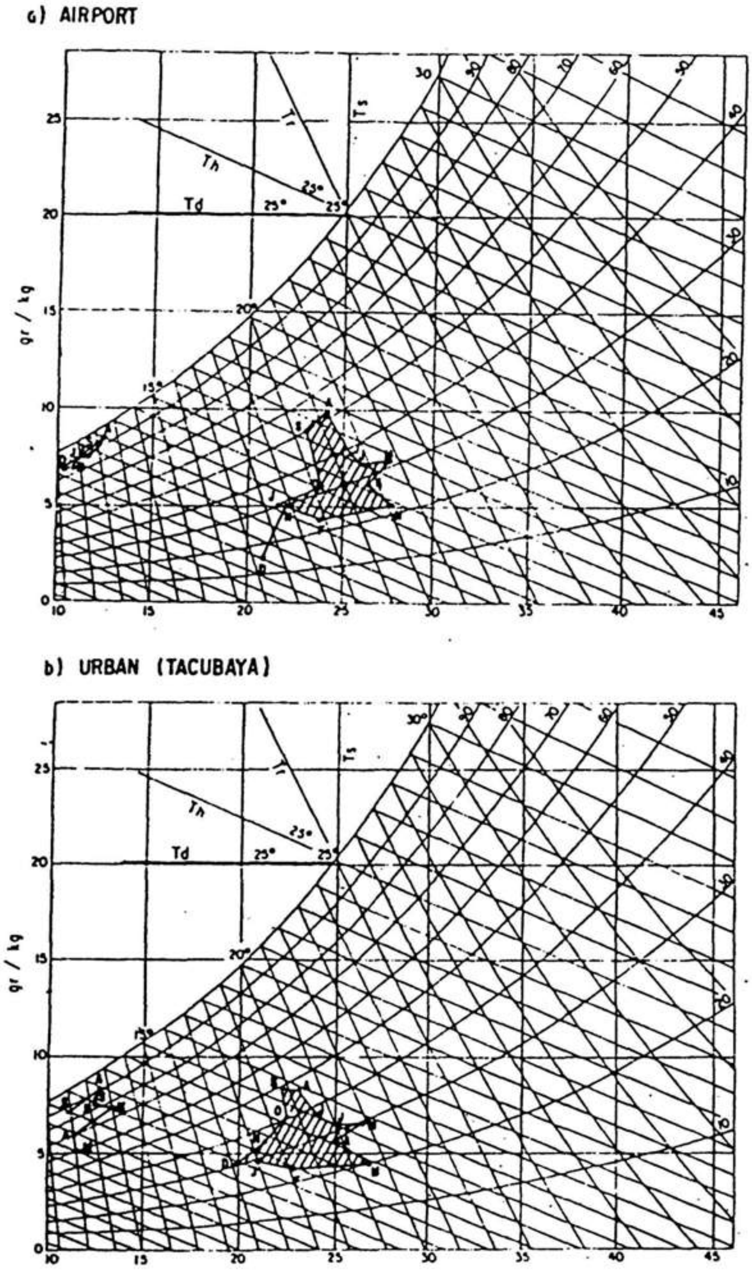

Figure 18. Morning and midday effective temperature climograms for two sites in Mexico City, 1980. (T – temperature, Tw - wet-bulb, Td - dewpoint, Tr - resultant temperature.)

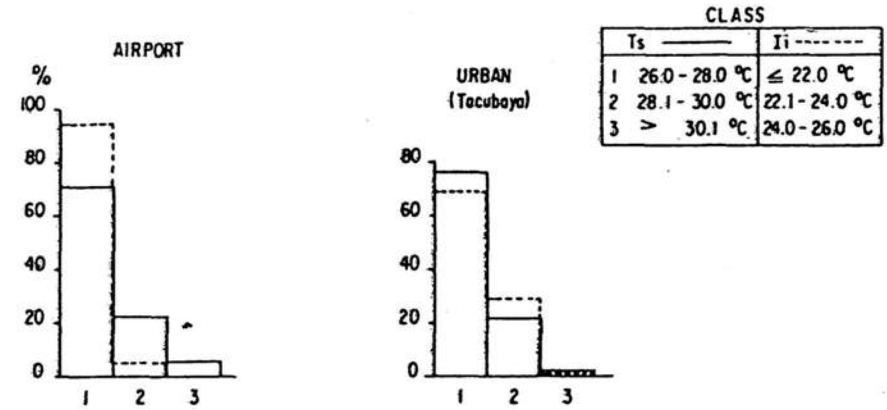

Figure 19. Frequency distribution of temperature and discomfort index at 1200 to 1800 h during the warm season (March-May) for a suburban (Airport) and urban (Tacubaya) stations in Mexico City in 1978-79.

Even with these limitations, knowledge about changes of climate in other important urban areas in the Tropics may be derived from analysis of standard data from urban networks. The observed changes of climate due to urbanization in Mexico City (with variations in magnitude and time) bear a resemblance to those that have been documented for mid-latitude urban areas.

The heat-island effect tends to reduce night comfort in inland tropical urban areas like Mexico City during the warm, dry season. The cool island seems to be a characteristic day-time phenomenon which tends to ameliorate human comfort during the afternoon when winds are accelerated within the city. For the tropical city it would perhaps be of more interest to investigate relationships between the cool island (rather than the heat island) and the associated acceleration of turbulent surface winds caused by day-time convective-advective processes.

Although the influence of cities on rainfall is difficult to evaluate, the urban area of Mexico City seems to enhance the intensity of afternoon showers downwind from the centre of the city during the wet season. This intensification could hardly be attributed to heat island effects (not present during the day) or anthropogenic heat release (which is relatively small).

Air pollutants (acting as freezing nuclei) and/or the increase in surface roughness, may perhaps play a more important role in inducing additional amounts of convective rain in a tropical urban area like Mexico City. During the warm season and on sunny days in the wet season, advection of hot surface air from semi-denuded lake-bed soils in the centre of the valley to the NE (upwind) may induce evapotranspiration losses that exceed the potential rate over the Eastern half of the city.

Finally, the pedestrian bioclimate in Mexico City, as assessed from simple discomfort indices, lies most of the time within the comfort zone, except during a few days in the warm season (March-May). It would be desirable however to revise mid-latitude comfort criteria in order to adjust them to tropical urban areas.

ACKNOWLEDGEMENTS

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SOME ASPECTS OF THE URBAN CLIMATE OF SHANGHAI

Chow Shu Djen
Department of Geography
East China Normal University
Shanghai 200062, People's Republic of China

1. INTRODUCTION

Shanghai is the largest and most important industrial and commercial centre in China. It consists of 11 urban districts and 10 suburban counties, with a total area of 6,192.4 square kilometres, of which the city proper occupies 24% of the area. Its regional climate belongs to the sub-tropical monsoon type.

This paper discusses the urban climate of Shanghai by making use of meteorological data obtained by the Shanghai Central Observatory covering a period of almost one hundred years (1885-1980). It also utilizes recent data furnished by stations in the ten counties of Shanghai, 170 rainfall stations distributed over the city and its suburbs covering more than twenty years; about 30 spot measurements at fixed stations; and mobile surveys both inside and outside Shanghai city on different occasions.

Shanghai is also the most rapidly growing city in China. This is the most obvious characteristic of Shanghai's urbanization (Table 1). Today Shanghai has a population of almost 12 million inhabitants (11,859,748; Chow 1983). During the interval 1865-1866 there were only 1240 inhabitants km^{-2}, but at present the urban population density has grown to 43,115 inhabitants km^{-2}. The contrast between the urban and rural areas is remarkable. As shown in Table 1 the urban population density is 47 times that of the rural area. Due to the high population density and the prosperous industry and commerce, more than 80% of the Shanghai urban area is built-up. Each inhabitant occupies only 0.466 m^2 of public greenspace. Therefore the anthropogenic modification of the land surface is quite striking.

TABLE 1. *The population density of Shanghai, 1865-1982.*

Period	1865-1866	1914-1915	1930	1935	1940-1942	1950	1960	1982	
								urban	rural
Population density (inhabitants km^{-2})	1,240	3,600	5,943	7,000	7,431	8,060	17,092	43,115	916

The coal consumption of Shanghai has risen from 6 million tons per year in 1965, to more than 20 million tons per year in recent years. Because of this, the city's atmosphere is notoriously liable to pollution, and this has effects which involve changes in the thermal properties of the atmosphere, cutting down the passage of sunlight, providing abundant condensation nuclei and adding anthropogenic heat to the environment.

In this paper the author deals with the urban heat island effect, urban wind field, urban humidity field and urban precipitation of Shanghai.

2. URBAN HEAT ISLAND

Multiple observations show that the urban area is always warmer. For example, on December 13, 1979, at 20 h (a calm, clear night) the warmest temperature (8.5°C) was associated with the highest density urban dwellings (Figure 1). At nearby rural stations the air temperature was only 2-3°C (Figure 2).

Average records of annual temperature, maximum temperature, minimum temperature, number of coldest days and hottest days all indicated that Shanghai has an urban heat island effect, as shown in Tables 2 and 3. Note that the urban heat island affects the minimum temperature more than the mean annual or the mean maximum temperature.

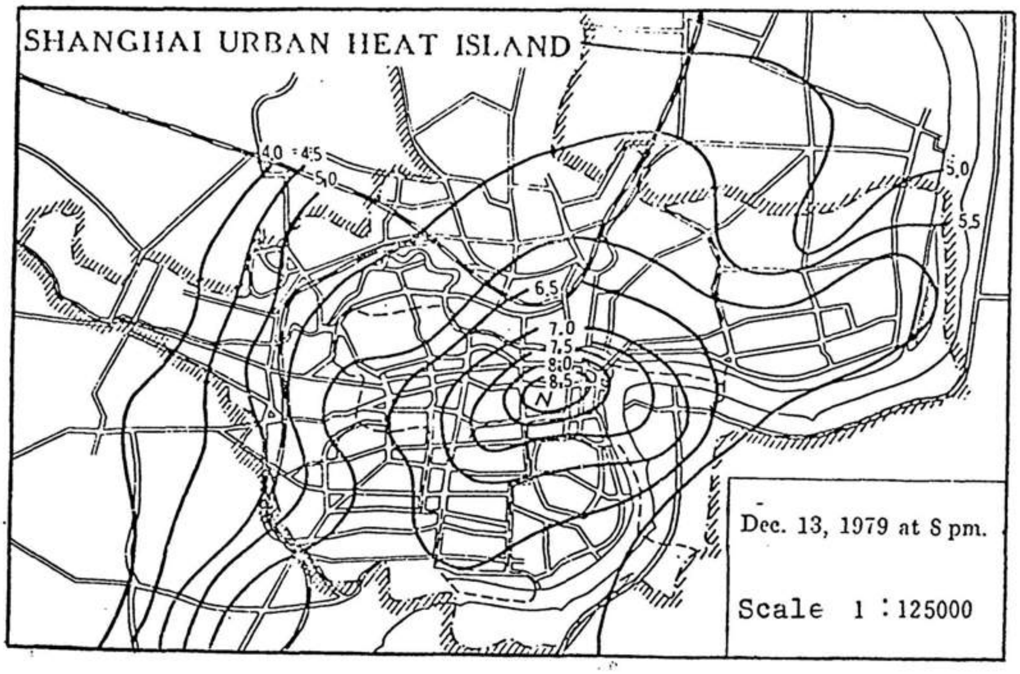

Figure 1. The urban heat island in Shanghai on December 13, 1979 at 20 h. For the larger context of this map see Figure 2. (after Chow and Chang 1982a).

TABLE 2. *Comparison of air temperature (°C) between Shanghai city and its suburbs (after Chow and Chang 1982a).*

	Mean annual temp.		Mean maximum temp.		Mean minimum temp.	
	Temp.	Difference	Temp.	Difference	Temp.	Difference
A Urban centre (Y)	15.5	A-C 0.8	20.2	A-C 0.0	13.4	A-C 1.6
B Urban area (Xu)	15.0	B-C 0.3	20.6	B-C 0.4	12.5	B-C 0.7
C Rural area (So)	14.7		20.2		11.8	

Stations - Y: Yitan, Xu: Xujihui, So: Songjiang.

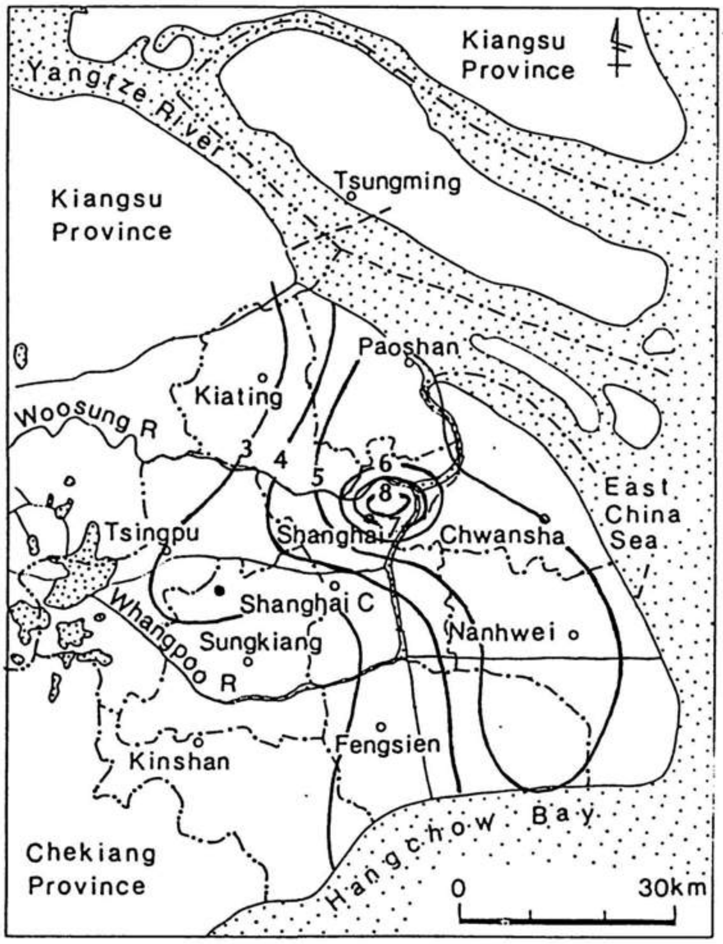

Figure 2. The distribution of air temperature in the Shanghai area on December 13, 1979 at 20 h (after Chow and Chang 1982a).

TABLE 3. *Comparison of air temperature (°C) between Xujihui (urban), Longhua (urban border) and Songjiang (rural) (after Chow and Chang 1982a).*

			No. of days on which a station recorded a temperature in the given range		
Year		Temperature range	Xujihui	Longhua	Songjiang
1956	Max. temp.	30.1 - 35.0	60	60	60
		35.1 - 40.0	14	6	5
	Min. temp.	-4.9 - 0.0	35	43	46
		-9.9 - -5.6	7	9	8
1957	Max. temp.	30.1 - 35.0	35	31	29
		35.1 - 40.0	16	11	11
	Min. temp.	-4.9 - 0.0	30	37	40
		-9.9 - -5.0	4	4	4

Diurnal and seasonal variation of urban heat island intensities in Shanghai are very evident. We find the urban heat island does not develop in the daytime, but in the interval from 15 to 17 h the urban-rural temperature difference increases rapidly. The urban heat island intensity remains at 2-4.5°C from dusk until sunrise, according to our summer measurements under the calm, clear synoptic conditions, as shown in Figure 3.

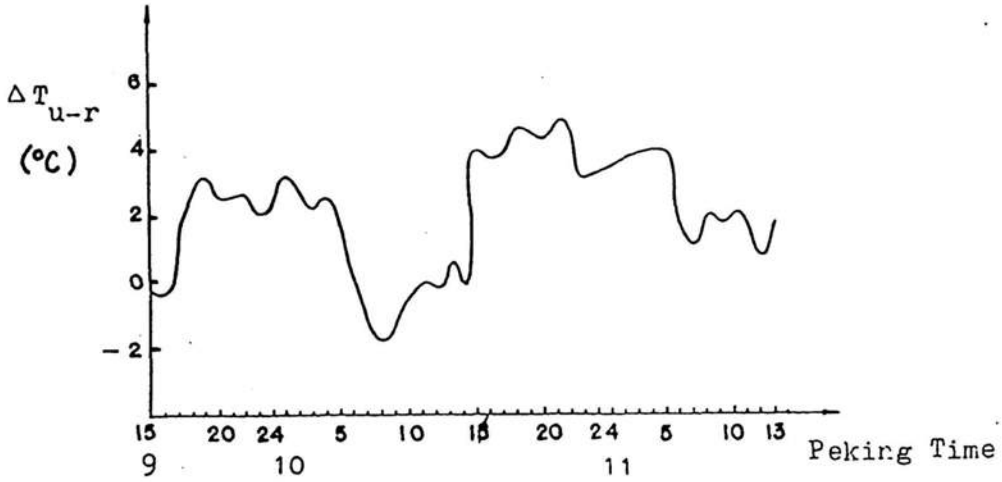

Figure 3. Diurnal variation of the urban heat island intensity of Shanghai during the period August 9-11, 1959 (after Chow and Chang 1982a).

From Figure 4 we can also see that the Shanghai urban-rural mean minimum monthly, and mean monthly temperature difference are largest in the late autumn and early winter (October to December), when cloud amount and wind velocities were at, or near, their minimum. During the spring and summer seasons the urban heat island intensity becomes weaker while the winds get stronger and there is more cloudiness.

Due to the urban heat island effect there is an obvious temporal trend toward higher temperature in Shanghai. By comparing Figures 5 and 6, we can see that from the end of the 19th century to the 1940's long-term annual temperature trends in Shanghai (Figure 5) are similar to those in both China and the whole World (Figure 6). This is the period of a general rise in temperature with the highest crest in the 1945-1949 period. After this the annual mean temperature decreased. Taking the average status of China in the past twenty years, each 5-year consecutive mean annual temperature has decreased below the secular mean annual temperature, and both the periods of 1955-1959 and 1965-1969 were the coldest. On the other hand Shanghai in the past twenty years, shows that every 5-year consecutive mean temperature was above the secular mean annual temperature (Chow, 1983). The recent 105-year temperature records kept by the Shanghai Central Observatory can be divided into four stages, with the first stage covering 15-yr and the other three covering 30-yr each. From Figure 5 we can see that Shanghai's mean stage annual temperature was increasing gradually, but the average status of China and the whole World, the 4th stage was colder than the third.

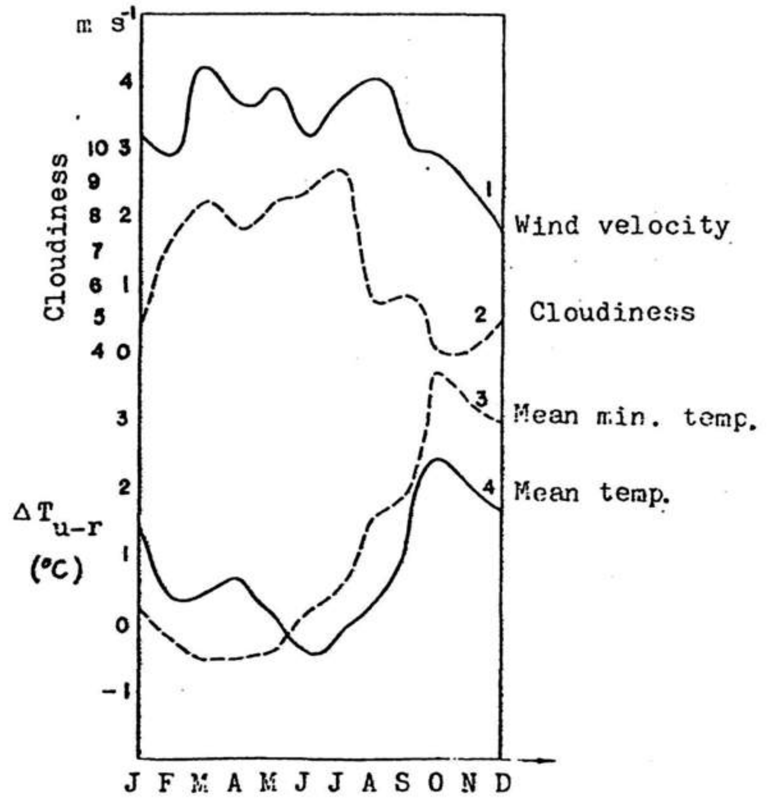

Figure 4. The annual variations of wind velocity (m s^{-1}) (1), cloudiness (2), and the urban heat island intensity, expressed in terms of the mean minimum temperature (3) and mean temperature (4) (after Chow and Chang 1982a).

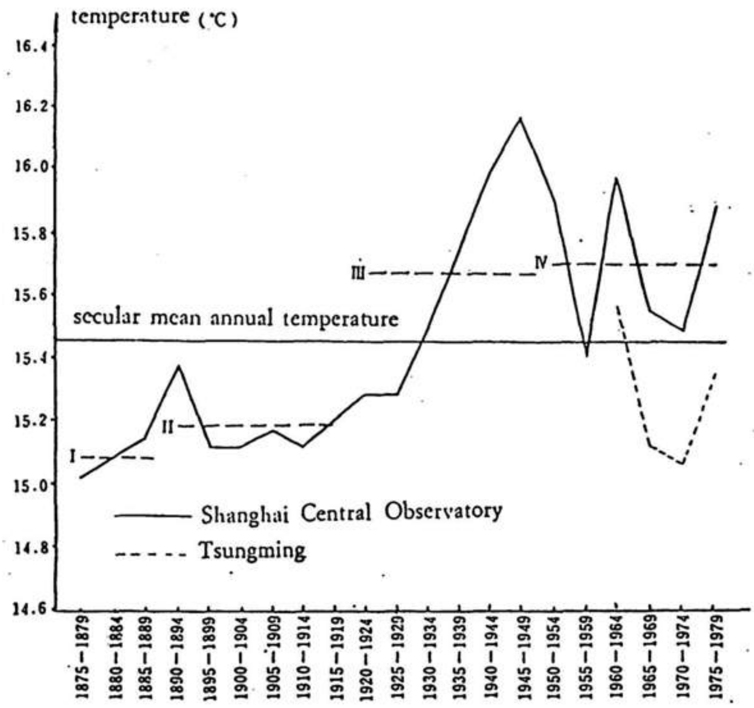

Figure 5. Long-term annual temperature trends (5-yr consecutive means) in Shanghai at the Central Observatory (1875-1979) and at Tsungming (rural, 1960-1979) (after Chow 1983).

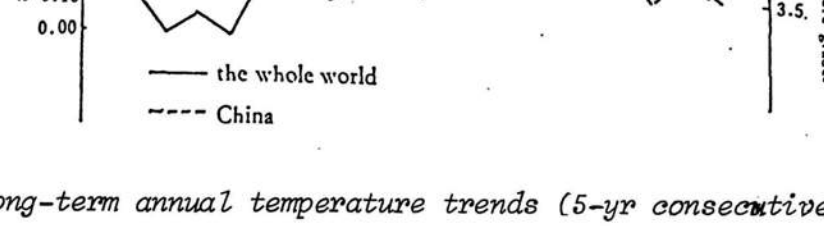

Figure 6. Long-term annual temperature trends (5-yr consecutive means) in the world (1870-1974) and annual temperature grades (5-yr consecutive means) in China (1910-1969) (after Chow 1983).

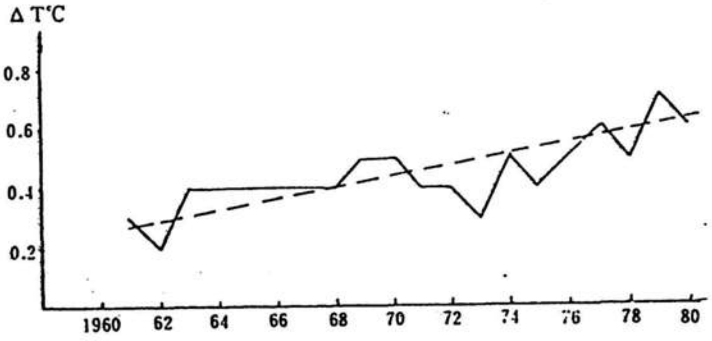

Figure 7. Evolution of annual temperature difference between Shanghai Central Observatory and Tsungming (rural) for the period 1961-1980 (after Chow 1983).

A comparison of the mean annual temperature for the period 1961-1980 at the Shanghai Central Observatory and the rural station at Tsungming shows a growing temperature difference from 0.2-0.3°C in the years 1961-1962, to 0.5-0.6°C from 1979 to 1980 (Figure 7). The difference of the annual temperature between the urban and rural areas of Shanghai increased by about 0.3-0.4°C in the past twenty years.

The secular trend of annual minimum temperatures in Shanghai were different from the mean annual temperatures in the following respects:
(1) The period of rising annual temperatures was longer for the minimum than the mean annual temperature by about 15-yr, as shown in Figure 8, and the highest crest appeared in 1960-1964.
(2) The average annual minimum temperature of the 4th stage (Figure 8) was much higher than that in the 3rd stage as compared to that for the mean in Figure 5.
These facts further prove that the urban heat island has a more pronounced effect on annual minimum temperature than on the mean annual temperature.

A comparison of the annual minumum temperatures (1960-1979) of Shanghai Central Observatory (31° 10'N), Shanghai County (31° 07'N) and Sungkiang (31° 00'N) also shows a gradual increase in the annual minimum temperature differences between stations (Figure 8). Shanghai Central Observatory is located on the edge of Shanghai city proper, and Sungkiang is the farthest of the three from the city. From Figure 8 we can see that Sungkiang has the coldest annual minimum temperature. This affords evidence that the urban heat island effect exceeds the latitude effect. The urban-rural annual minimum temperature difference between Shanghai Central Observatory and Sungkiang also exhibits a gradual increase (Figure 9).

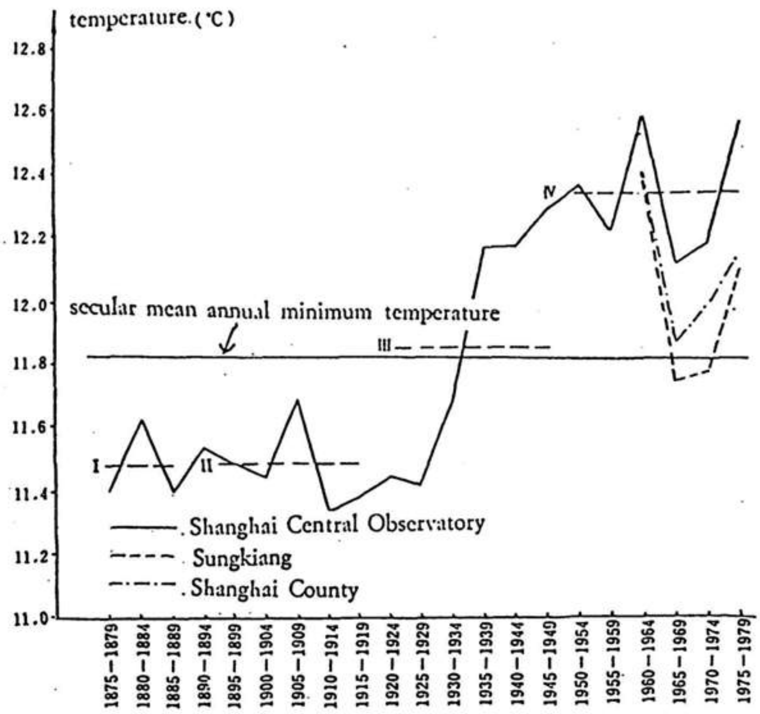

Figure 8. Long-term annual minimum temperature trends (5-yr consecutive means) in Shanghai Central Observatory (1875-1979), Shanghai county (suburban, 1960-1979), and Sungkiang (rural, 1960-1979).

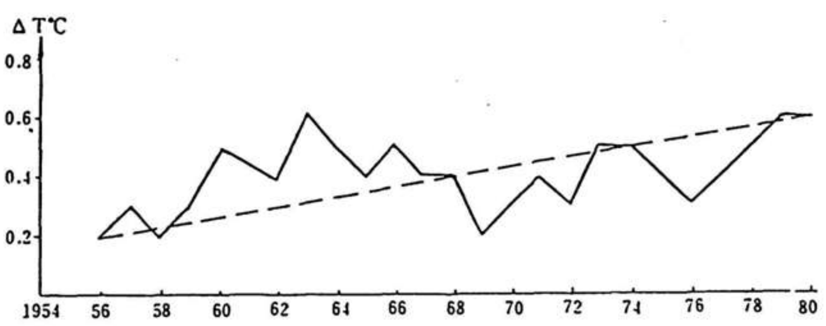

Figure 9. Evolution of annual minimum temperature difference between Shanghai Central Observatory and Sungkiang (rural, 1955-1980).

From the preceding discussion we can see that due to the rapid development of urbanization, the heat island effect of Shanghai city proper exhibits a greater temperature increase during the period of rising temperature in the whole region, and a smaller decrease during the period of cooling. This is the reason why the temperature difference between the urban and rural areas increased gradually. The influence of Shanghai's urban development on the mean annual minimum temperature is more obvious than on the mean annual temperature.

3. URBAN WIND FIELD

Due to the heat island effect and the change in surface roughness, the urban wind field is rarely simple. When the synoptic situation indicates a stagnation pattern with clear sky, and calm or very weak winds, the Shanghai city area develops an urban heat island and the temperature field often induces a heat island circulation. For example, on December 6, 1979 at 14 h, December 13, 1979 at 20 h (Chow and Chang, 1982), December 7, 1980 at 13 h (Fang, 1984) etc., we can see a converging surface flow toward the centre of Shanghai city, and on December 7, 1980 at 13 h divergent flow was apparent at higher levels. The heat island circulation is a very common phenomenon in Shanghai urban wind field, and has important influences on precipitation, as we will discuss further.

As a result of the rapid development of urbanization in Shanghai the increasing built-up area has caused a change in surface roughness. This has had obvious effects on the urban wind field including a trend toward lower wind velocities (see Table 4).

From Table 4 we can see that, although the height of anemometer at the Shanghai Central Observatory has been changed three times, the wind velocity at each level always decreased gradually. For instance, at the height of 12 metres the recent average wind velocity (1976-1980) compared with the average wind velocity in the years 1894-1900 has decreased by 21.1%; at the 35 metres height the average wind velocity in the years 1951-1955 compared with the average wind velocity in the years 1911-1920 has decreased by 23.4%.

TABLE 4. *Long-term trend of the annual wind velocity (m s^{-1}) at Shanghai in the period 1884 to 1980.*

Anemometer height (m)	1884-1893	1894-1900	1901-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1955	1956-1960	1961-1965	1966-1970	1971-1975	1976-1980
12		3.8							3.2	3.2	3.1	3.1	3.0
35				4.7	4.7	4.2	4.2	3.6					
40-41	5.6		5.4										

A comparison of the mean annual wind velocity in the Shanghai urban area with the rural stations in the same period (1961-1980) shows that the Whangpoo Garden station (located in the Shanghai city centre) has a mean annual wind velocity of 2.9 m s^{-1}, at the Shanghai Centre Observatory it is 3.1 m s^{-1}, at the farthest south rural station of Kinahan it is 3.7 m s^{-1}, and at the furthest north rural station of Paoshan it is 4.1 m s^{-1} (see Figure 10).

Figure 11 indicates the mean annual wind velocity for 1983 across the city of Shanghai, using six stations to form a N-S cross-section. We can see the lowest wind velocity appeared in the city centre, and as distance from the city centre increases, so does the mean annual wind velocity.

It must be pointed out that the wind velocity of Shanghai urban area is not always less than in the rural area. When the prevailing regional wind velocity is very weak, vertical thermal turbulence develops due to the urban heat island effect. As a result the upper layer momentum transfer to the lower near-surface layer is enhanced and hence the wind velocity of urban area becomes higher than the rural value. We find there is a critical wind velocity. When the prevailing wind blows above the critical wind velocity, the surface roughness effect dominates, and the urban wind is weaker than the rural; when the prevailing wind is less than the critical wind velocity, the heat island effect takes precedence and hence the urban wind is stronger than the rural. According to our observations and calculations the critical wind velocity is 1.5 m s^{-1} in the summer, and 2-3 m s^{-1} in the other seasons (Fang, 1984).

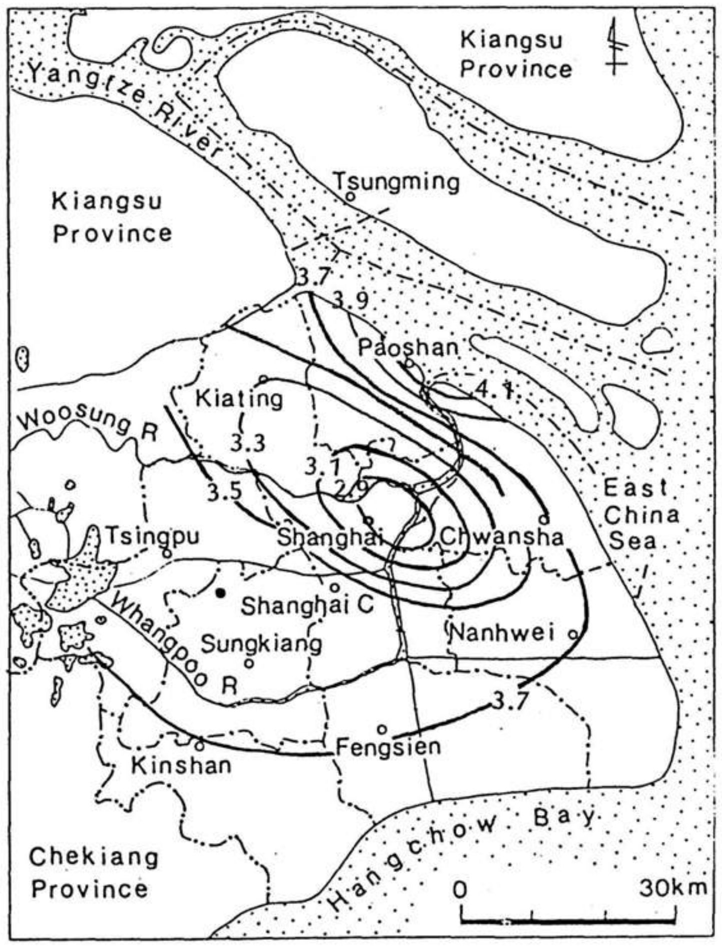

Figure 10. The mean annual wind velocity (m s^{-1}) in the Greater Shanghai area, in the period 1961 to 1980.

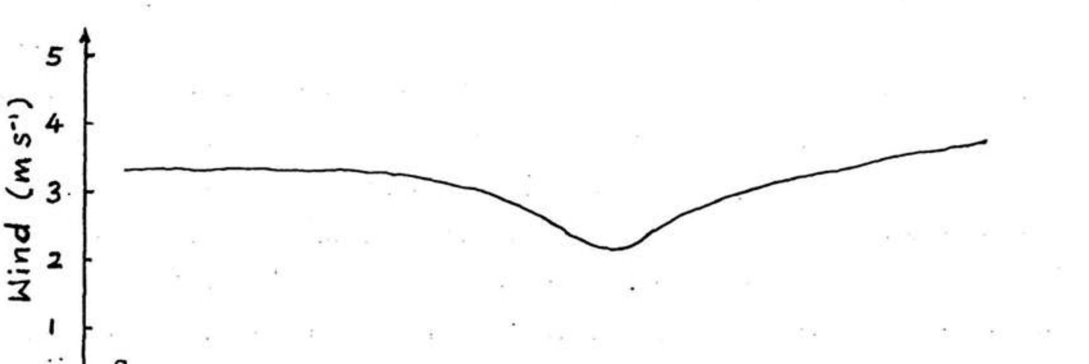

Figure 11. Wind velocity in a S-N transect of Shanghai. Mean annual wind velocity for 1983 (after Chow 1984).

In the Shanghai urban canopy, the wind is complicated by the different direction, width and shape of streets. We have conducted many surveys. For example, on September 28, 1981 we measured the wind velocity at different places near our East China Normal University and we found on the narrow path between the Electrical Building and the Natural Science Building that the wind velocity was stronger by about 42% as comparing with that on the Broad Square, due to the narrow-tube effect. The wind direction also changed at different places as indicated in Figure 12 (Wu, 1981).

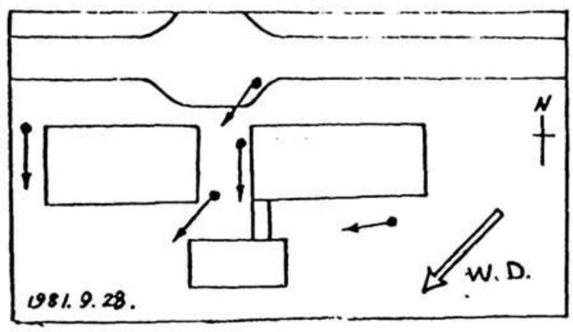

Figure 12. Wind directions found around the Electrical Building of the East China Normal University, on September 28, 1981 (after Wu 1981). W.D.: prevailing wind direction

4. URBAN HUMIDITY FIELD

By making use of 30 spot measurements at fixed stations, and mobile surveys inside and outside Shanghai city on August 9-11, 1959 at each hour, we are able to show the urban influences of Shanghai on the diurnal variation of humidity (Chow and Chang, 1983).

During the night-time (from midnight to 05 h, before sunrise) the reduced nocturnal cooling in the city results in lesser dew deposits than in the countryside, and a real humidity excess in the city, so that it exhibits a moisture 'island' similar to that of temperature. An example is shown in Figure 13 (at 05 h on August 10, 1959), but after sunrise at 07 h on the same day, the city was much drier, as shown in Figure 14.

In Figure 13 we can see the highest isohume (31 mb) is associated with the highest density of urban dwellings, and the boundary of the moisture island is also clearly related to the city's border. The moisture island centre 'W' and the heat island centre 'N' were located nearby. In Figure 14 the lowest vapour pressure was 26.9 mb which appeared at the Sian Primary School located near the city centre, while the humidity of the rural station at the West Rural Garden was 30.6 mb. Again the heat island centre 'N' was near the dry island centre 'D'. According to our measurements conducted from 15 h on August 9 to 15 h on August 10, 1959 we found the following diurnal humidity variation differences between Shanghai urban and rural locations (Chow and Chang, 1983):

(1) The diurnal amplitude of humidity in the city was larger than in its surrounding counties.

(2) Only in the period from midnight to 5 h (before sunrise) was the humidity in the city higher than in its surrounding counties, at all other times it was lower.

(3) The relative humidity in the city was lower than its surrounding counties throughout the whole time. The highest relative humidity difference between urban and rural areas appeared between 17 and 21 h.

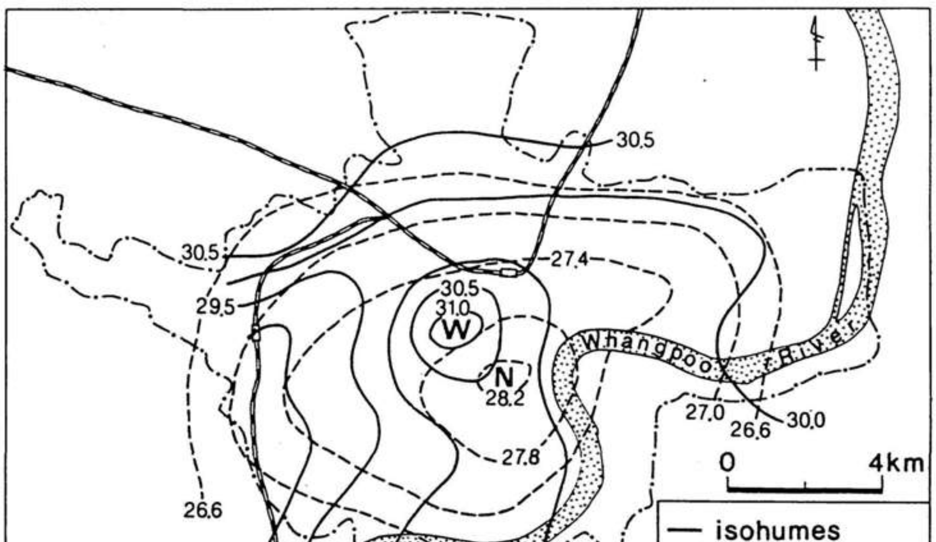

Figure 13. The distribution of humidity and temperature in Shanghai city at 5 h on August 10, 1959. Solid line: isohumes (mb) and W: The centre of the moisture island. Broken line: isotherms (^{o}C) and N: The centre of the heat island.

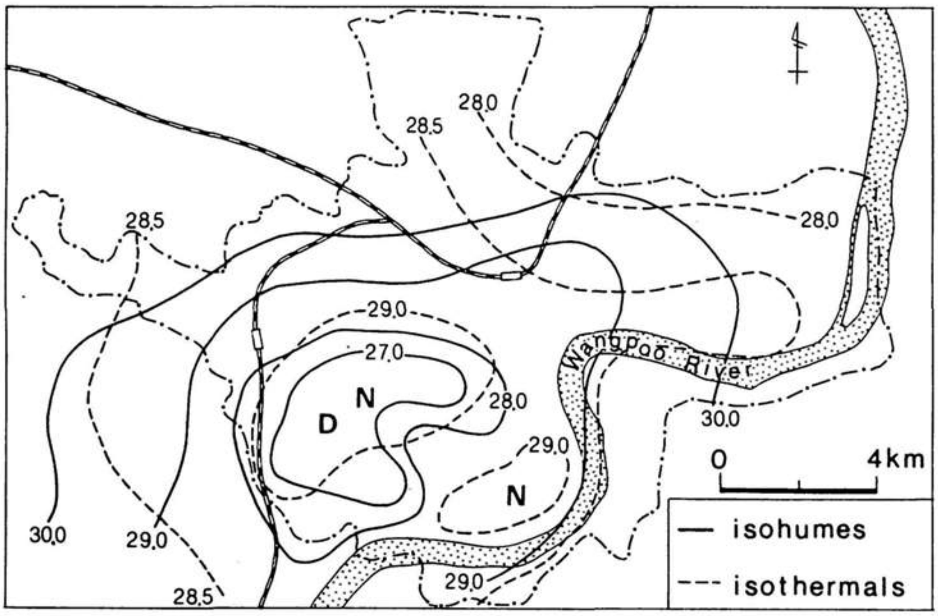

Figure 14. The distribution of humidity and temperature in Shanghai City at 7 h August 10, 1959. Solid line: isohumes (mb) and D: The centre of the dry island. Broken line: isotherms (°C) and N: The centre of the heat island.

TABLE 5. *Long-term annual humidity trends in Shanghai for the period 1941-80.*

Station	1941-1950 VP (mb)	1941-1950 RH (%)	1951-1960 VP (mb)	1951-1960 RH (%)	1961-1970 VP (mb)	1961-1970 RH (%)	1971-1980 VP (mb)	1971-1980 RH (%)
Shanghai	16.64	80.9	16.4	80.3	16.4	79.0	16.17	78.6
Shanghai C.					16.67	81.0	16.54	81.8
Chwansha					16.74	82.0	16.66	82.3
Nanhwei					16.8	82.0	16.76	83.1

Shanghai: Shanghai Central Observatory
Shanghai C: Shanghai County

VP: vapour pressure
RH: relative humidity

Due to the rapidly increasing density of the urban population and the built-up area in the past forty years, each 10-yr mean annual humidity and relative humidity of the Shanghai Central Observatory has shown a decrease. On the other hand, the humidity conditions of the surrounding counties such as Shanghai County, Chwansha and Nanhwei were very different, as shown in Table 5. We can see that during the 1961-1980 period, the water vapour pressure in districts of Shanghai containing urban or rural areas all decreased, but the decrease in the urban area was much larger than at the rural stations and hence the urban-rural difference of humidity gradually increased. For instance, in the years 1961-1970 the vapour pressure difference between the Shanghai Central Observatory and Nanhwei was 0.4 mb, but in the years 1971-1980 it was 0.59 mb. During the same period at many rural stations such as Shanghai County, Chwansha and Nanhwei the relative humidity gradually increased, and hence the urban-rural difference of relative humidity was more striking. For example in the years 1961-1970 the difference of relative humidity between Nanhwei and Shanghai Central Observatory was 3%, but in the years 1971-1980 it increased to 4.5%. Apparently it was affected by the increase of the heat island intensity (Chow, 1984).

Both the mean annual water vapour pressure and the relative humidity obtained by the Shanghai Central Observatory in the period 1961-80 were lower than those of the ten rural stations (see Figures 15 and 16). The lowest isoline was around the city proper, and as the distance from the city increases so does the humidity, and especially near the southern border the humidity gradient is quite remarkable.

The annual variation of vapour pressure and relative humidity at the Shanghai Central Observatory and at Sungkiang are shown in Figure 17. There is a larger urban-rural vapour pressure difference in the warm season but the highest urban-rural relative humidity difference appears in October. This is the month with the largest heat island intensity as mentioned before (e.g. see Figure 4).

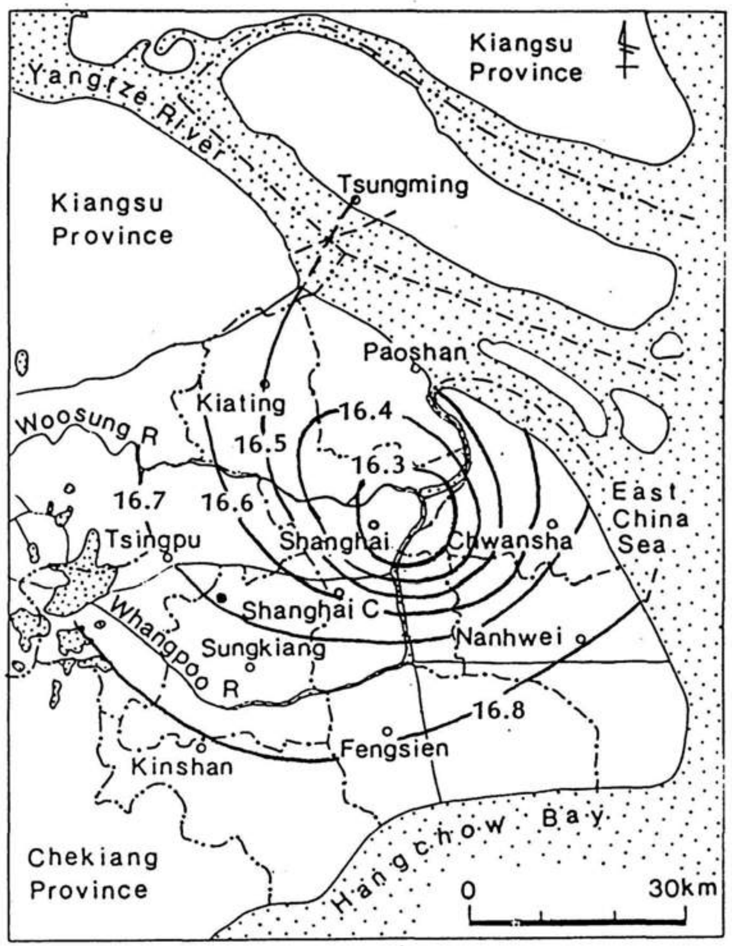

Figure 15. The mean annual humidity (vapour pressure) in Shanghai districts in the period 1961-1980.

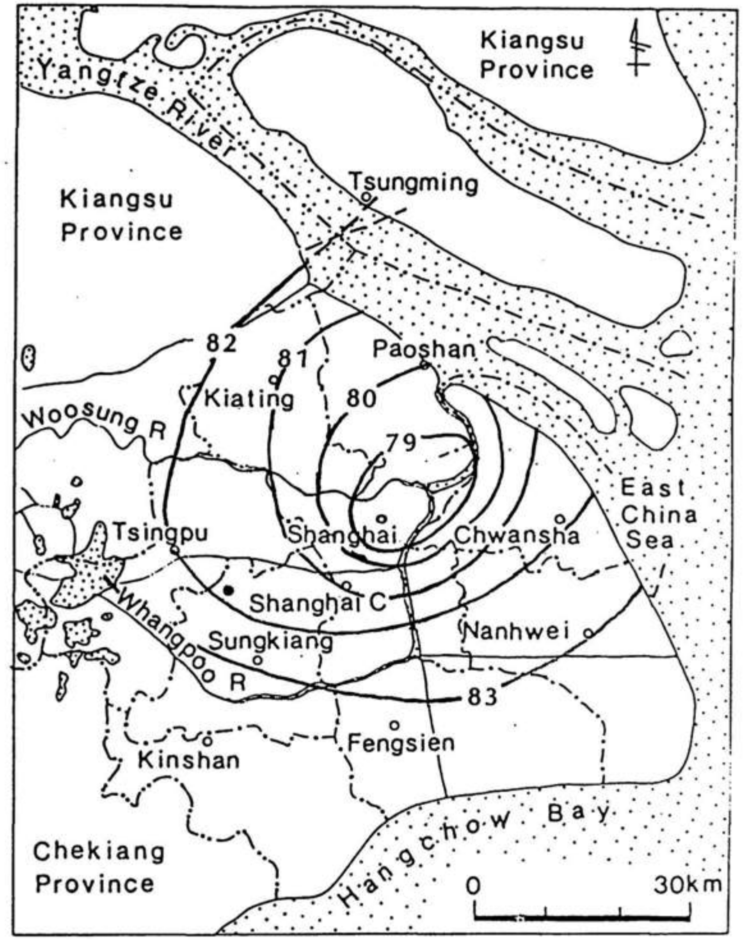

Figure 16. The mean annual relative humidity in Shanghai districts in the period 1961-1980.

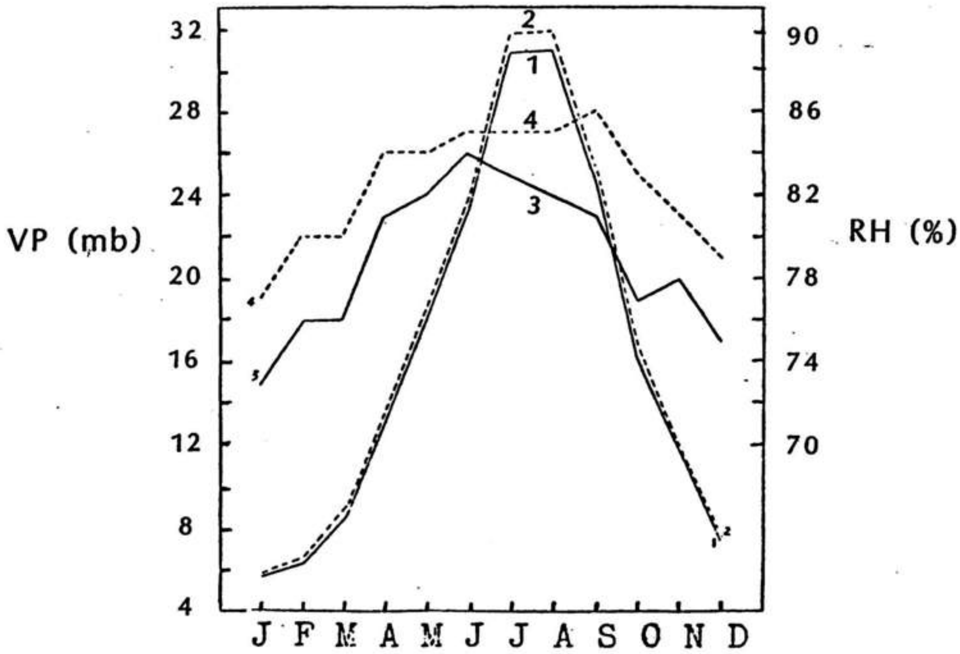

Figure 17. The annual variation of vapour pressure (VP) and relative humidity (RH) at the Shanghai Central Observatory and at Sungkiang in the period 1961-70.

Key-1: Shanghai: VP

2: Sungkiang: VP

3: Shanghai: RH

4. Sungkiang: RH

5. URBAN PRECIPITATION

Analysis of 20-years (1959-1978) of precipitation records for the Shanghai region has revealed evidence of urban influences on the distribution of annual precipitation (Figure 18) and the rainy season (May-September) precipitation (Figure 19). According to the annual precipitation distribution régime of the Yangtze River Delta, the amount of annual precipitation decreases from south to north, with more than 1100 mm near Hanchow Bay, to 1000 mm along the north side of the Yangtze River (Chow, 1959). But due to Shanghai's urban influences the amounts increase over the urban area, with a maximum to the lee of the city, and therafter it decreases again. Even more striking is the increase in the rainy season. During that period the precipitation amount over the urban area was about 50 mm higher than that occurring in the southern and northern rural districts. During the other seasons (October-April) the distribution of precipitation does not seem to be affected by urban influences.

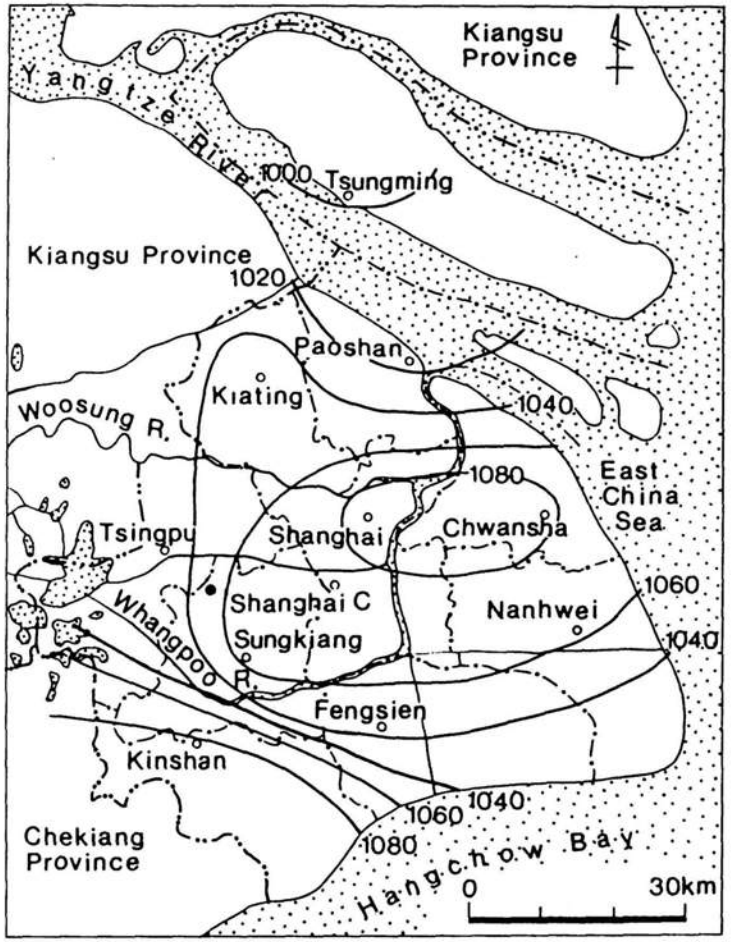

Figure 18. Mean annual precipitation over Shanghai districts (1959-1978).

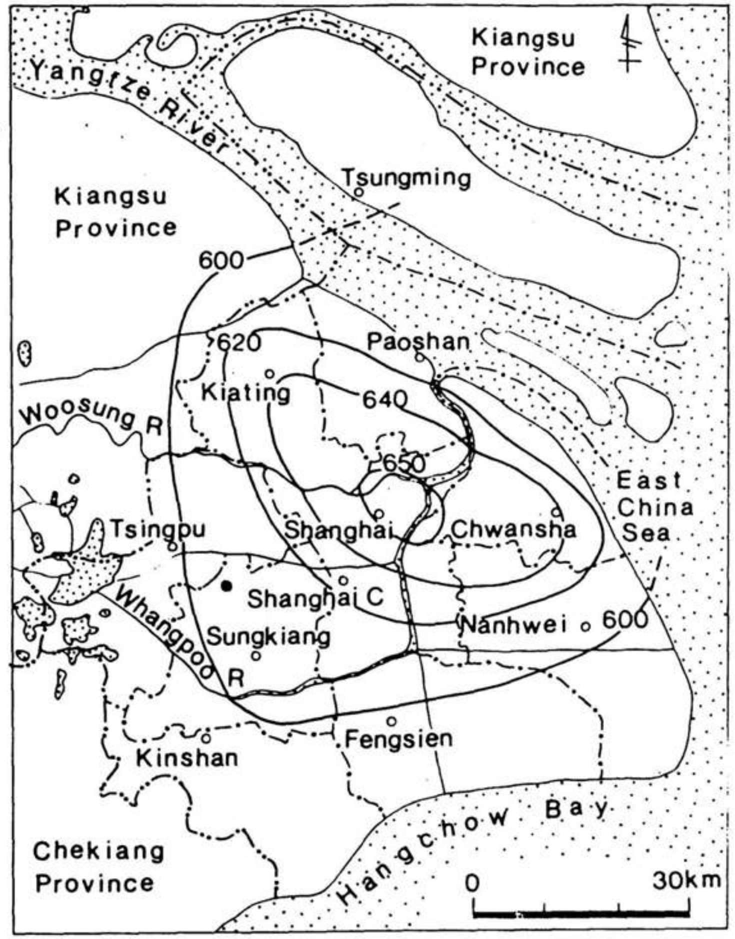

Figure 19. Mean precipitation during the rainy season (May-Sep.) (mm) over Shanghai districts (1959-1978).

CLIMATE OF SHANGHAI

Using synoptic climatological analysis we find that urban influences on precipitation might be dominant only under certain weather conditions, such as a weak low pressure pattern, the warm sector of a weak cyclone, stationary fronts and stationary shearing deformation (Chow, 1983). Many rain events were initiated by the rising vertical motion over the urban area with a heat island. For example, at 18-19 h on July 12, 1978 the southern sector of Shanghai city received 30.5 mm of precipitation from a single thunderstorm cell, while there were no other storm reported in the area. The perturbation wind field at 17 h on July 12, 1978 showed a convergent centre over Shanghai in the same sector and there was a $2^{o}C$ urban heat island.

There are many rain events showing that the urban 'obstacle' effect was the important cause for augmentation of precipitation. When rain-producing conditions like stationary fronts and stationary shearing deformation take place, they often linger longer over the urban area and hence increase the rainfall as compared with rural stations, where the fronts moved faster. For example, on the synoptic map of July 17, 1978 there was stationary shearing deformation over the district of Shanghai. At 08 h the wind direction was WNW with a velocity of 3 m s^{-1}. The rain began at 09 h and continued for 8-12 hours in the urban area but for less than 4 hours at the windward rural station of Kaiting. During this rain event the southeastern sector of Shanghai city received more 100 mm of rainfall, while the Kaiting station only received 6.8 mm. On April 10, 1978 weather conditions at Shanghai were under the control of a weak cyclone. Rain began to fall from 18 h on April 10, 1978 and continued until 08 h on April 11, 1978. The distribution of rainfall during this time is indicated in Figure 20 which shows that within the urban area the precipitation was greater than 50 mm, while the windward (during the rainy time the prevailing wind direction was ESE with a velocity of 2 m s^{-1}) rural station of Nanhwei only received 6.2 mm, and Fengsien only 6.5 mm. The isohyets show the urban area as a rain 'island' (Chow and Chang, 1983). Because of the growing use of energy, especially the rise in consumption of coal, Shanghai city is notoriously liable to pollution, as we have mentioned before. The pollution products provide abundant condensation nuclei and are probably another factor affecting the precipitation.

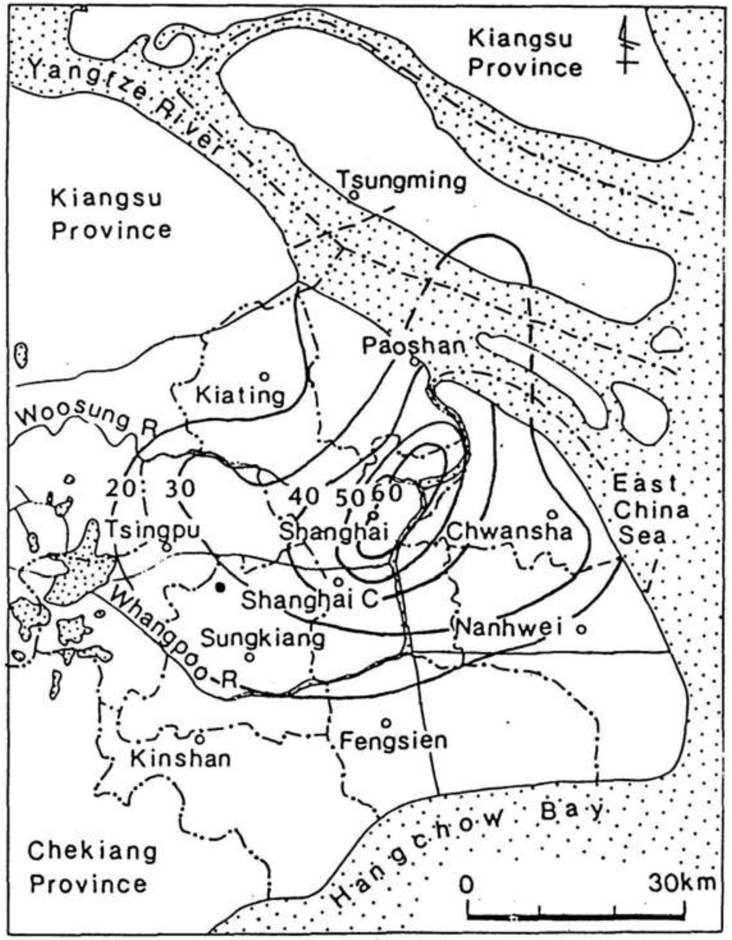

Figure 20. The distribution of precipitation over Shanghai districts at 18 h on April 10, 1978 to 08 h on April 11, 1978 (weak cyclone).

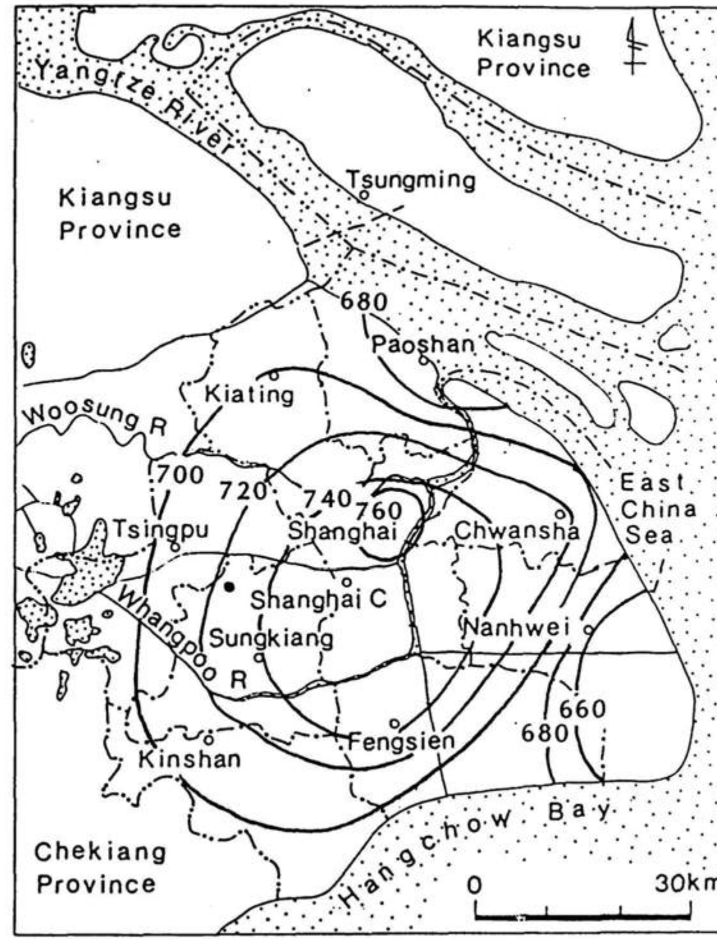

Figure 21. The distribution of annual precipitation over the districts of Shanghai for 1978.

The rain 'island' effect of the city of Shanghai was only dominant when the prevailing wind circulation was very weak. For instance, in 1978 the atmospheric circulation was very weak and in this year the whole of the Yangtze River Delta suffered a severe drought. According to the records of the Shanghai Central Observatory the precipitation received in this year was 772.3 mm which is only 56% of the amounts received in the previous year of 1977. From Figure 21 we can see that in this year the urban rain 'island' effect was very remarkable; but in 1977 with a strong general atmospheric circulation the distribution of precipitation did not seem to be affected by urban influences.

It should also be mentioned that due to air pollution acid rain has appeared in Shanghai since 1980. It was found that during the 1980-1983 period the area affected by acid precipitation has grown and pH values have dropped (Chow, et al., 1984).

6. CONCLUSION

From the preceding discussion it can be concluded that the urban influences of Shanghai on temperature, wind, humidity and precipitation are very pronounced. The long-term trend of temperature is towards greater warmth, winds have become weaker and the humidity has decreased. Under calm and clear weather conditions the urban area often appears as a heat island and a dry island; on summer nights the humidity excess in the city exhibits a moisture island and during the rainy season the urban area and its lee becomes a rain island. Hence we call them the 'four island effects' of Shanghai urban climate (Chow and Chang, 1982b). We find all these urban effects were dominant when the general atmospheric circulation is weak. It is very useful to apply the above rule for the forecasting of urban climate and for use in urban design.

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SOME ASPECTS OF THE URBAN CLIMATES OF TROPICAL AFRICA

J. S. Oguntoyinbo

Department of Geography
University of Ibadan, Ibadan, Nigeria

1. INTRODUCTION

Urban climatology is a relatively recent expansion of the frontier of knowledge in climatology. It has developed as a result of what Oke (1978) called inadvertent climate modification. Such inadvertent modification arose as Man built towns, cities, etc. in which various types of activities developed. As would be expected the need to undertake research in urban climate has been pursued most actively within the past fifty to one hundred years in the temperate regions where rapid urbanization, industrialization and the development of dense mass transportation systems have led to the recognition of Man's impact on climate. This awareness led to the development of urban climatology.

Such studies began with the monitoring of the basic climatic elements in the city centre and relating these to similar measurements in the rural areas (Howard, 1818). These studies were later extended to the taking of transect readings across cities (Chandler 1962; Oke 1982; Nakamura 1967). In more recent times research projects have been designed to study the fluxes of energy within the urban atmosphere (Kalanda et al., 1980; Nunez and Oke 1976,

1977) and to compare the effects of city size on urban climate (Oke 1973). These studies have evolved models and theories on urban climate in the temperate latitudes.

In tropical Africa, however, the slow rate of urbanization and industrialization and the general lack of expertise have, until recently, led to a lack of interest in urban climatology. Oke (1977) noted this lack of knowledge not only in the urban climates of tropical cities but also of polar regions and pointed out the need to intensify urban climatological studies in those areas in order to avoid the mistakes in planning made in some temperate latitude cities.

The recent rapid urbanization, industrialization and the increasing use of automobiles in tropical African cities has begun to generate interest in urban climatology. This paper attempts to utilize the few studies available to illustrate the characteristics of urban climate in tropical Africa; a case study approach will be adopted: first, to highlight the urban climate characteristics, secondly, to utilize the available results to outline the limitations of the studies already carried out and thirdly, to suggest areas for further research into tropical African urban climates. As may be expected the depths of the results are highly variable as the studies were not coordinated by the same individuals or groups. Prior to this it is pertinent to briefly outline the broad characteristics of the structural layouts of tropical African cities.

1.1 Characteristics of Tropical African Cities

Cities in tropical Africa can be grouped into two broad categories; first the pre-colonial cities onto which colonial and post-colonial extensions have been grafted and second, the colonial and post-colonial cities. The former category of cities is characterised by a traditional core which is sometimes surrounded by a city wall; examples include Kano, Benin City and Ibadan; such a city is marked by structural duality consisting of a core which is often occupied by the indegenes and is characteristically ill-planned, usually, one-storey low buildings with corrugated roof tops and mud walls. With the advent of the colonial era, strangers were allowed to settle on the city outskirts. The colonial administrators built their offices and European quarters in well-planned Government Residential Areas on the city outskirts; provision was also made for the native migrant civil servants in another part of the city. Lord Lugard replicated such a pattern in Ibadan in 1917 (Ayeni 1982). In the post-colonial era, modern housing and industrial estates have been added to such cities. Ibadan is a typical example (Figure 1).

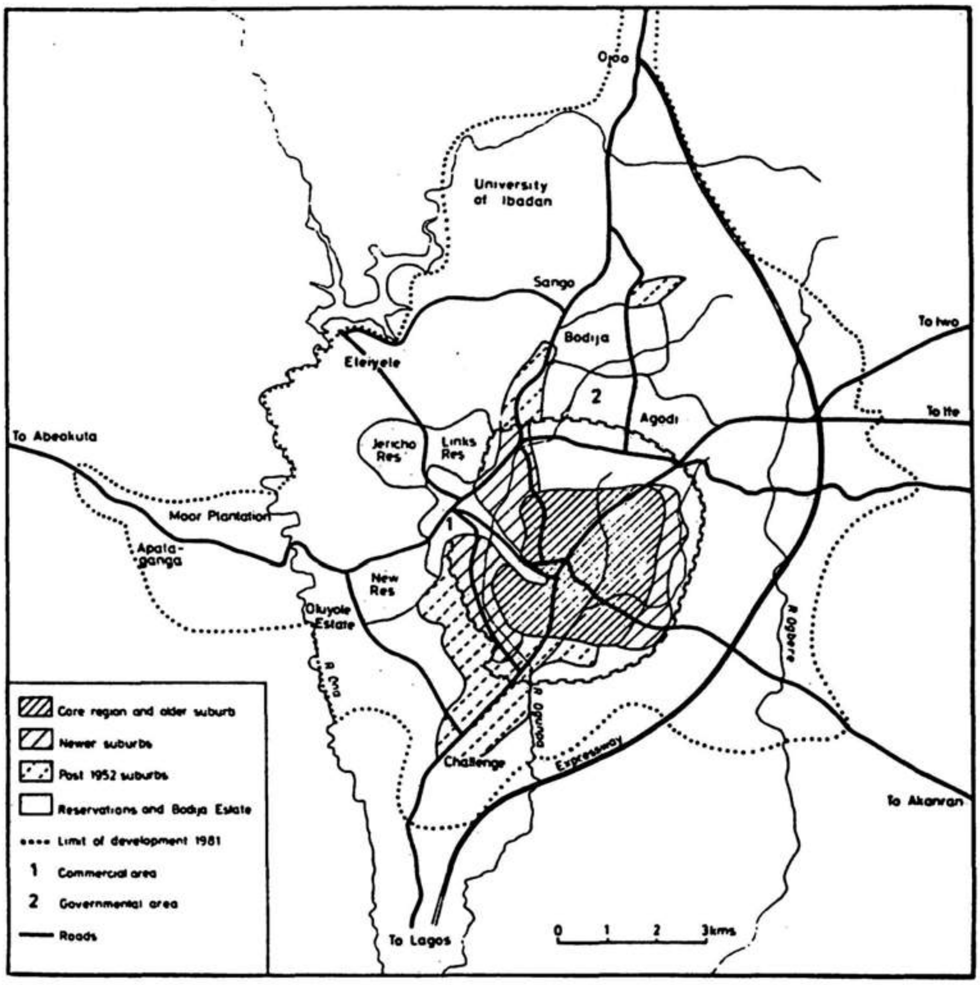


Figure 1. Ibadan: Land-use.

Colonial cities like Lagos, Nairobi and Dakar have been planned with West European standards with the commercial centre, railway station and a green belt separating the European part of the city on one side, from the African, etc. on the other (Figure 2).

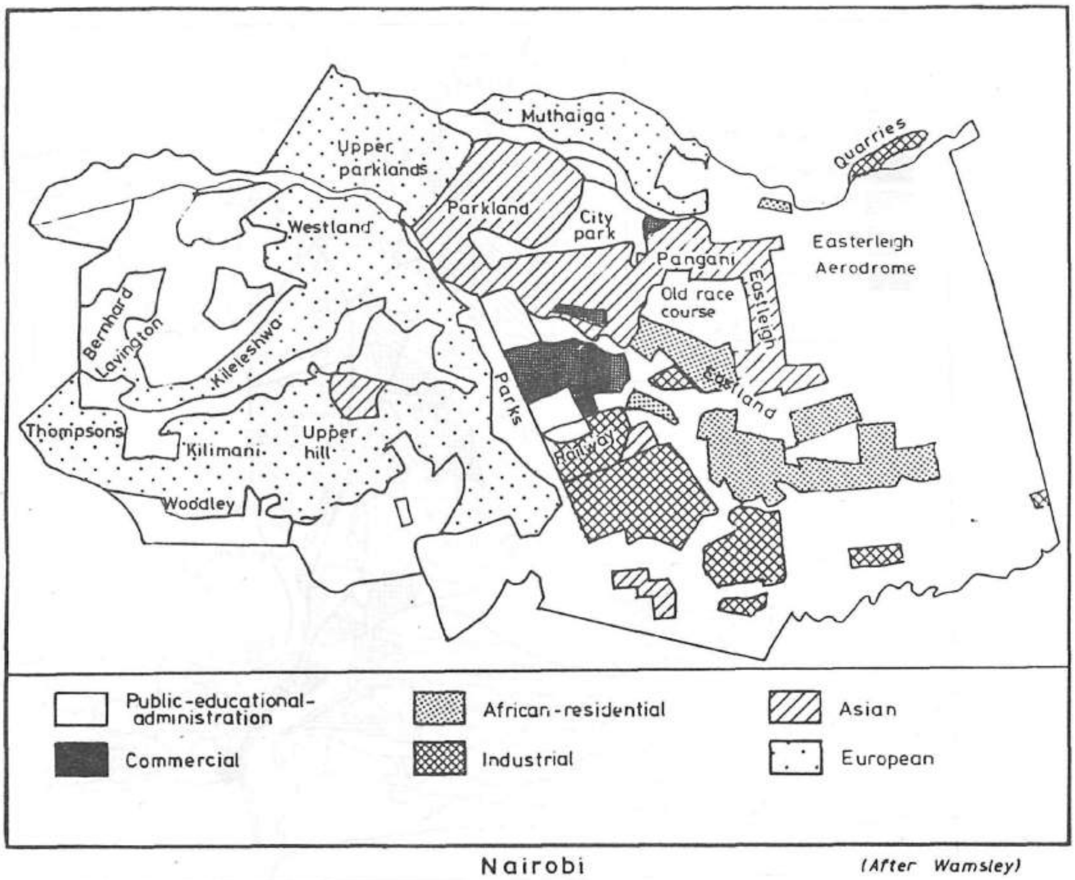
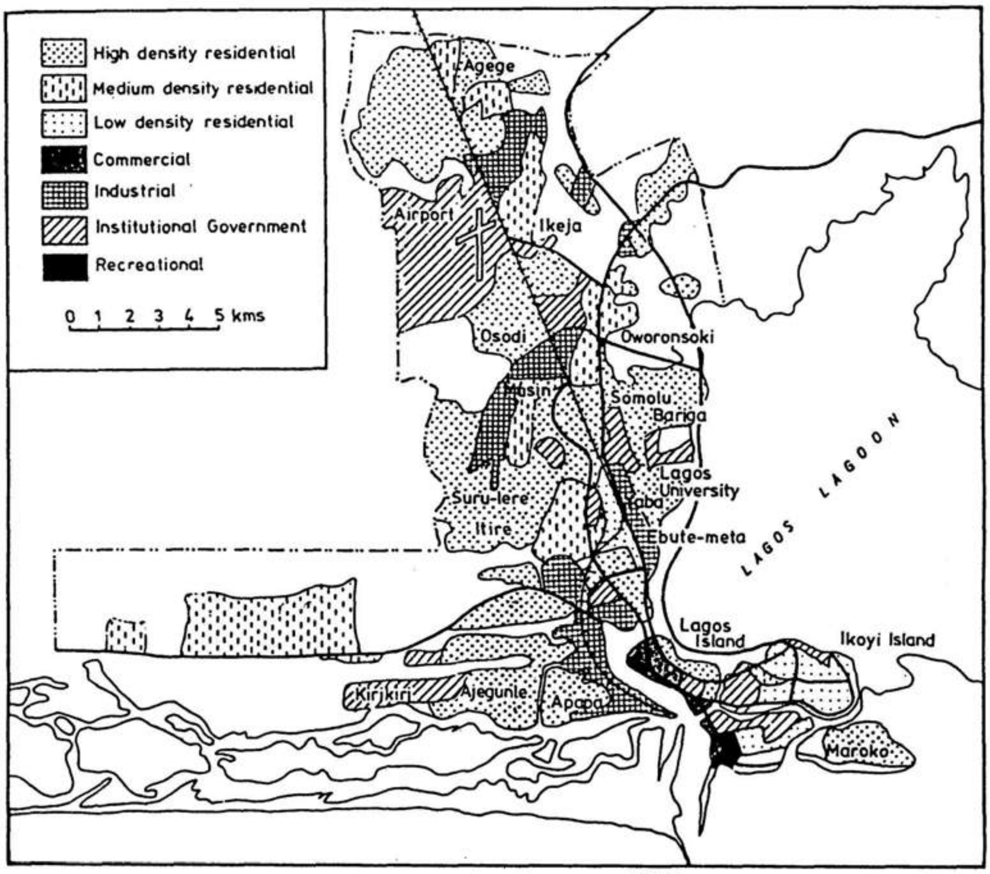


Figure 2. Nairobi: Land-use.

1.1.1 The Location of Lagos

The City of Lagos exemplifies the rapid rate of urbanization in Nigeria. It is the largest metropolitan area in Nigeria, and is located along the south-western coast, at the only outlet to the sea, of a lagoon that extends for about 2500 km. This fact made Lagos a very important port in the trading activities of the 18th and 19th centuries. As the seat of government since 1914, the largest sea port and having the most important railway and air termini, the city had a maximum significance in the predominantly export-oriented economy. Wholesale and retail activities expanded in the 1950s and 1960s. City development has therefore led to the evolution of a mosaic of land-uses in which functional and areal differentiation are well marked (Figure 3). By the middle of the 20th century the city rose to be the most important industrial centre in the country Ayeni (1981).



Land Use in Lagos, 1979

Figure 3. Lagos: Land-use.

Concurrent with the rapid industrial and commercial activities was the rapid increase in population: 73,766 in 1911 to 126,108 in 1931, 1,086,293 in 1963, 3,150,000 in 1975 and over 5 million in 1980 spread over an area of 272.8 km^2. Beside the population congestion in the city, traffic congestion is also acute. Tamer Golan (1975) puts the situation thus:

> *"Driving into Lagos centre...be it from Mainland, Ikoyi or Victoria Island, is an experience not to be repeated, and only the ordeal of coming into the city from Ikeja can be compared with it... Driving into Lagos you have ample time to look around as your car is stuck in innumerable traffic jams, your driver gets into long arguments with others who are trying to get an inch ahead of him."*

Although this traffic situation has been eased by a number of intensive road development measures and other traffic regulations, the convergence of traffic along the few traffic corridors to the city centre is a factor to be reckoned with in the pollution of the city atmosphere and the urban heat island effect.

1.1.2 The Location of Ibadan

Ibadan is located in the transition zone between the Tropical Rain Forest and the Savanna in south-western Nigeria. The location in this transition zone was deliberate. The forest provided a much needed protection for refugee populations in the 1830s, while the nearby grassland territory provided farmlands (Udo 1982).

The city grew rapidly from the 1830s such that by 1890 its population had spread over an area of 40 square miles (Millson 1891). The city was enclosed by a city wall. Subsequent British rule brought peace, trade and colonial administration. With the extension of the railway to Ibadan in 1901, commercial activities developed near to the railway station. In 1952 Ibadan became the capital of the then Western Region of Nigeria; its population rose from 60,000 in 1856 to 452,000 in 1952 (Mabogunje 1968). The colonial expansions include first the development of Government Reservation Areas to the east and to the northwest of the city, whilst post-colonial expansions include the development of housing estates, institutions of higher learning and industrial plants. The population of the city is now estimated to be 1,783,000 spread over an area of 130.5 km^2. With the addition of various activities over the years, definite land-use zones have emerged outside the original ill-planned and densely built-up areas comprising the core of the city (Figure 1).

A general characteristic of the features of these cities is that they are mostly residential cities in which commercial activity predominates; traffic density is very high and industrialization is only in its infancy.

2. CASE STUDIES IN URBAN CLIMATOLOGY

2.1 Lagos

2.1.1 The spatial variations of radiation over the city

Observation of day-time net radiation by Ojo (1981) shows that the highest values occur at 1000 h and 1500 h; the highest values of 0.280 ly min^{-1} were recorded in areas of high traffic and building densities on Mainland Lagos, Mushin and Oshodi areas and around the International Airport at Ikeja (Figure 4). Ojo (1981) ascribes these high values to the greenhouse effects of atmospheric pollutants ejected into the atmosphere from industries, aircraft and automobiles in the high traffic density areas. The effects of domestic and industrial pollutants account for the high values recorded in the high density areas of Mushin/Oshodi and the Apapa industrial complex, respectively. By noon the highest values of net radiation (over 0.138 ly min^{-1}), were recorded outside the densely built-up areas to the west and north of the city, where a greater amount of incoming solar radiation is able to reach the surface. Over Lagos and Victoria Island, and other less densely built-up areas, net radiation values were relatively lower. In the built-up areas over the Mainland, values range between 0.310 to 0.340 ly min^{-1}. In the late afternoon when traffic density is once again very high, the main traffic corridors such as between the Mainland and the Island, and the Mushin/Oshodi areas, again record relatively higher values than in other areas where traffic density is much lower.

2.1.2 Spatial and temporal variation of temperature

The analysis of temperature data taken from traverses across the city shows that the morning hours show higher temperatures (28°C) on the islands adjacent to the Atlantic Ocean. Here the marine influence appears to be the most dominant effect. Over the rest of the city, the urban heat island effect is conditioned by the characteristics of the land-use type: in the zone of dense traffic concentration, the urban heat island effect (ΔT_{u-r}) is experienced at noon or in the late afternoon hours over Tinubu Square, along the main traffic corridors and in the Mushin/Oshodi areas of the city. Over such areas ΔT_{u-r} ranges between 2° and 4°C. As the day wears on the difference decreases. In other words, the urban heat island effect appears to be more marked in the forenoon than afternoon. This type of observation appears to correspond with results obtained in tropical cities in different parts of the World (e.g. Bombay and Poona in India, Quito in Ecuador and Mexico City (Jauregui, 1973)). Early morning studies in the Indian cities showed heat islands to be well displayed. In both cities the largest heat islands had an intensity of 6°C with calm winds and cloudless skies. Similar early morning surveys in Mexico City found heat islands of up to 9°C under ideal conditions.

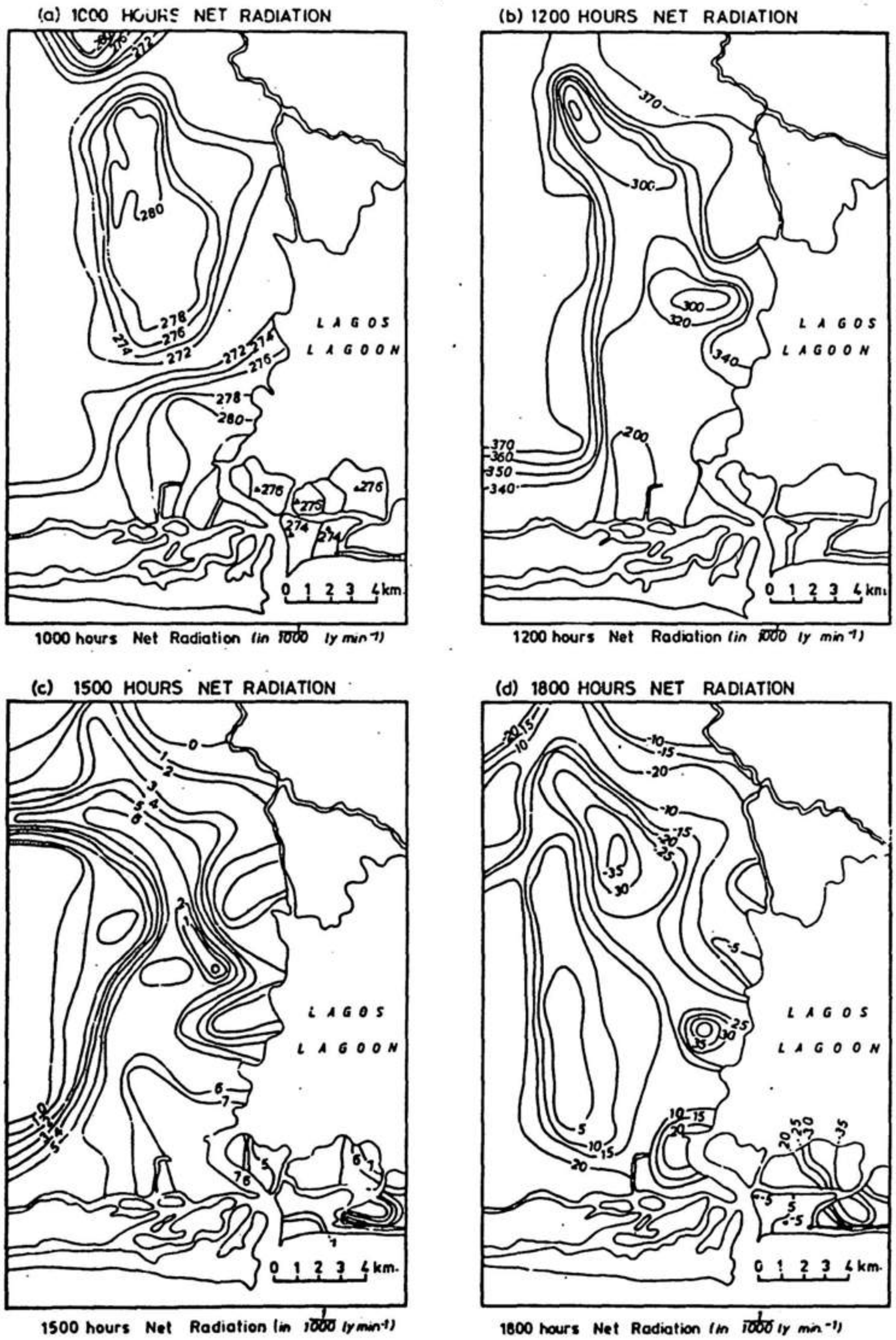


Figure 4. Spatial variation of net radiation over Lagos Metropolis.

2.2 Ibadan

2.2.1 Spatial and temporal variations in radiation and albedo

An analysis of the total incoming radiation over the city by Adebayo (personal communication) reveals a decrease of between 12.5 to 22% from the rural area to the city centre; mean values range from 0.3 ly min^{-1} in the rural area to 0.25 ly min^{-1} in the city centre, during the early hours of the day; in the late afternoon the difference drops to about 8-10% (Figures 5a, b). This situation has been ascribed to the increasing scattering and absorption effects of atmospheric pollutants towards the city centre.

The distribution of net radiation shows values between 0.086 to 0.12 ly min^{-1} in the rural suburbs, and between 0.126 and 0.166 ly min^{-1} in the city centre, thus there is an increase of about 20-30%. Such a phenomenon may be related to the absorptive effects of atmospheric pollutants for long-wave radiation.

Albedo measurements taken over different surfaces (Oguntoyinbo, 1971) in the city and the rural suburbs show that values range from 0.05 over tarred surfaces to a maximum of 0.15 over concrete surfaces in a petrol filling station; in rural areas values range from 0.12 over green tropical rainforest to 0.20 over thatched building roof tops (Table 1).

2.2.2 Temperature and relative humidity

Traverses made to measure temperature and relative humidity revealed the characteristic urban heat island effect. This effect is most marked at the height of the dry season in March when the rural/urban heat island ranges between 5^{o}-$7.5^{o}C$ in the city centre. At the same time the relative humidity is about 7% lower in the city centre than in the rural suburbs. Early morning observations revealed an urban heat island of $0.8^{o}C$ in the city centre (Figures 6a, b).

TABLE 1. *Mean values of albedo of urban and rural settlements (Ibadan and environs).*

Surface	Description of Surface	Albedo
(a) City Centre		
Corrugated iron	Very rusty	0.10
Roof top	Fairly new	0.14
Concrete surface	Petrol filling station	0.15
Tarmac	Car park in supermarket	0.08
	Road	0.14
	Mean	0.12
(b) Rural Settlements		
Thatched roof top	New	0.20
" " "	Old	0.15
Corrugated iron roof top	New	0.16
	Old and rusty	0.10
	Mean	0.15

Source: Oguntoyinbo (1970)

TABLE 2. *Seasonal variations in the urban heat island effect (ΔT_{u-r}) at Ibadan.*

Season	Month	Sky condition	Daily mean ΔT_{u-r} (°C)
Wet	June	Cloud bands with intermittent sunshine	3.3
	July-August	Uniformly cloudy day stratiform clouds	0.6-0.8
Dry	December	Dust polluted sky (Harmattan)	1-2.5
	February	Clear cloudless sky	5.0-7.5

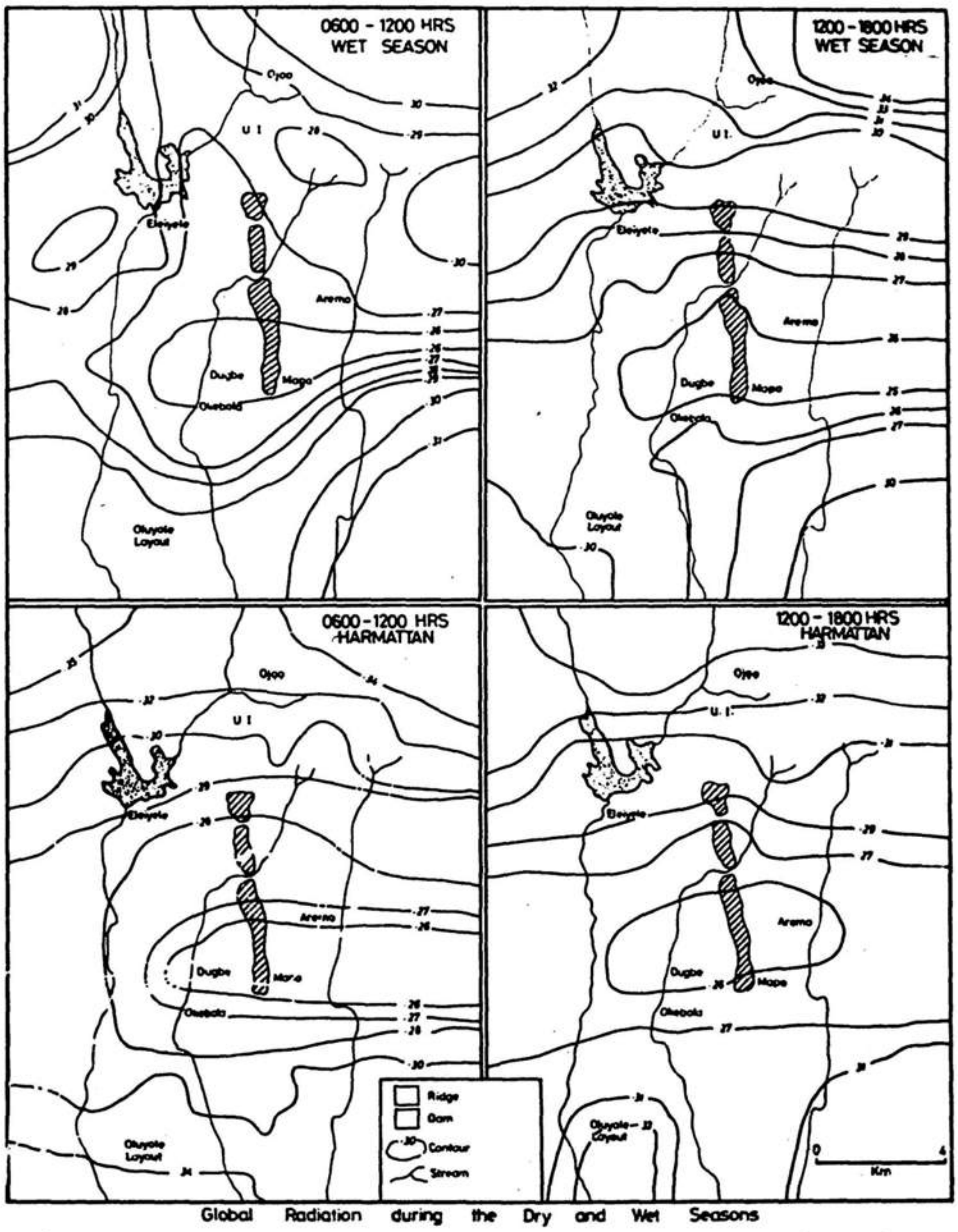


Figure 5a. Global radiation distribution over Ibadan.

Adebayo (personal communication) confirms that the early morning urban heat island effect is about $1^{o}C$, rising to a mean of $3\text{-}4^{o}C$ in the afternoon. Seasonal variations also occur (Table 2). During the wet season mean values of ΔT_{u-r} are around $1^{o}\text{-}3^{o}C$; in the Harmattan it is about $1\text{-}5^{o}C$, whilst in the clear cloudless period between January and March mean values are $5\text{-}7.5^{o}C$ but extreme values may be as high as $11.7^{o}C$. Relative humidity values decrease generally towards the city centre. During the afternoon in the dry season differences may be as high as 12%. This tends to confirm an earlier finding by Oguntoyinbo (1981)(Figure 6).

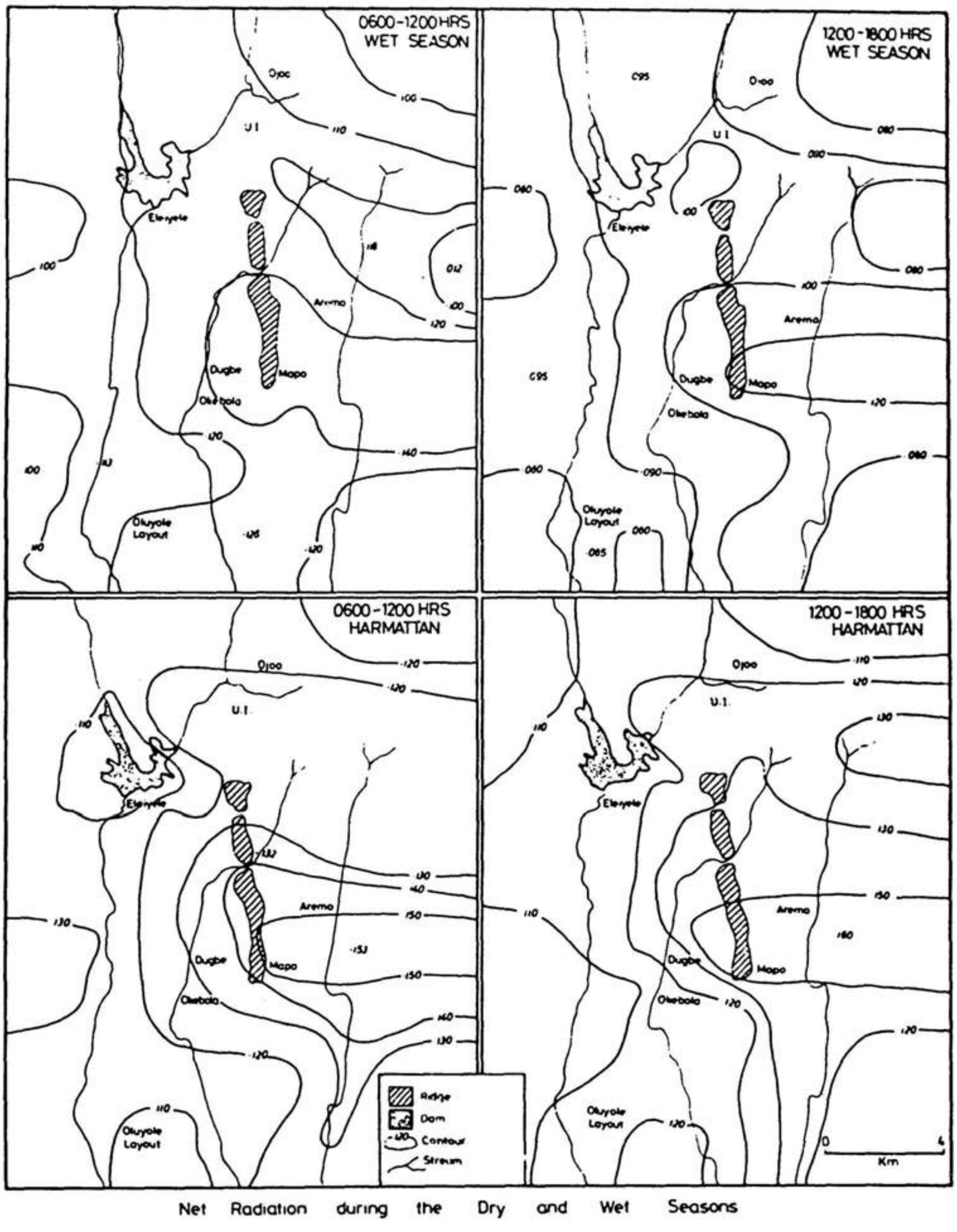


Figure 5b. Net radiation distribution over Ibadan.

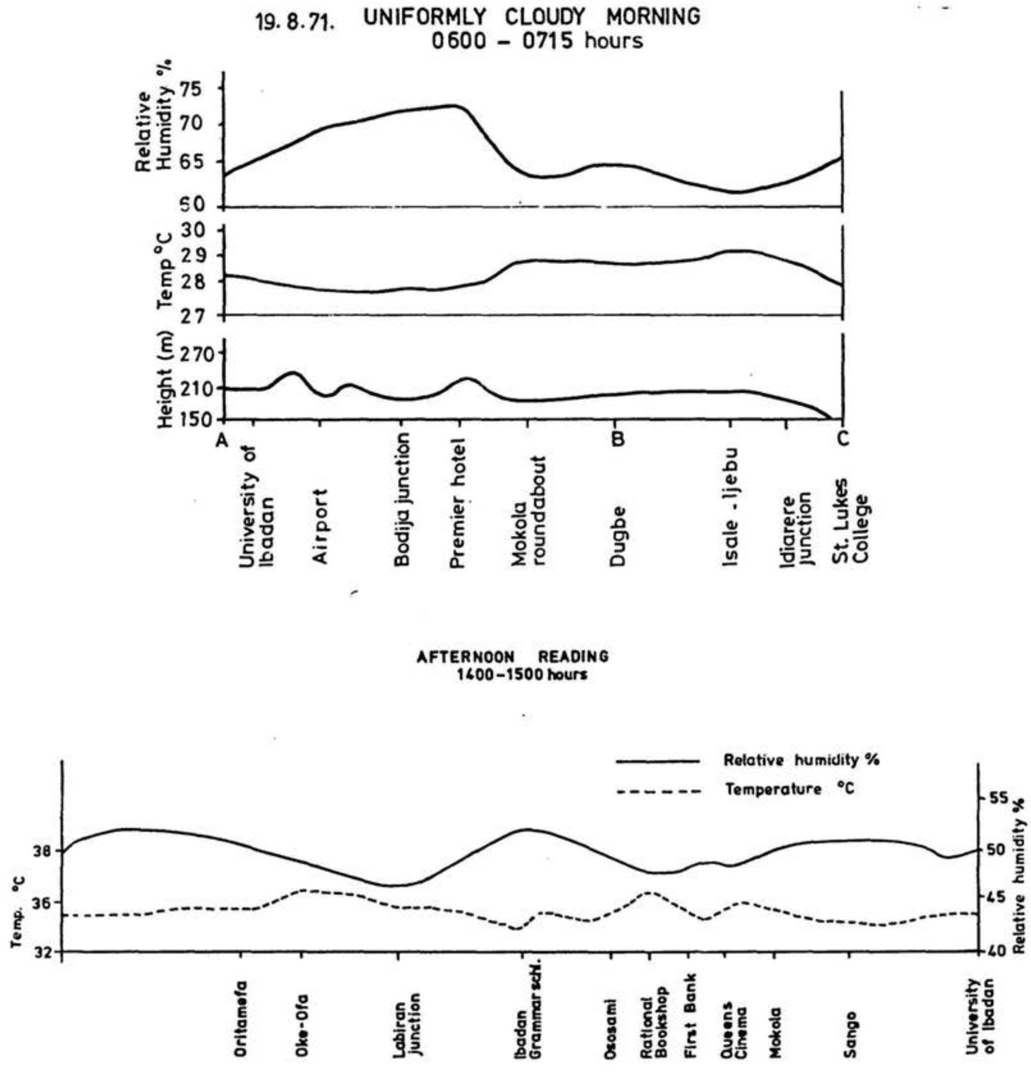


Figure 6. Urban heat island effect over Ibadan City (after Oguntoyinbo, 1981).

2.2.3 Atmospheric Pollution

Since industrialization is in its infancy in most tropical African cities, pollution from industrial sources is restricted to pockets of industrial estates in a few cities. Dust pollutants raised by moving vehicles on untarred laterite roads, and those transported by the Harmattan winds from the Sahara Desert, constitute the other main source of atmospheric pollution in cities. Only a few studies have been undertaken to assess the level of pollutants.

In a study to establish the level of atmospheric pollutants resulting from automobile exhausts, Oluwande (1977) compares the levels of atmospheric dust, particulate matter, carbon monoxide (CO) and sulphur dioxide (SO_2) concentrations in the air over the city of Ibadan with those in the rural surroundings. The results show that the level of dust and particulate matter is higher in the city than the rural suburbs, and in the dry rather than the wet season (Table 3).

TABLE 3. *Monthly variation of particulate matter (μg m^{-3}) at 3 sampling stations in the city of Ibadan (U_1, U_2, U_3) and at a rural station (R_1).*

Month	U_1	U_2	U_3	R_1
Oct. 1975	76	67	81	51
Nov. 1975	84	75	78	62
Dec. 1975	79	81	90	55
Jan. 1976	82	69	96	70
Feb. 1976	68	51	82	45
March 1976	70	68	75	53
April 1976	64	74	82	49
May 1976	68	59	67	42
June 1976	55	62	81	36
July 1976	52	49	52	41
Aug. 1976	71	52	63	32
Sep. 1976	63	56	64	37
Mean	69	64	76	48

Source: Oluwande (1977).

Measurement of SO_2 concentrations revealed that a major road junction in the city, the central business district and traditional parts of the city recorded the highest levels of SO_2; in the rural areas the concentration is very low. The highest concentration in the urban centre is as much as 300 times the highest concentration in the rural area (Table 4). The maximum occurs between 0900 and 1500 h which is the peak period of heavy traffic.

TABLE 4. *Typical mean daily variation in SO_2 concentration (ppm) of 3 urban sites in Ibadan and one rural site in the suburbs.*

Local Time (h)	U_1	U_4	U_3	R_1
06 - 09	0.10	0.05	0.008	0.001
09 - 12	0.31	0.10	0.16	0.001
12 - 15	0.64	0.31	0.50	0.002
15 - 18	0.34	0.09	0.20	0.001
18 - 21	0.23	0.13	0.06	0.001
21 - 00	0.06	0.02	0.02	0.000
00 - 03	0.01	0.00	0.003	0.000
03 - 06	0.05	0.01	0.008	0.000

Source: Oluwande (1977).

A similar pattern was also recorded for the CO concentrations (Table 5). Seasonal variations show that the maximum values of CO are obtained between November and March. During this period maximum values range between 75 and 100 ppm.

Table 6 shows that the levels of SO_2, CO and suspended particulates often exceed the WHO recommended long-term limits; such a situation should provide cause for concern.

TABLE 5. *Typical daily variation in carbon monoxide (ppm).*

Local Time (h)		U_1			U_4			U_3			R_1	
	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max
06 - 09	2.5	5	70	2	21	68	1	5.4	36	0.1	1.2	1.5
09 - 12	3.0	19	78	4	45	100	2	3.2	12	0.1	1.5	2.0
12 - 15	1.0	57	100++	6	33	80	7	19.3	100+	0.2	1.6	2.0
15 - 18	2.5	10	22	0.5	12	39	3	8	71	1.0	1.2	1.8
18 - 21	5.0	12	33	0.1	3	5	4	20	100+	0.1	1.2	2.0
21 - 00	0	3	45	0.1	2	5	1	21	6	0.1	1.0	1.6
00 - 03	0	1.5	14	0.0	1	3	0	3	4	0	0	0
03 - 06	1.5	5	16	0.0	3	11	0	2.5	7	0	0	0

Source: Oluwande (1977).

TABLE 6. *WHO recommended long-term limits of some air pollutants.*

Pollutant	WHO Limits	Ibadan Levels
SO_2	Annual Mean: 0.21 ppm, 98% of observations to be below 0.07 ppm	Annual Mean: 0.095 ppm, 40% of observations are below 0.07 ppm
CO	8-hour average: 8.66 ppm, 1 hour observation to be below 33 ppm	Daily average: 7.1 ppm, max. daily average 196 ppm
Particulate and suspended matter	Annual Mean: 40 $\mu g/m^3$, 98% of observations below 120 $\mu g/m$	Annual mean: 70 $\mu g/m^3$, 100% observations below 120 $\mu g/m$

Source: WHO (1972)

The occurrence of trace metal levels in some Nigerian mosses has also been used to study the level of atmospheric pollution in Ibadan (Onianwa and Egunyomi, 1983). This study revealed that lead (Pb) values in mosses collected in rural areas were significantly lower than similar values collected in the mosses in the city centre where traffic density is high. In the city centre mean concentration values for lead were as high as 157.2 $\mu g\ g^{-1}$; values in the rural area (Botanical Garden, University of Ibadan) varied between 13 and 30 $\mu g\ g^{-1}$ (see Table 7).

Table 8 shows the pattern of occurrence of other metals in samples from the city and the rural areas, irrespective of moss species type. The difference in the means and the standard deviation patterns between the city and rural area samples for zinc (Zn) is very significant. The authors could not identify any definite emission source for Zn; the differences, they suggest, may imply that the general level of human activities such as the burning of refuse, and welding within the city may be gradually elevating the zinc levels. For most other metals the level of occurrence in the city is still very low.

TABLE 7. *Concentration of lead (Pb), zinc (Zn), copper (Cu) in mosses from Ibadan City.*

Location	Species	Conc. $\mu g\ g^{-1}$ dry wt. Pb	Zn	Cu
Ibadan City Road Side	Barbula lambarenesis	66.3-232.3	115-1970 (55)	15.8-46.8 (33.4)
Ibadan City Road Side	Calymperes Palisotii	76.3-248.0 (157.2)	73.667 (167)	13-270 (19.0)
Botanical Garden	" "	14.8	70	22.5
Botanical Garden	Pinatelia sp.	29.7	113	32.3

Figures in parenthesis are mean values.

Source: Onianwa and Egunyomi (1983).

TABLE 8. *Average concentration ($\mu g\ g^{-1}$ dry wt.) of zinc, copper, cadmium (Cd), nickel (Ni), manganese (Mn), magnesium (Mg) and iron (Fe) in all moss samples at different sites.*

Metal	Urban sites	Rural sites
Z_n	188 ± 106	55.4 ± 17
C_u	23.3 ± 9.2	20.0 ± 9.2
Cd	0.78 ± 0.43	0.64 ± 0.35
Ni	10.32 ± 5.0	9.16 ± 3.8
Mn	351 ± 147	337 ± 206
Mg	2430 ± 860	2080 ± 1876
Fe	15370 ± 12100	(5300 ± 8200)

Source: Onianwa and Egunyomi (1983).

TABLE 9. *Monthly maximum and minimum temperatures (^{o}C) in and near Nairobi.*

		J	F	M	A	M	J	J	A	S	O	N	D	Yr.
Maximum temperatures	Dagoretti Corner (D)	24.6	25.7	25.6	24.2	22.9	22.3	20.9	21.9	23.7	24.8	23.2	23.4	23.6
	Eastleigh Airport (E)	26.6	27.8	27.3	25.7	24.4	22.5	22.5	22.9	25.4	26.3	24.6	24.8	25.2
	Nairobi Intl. Airport (N)	26.9	28.5	28.3	26.6	25.5	24.9	23.0	23.7	25.3	26.5	25.2	25.5	25.8
	(E-D)	2.0	2.1	1.7	1.5	1.5	1.2	1.6	1.0	1.7	1.5	1.4	1.5	1.6
	(N-E)	0.3	0.7	1.0	0.9	1.1	1.5	0.5	0.8	-0.1	0.2	0.6	0.7	0.6
Minimum temperatures	Dagoretti Corner (D)	11.4	10.6	12.5	13.7	12.9	10.5	9.4	9.8	10.2	12.4	12.8	12.5	11.6
	Eastleigh Airport (E)	13.2	13.3	14.5	15.4	14.8	13.1	11.8	12.2	12.6	13.8	14.6	14.0	13.6
	Nairobi Intl. Airport (N)	13.0	12.5	13.7	14.6	13.9	11.8	11.3	11.5	12.0	13.0	13.7	13.5	12.9
	(E-D)	1.8	2.7	2.0	1.7	1.9	2.6	2.4	2.4	2.4	1.4	1.8	1.5	2.0
	(N-E)	-0.2	-0.8	-0.8	-0.8	-0.9	-1.3	-0.5	-0.7	-0.6	-0.8	-0.9	-0.5	-0.7

Source: Nakamura (1967).

2.3 Nairobi

2.3.1 Urban heat island effect

In his study of the urban heat island effect in the city of Nairobi (1600-1800 m asl), Nakamura (1967), used the climatological data from three existing meteorological observatories (the East African Meteorological Department at Dagoretti Corner (1798 m) representing the Western suburban area; the Eastleigh Airport (1634 m) representing the urban centre and the Nairobi International Airport (1624 m) representing the eastern suburban area, to examine the mean variation of the urban heat island. In addition he carried out traverses across the city using a thermistor thermometer to take temperature readings at 120 stations. It took about one and a half hours to complete a round trip and adjustment was made for the time lag.

The results showed that the city temperature was characteristically higher than the suburban areas in so far as the minimum temperature was concerned. The difference between Eastleigh (city centre) and the International Airport (suburban) was 1.3°C (Table 9). Compared with larger cities in the higher latitudes, the urban heat island effect appears rather small. Nakamura speculated that the value could have been greater if observations had been available for the densely built-up city centre.

As for the maximum temperature, there did not seem to be a conspicuous difference between the city and the suburbs. The city centre therefore had a small diurnal range of temperature.

Dagoretti was cooler than the International Airport by 2.2°C for the maximum temperature, and by 1.3°C, for the minimum temperature. It was however noted from an altitude-temperature graph that the lower temperatures at Dagoretti might have been due to the altitudinal difference (Figure 7). On the same graph it could be seen that the minimum temperature at Eastleigh was appreciably higher than for its altitude, implying an urban effect.

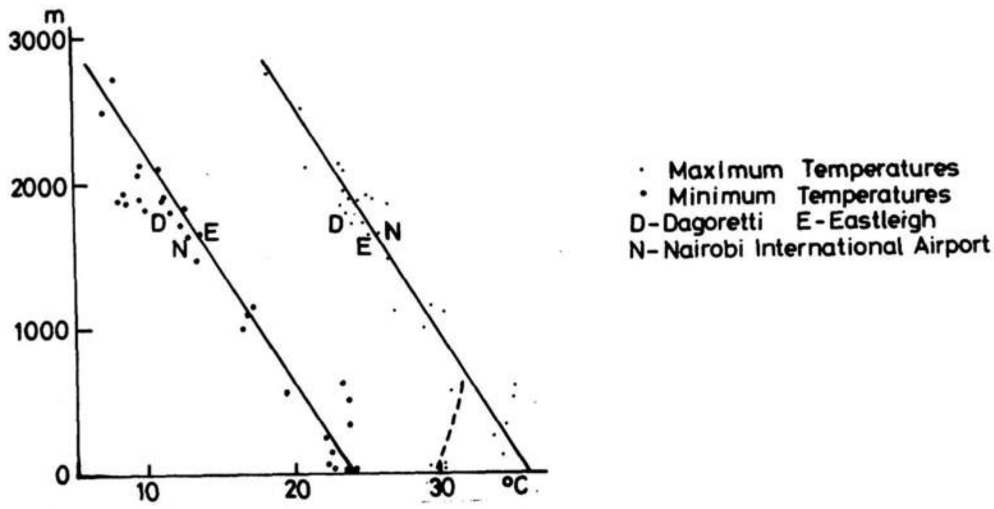


Figure 7. Relation between mean annual temperature and altitude in Kenya (after Nakamura, 1967).

Figure 8 shows the analysis of the urban temperature field. Two relatively warm areas were found on the maps. One was near the city centre; but it did not often coincide with the area of highest density of buildings. The vicinity of the Nairobi railway station was identified as the area that was most likely to be warmest.

Higher city temperatures were discernible even in the daytime. A relatively steep temperature gradient was observed in the northern and western periphery of the built-up area, but the temperature gradient became extremely gentle in the evening.

Nakamura noted that the climate of the city of Nairobi might be affected mainly by the density of buildings, the greater friction near the ground surface and the thermal characteristics of concrete or asphalt. The warming effect through heating by combustion was thought to be negligible in this tropical city. Dust levels were not thought to be large enough to produce a significant reduction of insolation such as is expected of a large city.

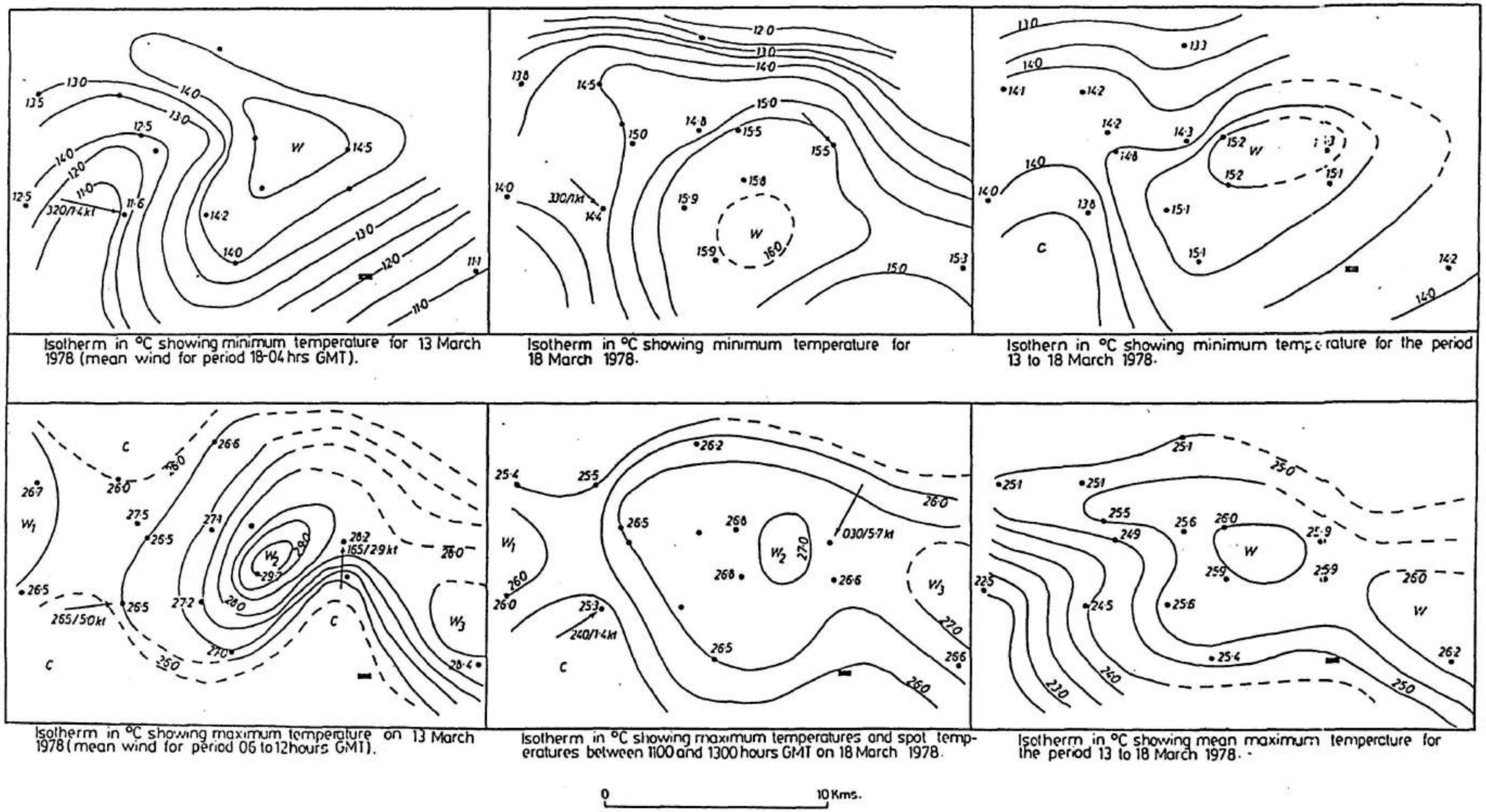


Figure 8. Temperature distribution in Nairobi.

In a similar study, Okoola (1980) established that the heat island effect is stronger for the minimum temperature than for the maximum, and that it reaches the highest monthly difference in minimum temperature between Eastleigh and Embakasi, with a value of 2.5°C during January and February. This covers an area of 5.0 km in diameter in an east-west direction, and 3.0 km in a north-south direction with its centre around Strahere Boys Centre/Pumwani Maternity Centre. There appears to be some controversy about the maximum temperature effect. Okoola (1980) observed that during January and February for the maximum temperature, the city is cooler than its suburbs by up to 0.5°C at the maximum temperature epoch. On the other hand, Meffert (1984) noted that during the hot period, i.e. February/March, the maximum temperatures show a heat island with an almost identical centre and area, but simultaneously another heat island centre developed outside the city in the Embakasi plains, a savanna-like area, with thermal properties close to those of a paved surface.

Observations of temperature maxima at Mombasa do not exhibit a heat island; the thermal difference between the two observation stations - Town Meteorological Station and the Airport Meteorological Station - is restricted to 1.3°C at the time of the minimum temperatures. Indeed, for maximum temperatures a reverse situation is observed (Meffert, 1984). A similar result has been observed for Lamu Town. One of the main conclusions from these observations is that the favourable exposure to the incoming sea breeze for most of the year, allows for a dynamic daytime through ventilation.

3. BASIC FINDINGS FROM EXISTING STUDIES

Before highlighting the salient points emanating from the studies in urban climatology in tropical Africa, it is necessary to state that the case studies discussed above are not exhaustive; the author is aware of similar studies for Lubumbashi (Zaire) and a few others. Efforts to gain access to these publications were not successful. One thing is certain, the quality of research reported for those other cities is similar to the three case studies treated above.

The results discussed above, show that the urban heat island phenomenon is well established; but it is not as pronounced as in temperate latitude cities.

Extreme values occur at the height of the dry season, in agreement with the results obtained in other tropical cities. When these high values are attained, and the relative humidity is drastically reduced, the heat island effect aggravates already unfavourable conditions adding to the discomfort and, in extreme cases, contributing to deaths amongst the elderly. In the case of Nairobi, altitudinal effects tend to reduce the urban heat island effect. A reduction in the amount of the global radiation towards the city centre has also been observed; this has been ascribed to the increase in the atmospheric pollutants emanating mainly from automobile exhaust emissions and other urban activities. The concentration of dust, gaseous and particulate matter has, in some cases, been shown to exceed the minimum standards recommended by WHO (1972).

With regard to precipitation, there is no conclusive evidence to show the impact of the city on precipitation. Studies carried out in Ibadan (Oguntala and Oguntoyinbo, 1982) show that the occurrence of floods in the city of Ibadan has been increasing since the 1950s; the worst disaster occurred on 31 August 1981, when over 200 mm of rainfall was recorded within 12 hours in the northern part of the city (Figure 9). The ensuing flood caused severe damage to property and many lives were lost.

4. CONCLUSION

Available information shows that urban climatology in tropical Africa is still in its infancy. Knowledge of these city climates is less than for the cities in southern Africa (Morkel, 1980; McGee, 1970; Goldreich, 1979). There is need for more studies to be carried out. About twenty years ago, when the writer contemplated a Ph.D. research project on the city of Ibadan, he was advised by senior colleagues that such a project was peripheral to the needs of Nigeria. It was only about 2 years ago that I was able to assign a Ph.D. student to carry out a detailed study of the climate of Ibadan City.

It is, however, relevant to note that planners are becoming increasingly aware of the need to study urban climate. With increasing urbanization, industrialization and the use of vehicular traffic, attention is now being paid to studies in urban climate. For example, the author contributed to a report as part of the input to decisions regarding the location of the site, facilities and land-use types in Abuja, the new Federal Capital in Nigeria.

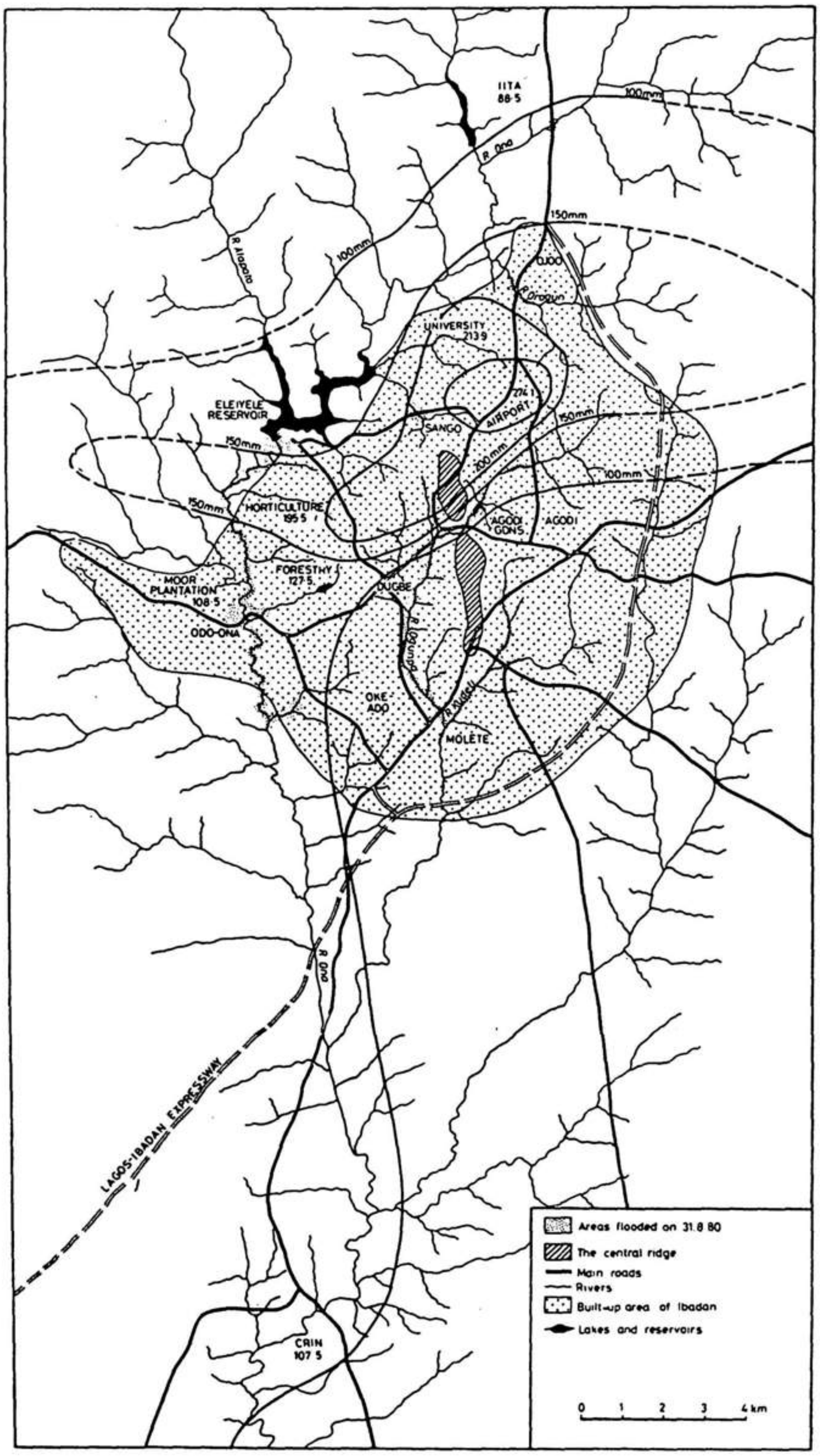


Figure 9. Urban rainfall and flood in Ibadan City, 31 August 1981 (after Oguntala and Oguntoyinbo, 1982).

Finally, the import of this paper is that governments should be advised to intensify studies in urban climatology in tropical African cities, especially now that the continent is experiencing rapid urbanization and industrialization. Such a step will help city planning, and avoid a number of mistakes made in temperate countries, where the location of urban activities was not considered with a view to their impact on the city climate.

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SOME ASPECTS OF THE URBAN CLIMATES OF INDIA

B. Padmanabhamurty
Meteorological Office, New Delhi 110003, India

1. INTRODUCTION

At the meeting of Experts on Urban and Building Climatology held under the auspices of World Meteorological Organization (WMO) at Geneva, 6-10 Dec. 1982, it was opined that although work on the climates of tropical cities has started to emerge recently, information is extremely sparse. From a climatological point of view more indigenous research is needed in tropical areas as well as the transfer of results from mid-latitude studies (WMO, 1982). It was proposed that a Technical Conference be held on Urban Climatology and its Application with Special Regard to Tropical Areas. The purpose of the Conference being to review existing knowledge in the field, particularly in tropical cities. Towards this objective the present paper presents some aspects of Urban Climate in India.

Urban climatic changes are caused by the increased surface roughness, the changed albedo and the changed heat storage capacities resulting from the replacement of forest and fields by concrete and buildings. Studies in the mid-latitudes established beyond doubt that urban agglomerations cause measurable changes in the atmosphere immediately adjacent to them. Temperatures are increased, low-level lapse rates are altered, horizontal winds slowed and updrafts induced. Turbulence and cloud formation are increased, summer rainfall is enhanced and possibly, some winter snowfall is stimulated. Snow on the ground is diminished and so are near-surface humidities. Most apparent is the increase in atmospheric pollutants by one to several orders of magnitude. They reduce solar radiation intensity, affect the long-wave radiation and shorten sunshine duration. Their effect on cloud formation and rainfall over, and in the vicinity of the cities, is still somewhat uncertain but evidence points to occasional cases of stimulation of precipitation and perhaps some rare cases of inhibition.

2. HEAT ISLANDS AND HUMIDITY FIELDS

2.1 Heat Islands

The fact that the centre of a city is warmer than its environs, forming a 'heat island', has been well known, extensively studied and documented around the World. To study the effect of urbanization on meteorological parameters a network of observatories needs to be established. In the absence of such a network, mobile temperature surveys can be conducted. An analysis of temperature observations from such a network and mobile surveys at Pune (18° 32'N, 73° 51'E), Bombay (18° 54'N, 72° 49'E), Calcutta (22° 32'N, 88° 27'E), Visakhapatnam (17° 41'N, 83° 18'E) and Delhi (28° 35'N, 77° 12'E) are shown in Figures 1, 2, 3, 4 and 5 respectively (Padmanabhamurty, 1979; Bahl and Padmanabhamurty, 1979; Philip et al., 1974; Sastry, 1982).

In all of these cities the existence of warm pockets and cold pools has been unambiguously established. The heat island intensities at Delhi, Bombay, Pune, Calcutta and Visakhapnatnam are 6.0, 9.5, 10.0, 4.0 and 0.6°C, respectively. The intensity, size and shape, and the position of warm pockets are found to depend upon wind speed and direction. Pune, owing to topography, exhibits twin heat islands. Delhi, Bombay and Calcutta also record multiple warm pockets. Delhi is inland and flat, Bombay is more or less surrounded by sea except in the north, and Calcutta is slightly inland but has maritime influences.

On the other hand, Visakhapatnam, a coastal station in the tropics, is controlled by topography, urban morphology and proximity to a large water

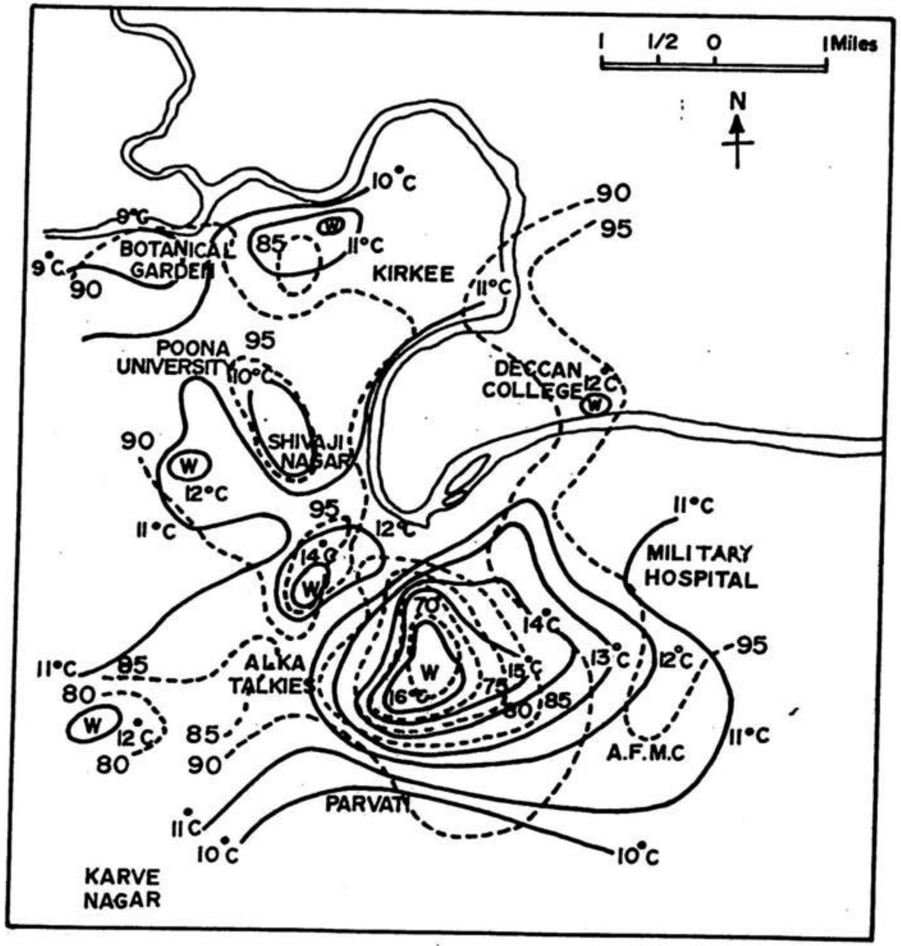

Figure 1. Isohumes (dashed, %RH) and isotherms (solid, °C) at Pune at the minimum temperature epoch, November 15-16, 1975.

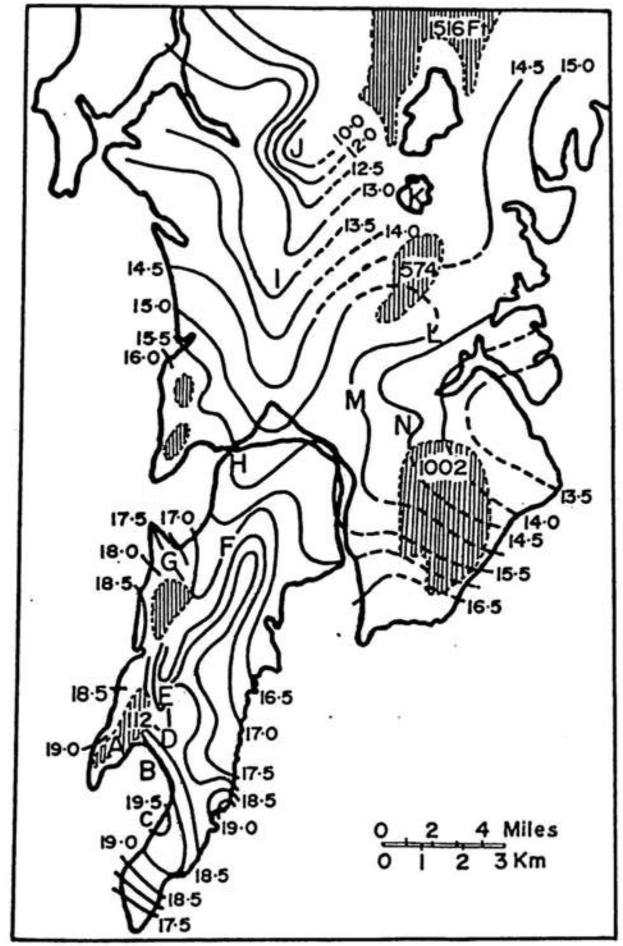

Figure 2. Surface temperature distribution (°C) over greater Bombay at the minimum temperature epoch.

body i.e., the Bay of Bengal. The hill ranges run inland on either side of the city from the coastline and the land and sea breeze circulation interacts with the heat island. Isotherms tend to run parallel to the coast and zones of high temperatures are located in built-up and congested areas. The temperature difference between the periphery and central areas is relatively small. A definite heat island over the residential and commercial districts of Visakhapatnam is established. The heat island intensity is about 0.6°C. Heat islands form under all meteorological conditions. Intense heat islands form under moderate wind conditions rather than on absolute calm days.

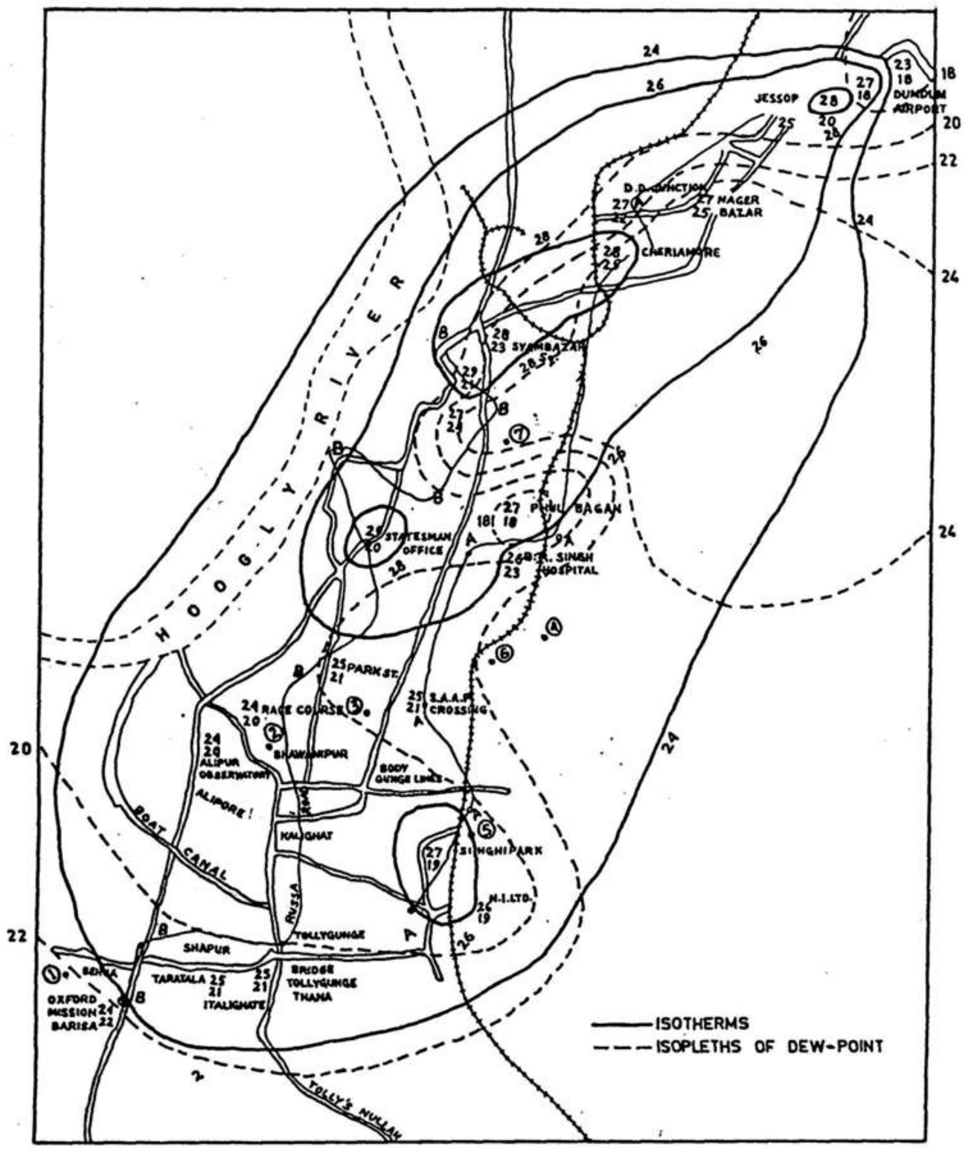

Figure 3. Isotherms and isopleths of dew-point temperature (°C) at Calcutta at the minimum temperature epoch, February 26-27, 1977.

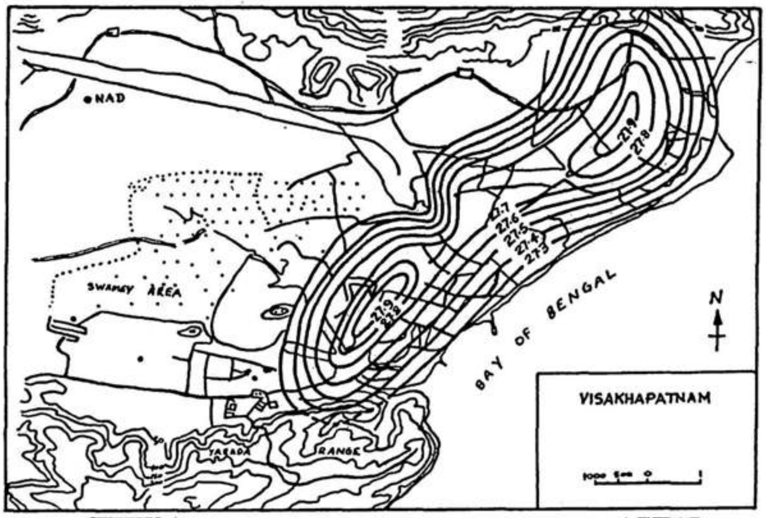

Figure 4. Surface temperature distribution (°C) at Visakhapatnam at the minimum temperature epoch, October 25, 1976.

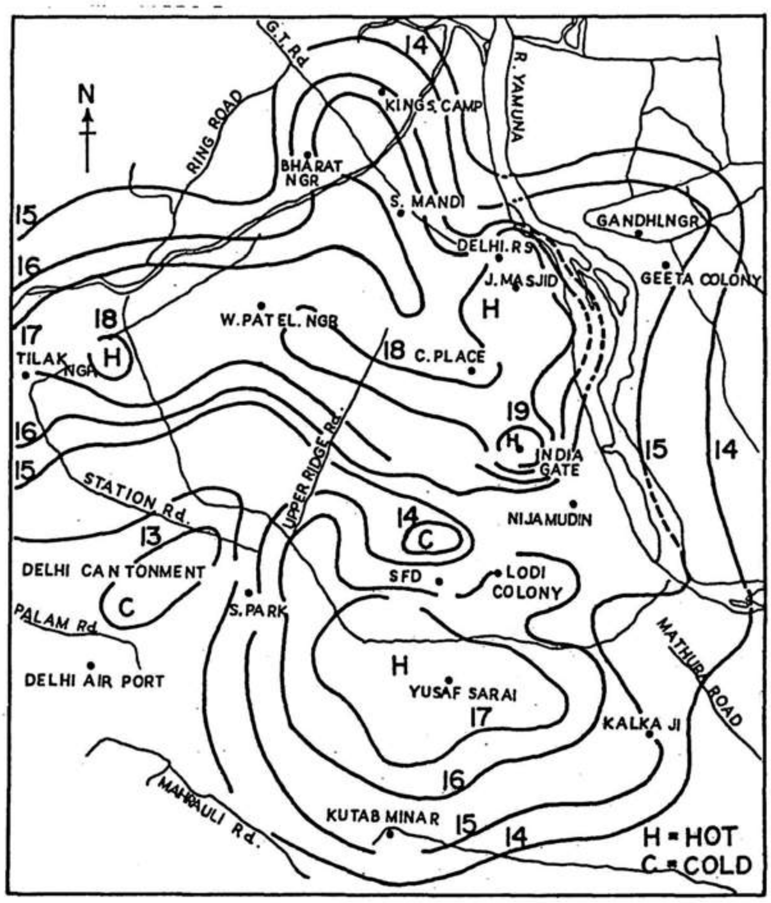

Figure 5. Isothermal (°C) analysis at Delhi at the minimum temperature epoch, March 23-24, 1978. Winds N at 10-14 km h^{-1}, calm by sunrise. Partly cloudy skies with Cirrus, 7/8 low and medium cloud by sunrise.

Table 1 gives the mean daily heat island intensities at the maximum and minimum temperature epochs, in different months, using data from the network of urban climatological observatories in Delhi (Padmanabhamurty and Bahl, 1984).

TABLE 1. *Mean heat island intensities (°C) at the times of the maximum and minimum temperature epochs at Delhi (after Padmanabhamurty and Bahl, 1984).*

Month	Heat island intensity (°C)		Month	Heat island intensity (°C)	
	Max.	Min.		Max.	Min.
Jan	4	6	Jul	2	5
Feb	3	4	Aug	2	4
Mar	4	6	Sep	2	3
Apr	3	6	Oct	4	6
May	4	5	Nov	2	6
Jun	2	3	Dec	3	6

2.2 Humidity Field

Relative humidities, being a function of the prevailing temperature, are normally found to be inversely related to the local intensity of the urban heat island. On an average urban-rural differences are reported to be 5%, but on individual nights these differences may approach 20%-30% (Figure 6) (Padmanabhamurty and Bahl, 1982).

The distribution of vapour pressure at Visakhapatnam is shown in Figure 7. In the city atmospheric temperature and vapour pressure seem to have a reciprocal relationship (Sastry, 1982).

2.3 Heat and Humidity Fields with Time

The heat island intensity in Pune attains one peak at 2200 h local time and another at 0600 h (Figure 8). The relative humidity field closely follows the heat island. The march of the heat and humidity distributions, wind speed and wind direction at Delhi (Figure 9) show the occurrence of an early night peak (2000 h), steadiness until the early morning and another rise in the small hours of the morning. The early morning peak is stronger than that in the early night (Padmanabhamurty, 1979). The times of occurrence of the peaks at Delhi are earlier than at Pune (compare Figures 8 and 9).

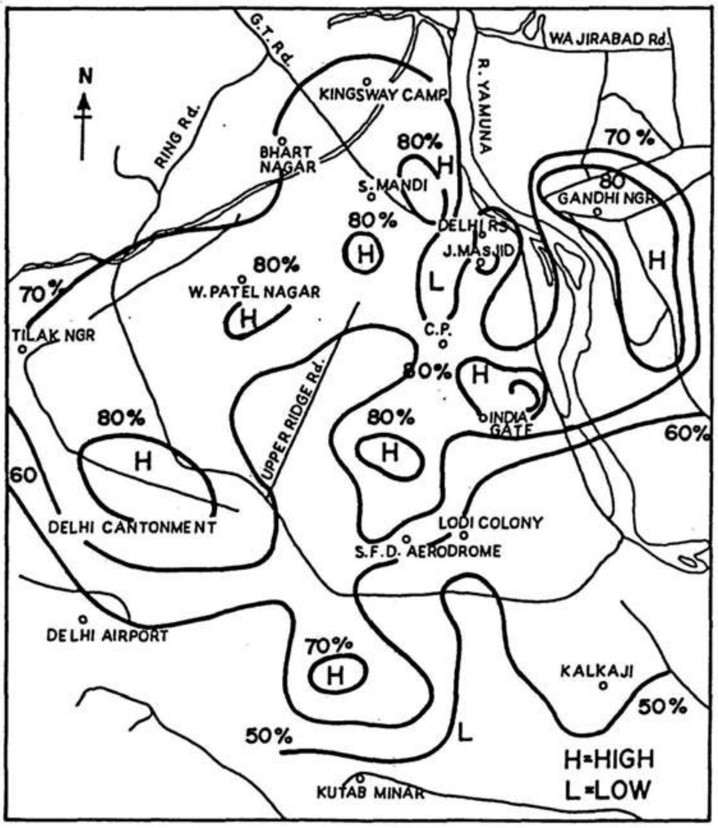

Figure 6. Isohumes (% RH) at Delhi at the minimum temperature epoch, February 25-26, 1978.

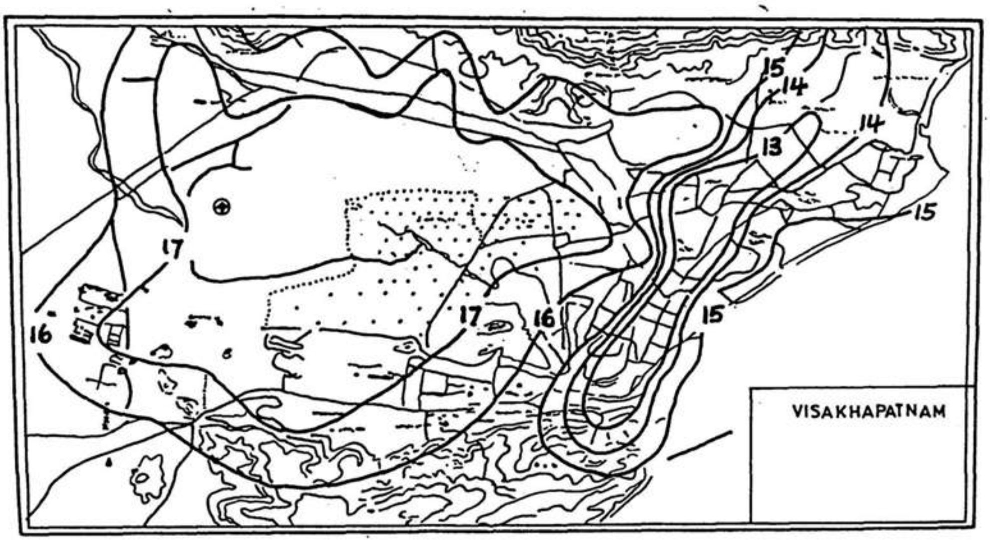

Figure 7. Vapour pressure distribution (mm Hg) at Visakhapatnam at the minimum temperature epoch, December 4-8, 1975.

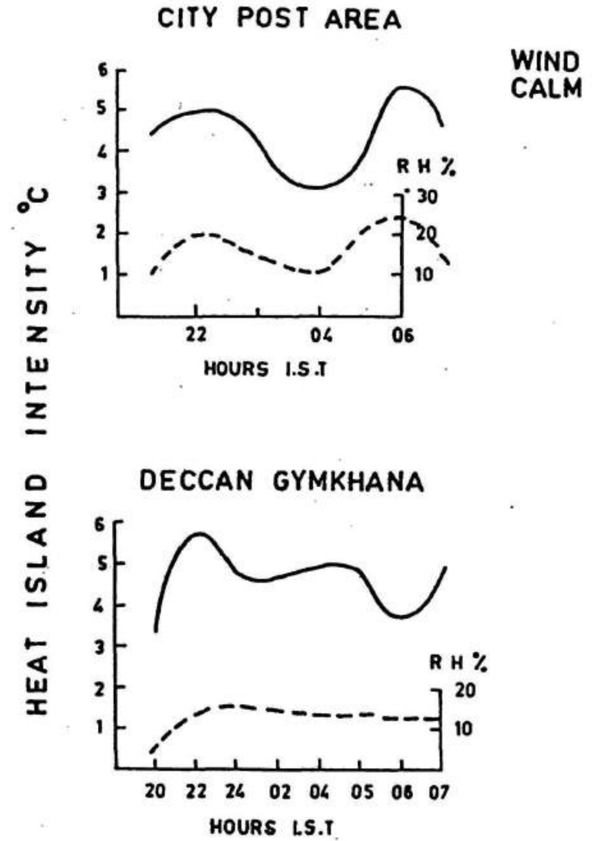

Figure 8. March of urban-rural heat and humidity intensities at Pune, December 7-8, 1974.

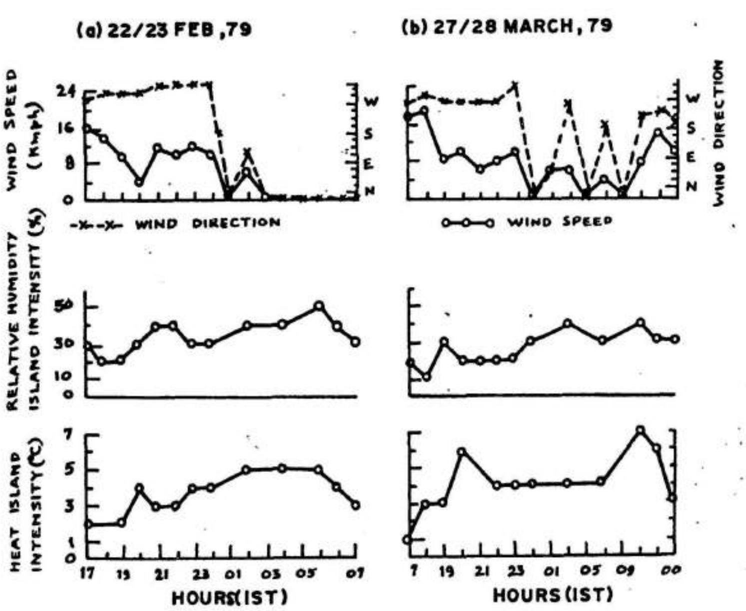

Figure 9. March of urban-rural heat and humidity differences, wind speed and wind direction at Delhi.

The first peak in either case is mainly due to large differences between urban and rural cooling. After sunset rural areas radiate faster than urban areas owing to the nature of their surface. These rural areas cool more in the early night and by 2000 h or so the radiation from both the rural and urban surfaces stabilize and result in the maximum heat island intensity, confirming the observations of Ludwig (1970), Hage (1972) and Oke et al. (1972). The radiation from both surfaces remain steady until the early morning and register a minimum value in the early hours.

2.4 Effect of Wind on Heat and Humidity Fields

It is generally observed that wind speeds are low when urban-rural heat/ humidity differences are large, suggesting an inverse relationship. When wind speeds are strong it is also observed that urban-rural heat and humidity fields are displaced downwind.

2.5 Urban-rural Cooling Rates and Thermal Radiant Emittance

Oke et al. (1972) recognized that urban/rural cooling rates and thermal radiant emittance are causes of the dynamic nature of the urban heat island. The rates of cooling of different surfaces differ thereby causing different heat island intensities. Hourly rates of cooling and thermal radiant emittance from different surface were calculated assuming that the surfaces radiate like blackbodies (Figure 10).

The urban-rural thermal systems identified were: (1) tar roads, (2) concrete surfaces, (3) built-up areas and (4) green surfaces. The figure exhibits characteristic features of the surfaces. The rate of cooling of tar roads is greatest immediately after sunset followed by green surfaces. Concrete surfaces and built-up areas cool slowly. It is this differential rate of cooling between urban concrete and built-up areas on the one hand, and green areas on the other, that results in the early night peak. Likewise, the larger rate of cooling of green surfaces in relation to urban areas resulted in another peak in the early morning hours. The thermal radiant emittance is highest from green surfaces and lowest from concrete surfaces followed by built-up areas and tar roads. This is the reason why Delhi, which is a mixture of built-up areas, tar roads, concrete buildings, wide medians, parks and lawns with greenery, produces a number of small warm pockets in contrast to Pune where a more monolithic heat island is evident (Padmanabhamurty, 1979; Bahl and Padmanabhamurty, 1979). Built-up areas and concrete surfaces interspersed with wide lawns and parks tend to mitigate the formation of intense heat islands. This prevents the air from the surrounding countryside from flowing towards the urban centre. This type of landscaping and building construction does not allow the formation of intense heat islands which otherwise might have produced centripetal near-surface winds across the steep thermal gradient of urban periphery that would tend to bring pollutants from the surrounding areas towards the heat island.

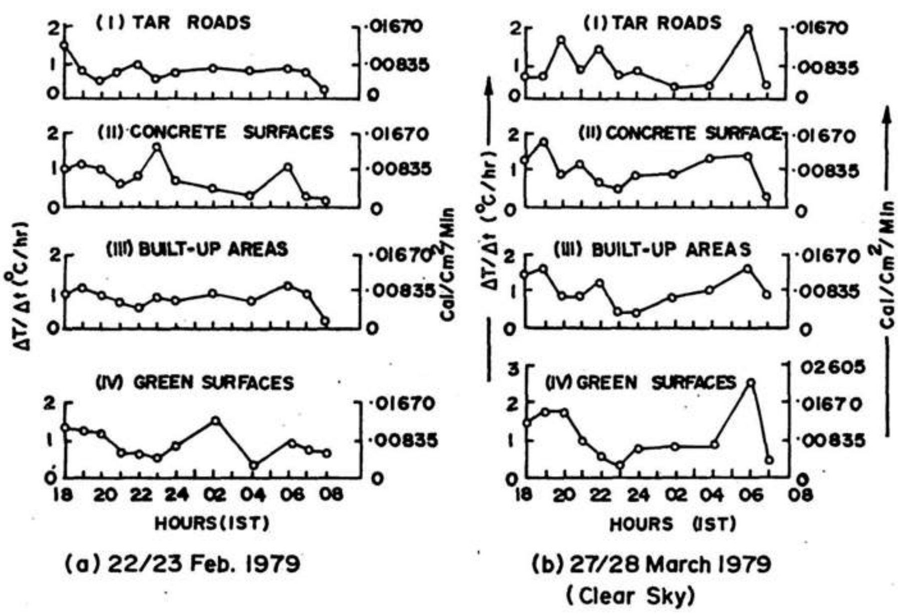

Figure 10. Rate of change of temperature ($^{o}C\ h^{-1}$) and thermal radiant emittance (cal cm^{-2} min^{-1}) in the night from different urban surfaces at Delhi.

2.6 Temperature Patterns during Special Weather Conditions

2.6.1 Temperature Patterns at the Onset/Withdrawal of Monsoon

The temperature pattern prior to, on the day of, and after the onset and withdrawal of the monsoon during the years 1976-78, at the maximum and minimum temperature epochs, has been studied (Padmanabhamurty and Bahl, 1984). Temperatures are generally observed to decrease after the onset as well as the withdrawal of the monsoon. The intensities of heat islands observed prior to, on the day of, and after the onset and withdrawal of the monsoon at maximum and minimum temperature epoch are given in Table 2.

2.6.2 Temperature Pattern on the Day of Duststorms

A few of the duststorms which occurred during 1978 have been studied to understand their effect on the temperature pattern at the maximum and minimum temperature epochs, both before and after their occurrence. The heat island intensities at the maximum temperature epoch decrease on the day of a duststorm and thereafter, when compared to that before the duststorm (Table 2). At the minimum temperature epoch heat island intensities decrease on the day of a duststorm compared to that before, but after the duststorm it may decrease or increase.

2.6.3 Temperature Pattern on the Days of Thunderstorms

Six thunderstorms which occurred in Delhi between February and July 1978 have been studied and isotherms drawn before and after their occurrence. Heat island intensities at the maximum temperature epoch mainly tend to increase on the day of a thunderstorm. Afterwards they generally increase whereas at the minimum temperature epoch they may either decrease, stay the same, or even increase on the day and thereafter (Table 2).

TABLE 2. *Intensities (^oC) of heat island at maximum and minimum temperature epochs at a) onset of the monsoon, b) withdrawal of the monsoon, c) on the days of duststorms and d) on the days of thunderstorms. Data for the period 1976-78 (after Padmanabhamurty and Bahl, 1984).*

	At max. temp. epoch			At min. temp epoch		
Year	Prior	On the day	After	Prior	On the day	After
(a) Onset of monsoon						
1976	4	8	4	1	3	2
1977	3	4	4	5	5	5
1978	8	6	3	4	4	2
(b) Withdrawal of monsoon						
1976	4	5	7	4	3	6
1977	7	4	3	5	8	6
1978	2	2	3	3	3	3
(c) Days of duststorms						
17 Apr 78	8	7	4	8	8	10
31 May 78	10	4	4	4	4	3
5 Jun 78	2	2	2	4	4	5
(d) Days of thunderstorms						
17 Feb 78	7	4	10	5	4	8
30 Mar 78	8	6	7	8	8	7
28 Apr 78	6	4	3	9	5	5
7 May 78	3	3	1	5	6	6
24 Jun 78	7	3	3	3	6	4
12 Jul 78	5	2	7	3	2	4

2.7 Vertical Structure of Heat Islands

One of the most important reasons for studying the vertical structure of the heat island is that its upper boundary normally coincides with an elevated inversion, thereby defining the effective depth of the air layer within which pollutants may be dispersed. The vertical temperature distribution has been studied at Visakhapatnam (Sastry, 1982) up to a height of 500 m in the core region of the established heat island. This has been accomplished with the aid of a tethered balloon to which is attached a simple thermograph, for recording dry and wet-bulb temperatures, and using two Bourdon tubes as sensing elements. The Bourdon tubes, extracted from old Benedix-Friez recording thermographs, were mounted on a thick wooden plank and their movements resulting from temperature changes were, after suitable lever modifications, recorded on a small drum (about 75 mm in diameter) which rotated once an hour via a spring-driven clockwork mechanism. The sensitivity of the instrument was 2 mm per degree Celsius on improvised chart paper. This result was obtained by calibration against an accurate mercury thermometer placed beside the sensing element of the above instrument in a laboratory chamber. Calibration of the set-up was performed prior to each field run over a 10°C temperature range centred on the ambient temperature, using a 100 W incandescent filament lamp placed inside the thermometer chamber along with light ventilation through a small motor fan. The instrument was sturdily fixed on a thick iron frame and thoroughly tested for errors induced by shocks, rotations or other disturbances encountered in actual field work). Testing was accomplished by attaching the instrument, by means of a cord, to the blades of a ceiling fan and set in slow rotation whilst being gently tapped from all sides. The performance of the instrument was found to be quite satisfactory, both in the laboratory and in the field.

In the rural area (near Andhra University), ground-based inversions are observed while at the urban centre (Jagadamba area) there is a lapse condition up to 300 m and above that it is isothermal (Figures 11 and 12).

Vertical temperature cross-sections at a number of rural locations revealed horizontal temperature gradients directed towards the central portion of the city, from either side, at the height of inversion layer (which was about 100 m deep). The inversion surface was found to be warmer on the eastern than on the western side. The vertical temperature variation, both below and above the inversion layer, are also steeper on the eastern side. The vertical temperature variation over the highly built-up, and heavily populated urban centre (Jagadamba region), shows the absence of an inversion compared with the rural profile, but the existence of isothermal conditions above

300 m at many points. Up to 300 m there exist weak lapse rates, but these do not preclude the occurrence of reversals of the horizontal temperature gradients. These may occur above as well as below this level, though they are very much weaker than in the rural areas. These studies show that because of increased thermal and mechanical convection, nighttime inversions of temperature are less frequent, are weaker and are located higher over the urban centre than over rural areas, although there is often little difference between the two environments by day. By night, the mixed layer shrinks in depth but, except in the lower 50 m or so, still exhibits a weak stability structure.

3. WIND FIELD

Urban climate is influenced considerably by wind. When winds are light, near-surface speeds are greater in the built-up area than outside, whereas the reverse relationship exists when the winds are strong. With winds of less than 4 m s^{-1} there is a 20% increase in speed over the city, the greatest increase occurs with winds of less than 1.3 m s^{-1}. There exists evidence of cyclonic curvature of the wind trajectory over urban areas in strong winds, and anticyclonic curvature when winds are light (Figure 13) (Padmanabhamurty and Bahl, 1981).

3.1 Wind Profile in Heat Island Conditions

The vertical wind profile was estimated from the angles made by the tethered balloon cord with the vertical.

In urban areas the airflow is very turbulent and wind direction is variable both in space and time. The urban wind profile is often rather complex, especially in light wind conditions at night. Under these circumstances it is quite common to find a low-level wind speed maximum ('jetlet') in both urban and rural areas, but the urban one tends to occur at a higher elevation (Albert *et al.*, 1973; Ackerman, 1974 a, b; Moses, 1974). Urban winds also exhibit greater temporal variability or 'unsteadiness' than their rural counterparts. Even though deceleration may be occurring at low level, it is quite common to observe a relative acceleration of air flow at higher levels over the city (Albert *et al.*, 1973).

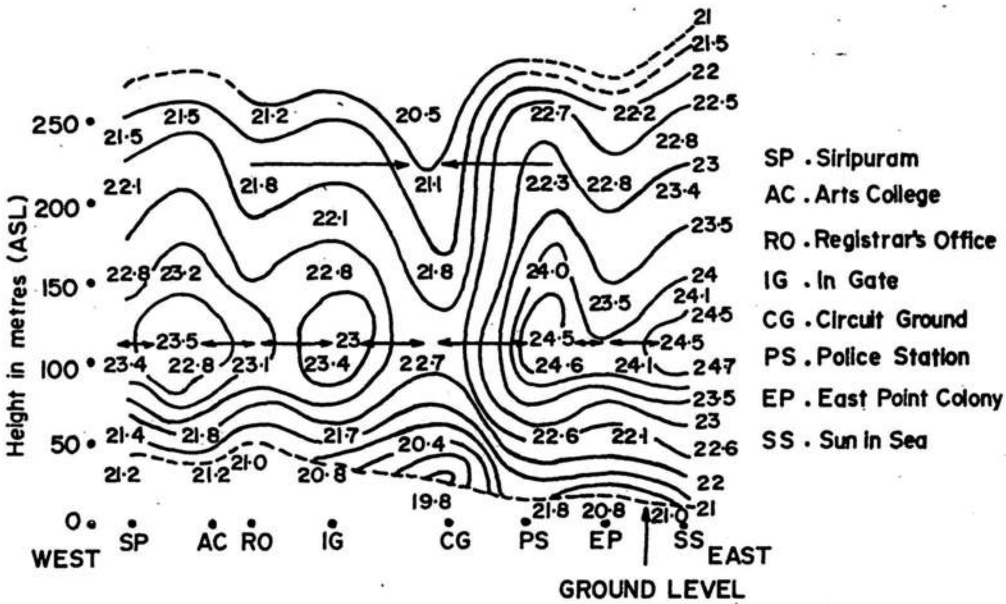

Figure 11. Vertical temperature cross-section (°C) at Visakhaptnam (rural) at the minimum temperature epoch. Andhra University 0600 h, January 29, 1978.

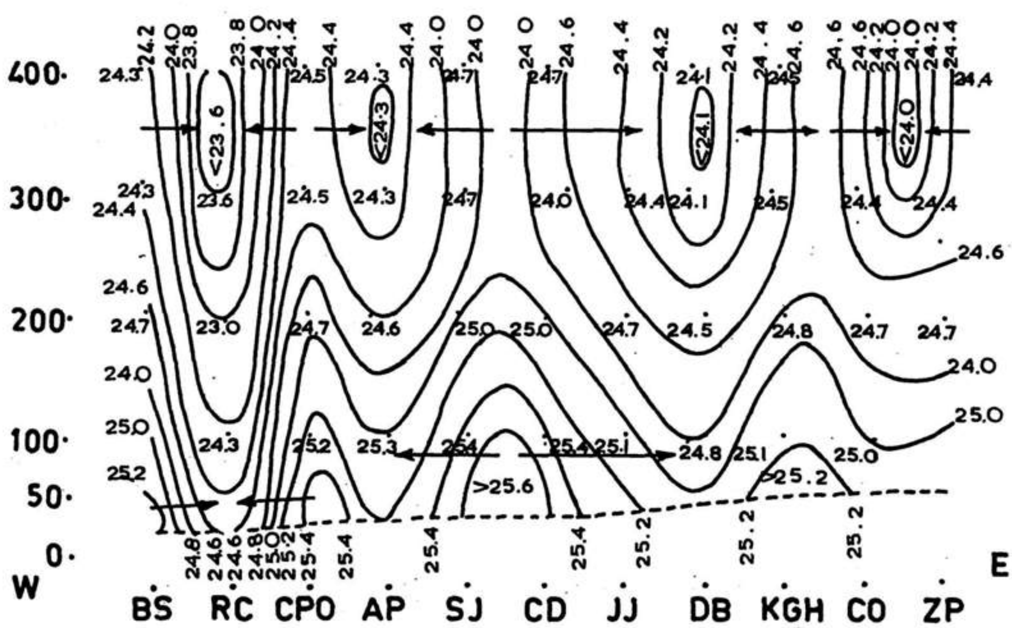

Figure 12. Vertical temperature cross-section (°C) at Visakhapatnam (urban) at the minimum temperature epoch. Jagadamba area 0600 h, September 23, 1984.

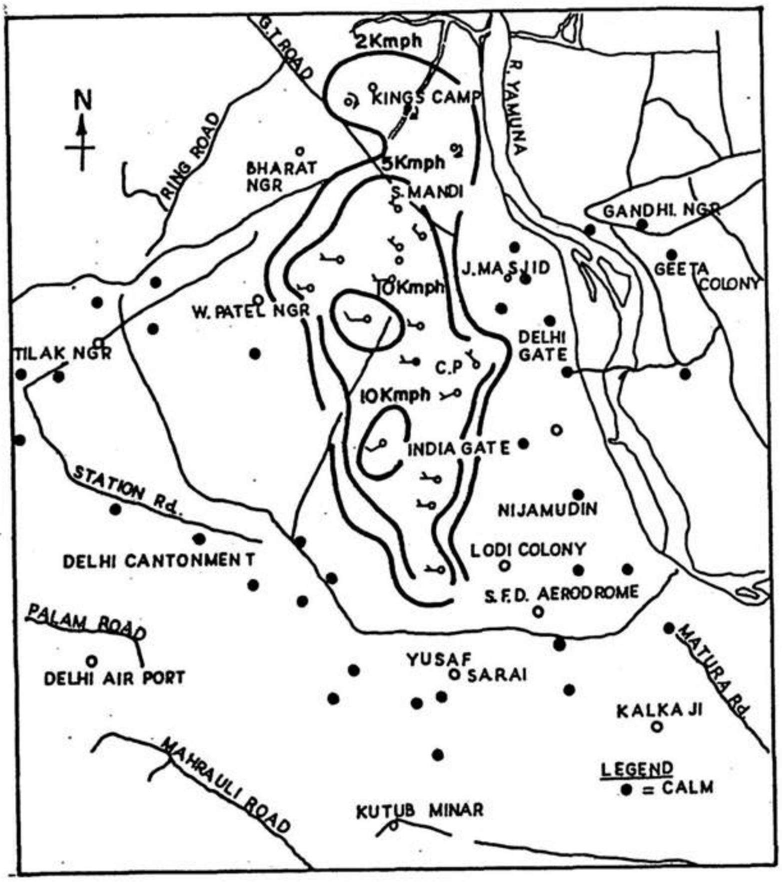

Figure 13. Isotach analysis (km h^{-1}) at Delhi at the minimum temperature epoch, February 25-26, 1978, between 0100 and 0730 h.

The vertical wind profile at an urban centre (Visakhapatnam) are shown in Figure 14 (Sastry, 1982).

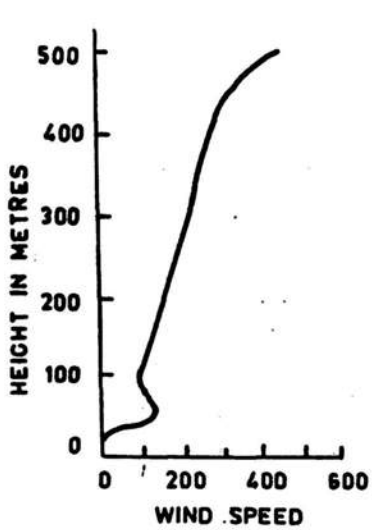

Figure 14. Vertical wind profile at Visakhapatnam (urban) at the minimum temperature epoch. Jagadamba area 0600 h, March 29, 1978.

There is a steep increase in the wind speed from about 20 m upwards to a height of 70 m and a decrease thereafter up to 100 m. Above 100 m the wind speed increases gradually again up to 400 m and more steeply still above that. The maximum is recorded at 500 m in the 500 m-layer under observation. This profile was more or less repeated several times. The vertical wind structure in this city therefore, seems not to follow the logarithmic law and the wind speed maxima are found to be at about the same height as the top of the heat island.

4. VISIBILITY

Particulate matter in the atmosphere causes a deterioration in visibility. Studies at Bombay show that the number of occasions of poor visibility has increased by over fifty-fold within a 15 year period (Figure 15). Poor visibility in the mornings of the cold weather period, from December to February, is not due to mist or fog. The deterioration of visibility occurs under calm or light wind and low inversion conditions.

Studies in Delhi also indicate that the frequency of occurrence of fog of low density and haze and mist is greater, and of longer duration, in the urban area of Safdarjung compared to the more rural area of Palam. On the other hand, the occurrence of dense fog, with visibility less than 100 m, was more frequent at the rural location. This may be due to the urban area around Safdarjung being more populated with larger hygroscopic nuclei, creating conditions favourable for the occurrence of shallow fog, mist or haze, even at lower humidities.

5. TOTAL INCOMING SHORT-WAVE AND NET RADIATION

Total incoming radiation refers to the quantity of short-wave radiant energy received as a beam from the Sun's disc as well as that scattered by atmospheric particles and clouds falling as diffuse radiation on unit area in the horizontal plane. Net radiation refers to the difference between total incoming and outgoing short- and long-wave radiation. Rural observations have been collected over a grass surface but the Delhi urban data come from above roof-level over bare ground.

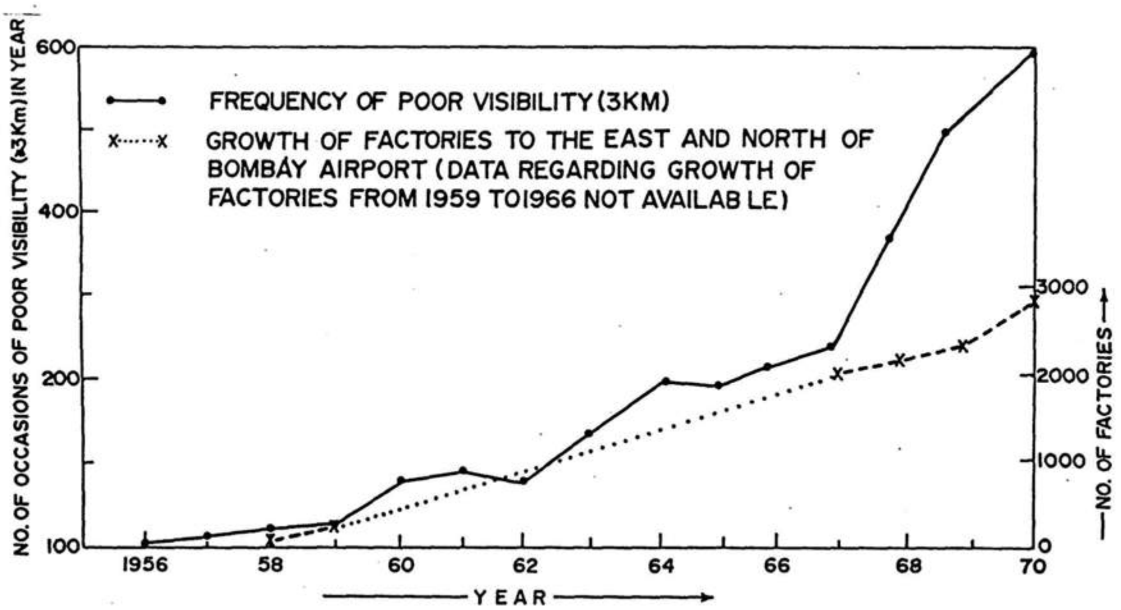

Figure 15. Visibility vs growth of industries at Bombay, 1956-70.

Urban-rural incoming short-wave radiation differences in winter at Delhi show that the urban area receives less radiation. This may be attributed to the comparatively higher pollution levels in the urban area. There were occasions when rural radiation was less than that received in the urban area. This may be due to a change of wind direction resulting in transport of pollutants from the urban complex to rural locations (Figures 16 and 17; Padmanabhamurty and Mandal, 1982). Net radiation was higher at urban locations until 1400 h local time and thereafter it was lower (Figure 18).

5.1 Urban Pollution, Incoming Short-wave Radiation and Maximum Temperatures

Urban pollution depletes incoming solar radiation which in turn affects the air temperature. Comparison of solar radiation (T_R) and maximum temperatures (T_x) on Sundays (Industrial and Official holidays) with those of weekdays at some industrial cities are shown in Table 3 (Padmanabhamurty, 1976).

At all stations the Sunday maximum temperature and solar radiation input increased on more than 50% of occasions when compared to that on week days. This was found on both a whole year, and a clear month basis. Of the two parameters the solar radiation exhibited the highest Sunday increase, and of the stations Calcutta showed higher values on Sunday vis-a-vis week days.

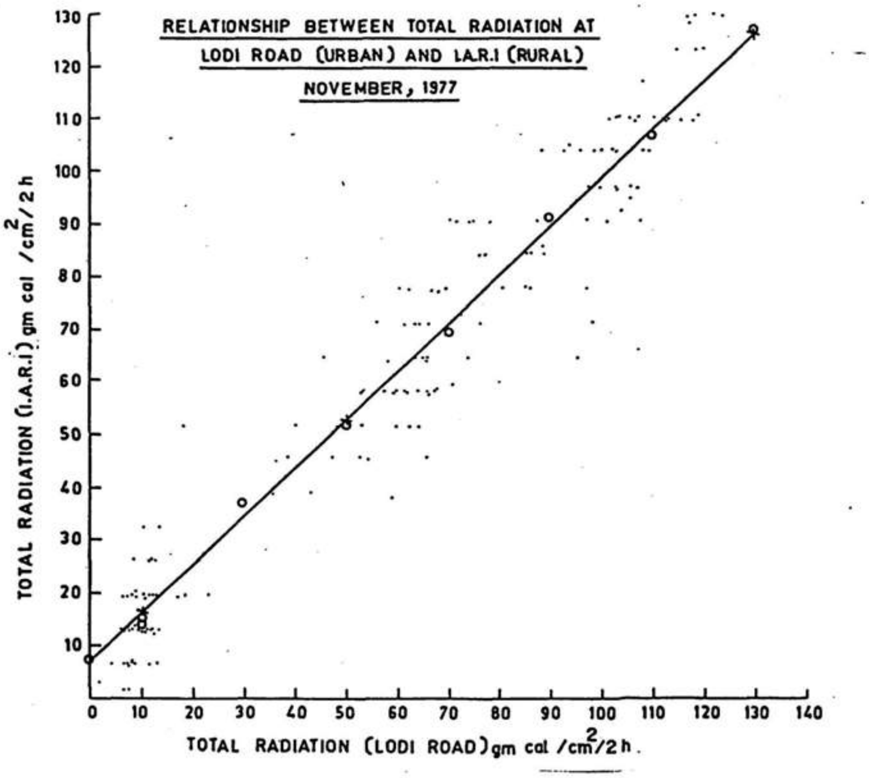

Figure 16. Urban vs rural total incoming solar radiation at Delhi.

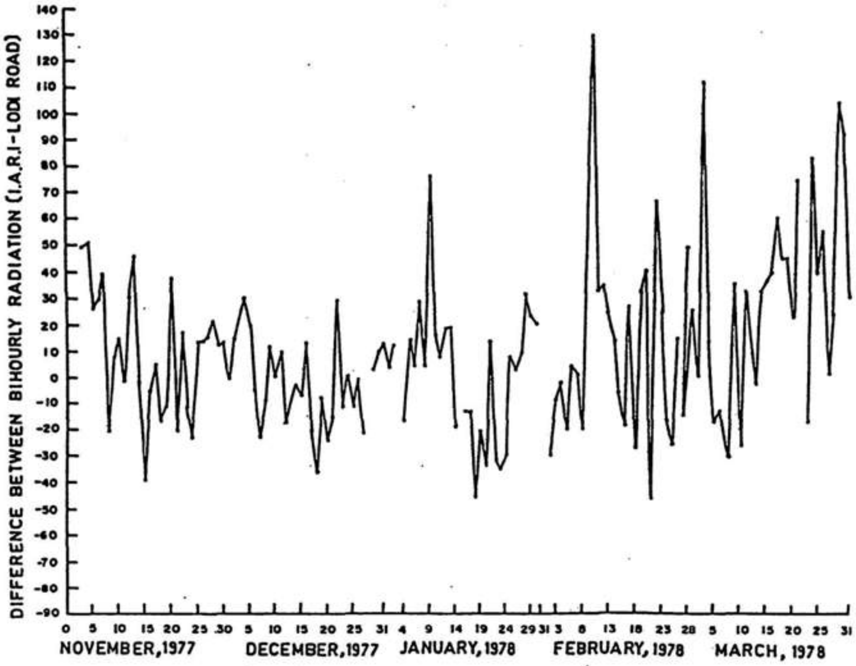

Figure 17. Daily march of rural-urban total incoming solar radiation at Delhi.

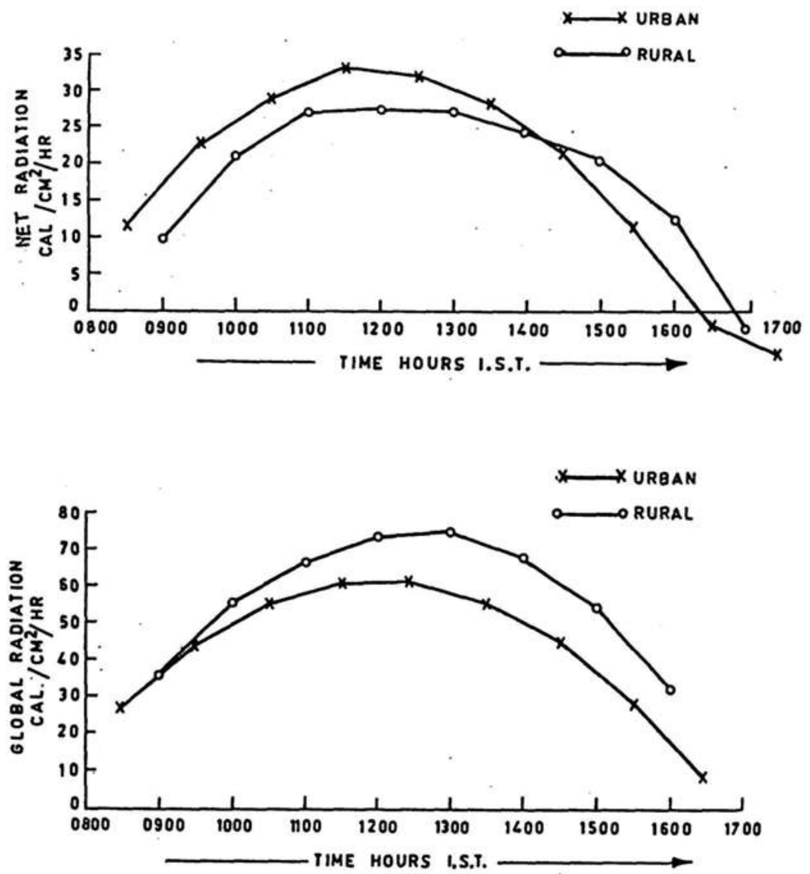

Figure 18. Urban-rural net and global solar radiation at Delhi.

TABLE 3. *Urban Pollution vis-a-vis Total radiation and maximum temperature. Data are percentage of occasions on which the Sunday value is greater than those for all week-days. Based on data for the period 1965-67. [Note T_x = maximum temperature and R_t = total incoming solar radiation.]*

STATION	WHOLE YEAR		CLEAR MONTHS	
	T_x	R_t	T_x	R_t
TRIVANDRUM	56	61	61	55
MADRAS	64	70	72	66
VISAKHAPATNAM	61	61	67	66
AHMEDABAD	61	58	61	61
CALCUTTA	75	72	67	78
NEW DELHI	50	64	49	62

6. URBAN-RURAL MIXING DEPTHS

The inadvertent modification of the mixing depth, and the ventilation coefficient, due to urbanization at Delhi have also been examined (Padmanabhamurty, 1977). Figure 19 presents the mean diurnal variation of urban-rural differences in mixing depths and ventilation coefficients from October to March. This is considered to be the worst period from the air pollution dispersion point of view. In all the months, and at all hours, both mixing depths and ventilation coefficients are larger over urban areas. In general, mixing depth differences are small at night reaching a minimum at midnight and increase after day break recording a peak value in the afternoon. The variation of the ventilation coefficient runs in parallel to the mixing depth, but is generally greater than zero, suggesting that even at night turbulence prevails in urban areas.

7. PRECIPITATION

Reports in the literature are divergent on the effects of urbanization and industrialization on precipitation. Arguments are advanced that large cities, with a super abundance of condensation nuclei, influence precipitation processes towards a reduction in precipitation by increasing the number of small droplets in the form of clouds and smog. On the other hand smaller urban complexes may supply the right amount of additional condensation nuclei to increase precipitation amounts.

The isohyetal distribution at Delhi from June to September shows pockets of higher urban rainfall in all months, but being most marked in July/August (Figures 20 and 21). These areas of higher rainfall correspond to the congested urban agglomeration which tends to support the hypothesis that urbanization leads to increased buoyancy and convection thereby resulting in increased precipitation (Padmanabhamurty and Bahl, 1984).

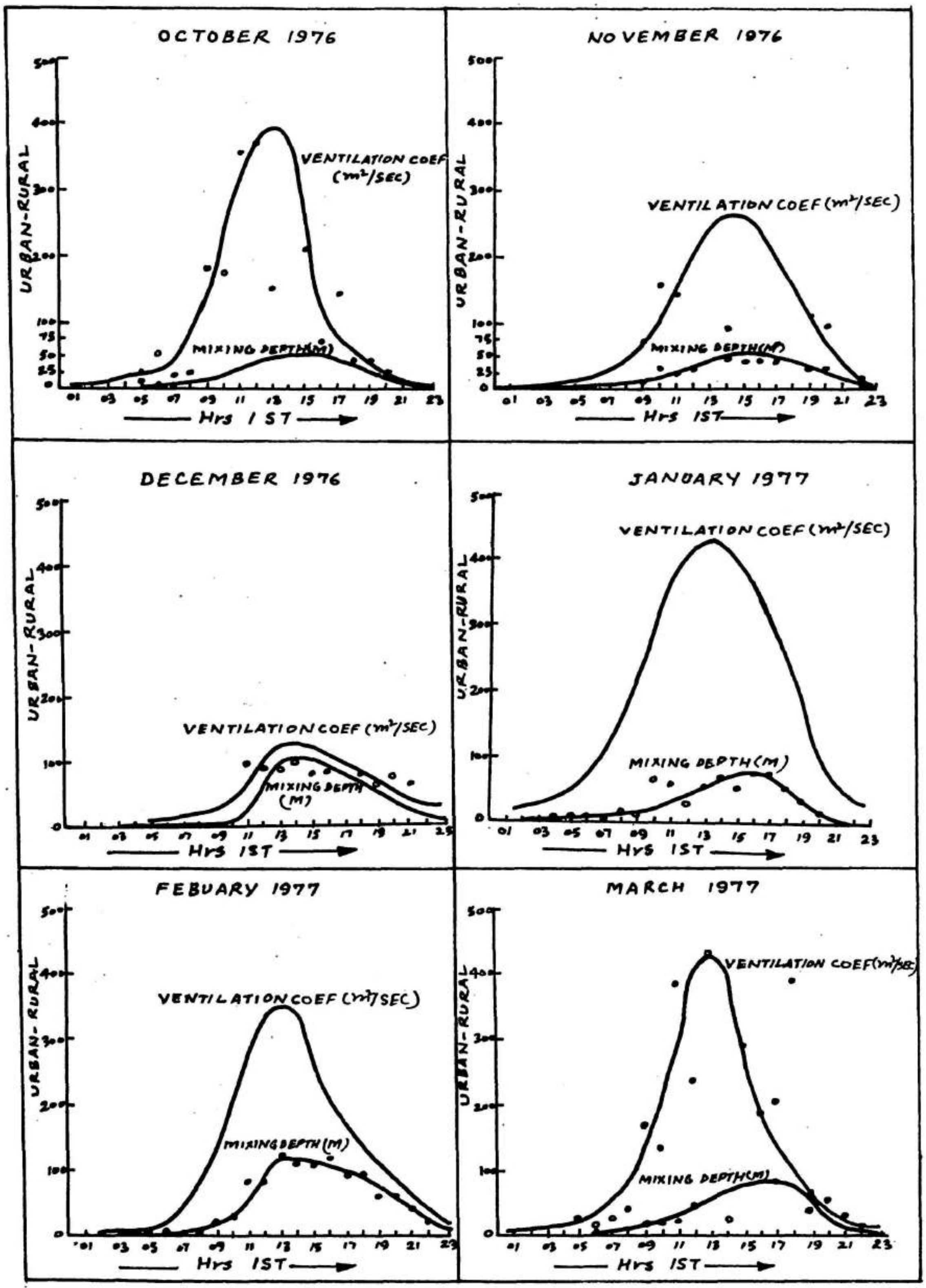

Figure 19. Diurnal variation of urban-rural mixing depths and ventilation coefficients.

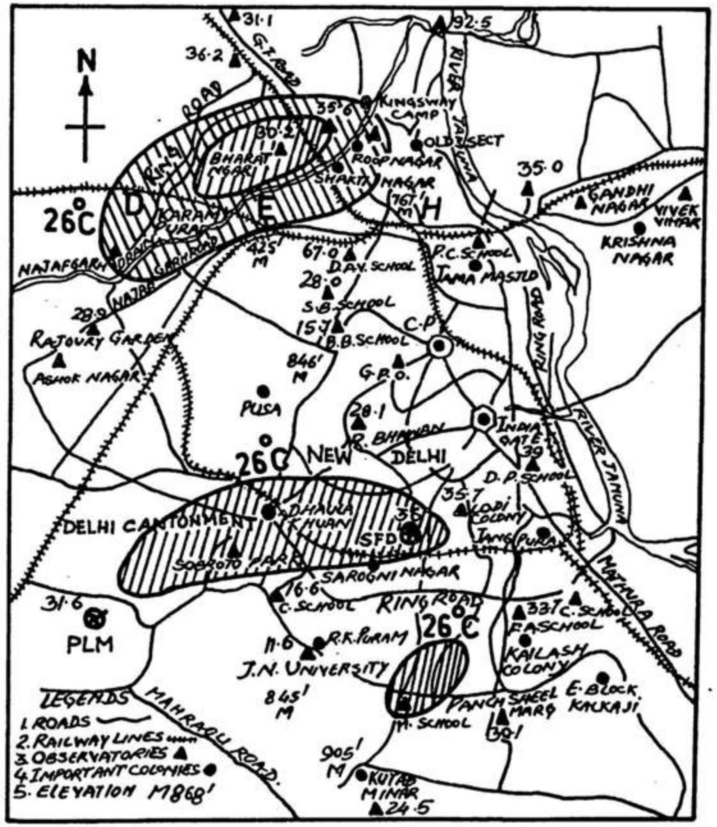

Figure 20. Mean monthly isohyetal distribution (cm) at Delhi - July. Hatched areas are heat island warm cores.

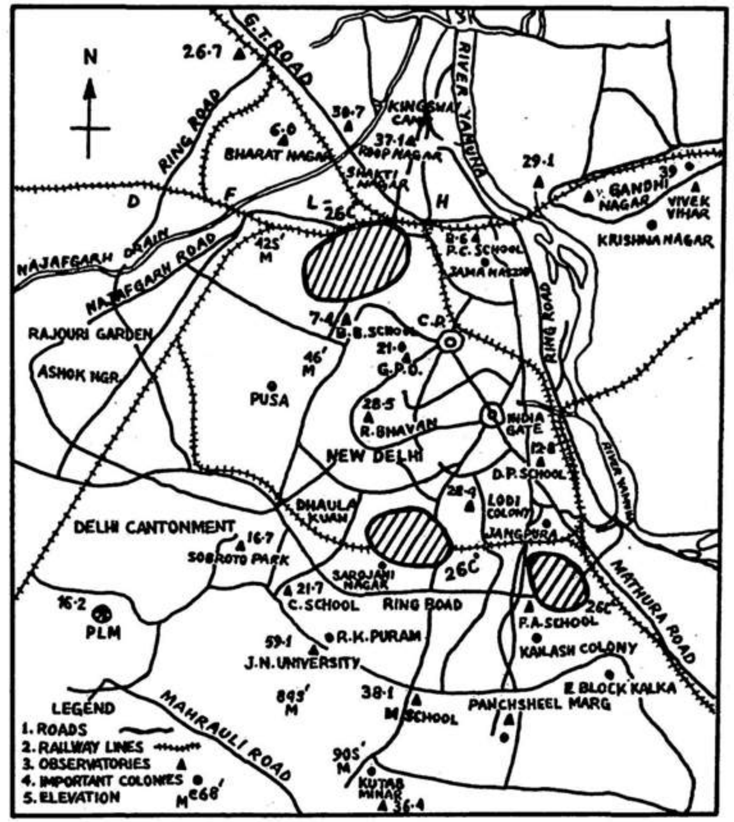

Figure 21. Mean monthly isohyetal distribution (cm) at Delhi - August. Hatched areas are heat island cores.

8. CITY-AIRPORT MOISTURE INDICES

As we have seen urbanization and industrialization may cause local climatic changes by modifying the radiation and precipitation. To adjudge the impact in tropical cities, moisture indices of some Indian stations (city centres) along with airport (country) locations are presented in Figure 22 (Padmanabhamurty, 1981). The trends are marked with lines by joining the mean of the first half and second half. All the semi-arid stations remained in the same category but showed decreasing aridity. The corresponding country data are very meagre, hence no attempt has been made to compare the trends in their case. However, even with short period of data in the 1960's the cities tend to be more moist than the aerodromes.

The three stations in the dry sub-humid zone viz, Bangalore, Madras and Kanpur behaved differently. Bangalore city tended to be more moist. Madras and Kanput tended to be more dry. Kanput particularly turned out to be semi-arid. The aerodrome at Bangalore is drier than the city, but Kanpur city and aerodrome showed no difference.

Inadvertent modification of climate therefore takes place in the tropics, but each urban-industrial complex, behaves in its own peculiar way rendering generalization difficult.

9. EVAPORATION

Evaporation has been obtained from mesh-covered pan evaporimeters under standard exposure conditions. These data are not used in evaluating the water balances (Section 10). Urban-rural evaporation differences (Figure 23) measured over a two year period point out that rural evaporation is greater than urban, and this is in tune with the higher radiation at the former place (Padmanabhamurty, 1983).

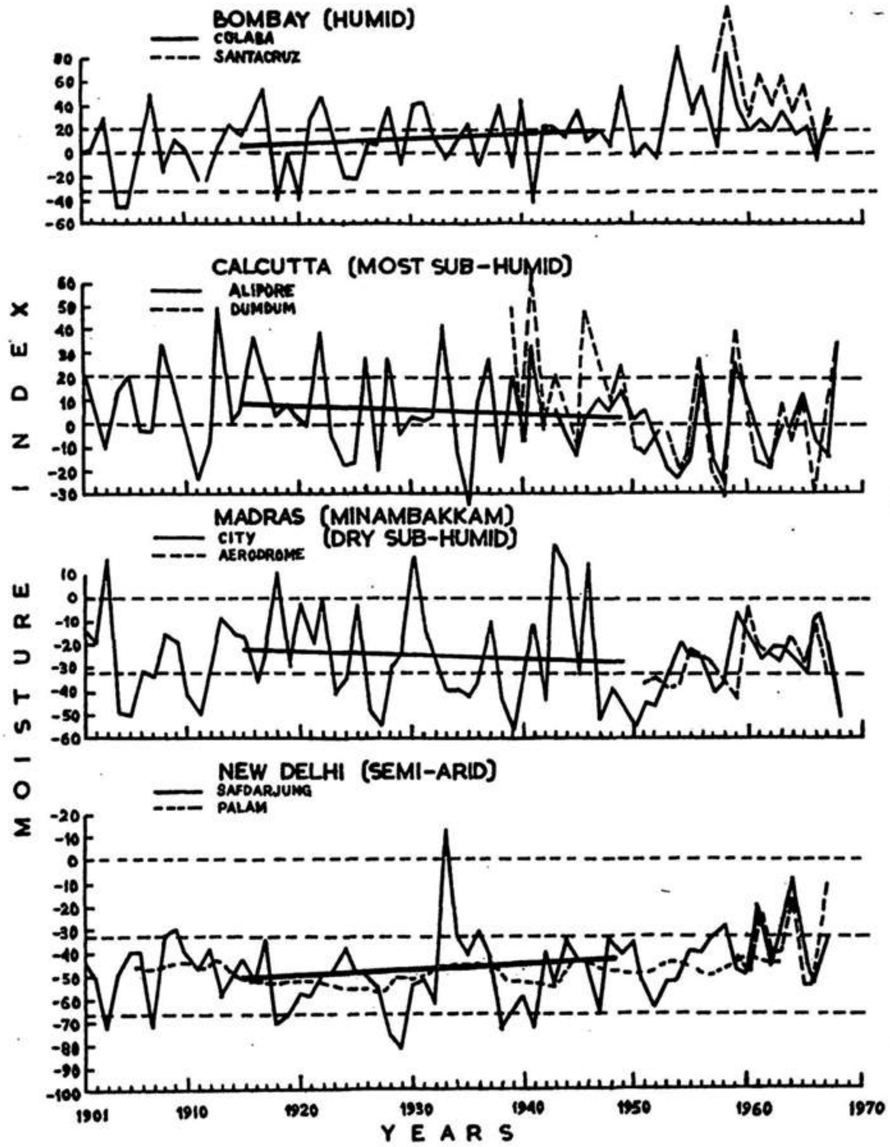

Figure 22. Moisture indices at city-aerodrome pairs for Bombay, Calcutta, Madras and New Delhi.

10. URBAN-RURAL WATER BALANCES

In view of the inadvertent modification of meteorological parameters brought about by urbanization, climatic water balances were computed for urban and rural locations of Delhi (Padmanabhamurty, 1983). In these computations the heat island effect, both by day and night, and the variation in precipitation in the region of heat island and surrounding rural areas, were given due consideration. The resultant water balances are shown in Figures 24 and 25. Urban Delhi has more precipitation and water surplus compared to its rural areas. This results in a more moist climate at urban Delhi. According to Thornthwaite's climatic classification by moisture regime, urban Delhi falls under his Dry Sub-humid type, while rural Delhi remains under the semi-arid category (Thornthwaite and Mather, 1955). These differences in climatic type could contribute to different conditions of comfort at the two locations.

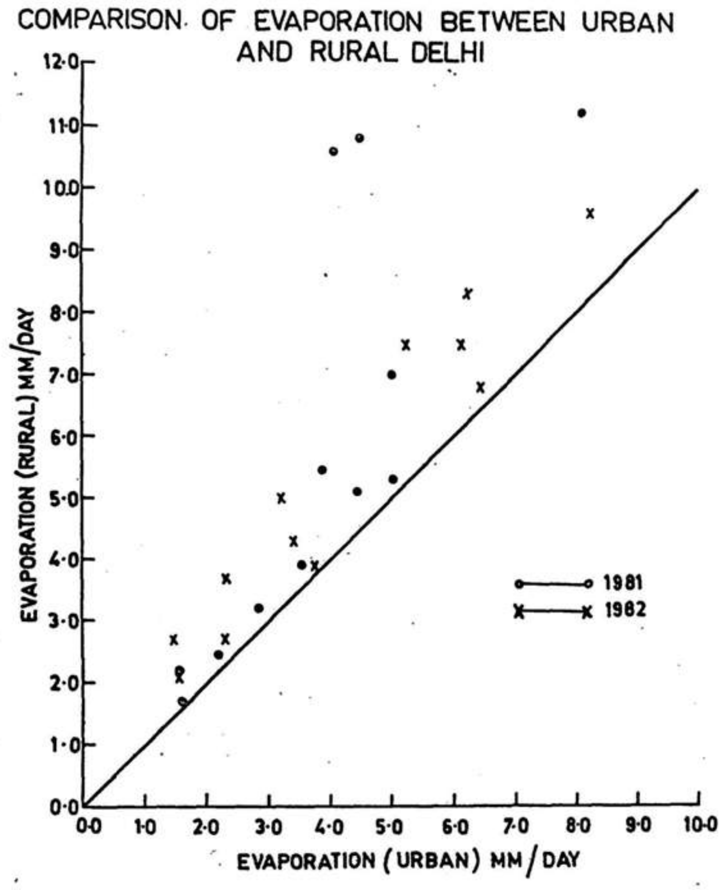

Figure 23. Urban-Rural evaporation in the Delhi region.

11. HUMAN COMFORT AT DELHI

The effect of the heat island on comfort or discomfort in Delhi and environs have been examined. Daytime conditions (Figure 26) show that February, March, November and December are comfortable at rural Delhi, but in urban Delhi January, February and December are the comfortable months.

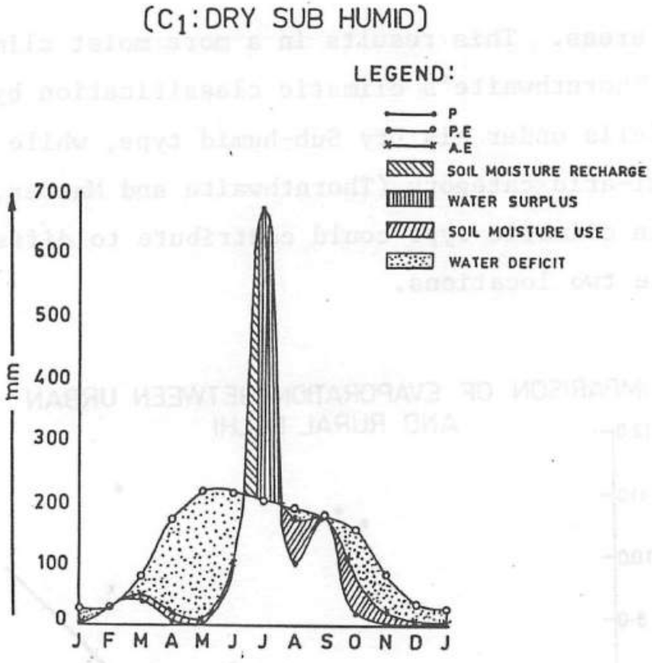

Figure 24. Annual water balance of Delhi (urban).

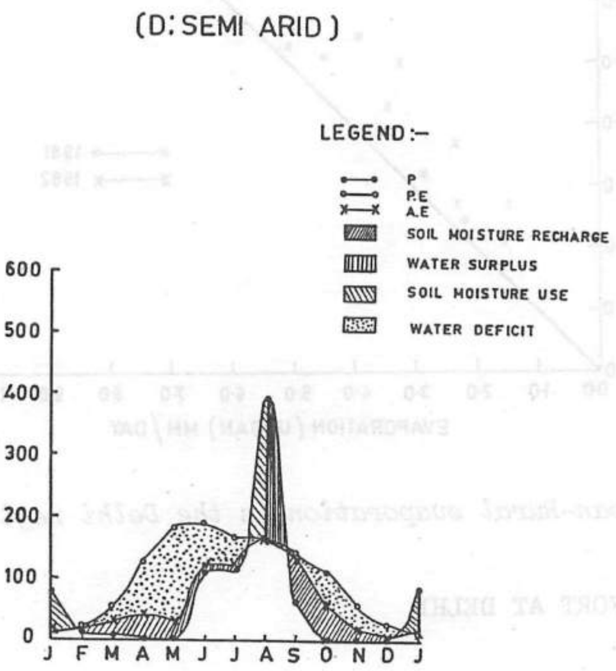

Figure 25. Annual water balance of Delhi (rural).

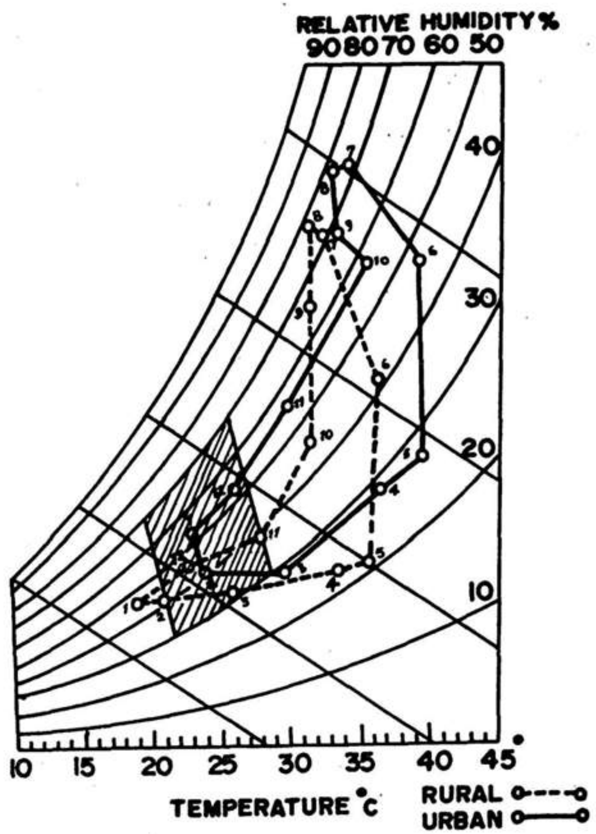

Figure 26. *Urban and Rural climograms of Delhi at the maximum temperature epoch. Note: the cross-hatched area on this and the next graph indicates the comfort zone.*

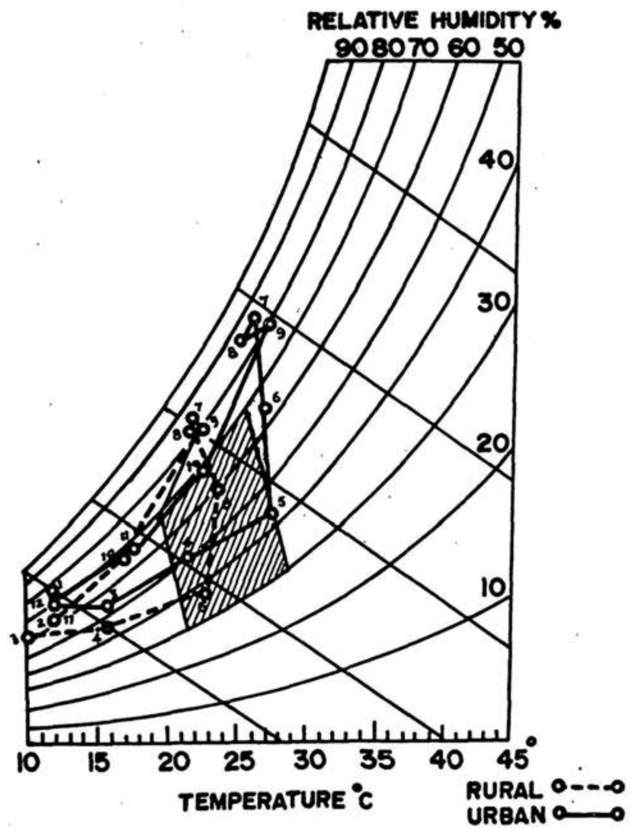

Figure 27. *Urban and Rural climograms of Delhi at the minimum temperature epoch.*

The heat island in January enables urban Delhi to be considered comfortable whereas rural Delhi remains uncomfortable due to coldness. From April to October rural Delhi is uncomfortable due to heat, but urban Delhi is uncomfortable from March to November.

Considering night-time conditions (Figure 27), rural Delhi is comfortable in May and June only. July, August and September are uncomfortably warm and humid months and October to April are uncomfortably cool. At urban Delhi, because of the heat island, April, May and October are comfortably warm (and humid) but June to September and November to March are uncomfortably warm (humid), and cold, respectively (Padmanabhamurty, 1983).

12. CONCLUSIONS

Inadvertent modification of local climate by urban complexes, even in the tropics, are likely to result in signficant changes in meteorological parameters. Some of the changes, particularly the heat island effect, could be taken advantage of in air conditioning and refrigeration. However, adverse effects, for example transport of pollutants from the periphery of urban areas to the downtown area, higher precipitation, rapid runoff, etc. outweigh the advantages. It is, therefore, desirable that in planning urban complexes built-up areas and concrete surfaces should be interspersed with wide lawns and parks to mitigate the formation of intense heat islands and other malevolent effects.

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SOME ASPECTS OF THE URBAN CLIMATES OF TROPICAL SOUTH AMERICA : THE BRAZILIAN CONTRIBUTION

Carlos Augusto de Figueiredo Monteiro
Department of Geography
University of São Paulo, São Paulo, Brazil

1. FOREWORD

In the same year in which Chandler (1965) published his study on the Climate of London, Brazil's urban population outgrew its rural one. From Landsberg's (1956) first synthesis of the general laws concerning urban climates, to Chandler's first monograph on a metropolitan climate, the basic knowledge about climatic changes caused by urbanization was established in the Western industrial cities of the mid-latitudes. Successive WMO symposia gave us the main results and the outline of progress achieved in the subject. On the other hand, the lack of information concerning the climates of urban agglomeration in the tropical regions has been deplored (Oke, 1982).

As in other Developing Countries the urban studies in Brazil, especially from the late 1950s, gained special attention from geographers. Despite many signs that the process of urbanization was intimately connected to the deterioration of the local environment, the overriding importance of economic and social problems left environmental problems with a low priority. Indeed no attention at all was paid to climatic changes within the cities. By the early 1960s, São Paulo became a great national metropolis, and the city was beset by serious environmental problems; mainly air pollution and flooding.

URBAN CLIMATES OF BRAZIL

When the first environmental watch agencies were set up, the University of Sao Pãulo Department of Geography, started the first graduate lectures in Urban Climatology in 1971. It was realized that the large amount of foreign literature demanded special perusal because simple transfer of methodologies into this very different geographical reality was not possible. At the same time, the limited grants set serious technical barriers to the development of urban field studies. To begin with the lectures emphasized the design of a more suitable theoretical framework, and a modest research programme was started.

Mention of this pioneer effort does not exclude other spontaneous, parallel and convergent interest which developed in other university geographical centres, as well as among meteorologists, and those engaged in environmental research agencies.

Unfortunately, we cannot say that great progress in urban climate studies has been accomplished in the last twelve years. But this contribution on that subject allows us to disclose information on a few basic topics concerning the influence of urban variables on climate modification across a hierarchical range of Brazilian cities.

Attempts to find similar information in other countries in South America proved to be quite frustrating. Nevertheless, if we consider that Brazil occupies about 2/3 of the continent, so except for the mountainous and extra-tropical character of many other South American countries, it may be possible to consider the present Brazilian contribution to be a suitable preliminary sample of continental tropical urban climates.

The present paper is largely based on a review of several different case studies. It tries to disclose the basic facts concerning the problem. Due to differences in thematic purposes, approaches or urban dimensions in those studies it demanded considerable effort to produce a reliable synthesis.

The main purpose of this paper is to bind together the available information on the urban climates of Brazil, and to uncover preliminary features and to interpret their possible meaning so as to discover some of the traits of our urban climates. We hope this preliminary information will be of some comparative value for colleagues from other regions. Brazilian geographers would feel rewarded if it provides a stimulus, an invitation, or even a challenge for future research.

Figure 1 gives a summary of the cities or urban nuclei which are dealt with in this paper.

2. BIBLIOGRAPHICAL SURVEY

There are presently available in Brazil, twenty-eight studies linked directly or indirectly to the urban climate issue. They include: two Ph.D. theses, six Master's dissertations, seven scientific review articles, seven short papers, four technical papers and preliminary meteorological reports, and two newspaper articles. Most of these items are of a geographical nature, and twenty are associated with the Institute of Geography's Laboratory of Climatology, at the University of São Paulo.

From 1972 until 1975 there was a preliminary phase of work. Heading the laboratory was the author of this paper, together with a group of graduate students, and they started the first attempts to understand the relationship between weather dynamics and air pollution. This pioneer effort was aimed towards our main cities: São Paulo and Rio de Janeiro. While the studies of the first failed for lack of reliable information, the other was successful, producing the first insights into the problem (Gallego, 1972).

After an effort to elaborate a suitable theoretical framework for the Brazilian urban case (Monteiro, 1976), we started a modest, but persistent, programme in which priority was directed to the São Paulo metropolitan area, including a comparative view over a range of Brazilian cities.

Given the limited grants of resources, tools and personnel, the subjects for study were mostly chosen according to our capability, rather than to their relevance. The thermal structure of the city, for instance, was discarded for the moment. We started with the study of rainfall impact, and the effects of flooding on urban life (Monteiro, 1980a, b; Paschoal, 1981).

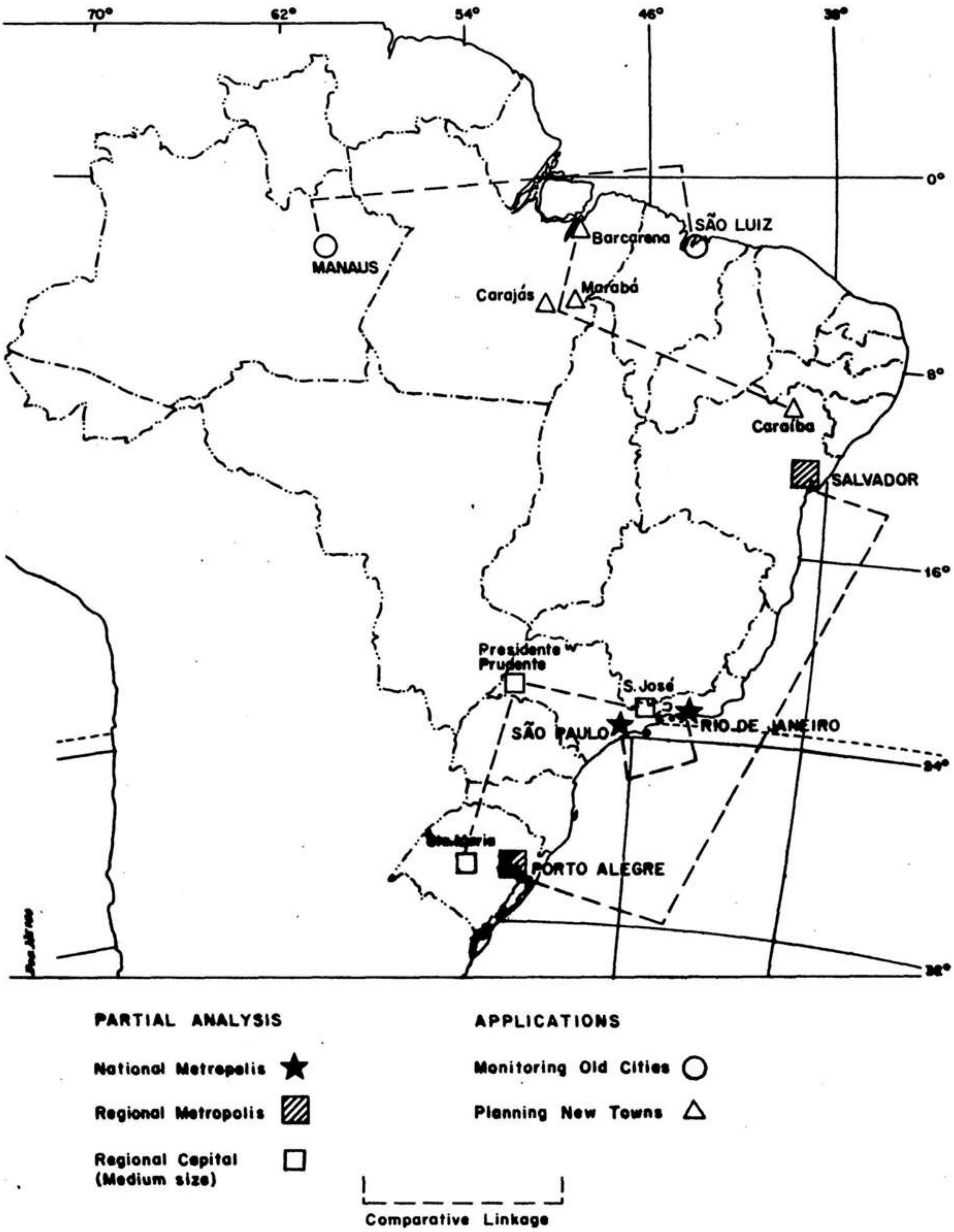

Figure 1. Location of urban climate studies in Brazil in the period 1975-1984.

From the projects of Masters graduate students Sartori (1979) and Fonzar (1981) obtained the first information about the "heat island effect" in we intermediate-size urban centres. The contributions of Ribeiro (1975) and Sampaio (1981) added important information from other urban areas.

Our colleague and collaborator Conti (1978 and 1979) summarized the first signs of São Paulo's local climate modifications, and Titarelli (1982a) noticed the effects of the regional circulation and weather dynamics on air pollution. The most active researcher in our laboratory, Dr. J.R. Tarifa, gave special help with the first attempts to apply urban climate knowledge to urban planning and building. Some interesting field work was accomplished together with architects and urban planners in support of urban designs for new settlements in Amazonia and the Northeast. Dr. Tarifa is now the Head of the Laboratory, and together with his graduate students, is working on new projects related to metropolitan area climatic problems. The first complete study of the heat island configuration in one of our major cities came from Rio Grande do Sul (Danni, 1980) which shows a convergence for this important climatological issue.

Recent contributions, mostly aimed at technical problems concerning the observation of São Paulo's air and its pollution, have been made by our meteorological colleagues (Oliveira et al., 1983a, b; Orsini et al., 1982; and Setzer et al., 1979).

An auspicious collaboration has been recently established in Rio de Janeiro, with the University of Tsukuba, Japan, for the study of urban climate problems.

3. A SYNTHESIS OF THE AVAILABLE KNOWLEDGE

3.1 The National Metropolis (São Paulo)

Only 400 km apart from each other, São Paulo and Rio de Janeiro display many different traits, not the least of which is their physical setting (Figures 2 and 4).

The Greater São Paulo region, which includes 37 counties concentrated in an 8,000 km^2 area, had a total population of 12,719,072 inhabitants in 1980. The conurbation of Rio spread over a more discontinuous area, had a population of 8,776,753.

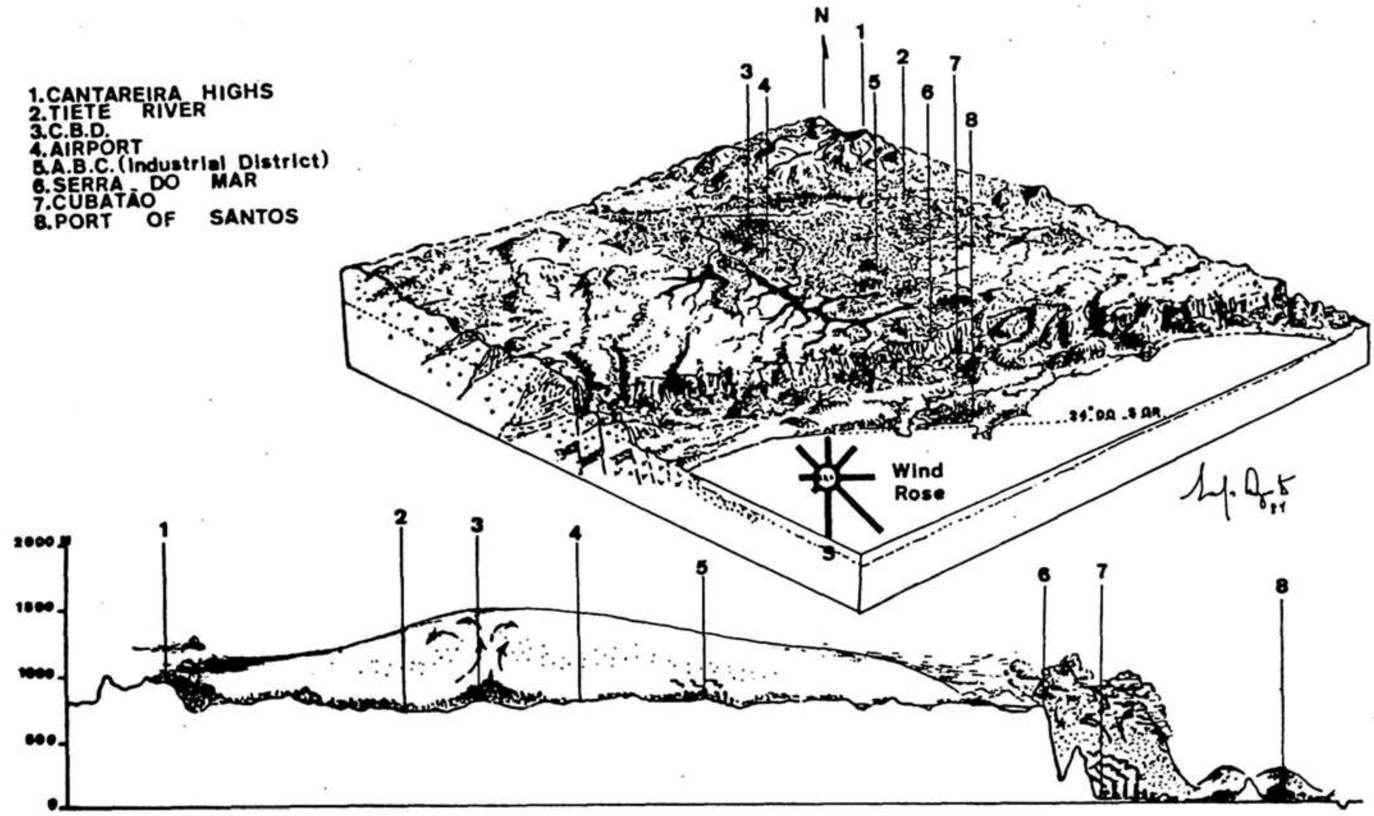

Figure 2. The metropolitan area of São Paulo and its physical setting.

The industrial growth, and the rapid pace of expansion in São Paulo astonishes policy makers in their attempts to manage this giant urban agglomeration where the spontaneous outsmarts the planned. Thus the environmental quality of this urban area presents a large number of problems including those of urban climate. Despite the fact that it has not yet been studied or explained, its negative effects are clear enough in the minds of its people. As the pace of urbanization accelerated after the 1950s many city dwellers can easily recall the differences between the climate characteristics then and now.

There are many signs of general change when we compare the climatic elements in two different decades (e.g. Conti, 1979). From 1947-56 to 1967-76, a rise in mean temperature is noticeable, from about 17^{o} to 19^{o}. For rainfall, the differences are registered more in changes of frequency and spatial distribution. Especially important are the rising rates of fog (from a total of 1,021 days in the first decade, to 1,401 days in the second), and especially of haze (from 397 to 1,325 days).

Although there are signs of change, the ranges in Rio de Janeiro are certainly not so impressive. Unfortunately, Brazil's urbanization process has been looked at mostly in its economic and social aspects. The study of environmental issues is still in its infancy, and the lack of reliable data makes comparison difficult.

A starting point for the study of climatic problems within the metropolis would certainly be its thermal structure. Lombardo and Tarifa (1983) first looked at this problem in São Paulo. They produced a model to explore the LANDSAT thermal infra-red image for the heat island boundaries. With the help of the National Institute for Space Research (INPE), they devised an algorithm with a temperature field control, which allowed them to obtain a reliable technique for the heat island studies. Miss Lombardo has just finished her Ph.D. thesis on this subject (Lombardo, 1984). She was kind enough to allow us to use some of her basic data, from which it is possible to present the first view of the spatial configuration of the São Paulo heat island as shown in Figure 3. This is only the beginning, many more facts and insights are being expected as a result of her accurate research.

The coincidence of the CBD and the heat island is evident at first sight. As the prevailing winds blow from SW a tendency to displace that hottest spot towards the confluence of the Tietê and Pinheiros rivers becomes noticeable. According to Miss Lombardo's research and personal information, the temperature field shows large intra-urban temperature differences, including daily contrasts rising to 12°C.

As a result of the very different site and urban morphology to be found in Rio, we may expect to find a very different thermal structure for that metropolitan area.

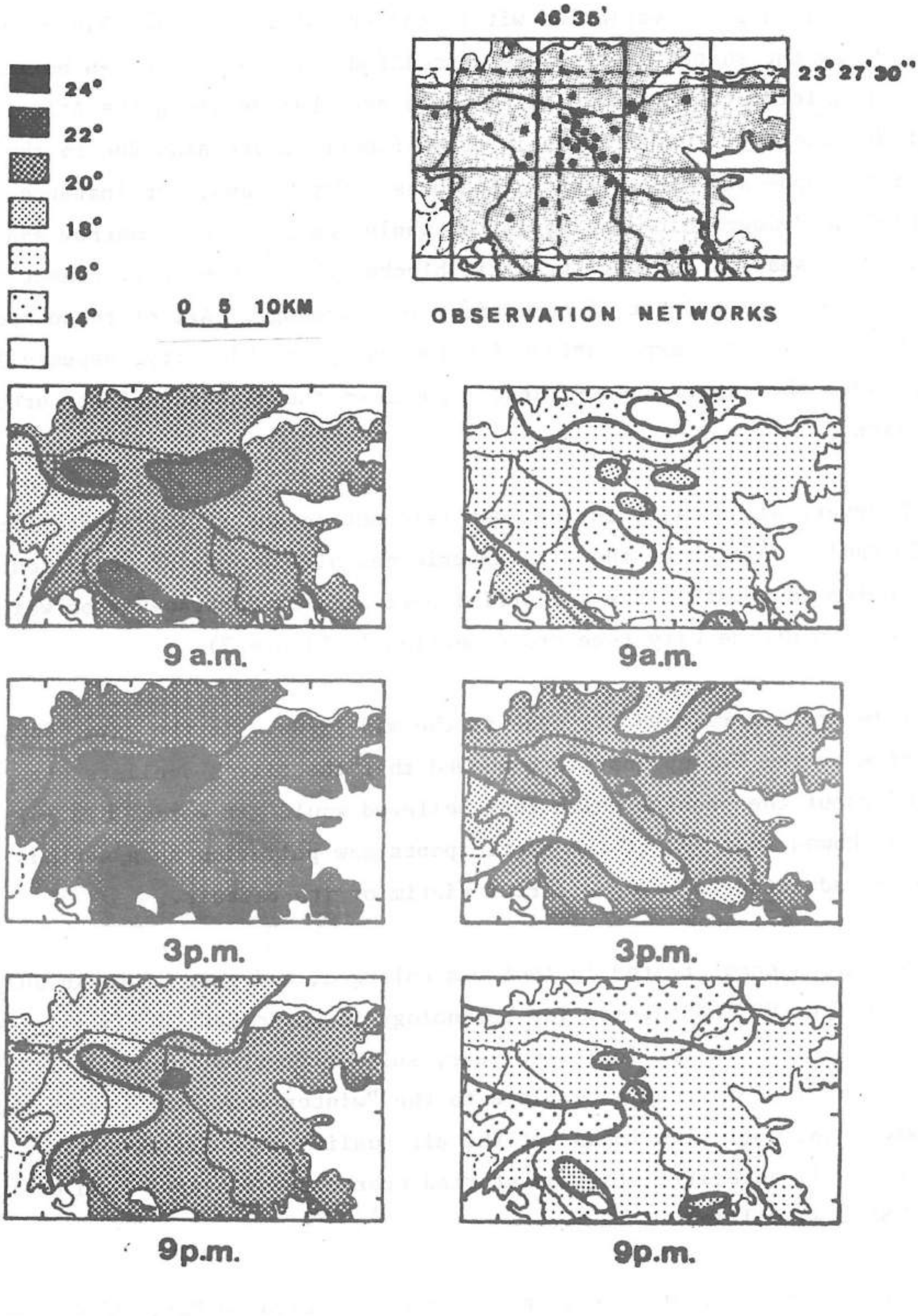

Figure 3. Spatial configuration of the heat island in São Paulo in 1982 (after Lombardo, 1984).

There is a great variation within the CBD of the Greater Rio conurbation, where different shapes of site are associated with variations in building form. Sensitive topoclimatic differences are obvious along the Atlantic coast and the bay. Differences in urban functions are also due to the different topo- and microclimatic features. Copacabana, for instance, has the highest demographic density in the whole country. On a narrow sand belt between the sea and the huge granitic blocks, the high mass of cement building blocks make a special set of conditions for exchange. All of these special features broaden our expectations for the study of this city, especially when we consider the importance of these impacts on the planning of its urban expansion.

However, air quality is the most relevant aspect of the urban climate of São Paulo. Air above the city experiences high levels of pollution. The problem is worst in the industrial port area of Cubatão-Santos which is an extension of the city (see cross-section in Figure 2).

This problem reached its peak in the mid-1970s. In the late 1960s inquiries by the Gallup Institute showed that the city's dwellers were deeply worried about the problem which they believed would get worse. In 1973 another inquiry showed that 80% of the participants saw pollution as a serious problem, while 58% admitted to being a direct victim of its effects.

A State agency created in 1968 was enlarged, and gave birth in July 1975 to the present CETESB (Agency for Technology in Basic Sanitation and Environmental Control). In the following year, sulphur dioxide reached a level of 2,100 mg cm^{-3}. This peak gave place to the "winter operation", when thermal inversions and pollution loads set the air quality at a "watch point". A network of 217 automatic stations started operation at a cost then estimated to be US$ 2.44 million.

Between the port of Santos and the foot of Serra do Mar, Cubatão now has a concentration of about one hundred high pollutant industries; including steel mills, oil refineries and petrochemical industries. This industrial district which is located in an especially fragile and delicate ecosystem, became the most polluted place in Brazil, or perhaps in the World, all because of the lack of control of industrial emissions. Thus it reached the status of a sanitation calamity requiring urgent solution.

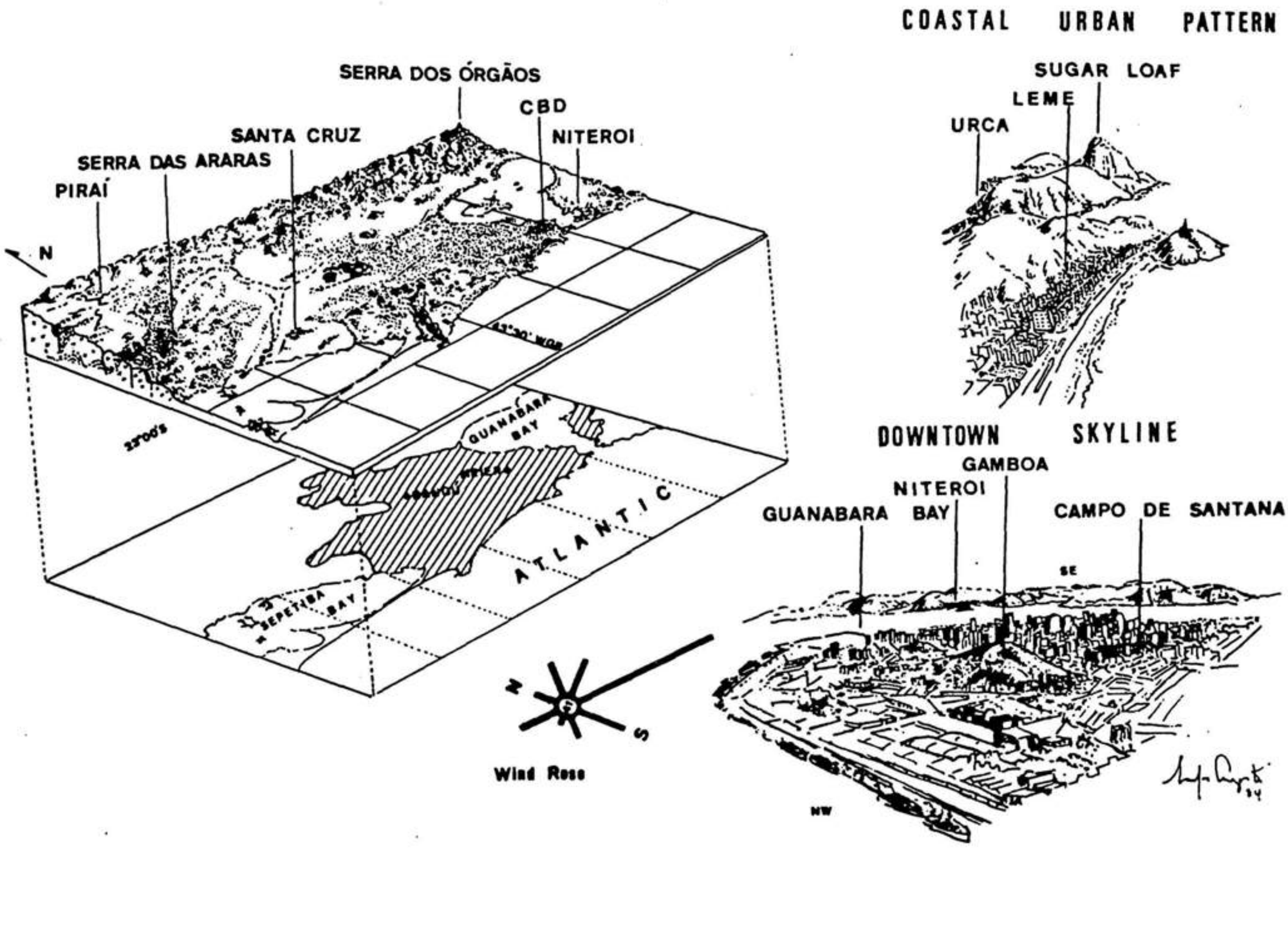

Figure 4. The metropolitan area of Rio de Janeiro and its physical setting.

A biogeographical investigation using lichens as biological indicators of air pollution (Ferreira, 1984) demonstrated how serious the pollution effects in Cubatão were, and that the damaging effects of pollution on the forest covering the slopes of the Sierra do Mar were quite evident, and continuously rising.

Documentation is desperately needed concerning the spatial variation of air quality within the metropolis, on the plateau and in the lowlands of

Santos-Cubatão including clarification of any link between them. A number of institutions are presently carrying out research projects on these and other issues.

Air quality in Rio is also a problem, but is not comparable to that of São Paulo. This may be because the concentration of industry is not so high, or because the complex configuration of the physical setting does not lead to an accumulation of the negative aspects of urban climate as is the case in the São Paulo basin.

According to the contributions of Gallego (1972) and Titarelli (1982b) on the relations between weather types and the degree of pollution in Rio and São Paulo, it is not difficult to observe certain areas of agreement. Although the local configurations are very different, the dynamics of weather systems have the same regional mechanisms. It has been observed in both cities that a wide spectrum of weather conditions has to be taken into account in relation to pollution levels. Anticyclonic weather is not always that which is most closely connected to the increase in pollution. Sometimes high peaks are found in pre-frontal weather conditions. This subject is still open to further careful research. A real difference between the two cities may be the role of altitude on cooling and its impact on the potential for low-level thermal inversions.

Although the signs of an increase in rainfall in the city of São Paulo is not clear enough in terms of annual averages, there is plenty of evidence in terms of episodic showers; sometimes resulting in heavy impacts. Undoubtedly, the most spectacular of these events, in the category of 'climatic hazards', are connected to the wider causal framework of the regional atmospheric circulation. Stationary fronts in the spring-summer (September-March) northerly flow, generate the most calamitous events. On other occasions general synoptic analysis reveals that during periods of calmness, there is a clear production of showers that are coincident with the central area of the metropolis and which could be associated with the heat island effect.

An analysis of rainfall impacts in the 1960s was undertaken. Twelve events, chosen because of their implications in flooding and its disruption of urban life, showed that, both through the traditional drawing of isohyets and by means of a computer "trend surface analysis", there is a clear association with the central area (Monteiro, 1980b).

Rio can also be impacted by rainfall events. From the mid-1950s to the 1960s many damaging events were registered in the city's history. Landslides, and other violent kinds of mass-wasting at this peculiar geomorphological site brought severe harm and flooding. A serious geo-technical programme on slope stability brought forth considerable progress in the solution of this issue. The problems of heavy showers in Rio are still to be noticed but now mostly only in terms of climatic hazards. In São Paulo, the flooding problem shows evidence of continuous growth. This shows that urban growth,progressive soil water-proofing, and lack of work on the urban drainage system, in such a peculiar hydrographic basin (upper Tiete river) must be dealt with. The study done by Paschoal (1981), on the central area of São Paulo, showed that the number of flooding events during the 1970s was considerable. In addition to the twelve cases studied by Monteiro (1980b), the author points out a further fifty six events between 1970 and 1978.

The examples given here regarding the two national metropolis, may give some idea of how important the study of urban climate is in the understanding of the urban problems. A wide spectrum of subjects demands our attention, and is an open field for research which deserves attention.

3.2 Two Regional Metropolis (Porto Alegre and Salvador)

Porto Alegre (30°S) in the extreme south of Brazil, and Salvador (13°S), the oldest Capital of Brazil, offer interesting parallels in preliminary observations on their heat island effect.

These two capital cities, which are not very different in area and population (see Table 1), exhibit contrasts in physical setting and urban structure (Figures 5-6).

	CITIES	SALVADOR (BA)	PORTO ALEGRE (RGS)	SÃO JOSÉ DOS CAMPOS (SP)	PRESIDENTE PRUDENTE (SP)	SANTA MARIA (RGS)
GEOGRAPHIC CHARACTER	Latitude Longitude Altitude	$13^{\circ}01'S$ $38^{\circ}31'W$ 0 to 100 m	$29^{\circ}20'S$ $51^{\circ}16'W$ 0 to 300 m	$23^{\circ}15'S$ $45^{\circ}55'W$ 580 m	$22^{\circ}07'S$ $51^{\circ}27'W$ 480 m	$29^{\circ}41'S$ $53^{\circ}48'W$ 150 m
	Urban population	1,504,219	1,115,291	268,034	127,902	154,619
URBAN CLIMATE FIELD OBSERVATIONS	Period Observation hours	1 April 1980 6,7,8,..to 18h	15 days May-June 1979, 9,15,21h	2 to 6 December 1974 9,11,13,15,17,21h	2 to 29 January 1980 7,9,11,15,17,21h	19 to 21 March 1979 9,15,21h
	Number of observation points	11	35	2	9	3
	Variables monitored	Temperature, moisture	Temperature	Temperature, moisture, cloud cover, wind direction, wind intensity	Temperature max. and min., moisture	Temperature, moisture
	---------					
	Weather conditions	Fair		Unstable	Fair, Rising temperature	Fair, Heat-wave
	Acting Meteorological system	Atlantic Tropical air mass	-	Frontal	Post-frontal	Pre-frontal
HEAT ISLAND	Maximum daily urban heat island intensity ($\Delta T_{u-r(max)}$)	$6.0^{\circ}C$	$4.0^{\circ}C$	$3.4^{\circ}C$	$3.3^{\circ}C$	$7.0^{\circ}C$

TABLE 1. *Physical characteristics of the cities studied, the period of observation, variables monitored, weather and heat island results.*

In Porto Alegre, which is on the banks of the Guaiba, a large estuary, the setting is rather simple. A plain at sea-level is divided by a line of hills extending from SW to NE. The original city core which is now the downtown area, is on a small promontory, formed by a string of low hills (less than 40 m in height) (Figure 5).

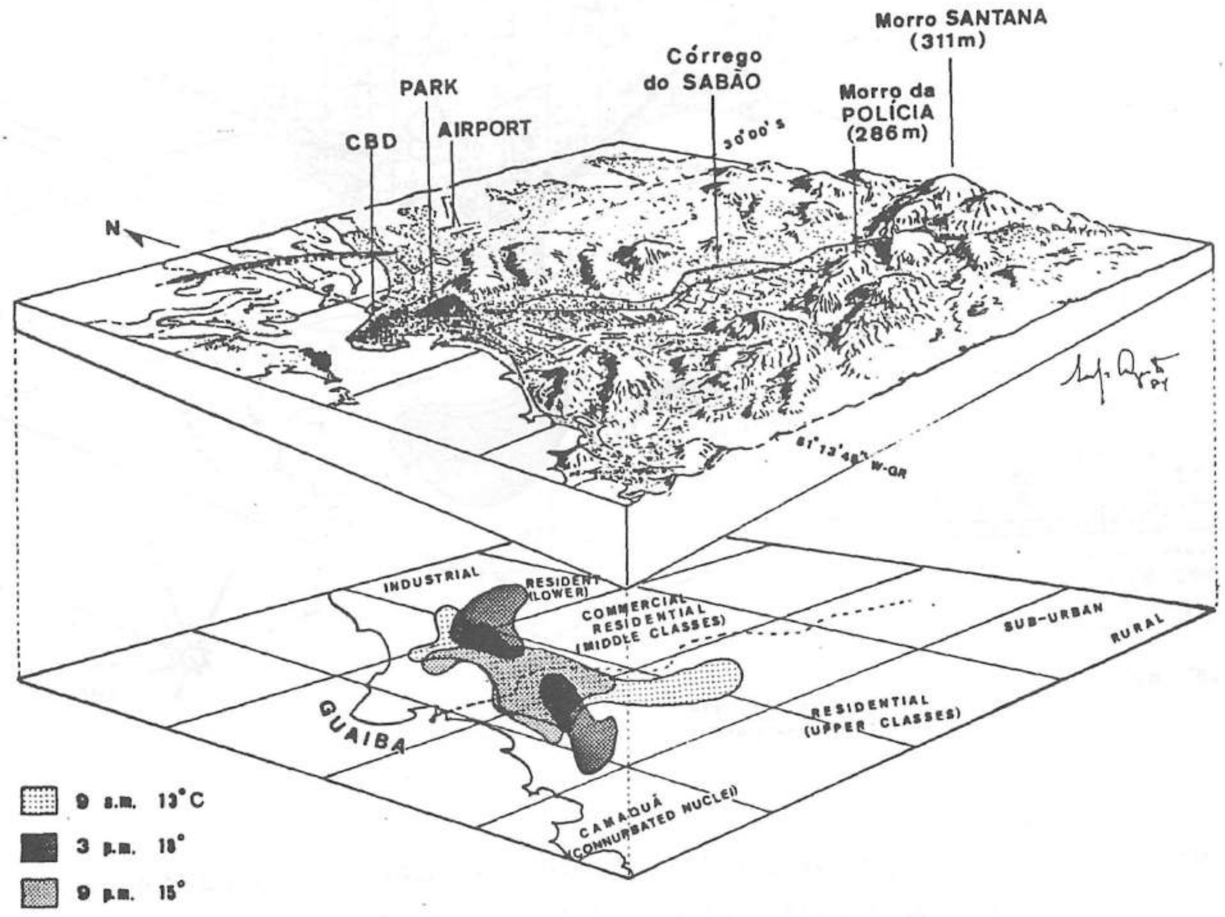

Figure 5. (Top) The physical setting of Porto Alegre (Rio Grande do Sul). (Below) The spatial configuration of the heat island observed in May-June 1979 by Danni (1980).

The site of Salvador offers a long, but not very high, fault scarp, which divides the city into two sections. A very narrow lowland belt lies between the scarp and the sea and does not allow enough space for the port and the business district. The upper part outgrew the lower and spread widely across the plateau (Figure 6).

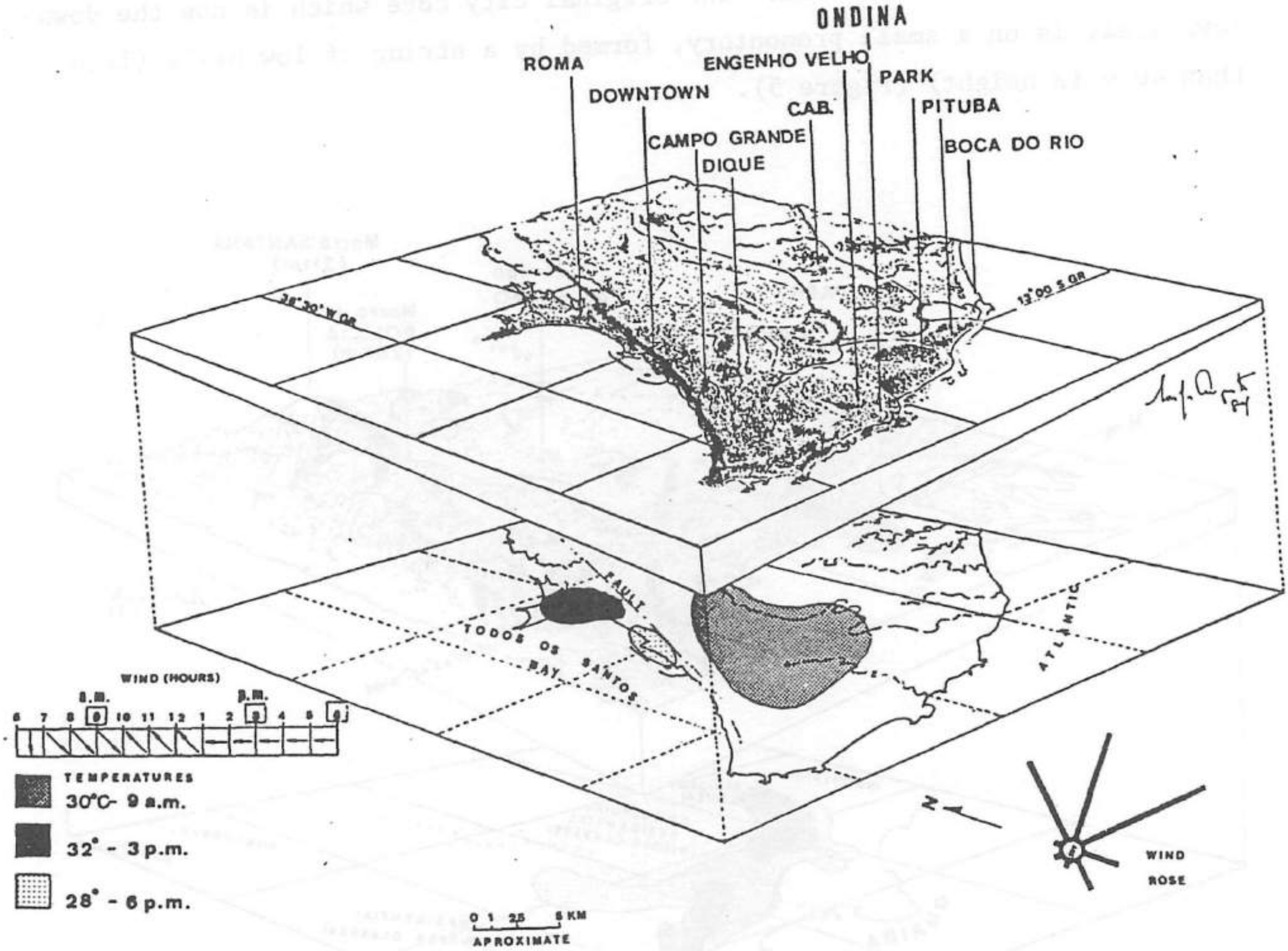

Figure 6. (Top) The physical setting of Salvador (Bahia). (Below) The hypothetical distribution of heat island isotherms at three times during the day of April 1, 1980 based on the results of a temperature/ land-use correlation devised by Sampaio (1981).

The modern parts of Salvador are directed eastwards. The attraction of the coast with its scenic area, beaches, and the construction of a civic centre (CAB) on its outskirts help preserve the old upper town. This dates back to the colonial days with its architecture and golden churches. Between the first city and its modern expanded areas, there are shopping centres, the new bus terminal, and several new settlements which create a new set of urban landscapes.

Here, the higher classes residences and tourist hotels are located along the coast and dunes. The middle- or lower class areas are located inland.

On another scale, the different sites of these two cities provides a duality of similarities and differences which we noted in regard to the two national metropoli.

The first study on the Porto Alegre heat island was due to the great efforts of a young student (Danni, 1980). With the help of colleagues and friends, she gathered temperature observations at 35 points in addition to those of the official meteorological network. Observations were conducted over a 15-day period (May-June, 1979), with three readings per day. It was possible to draw the sketches of the urban thermal structure (Figure 5).

In the central part of the city, the contrast between the CBD and the large Farroupilha Park is shown as a complex pattern of isotherms. However, it is important to note that the higher values in the core of the heat island seem to be more connected to the morphology of the site itself than to the urban building structure. There is a clear tendency for the heat island to be associated with the valley of the Córrego do Sabão. In Figure 5 we have tried to create a composite of the centre of the heat island that is representative of the daily hours. During the hottest part of the day (15h), the 'core' divides itself into two cells.

Although the observation network was largely randomly distributed over the city, and there were no wind observations to help understand the thermal patterns, the results do show temperatures above normal in the autumn-winter transition period. Danni is now extending her study by adding summer observations as part of a Masters-level study. Her preliminary results suggest the existence of two islands with special stress on the northern sector, which is linked to the industrial area and heavier automobile traffic. The influence of the central park is significant in lowering temperature, and the CBD still does not appear as the warmest spot.

Another research team from the Interdepartmental Nuclei for Ecological Studies (NIDECO), which belongs to the Federal University of Rio Grande do Sul, is undertaking a new programme. With the help of a visiting professor from the University of Saarbrück, FRG, a team of geographers, biologists and physicists is testing equipment for mobile thermal observations. (In other words, observations conducted whilst in motion rather than in a stationary position.) The first news of this study were presented during the 5th National Geography meeting in Porto Alegre (Hasenack et al., 1982).

The work was done on clear sky, calm, winter nights. Cross-sections of the city covered 180 observation points, in an area of 80 km^2 of the down-town zone. Under such conditions, the influence of the night thermal exchange is observed, and the heat island appears to be linked to the CBD.

The first information on the heat island effect in Salvador, came from an architect from the University of Bahia, who was working on his Masters project at the University of São Paulo (Sampaio, 1981). He used a completely different approach to that in Porto Alegre. The main purpose was to emphasize the relationship between urban land-use patterns and heat transfer.

On April 1, 1980, simultaneous observations were carried out, every hour, at 10 observation points, between 06 h and 18 h. The 10 sites were chosen as important samples of land-use patterns. The sites were arranged in a kind of cross-section. Half of them are open spaces (Table 2) and the other half represent different urban land-use patterns according to the indicators shown in that table.

The author subjected these preliminary data to an accurate statistical analysis, which deserves special attention. With such a small number of observation points, the author did not attempt to map the results. Here we take some aspects of the daily temperature variation and seek hypothetical insights; even if they are only for comparative purposes.

The author was quite surprised with the fact that the highest thermal values were not associated with the CBD, but with the peninsula in the bay (Figure 6 and Table 3).

TABLE 2. *Land-use parameters for the sample areas in Salvador (after Sampaio, 1981). For location of sites, see Figure 6.*

INDICATORS	SAMPLES				
	Roma	CBD	S.Pedro	E.Velho	Pituba
Densities (Persons/ha)					
Gross	239	2.145	1.398	563	223
Net	418	4.564	1.942	867	410
Land Occupation (%)	51	90	73	44	39
Total Building Area ($10^3 m^2$)	54	330	221	33	62
Per capita space ratio (m^2/person)					
Lanes	11.3	2.2	1.5	1.9	12.8
Blocks	16.8	15.4	15.8	5.5	26.8

TABLE 3. *Maximum temperature contrasts (^oC) between built and open sites in Salvador on April 1, 1980 (after Sampaio, 1981). For locations, see Figure 6.*

Built sites	Open sites					
	CAB	Park	Dique	C.Grande	Beach	ΔT,mean
Roma	+3.6	+3.5	+2.5	+6.0	+4.6	+4.0
CBD	+3.1	+2.6	+1.4	+3.6	+3.1	+2.8
São Pedro	+2.4	+1.9	+1.4	+2.9	+2.1	+2.1
E. Velho	+3.6	+3.1	+1.7	+4.1	+3.6	+3.2
Pituba	+2.7	+2.2	+1.3	+3.9	+2.8	+2.6

Positive values refer to built sites warmer than open sites.

In the case of Salvador, we think that these observations should be seen to have limits. They are only for one day and cannot be considered to be general. However, they do give us an important view of the diurnal pattern to be found under typical conditions of fair weather. It must also be recalled that at 13°S, the annual thermal spectrum is quite subdued compared to the highly variable conditions found in Porto Alegre. Therefore the following daily analysis is probably quite reliable.

In the morning, the built areas on the plateau, that is sufficiently inclined eastward, are open to insolation and therefore reach higher temperature values than those of the CBD which is still in the shadow of the scarp. The higher temperatures found on the Itapagipe Peninsula (Roma), are due to both the urban pattern and effects of the water. We must remember that these waters are quite warm (about 28^{o}C), because they are shallow and behind the peninsula the dark mangroves absorb more heat.

Unfortunately there are no observations from the middle of the night. However, taking note of the 18h temperature, it is easy to accept the fact that the CBD, in its narrow belt at the scarp foot retains heat most readily. In this manner, the tall buildings and the shield of the fault scarp outline the heat island. At such a complex site a daily spatial displacement of the heat island would not be surprising. This may indicate quite a different situation in comparison with that at Porto Alegre. But, in accord with Porto Alegre, the influence of the physical setting seems to be more important than the urbanization effect in terms of defining its spatial thermal structure.

3.3 Three Medium-Sized Cities (São José, Santa Maria and Presidente Prudente)

There is the opportunity to establish comparison between three urban centres in sub-tropical latitudes. From São José dos Campos, below Capricorn and Presidente Prudente in the State of São Paulo to Santa Maria in Central Rio Grande do Sul, of almost 30^{o}S.

From the urban hierarchy point of view, São José with nearly 250,000 inhabitants, and the main centre in the Paraíba Valley (an important economic axis between São Paulo and Rio), is superior to the others. Presidente Prudente and Santa Maria may be considered in the same category (Davidovitch, 1980), they are important regional centres in their State's urban network, each with about 150,000 inhabitants (Table 1).

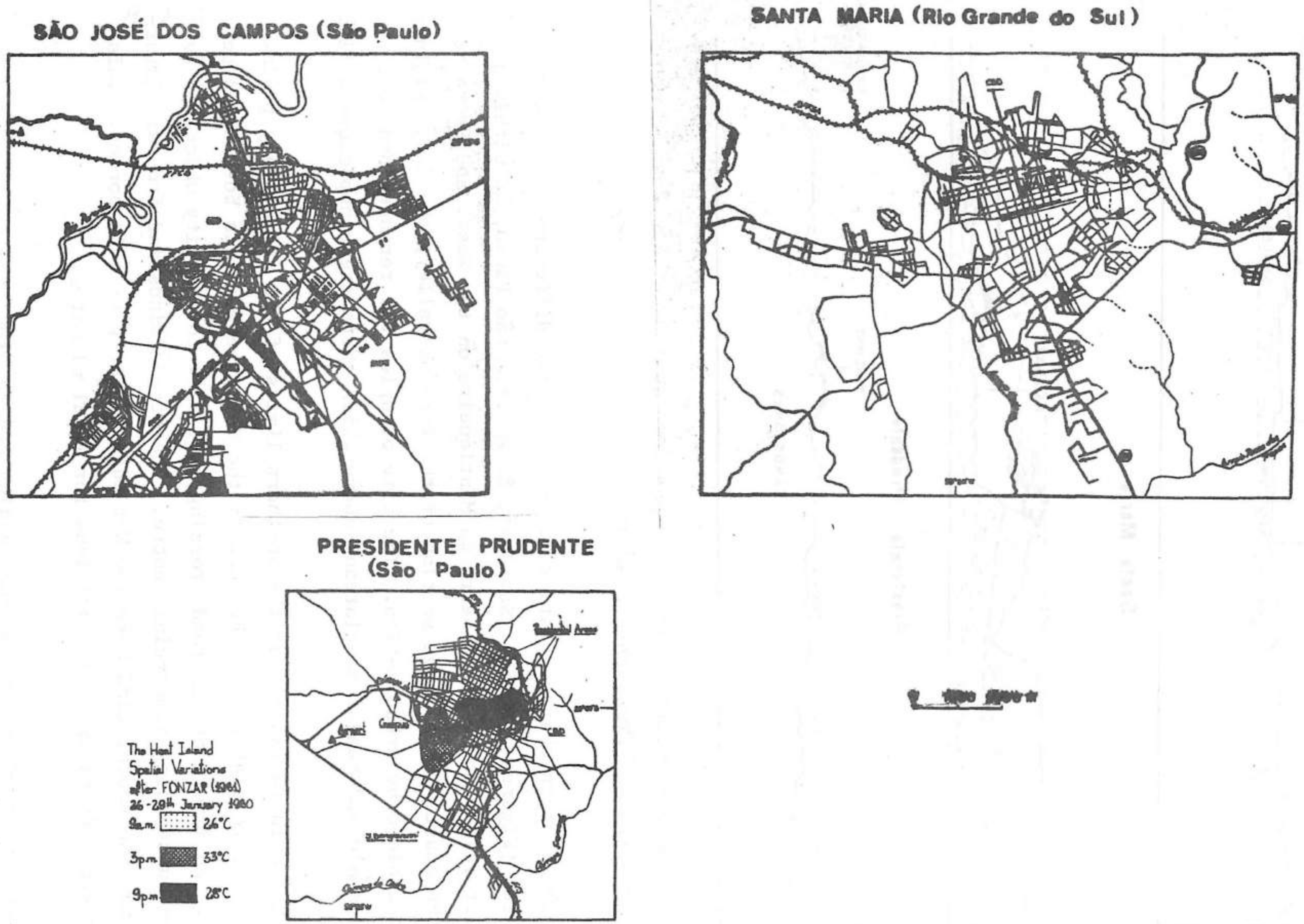

Figure 7. Comparative sizes and urban morphologies of three intermediate-size urban centres: São José, Santa Maria and Presidente Prudente. The latter includes observations of the heat island for January 26-29 1980 from Fonzar (1981).

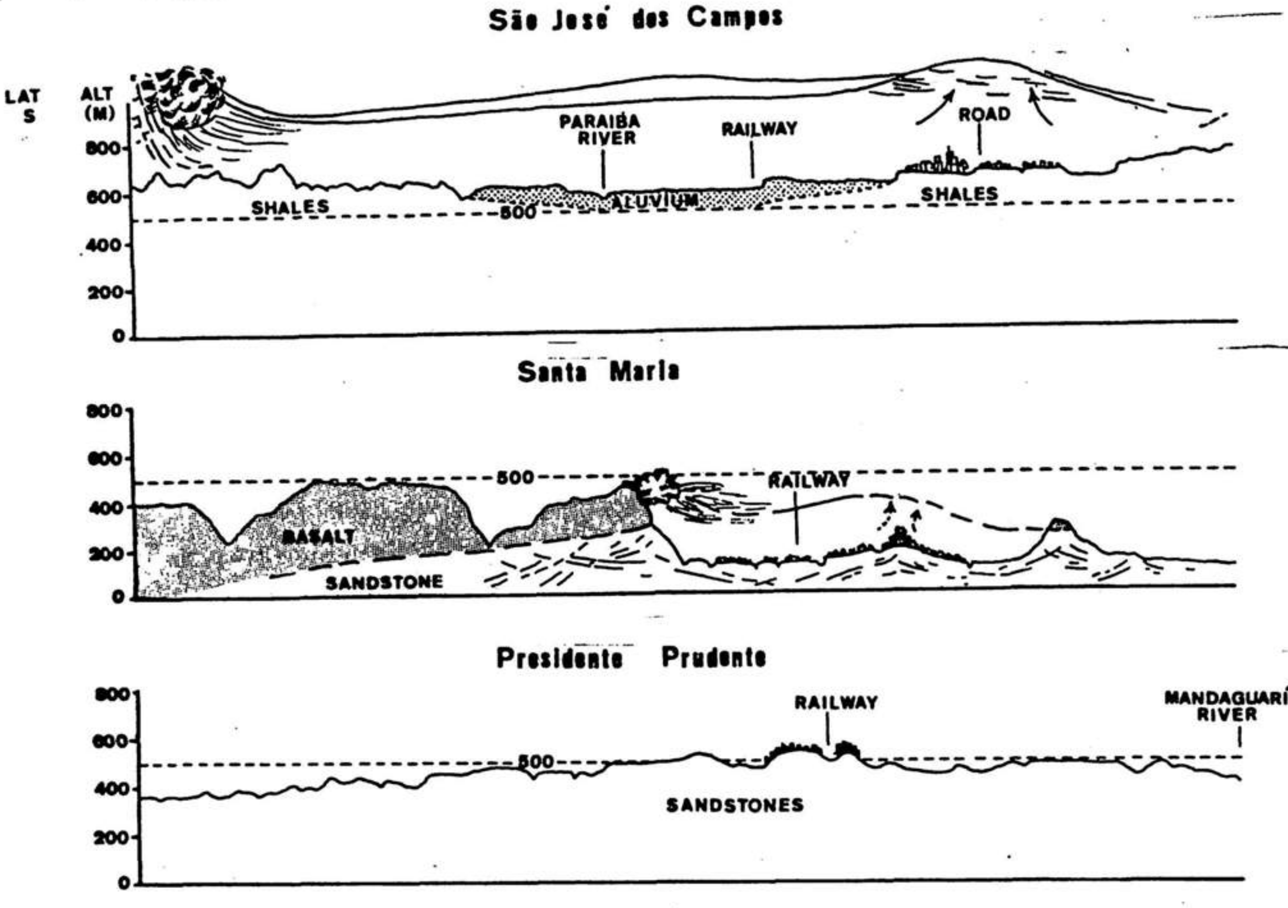

Figure 8. Cross-sections illustrating physical setting of São José, Santa Maria and Presidente Prudente.

To these urban characteristics, we must add the different attributes of their sites (Figures 7 and 8). São José, 82 km from São Paulo, is within a large rift valley between the Serra da Mantiqueira on the West, and Serra do Mar on the coast. In a large section of the Paraíba valley, the flood plain has been avoided by urbanization. The site occupies the terraces and most of a low shale and sandstone plateau, above which there are conspicuous hills.

Santa Maria is exactly at the southern limits of the sedimentary plains and the basaltic plateau; at the foot of the Serra between its border and some "buttes". An important railroad crossing gave rise to the city which has now become an outstanding commercial centre. The strong winds and frontal disturbances from the south, find here the W-E edge of the plateau's border. This peculiar site offers special conditions for local climates.

Presidente Prudente is now the leading centre along the Sorocabana Railway of São Paulo State. A number of settlements dated as far back as the first half of the century are located along this route. The city is on the water divide of a large plateau, at an altitude of almost 500 m.

Tarifa's (1977) study of São José was conducted as part of an urbanization project. It included a comparative analysis of the contrasts in temperature and humidity between São José and the surrounding rural areas. The study was based on field work done in July of 1974, during the daytime. Under weather controlled by a polar anticyclone, measurements using Assman-Ivess psychrometers at 0.8 m above the ground showed a net temperature difference between the city and its rural surroundings of 3.4°C. The author noted that these differences must be considered to be less than the maximum because the field operation was held with winds of 3 to 4 m s^{-1}.

The author gives special attention to a comparison of these preliminary data with those of other regions as found in the Oke's model for Canada and Europe (Oke, 1973). Considering the possible effect of wind interference, and the fact that daytime observations were being used, the value found for São José was fairly close to the values of 7.0 to 9.0°C in Canada, and 5.0 to 6.5°C in Europe, for the urban category of 150,000 to 200,000 inhabitants.

The value found for São José (São Paulo) is in accord with that for San José, California from twenty years ago when that city had 100,000 inhabitants and an urban-rural difference between 3.9 and 5.0°C (Duckworth and Sandberg, 1954).

At a higher latitude, Santa Maria presents a maximum daily difference of 7°C (Table 1). This information came from a Masters dissertation (Sartori, 1979) in which the emphasis was put on a comparison of the local climatic conditions in Santa Maria with those of Julio de Castilhos, on the plateau, and Sao Gabriel, southwards on the "Campanha" plains. These data were taken on three days in the summer of 1979, during a period of weather just before a frontal passage. Three points of psychrometric observations were related to those of the meteorological stations in a transect from the CBD to the city outskirts. This first information is to be followed by other studies. The CBD is projected to experience vertical growth and the planned streets orientation shows recognition of the influence of the urban "canyons" on airflow.

In Presidente Prudente, the field work on the thermal structure was necessary to clarify the role of the regional urban model in terms of comfort. The settlement of this area, guided by the immediate profits of the agricultural economy of cash crops, devastated the area compared to the original forest. In its early years, the city had woods and parks, but real estate speculation finished them by building new residential districts.

Five sites were chosen from the CBD (three observation points) to the outskirts. Some were associated with the meteorological stations located at the Airport and the University Campus. The simple topography of the area and the urban status of the building environments offered many interesting effects to balance these dual variables in determining the climate.

On the plateau, the CBD with its concentration of high buildings, makes a strong impact. Jardim Bongiovani, for instance, is a new residential area for the wealthy, where green areas are of some significance. The Airport and the University Campus on the outskirts located in open areas, behave as rural areas. The influence of a park square with shade trees is quite clear, even in the CBD (Table 4).

Nine points in a medium-sized city is not enough to fully document the climate, however we were able to "suggest" the heat island configuration. A summary sketch of the maps made by Fonzar (1981) in relation to the city morphology, is presented in Figure 7. During those four days of the study the weather was fair, following a frontal passage with rainfall on the 25th. After the frontal instability, a weak polar anticyclone dominated the weather. In her analysis Miss Fonzar considered the temperature variations, both in time and space, with other elements, especially the local wind flow (as registered by the meteorological stations). On the 27th and 28th, the prevailing winds were from the W and SW. This inland flow overpowered the heat island effect at night. On the 29th, with the turning of the winds to a SE direction the heat island was practically erased.

TABLE 4. *Mean temperature (°C) and relative humidity (%) variation from January 26th to 29th, 1980 at selected sites in Presidente Prudente (after Fonzar, 1981).*

	Hours											
	07		09		11		15		17		21	
Sites	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%
C.B.D.												
Itaú Bank Corner	23.6	88.5	26.5	74.5	29.4	62.2	30.6	54.5	30.1	57.8	27.1	67.2
Shopping Mall	23.1	89.8	25.7	75.8	28.4	67.8	30.2	57.0	29.4	59.8	26.5	72.0
Church Square	22.9	91.5	25.3	80.5	27.8	70.0	30.1	57.2	29.5	61.0	26.1	75.8
RESIDENTIAL AREAS												
Vila Marcondes	23.9	87.8	26.1	79.8	27.9	72.8	30.7	58.8	29.1	61.2	26.9	70.2
Bairro do Bosque	24.3	85.5	25.9	79.5	27.4	77.0	29.6	63.5	29.3	63.0	27.1	72.2
Jardim Bongiovani	25.1	81.5	26.1	79.0	27.7	75.8	29.7	68.2	29.0	68.2	27.1	82.8
Jardim Paulista	23.3	91.2	25.5	80.0	27.3	73.0	29.5	61.8	28.9	64.5	26.4	77.8
OUTSKIRTS												
(Meteorological Stations)												
Airport	23.2	89.0	25.5	80.2	27.8	71.5	30.8	60.2	30.0	62.0	25.8	81.0
University Campus	22.9	93.0	24.8	80.0	26.8	74.0	29.5	62.2	29.0	64.8	26.1	78.2

Although not very impressive on this gentle plateau, topographic effects are quite significant. The best example can be found in the "Corrego do Veado" Valley. Depending on the wind flow, the temperatures at Jardim Bongiovani seem to have a special meaning throughout the day. Airflow is capable of producing daily displacements in the position of the heat island.

4. THE APPLICATION OF URBAN CLIMATE KNOWLEDGE IN PLANNING

Brazil, with its continental dimension, offers many opportunities for the creation of new settlements. Generally, the exploitation of mineral districts, or the building of a dam, requires urban support. The creation of new towns is becoming almost routine.

On the other hand, old cities in archaic or economically backward regions are put under a new focus and pushed towards development. Unfortunately, in most cases, anxiety for immediate profit leads to ecological harm perpetrated in the name of development. At other times, there are attempts to make better decisions.

A few examples can be given to show direct collaboration between geographers, urbanists and regional planners. In these cases, knowledge about urban climate is of great help. The facts and principles must first be put into the context of our zonal and regional perspective. Local realities are then taken into consideration, and should be tested, using numeric data or parameters.

Once again the Institute of Geography's Climatology laboratory has made the first step towards supplying climatological information. Despite our equipment limitations, some interesting field work has been done, and useful papers have been produced (Monteiro and Tarifa, 1977; Monteiro, 1980b; Tarifa, 1977; Tarifa and Vasconcellos, 1980).

These applied studies are too long to be fully explained in this paper, so we will examine only the Marabá case. Located in the Tocantins Valley, it has been a traditional Brazil nut and commerce centre. The discovery of iron ore, gold and other minerals in Carajas (one of the richest mining districts in our country) required urban management to make it a regional development pole. The village, set on a precarious site was submitted to severe flooding almost every year. The first decision was to displace the nucleus up to a nearby plateau, safe from the floods.

From September 4th to 9th, 1973, a special field survey was undertaken (Figure 9). The primary purpose was to compare some climatic attributes in different land units of the old and new sites. Different kinds of environmental setting were involved, so "local", "topo-" and "micro-" climate scale information was needed. Microscale data on temperature and humidity were required for better building. The lack of enough meteorological equipment for field observation made it impossible to cover all of the selected places with simultaneous observations. Therefore at different times the measurements were compared with those at the meteorological station at the Airport.

In addition to the points that can be seen on the map (Figure 9) another important place was chosen: the Indian reservation at kilometre 34 of the Pa-70 road.

Even though on the previous days the country was covered by a very large polar anticyclone, which produced a cold wave southward, refreshing considerably those low latitudes (Figure 1), the weather conditions were fine. Occasional showers (a zonal trait) were registered during the operation.

In 1970, Marabá was only a village. Therefore we did not expect to register an "urban climate" with a clearly defined heat island. Would different land units in the ecological compound show some difference in temperature? When we compare the measurements taken in open spaces at different points, the changes are hardly noticeable or significant. These places, including their backyards, were only a little warmer than the Airport. Within the old urban nucleus, noticeable differences between the inside and outside of the built area were seen.

On September 6th between 13 and 1330h, simultaneous comparative measures showed the highest temperature to be located in the arena of the small local stadium: open, treeless and surrounded by cement bleadras (32.0°C). The gardened square in front of the church was a little lower (31.6°C), while in the interior of a house it was rather lower (28.8°C). At 15h the inside of the house became warmer than outside. One hour later, when the house showed a slightly higher temperature (+0.2°C) the street temperature in open air, was lower (-1.2°C). The thermal exchange in the interior became rather uncomfortable, which explains the custom that people have of going outside to the backyard or out on the sidewalk, on the shadowed side in the late afternoon (16 to 18h) to talk or go on with their house chores.

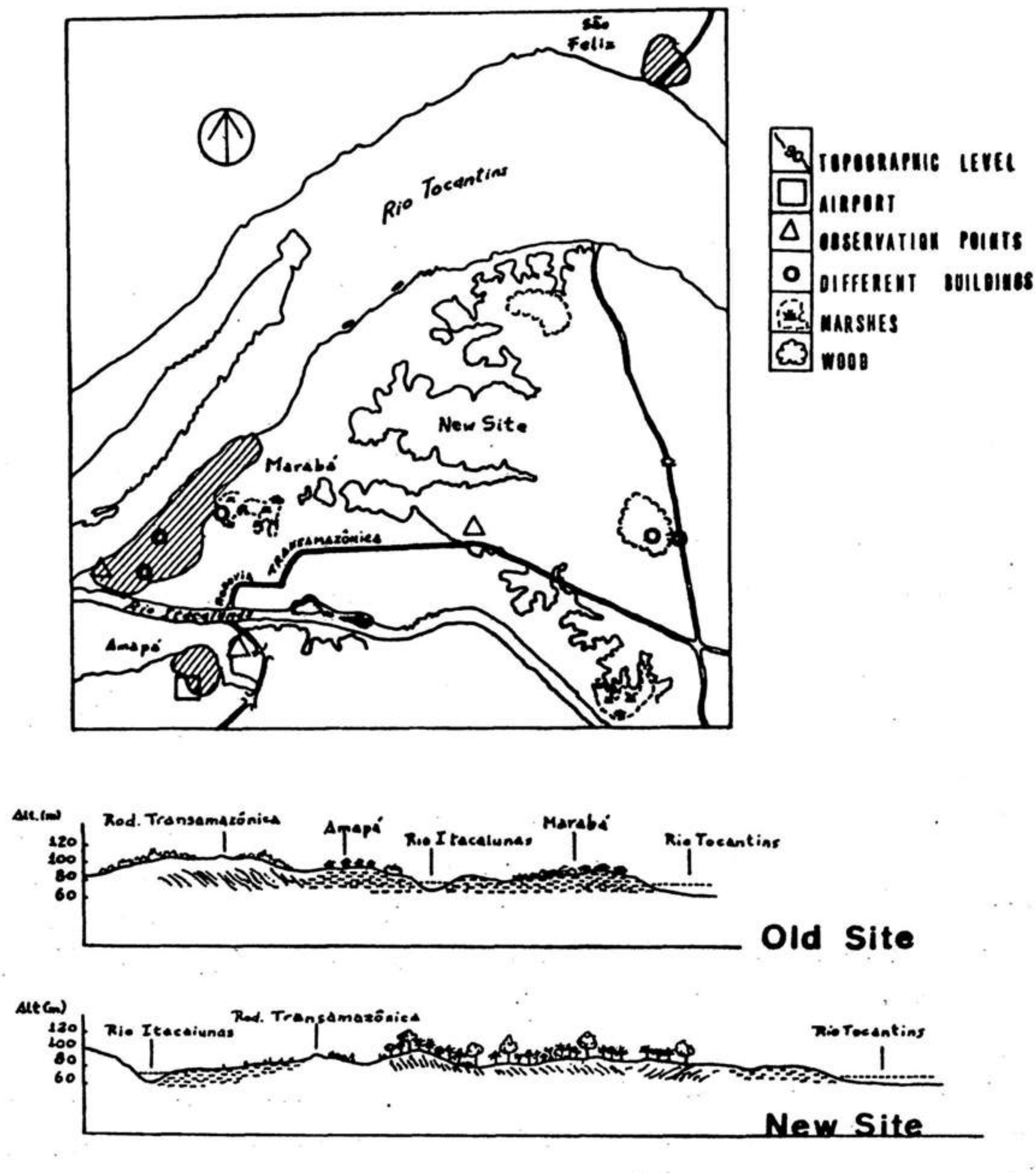

Figure 9. Map and physical setting of the village of Marabá (Pará) where field observations were conducted September 4-8, 1973 (after Monteiro and Tarifa, 1977).

Differences of 1.2 to 1.5^{o}C can be felt at the same time between a paved and a dirt road.

On September 6th, at 10h, measurements were made at the "new site" on the road, in the open air, at the edge and within a remaining patch of the forest. Even though it had been rather modified, it was taken to be part of the new town. The difference between the road and the middle of the woods was only 0.4^{o}C. This is understandable because of the high humidity within the vegetation at that time of the morning (97%). The differences between this patch of vegetation and the better points were small (less than 1^{o}C), but always lower.

At the Indian reservation, on September 9th at 1230h some interesting information was obtained. Between the interior of the forest (near the original one) and the clearing where the Indian village is located, the difference in temperature and humidity was impressive. In the interior the temperature was 27^{o}C with a relative humidity of 86%, while the open area 30^{o}C and 70%, an increase of 3.0^{o}C and a decrease of 16%.

These and many other points have been talked over with architects and urbanists since they are also interested in producing something favourable for the ecological setting. Often the main point to be pursued is the articulation of the different climatic scales - from the local, through the regional, to the zonal. This can be easily expressed by considering the wind. In Marabá's case, it was necessary to explain that an important trait at the zonal-scale (backed up by field work) is the "calmness". But this information is taken from a single, isolated, mean average "wind rose". The importance of the daily flow mechanism, and its close connection with the daily temperature variation, is much more important on the designer's work scale, and must be emphasized. The chances are that the designer will get general information on the local climate - or will have to extend from other sites in the same region. Unfortunately, they probably will not have special field work to give the planner the more reliable and useful information he needs.

Even if there is collaboration and the integration of climatological information into the urban design it does not necessarily mean the plan will be accepted. In the Marabá case, the proposed urban design, after being accepted by the government development agencies, was put aside and another one is being used.

Sometimes the design demands a high amount of investment, at other times, political influence interferes. Most frequently, there is a lack of feeling towards ecological considerations and the almost permanent desire for short-run profit by those developing the plans.

5. CONCLUDING REMARKS

We are not sure if the preliminary character of these studies make it possible to reach some conclusive insights. At any rate, it would not be imprudent to note some points that stem mostly from doubt and, exactly for that reason, require some comment to stimulate discussion and further research.

It seems that the main points to be put under discussion are as follows:

(a) Although defying detailed description, it is quite clear that the heat island effect - a basic climatic response to urbanization - is observed in medium-sized cities, with a population between 150,000-200,000 inhabitants.

(b) In the case of a regional metropolis, when the population reaches 1,000,000 to 1,500,000, and the urbanized area expands over a wider area, the configuration and time variation of the heat island becomes rather complex. For the moment the role of the urban structure and the physical setting is not quite clear. The latter seems to play the lead in determining the urban thermal structure.
This question would, at least in our case, have to be considered in parallel with the problem of the relationship between the size of the city and its population to the intensity of the heat island effect.

(c) In the great metropolis, where urban climate effects are very apparent, the relationship between the urban structure and homogeneity or heterogeneity of the physical setting is a fundamental character in determining the urban thermal structure.

Because of the lack of sufficient information, the subject is still open for further and important research. To be successful in these studies, we would do well to consider the following points:

(a) Considering the high cost of the analytical tools required for the study of urban climates, and the permanent shortage of funds, import restrictions, etc., it may be necessary to manufacture them on a national basis. Emphasis on inventiveness may substitute simplicity for sophistication in this equipment.

(b) Some agreement among the researchers is required to foster the use of standardized technical procedures. On this important point, it will be necessary to emphasize interchange and collaboration between institutions and research teams.

(c) These technical needs must be complemented by methodological and theoretical discussion aimed towards achieving a holistic feeling of urban phenomena within the special circumstances of the Brazilian urban reality. That is to say, "urban climate" must be seen as a part of the wider context of urban environmental quality where it is very difficult to put aside social and natural processes.

(d) There is need for a new perception and changed attitude towards urban studies in the Brazilian system, where economic variables are always put before environmental ones. This is regrettable practice because social problems are almost always closely related to environmental quality and are a by-product of economic disarray.

(e) It will be necessary to improve research in urban climate. The eight metropolitan areas must be compared, and a representative selection of other Brazilian urban systems must be studied.

(f) Mathematical models including computer simulation should be tried, as well as the use of remote sensing. They could be used in analysis of the energy at the whole city-scale. In support of this, urban land-use documentation deserves to be improved.

(g) Rational research planning must be undertaken to avoid overlap and waste of resources in the grants. Collaboration, interchange and more fruitful division of labour must be tried among meteorologists and geographers, as well as their institutions.

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URBAN CLIMATOLOGICAL METHODS AND DATA

Roger Taesler
Swedish Meteorological and Hydrological Institute
S 601-19 Norrköping, Sweden

1. INTRODUCTION

Urban climatology has a long history. The scientific literature on the subject dates back at least to 1818, when Luke Howard published his famous book on London's climate. Urban air pollution was a problem already in ancient Rome, if not earlier, and legal measures to improve urban air quality were taken in London during the Middle Ages. In our time, and in particular during the last 15-20 years, the science of urban climatology has expanded rapidly as reflected in several publications (WMO, 1970; Oke, 1974, 1979; Chandler, 1976; Landsberg, 1976, 1981).

The vast majority of studies, however, deal with urban climates in mid-latitude industrialized countries, whereas conditions in tropical and sub-tropical latitudes are much less studied. Today urbanization in these latitudes takes place at an extremely rapid rate. This often leads to severe problems associated with environmental deterioration, unhealthy living conditions, shortage of energy, food and water and increased exposure of the population to floods or extreme winds.

Many of these problems could undoubtedly be reduced if climatological principles and experiences were incorporated in the planning of the rapidly growing urban areas in low latitudes. General guidelines can be - and have been - formulated for the siting and layout of human settlements (Olgyay, 1963;

Givoni, 1969; Koenigsberger et al., 1973; Chandler, 1976; Glaumann, 1982). Yet, with the exception of air pollution control, it is difficult to find cases, where climatological advice has played a significant role in urban planning. This is even so in mid-latitude regions, where substantial knowledge exists about the urban climate. This striking gap between science and application has been realized and discussed before (Page, 1970). It appears, however, that such discussions need to be carried further and, possibly, in new directions if applied urban climatology is to become a viable element in urban planning.

Urban climatic effects are best developed, and most frequently investigated, in certain meteorological situations. Heat island studies, for example, are typically conducted during anticyclonic weather conditions with clear skies and weak regional winds. Thus, our empirical as well as theoretical knowledge about the urban climate is mainly based on case-studies which represent only a rather limited part of the 'climatological spectrum'. The case-study approach is indispendable both in order to document certain local climatological characteristics of an urban area and to provide a basis for calibration and verification of theoretical models. However, in order to make aproper climatological analysis of an urban area and, in particular, to make statistical evaluations of the impacts of climate in different urban planning alternatives, we need more than a collection of examples obtained under more or less idealized conditions.

Urban climatological studies are usually focussed on the particular anomalies in various climatic elements caused by the urban area itself. It must be kept in mind, however, that the main control of climatic conditions in urban areas is still exerted by large scale (macroscale) atmospheric processes. In addition, mesoscale effects due to the rather special settings of cities (in coastal areas, near rivers and lakes in valleys, etc.) often have a strong influence.

It is essential to make a distinction between, on the one hand, studies of general climatological conditions in an urban area, which need to include the characteristics due to macro- and mesoscale processes, and, on the other hand, studies of the specific urban anomalies, in which the macro and mesoscale effects need to be sorted out.

URBAN CLIMATE METHODS AND DATA

From a climatological point of view, the main interest in to study the impact of the urban area on the atmosphere. In urban planning and building design the prime interest is in the opposite direction, i.e. to study the impacts of the urban atmosphere on the function, economy and safety of the built environment and on the health and well being of its occupants. Having identified such impacts, which is not always an easy task in itself, the next step is to develop methods to modify these impacts. Some limited success may be obtained here by qualitative reasoning on the basis of climatological experience and general principles. What is really needed, however, is a methodology for quantitative assessments using 'input-output' models incorporating both the particular urban climate and the 'system' affected by this climate. The 'system' may be human beings, climate sensitive operations, single buildings or an entire urban area.

2. GENERAL CHARACTERISTICS OF URBAN CLIMATES

2.1 Synoptic Controls in Urban Climatology

Urban-rural as well as intra-urban differences in a climatic element are best developed in certain synoptic situations. Depending on the type of synoptic situation, different urban effects become more prominent than others. The urban heat island, for example, typically shows maximum intensities during calm clear nights with strong radiative cooling (Oke, 1982). During the daytime a less intense urban cool island is sometimes found. Urban effects on wind speed, on the other hand, are usually most pronounced during windy situations, though urban heat island circulations may develop in large or medium size cities (Oke, 1979). High levels of urban air pollution are usually, though not always, associated with anticyclonic conditions and weak wind speeds at low levels. The same holds for fogs or low visibility in urban areas. Strong urban precipitation anomalies appear to occur as a result of enhanced convective activity, possibly in combination with excessive concentrations of condensation nuclei (Landsberg, 1981).

It follows that the frequency and duration of different synoptic situations have significant importance not only for the general climate but also for the urban impacts on climate.

2.2 Urban and Local Non-urban Controls

The occurrence and magnitude of urban anomalies also depends on the size of an urban area. Very large urban agglomerations may even slow down the movement of cold fronts or intensify mesoscale systems such as sea breeze circulations or squall lines (Bornstein and Thompson, 1979). Intra-urban variations in temperature or wind speed are also strongly related to urban land-use patterns and urban morphology. Radiation conditions, both long-wave and short-wave, at ground level are very strongly influenced by the detailed geometry of the nearest surroundings (buildings, trees, topography). In addition, the radiation climate may be significantly influenced by urban air pollution or increased cloudiness.

Cities are usually situated in certain, preferred types of locations - for example in valleys, coastal areas or near rivers and lakes - which by themselves have special climatic characteristics. The local topography within an urban area can also cause significant climatic anomalies. Such effects may be difficult to distinguish from the genuine urban effects. It also complicates simulations (theoretical or physical) of the urban atmosphere as well as predictions of urban climatic characteristics.

It has been common practice for a long time to assess the magnitude of urban effects by comparison with rural background values. This involves the implicit assumption that a rural reference station represents conditions at the urban location in the absence of urban development. Unless the geographical and topographical situation is very simple, there may be considerable difficulties and uncertainties involved in this approach (Lowry, 1977). With regard to urban air pollution studies, particular problems arise in selecting a rural background station since pollutants may be advected over long distances downwind of an urban area.

2.3 Scales Associated with Urban Effects

Among the first problems in planning an urban climatological investigation is the question of time and space scales of the atmosphere phenomena to be studied. This question relates to the choice of measuring sites and instruments as well as to sampling strategy and methods of data analysis. A complete survey of the urban atmosphere would require continuous measurements in a three-dimensional space, including the subsurface layer, the air layer between buildings and the layers above roof-level up to several hundred metres or even kilometres above ground. Such an undertaking is hardly ever possible - hence it is necessary to restrict and concentrate the investigation to scales most relevant for a particular phenomenon.

The persistence of synoptic situations may be taken as a typical time scale for urban anomalies associated with a particular type of weather. In addition, urban effects usually also exhibit a typical diurnal variation, closely related to the net radiation cycle.

There is evidence of a weekly change in the urban temperature excess and air pollution levels in big cities (Oke, 1974; Landsberg, 1981). This indicates that urban influences may be strong enough to be significant in all or most synoptic situations.

Monthly or annual climatological longterm averages may also show urban influences, e.g. in winter minimum temperatures, in the diurnal amplitude of temperature, in air pollution concentrations, visibility, sunshine duration or in monthly rainfall (Oke, 1974, 1979; Landsberg, 1981; Baumgartner et al., 1984).

There is also evidence for long term trends in urban-rural temperature differences (Horie and Hirokawa, 1979; Landsberg, 1981) which may reflect the effect of urban growth and/or changes in urban structure and building density.

The assessment of typical scales for the spatial structure of urban anomalies requires closer consideration. This is discussed in the following section.

2.4 Conceptual Models of the Urban Atmosphere

As the air moves across an urban area the vertical profiles of wind, temperature, humidity and turbulence characteristics above the urban surface are gradually changed. The depth of the layer, thus modified, grows with downwind distance and may, depending essentially on city size and on the synoptic situation, eventually include the entire planetary boundary layer (PBL). The formation of such internal urban boundary layers (UBL) is now well established through theoretical modelling as well as experimental studies. Available data indicate that horizontal gradients of meteorological variables in the UBL are generally weak. In contrast, the corresponding fields at street-level often show a very detailed micro-structure which is closely related to urban land-use patterns, building density and street layout. The layer approximately below roof level has been interpreted as an urban canopy layer (UCL) (Oke, 1981), in which the forcing functions and controlling parameters are different from those in the UBL.

Existing experimental data are almost entirely restricted to conditions either in the UBL or UCL or, in some cases, both layers. However, very few studies provide continuous profiles extending from street-level, through the layer near roof-level and into the UBL. Figure 1a, b shows an example of experimentally determined urban and rural profiles of potential temperature from ground level to approximately 300 metres above ground in Uppsala, Sweden during a well developed heat island situation (Taesler, 1980). Profiles below roof-level were measured with a mobile mast, positioned at two different urban sites (RA and R in Figure 1a and 1b respectively). At both sites, the stratification below roof-level is seen to be close to neutral. In the city centre there is a pronounced transition in thermal structure from levels just below roof-level (site RA) to levels just above (site U). In the transitional layer, below the elevated inversion, the stratification is seen to be unstable, implying a strong vertical convergence of sensible heat flux around the inversion base.

It has been proposed recently (Oke, 1984) to distinguish the transitional zone as an 'urban wake layer', extending vertically to 2-3 times the spacing between buildings. The properties and physical processes of this layer are however as yet largely unexplored.

Figure 2 illustrates the above conceptual model for the vertical structure of the urban atmosphere. This model has several implications with regard to the design of urban climate investigations, to be discussed below.

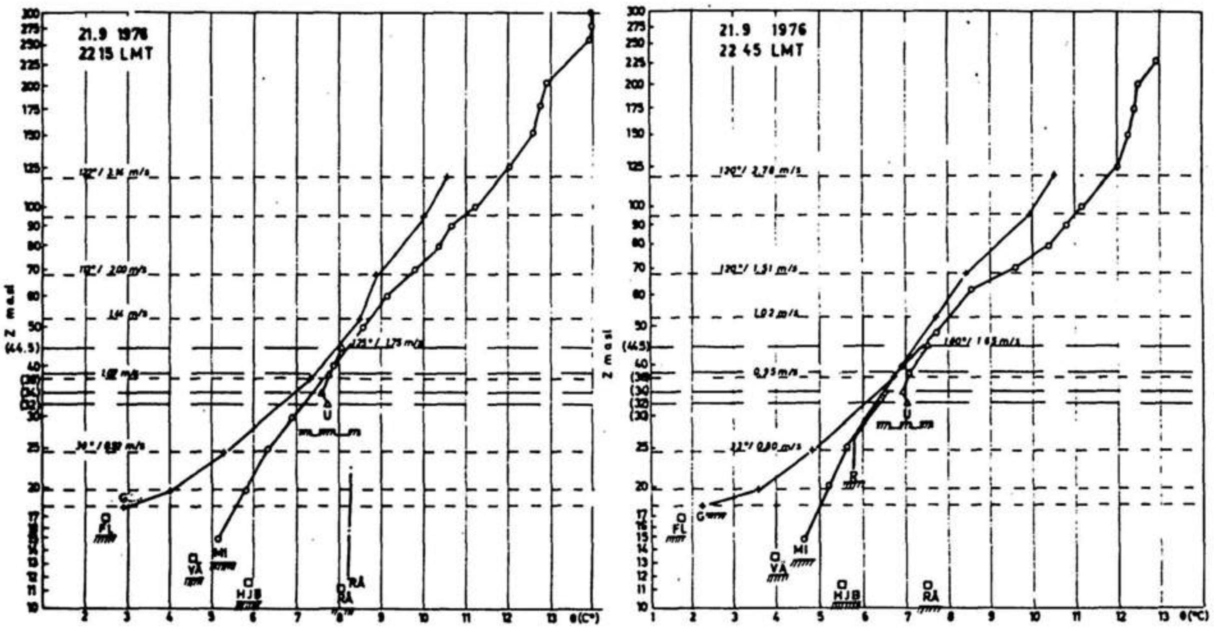

Figure 1a, b. Examples of urban thermal stratification (potential temperatures) during a well developed heat island situation in Uppsala, Sweden (Taesler, 1980).

Symbols:

Screen temperatures, rural upwind (site FL), urban residential (sites VA, HJB) and city centre (site RA).

Upwind rural tower (site G).

Urban park tethered balloon (site MI).

Urban, mobile mast (sites R, RA).

City centre, roof top mast (site U).

Also shown are wind directions and wind speeds at sites G and U.

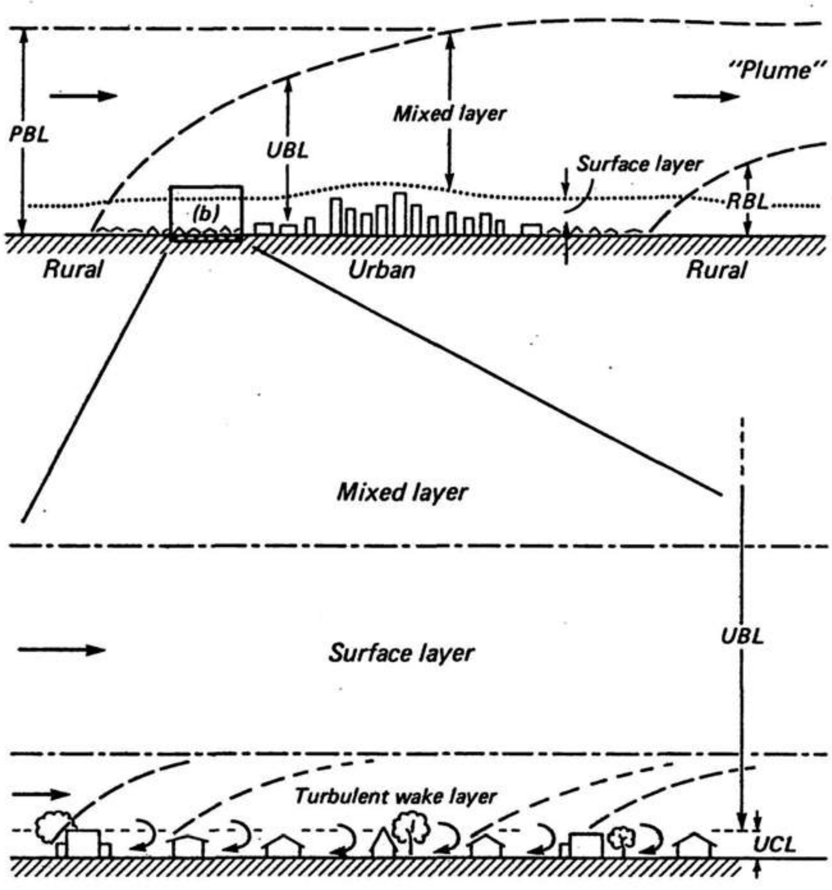

Figure 2. Idealized arrangement of boundary layer structures over a city (after Oke, 1984).

3. EXPERIMENTAL METHODS AND DATA

3.1 Full-Scale Measurements

A great variety of measuring equipment and methodologies has been applied in urban field studies. Referring back to the previous section, a broad classification of experimental methods may be as follows.

3.1.1 UCL-Measurements

Urban-rural differences

The gross characteristics of urban anomalies in temperature, humidity, precipitation and wind speed may be established by continuous operation of a limited number of urban and rural fixed reference stations. Here the selection of representative sites is a crucial question, in particular with regard to wind speed. To minimize advective effects, sites should be selected, as far as possible, inside urban districts with uniform building heights and density. Topographical variations should be covered systematically. However this may increase the number of sites considerably.

A network of fixed reference stations should be operated over a minimum period of one year, preferably up to three years to produce a sample of seasonal and synoptic variations sufficient for statistical analyses.

Considerable care should be taken to ensure repeated calibrations - in particular inter-calibration - and functional checks of instruments during the entire measuring period. Detailed, systematic records of site conditions are also essential for the analysis and interpretation of data.

Some climatic elements (wind direction, solar and net radiation, street level air pollution concentrations) are extremely sensitive to microscale features in the UCL. For such elements it may be very difficult or even impossible to choose generally representative urban sites within the UCL.

Intra-urban Variations

Mobile surveys are useful to establish the detailed, horizontal fields of several elements in the UCL. Using fast-response temperature sensors it is possible to sample large amounts of data while driving, thus covering large distances in short periods of time. Such measurements should always be combined with continuous recordings at a few fixed stations in order to obtain reliable trend corrections for the mobile measurements.

Measurements of wind speed, net radiation, humidity and temperature profiles in the UCL may also be carried out using mobile equipment. In these cases, however, it is advisable - or necessary - to take readings during stops at pre-selected sites in order to obtain proper exposure of instruments or sufficient sampling time. The time needed for such surveys will be several hours in each case. During this period intra-urban differences may change significantly. It will thus be necessary, in particular regarding wind speed comparisons, to make trend corrections on the basis of continuous records from fixed stations, preferably in open locations within the urban district under investigation or at roof-top sites. Unless several mobile units are available, it may be difficult to cover an entire urban area during each survey. It is better, then, to select a limited portion of the urban area and to make repeated measurements at each site during one survey.

Mobile surveys should be carried out repeatedly under different synoptic situations and during different seasons. Even minor differences or changes in synoptic conditions (e.g. wind speed, wind direction or cloudiness) may significantly influence the magnitude and structure of intra-urban variations.

Mobile measurements have a considerable advantage in being easily carried out by only one or two persons, at relatively low cost, while still giving high temporal and spatial resolution. Urban temperature patterns have been measured in this way during the past 50 years in innumerable cities all over the World. It is a useful way of gaining first estimates of some characteristic climatic features of a particular urban area. In general, however, the results from mobile surveys are mainly of a descriptive nature. To gain a deeper insight into the physical processes operating to produce the observed urban anomalies, other and more sophisticated methods are required.

In general, the physical environment in the UCL is distinguished from its rural counterpart by one or more of the following characteristics.

- Regular arrays of surface elements
- Surface elements whose vertical dimensions are of the same order of magnitude as their horizontal dimensions
- Dense surface materials with high values of thermal conductivity and heat capacity
- Low soil moisture content due to rapid runoff and impervious surface materials
- Internal sources of heat, water vapour and pollutants
- Moving vehicles acting as turbulence generators

Furthermore, conditions in the UCL are distinguished in general by pronounced spatial inhomogeneities in surface properties. Consequently theoretical analysis as well as full-scale experimental studies of thermodynamic, radiative or aerodynamic processes in the UCL have to be confined to carefully selected, simple environments. Even so, the requirements on experimental equipment and strategy are very high, involving data sampling with high accuracy in three space dimensions and in time. As a consequence, very few full-scale investigations of the UCL have been carried out, which go beyond the descriptive stage. As regards the nocturnal energy budget of the air below roof-level the role of three-dimensional radiative flux divergence has been demonstrated by full scale measurements in an 'urban canyon' (Nunez and Oke, 1976). The role of turbulent flux divergence of sensible heat and advective effects still awaits experimental investigation.

Air flow in the UCL is likely to be strongly influenced or even dominated by horizontal and vertical vortices generated by buildings and small scale objects. The representativity of measurements in such flows is generally very low due to the lack of spatial homogeneity even in the mean properties of the flow. The statistical properties of velocity fluctuations are also likely to show pronounced horizontal and vertical inhomogeneities, contrary to conditions at 'ideal' micrometeorological sites. Airflow measurements in the UCL are probably most useful for the purpose of verifying theoretical or physical model simulations. Even then, measuring sites should be carefully selected in areas of uniform urban morphology and spaces with uncomplicated microstructure.

3.1.2 Wake Layer Measurements

Of the three layers identified in Figure 2, the transition zone between the UCL and the UBL appears to be the least studied. The structure and dynamics of this layer probably play a crucial role for the energy budgets both of the UCL and of the UBL (Fuggle and Oke, 1976).

Wake layer measurements have to cover a height interval beginning below average roof-level and extending to heights corresponding approximately to 2-3 times the average roof-level. Ideally, measurements should include profiles of temperature, wind speed and net radiation as well as of turbulent fluxes of sensible heat and water vapour. Such requirements are of course very difficult to meet in practice due to economic as well as technical limitations. In addition, the selection of representative measuring sites poses a problem also in this case. It is difficult at present, due to lack of comparative experimental results, to establish relevant criteria for the selection of representative sites for wake layer measurements (Evans and Lee, 1980).

In spite of the difficulties mentioned, wake layer measurements are believed to be most important and should be encouraged in order to gain a deeper understanding of the urban-atmosphere interactions and the inherent exchange processes of energy, mass and momentum. In particular, such studies are needed to provide improved inputs to numerical UBL-models.

3.1.3 Urban Boundary Layer Measurements

Within the planetary boundary layer, the UBL develops in response, primarily, to different (usually increased) surface roughness and surface energy budgets (albedo, long-wave absorption/emission, sensible and latent heat). Additional effects are caused by direct emissions of heat and pollutants, which in turn may influence radiative heating or cooling in the urban atmosphere. The resulting changes in vertical wind and temperature structure usually implies a less stable nocturnal stratification and, sometimes, more unstable daytime conditions.

The UBL grows vertically downwind from the urban-rural border. Since the growth rate is slow ($\sim$ 1/100), the depth of the UBL at a particular urban site will vary considerably depending on the urban fetch associated with different wind directions. There may also be variations in UBL-thickness associated with different urban land-use and, in particular, large urban green areas or water bodies.

UBL-measurements are usually carried out as part of a programme for air pollution control, involving the determination of atmospheric diffusion parameters and urban mixing depths. Measurements are needed for verification or calibration of models for simulation of such quantities.

A variety of techniques has been used for measurements in the UBL. The lower parts of the layer, up to 100-200 metres above ground, may be probed by towers carrying fixed instruments at several levels.

Tower systems can be used for continuous sampling of wind, temperature and humidity profiles. Such installations will always be very expensive both to build and to operate. The sensors used must meet very high requirements of accuracy as well as being durable. Frequent functional checks and repeated calibrations are essential to obtain data of good quality. If possible, tower systems should also include instruments for measurements of turbulent and radiative fluxes at several levels. Considering both the technical difficulties involved and the amounts of data to be sampled, it is hardly feasible to carry out such measurements on a continuous basis. Instead, a strategy is needed for taking measurements during well defined episodes in stable synoptic situations.

To make the most efficient use of an expensive tower system, it is advisable to choose a site for the tower measurements at the border between areas with distinctly different surface properties (e.g. urban-rural cf. Taesler, 1980) rather than well inside areas with a certain type of urban morphology. In this way different upstream surface conditions will be associated with different wind directions.

In order to extend measurements throughout the entire UBL one may use instruments carried by airplanes, helicopters or balloons. In recent years remote sensing techniques (sodar, lidar, radar) have become available which may be suitable also for measurements of mean and turbulent quantities in the UBL. Infrared sensing from airplanes or satellites has been used in some cases to determine urban surface temperatures. Although there are several problems in determining surface emissivities and correcting for infrared atmospheric absorption, IR-measurements are attractive since large areas are covered while still maintaining high spatial resolution. An old technique, which still is attractive due to relatively low cost and simple operation is to use tethered balloons to carry a low-level radiosonde for measuring temperature and humidity profiles. This may be combined with pilot balloon observations, preferably using double theodolite tracking, for wind measurements in the UCL. Alternatively, though more expensive, radar tracking of constant level balloons may be employed.

Measurements using various types of flying platforms are all difficult to carry out continuously even over short periods of time. Remote sensing systems may be operated continuously over long periods of time. The amount of data to be sampled will however create substantial problems in storage and subsequent analysis. Hence, it is probably most practical to restrict such measurement to diurnal cycles during well defined, stable synoptic conditions.

All of the techniques mentioned above have been employed for measurements in the UCL. The most comprehensive investigation carried out so far is probably the METROMEX-project in St. Louis (Participants, 1974; Ching et al., 1978; Method and Carlson, 1982). In addition to demonstrating the application of several of the measuring techniques mentioned above, this project also included a number of other aspects related to urban air pollution and aerosols, air and rain chemistry and urban modification of clouds and precipitation.

4. MODEL SIMULATIONS

4.1 General

There are two main reasons for simulations of urban-atmosphere interactions, viz.

- the economical and practical problems involved in full-scale measurements
- the need for extension of results from case studies to obtain data for different synoptic situations

Several different methods have been used to simulate various processes in the urban atmosphere. This is a very large field and it is only possible here to review briefly the main lines of approach. These include physical scale models, analytical mathematical models and numerical, computer-based models.

4.2 Urban Canopy Layer Modelling

In spite of the complex situations encountered in the UCL, it is possible to simulate certain processes and characteristic conditions in this layer quite successfully.

Nocturnal heat island development has been studied using a physical scale model which simulates the effects of thermal admittance and 'canyon' geometry on the long-wave radiation exchange (Oke, 1981). Model measurements of 'urban' and 'rural' temperature decrease after sunset agreed well with results from full-scale measurements. The main controlling factor is found to be the canyon height to width ratio (H/W) or, alternatively, the sky view factor (ψ_s) of the floor at the mid-point of a canyon cross-section. Good agreement is also found when using this measure as a basis for comparison of data on full-scale maximum heat island intensities ΔT_{u-r} in the central areas of cities in various global climatic regions (Figure 3).

The daytime urban short-wave radiation budget is also closely related to the morphology of the urban area. The complex variations in time and space of direct and diffuse solar radiation within the UCL may be simulated by computer models (Terjung and Louie, 1973).

Air movements within the UCL are extremely complex both as regards mean flow and turbulence characteristics. Wind tunnels have been used to simulate the microscale flow patterns. An example of flow visualization in a wind tunnel is shown in Figure 4. Microscale, 3-dimensional airflow patterns around buildings may also be simulated by numerical modelling, as illustrated in Figure 5 (Taesler and Andersson, 1984a).

Concentrations of air pollution below roof-level can be calculated in considerable detail for a particular street. An example is shown in Figure 6. The calculations involve a combination of UBL-modelling of urban mixing depth and urban background CO-concentration, using data on synoptic conditions and urban sources of CO, and UCL-modelling of air flow and diffusion, using specific data on street geometry, traffic conditions and emissions from vehicles. The model is being extensively used in urban traffic planning in Sweden.

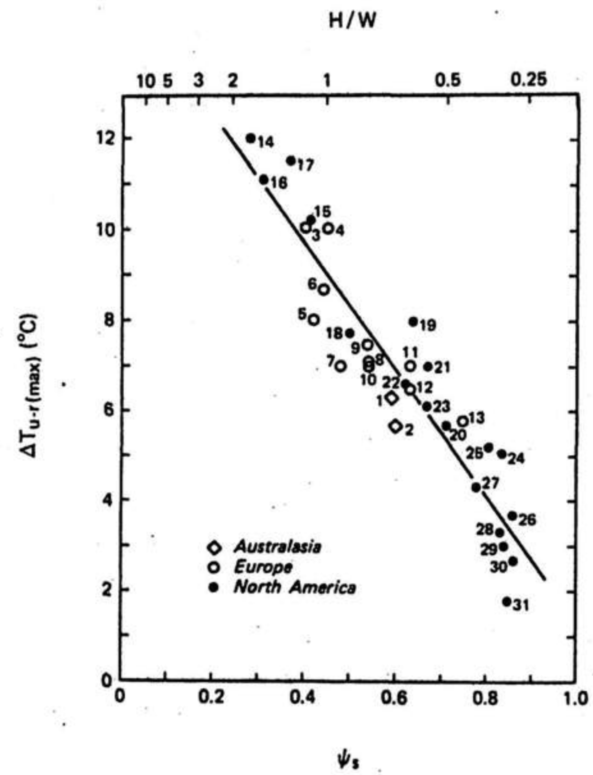

Table III. Maximum urban heat island intensity ($\Delta T_{u-r(max)}$) and urban geometry information for Australian, European and North American cities. Ordered according to population (P)

Settlement	Year	P ($\times 10^3$)	$\Delta T_{u-r(max)}$ (°C)	ψ_s†
AUSTRALASIA				
1. Christchurch, N.Z.	1968	258	6·3	0·59
2. Hobart, Tasmania	1978	130	5·7	0·60
EUROPE				
3. London, U.K.	1960	8,500	10·0	0·40
4. Berlin, Germany	1936	4,200	10·0	0·45
5. Vienna, Austria	1927	1,870	8·0	0·42
6. Amsterdam, Neth.	1975	870	8·7	0·44
7. Munich, Germany	1933	822	7·0	0·48
8. Sheffield, U.K.	1977	500	7·1	0·54
9. Karlsruhe, Germany	1972	260	7·5	0·54
10. Karlsruhe, Germany	1929	150	7·0	0·54
11. Uppsala, Sweden	1975	100	7·0	0·63
12. Uppsala, Sweden	1950	63	6·5	0·63
13. Lund, Sweden	1972	50	5·8	0·75
NORTH AMERICA				
14. Montréal, P.Q.	1970	2,000	12·0	0·28
15. Vancouver, B.C.	1971	1,100	10·2‡	0·41
16. San Francisco, Cal.	1954	784	11·1	0·31
17. Edmonton, Alta.	1965	401	11·5	0·37
18. San José, Cal.	1954	101	7·7	0·50
19. Fairbanks, Alaska	1976	65	8·0§	0·64
20. Brandon, Manitoba	1979	37	5·7	0·71
21. Columbia, Md.	1974	28	7·0	0·67
22. St. Hyacinthe, P.Q.	1970	24	6·6	0·62
23. Corvallis, Oregon	1967	21	6·1	0·67
24. Chambly, P.Q.	1970	12	5·1	0·84
25. Marieville, P.Q.	1970	4·3	5·2	0·81
26. St. Basile-le-Grand, P.Q.	1970	4	3·7	0·86
27. St. Césaire, P.Q.	1970	2·4	4·3	0·78
28. St. Pie, P.Q.	1970	1·6	3·3	0·83
29. Columbia, Md.	1970	1·6	3·0	0·84
30. Ste. Angèle de Monnoir, P.Q.	1970	1·2	2·7	0·86
31. Ste. Madeleine, P.Q.	1970	1·1	1·8	0·85

Figure 3. The relationship between maximum heat island intensity observed in a settlement ($\Delta T_{u-r(max)}$) and the canyon sky view factor in its central area (ψ_s). Consult Table III for numbers identifying settlements (after Oke, 1981).

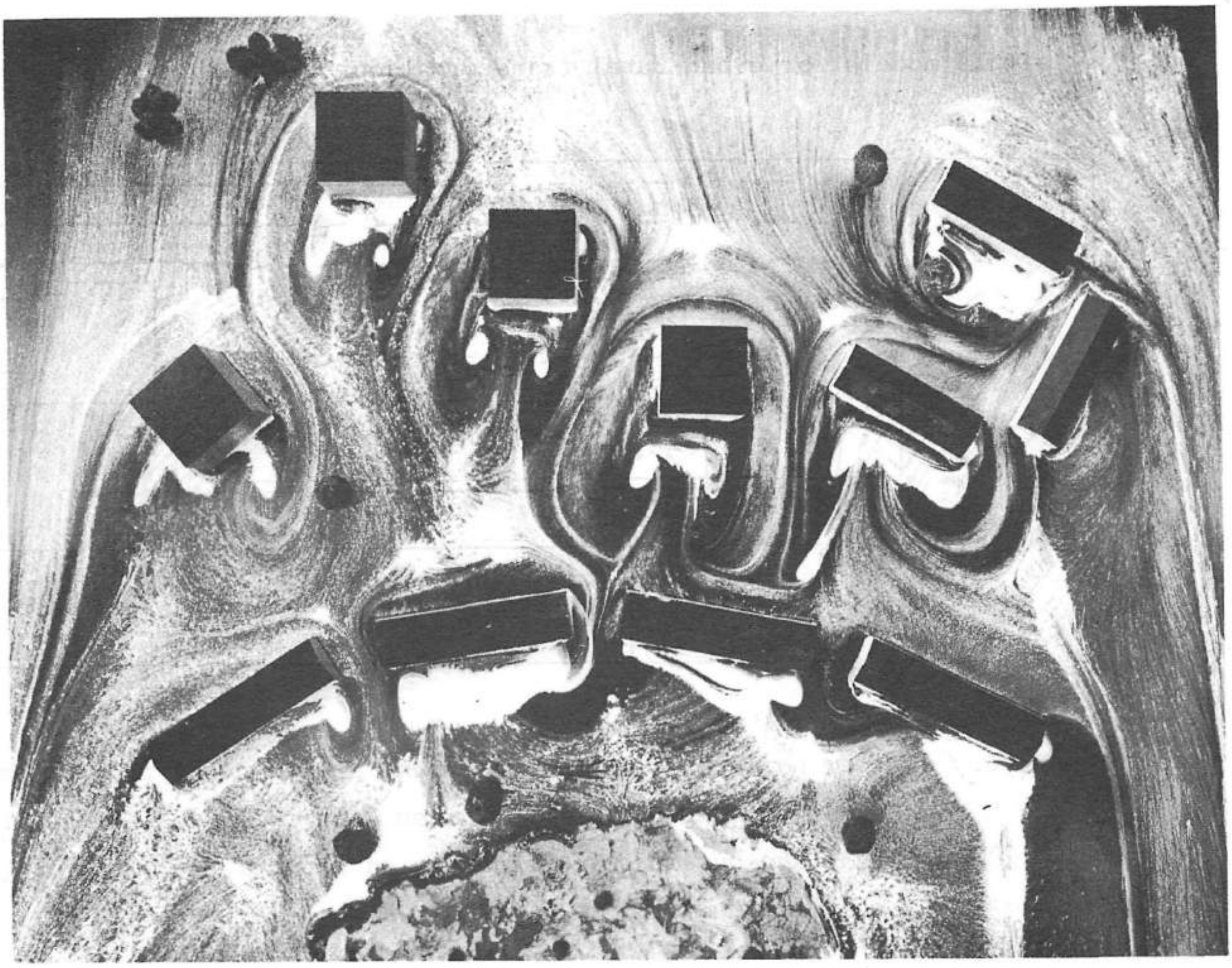

Figure 4. Visualization of complex airflow pattern around buildings by scale modelling in a wind tunnel at the Royal Institute of Technology, Stockholm.

4.3 Wake Layer Modelling

Wind tunnels may be used also for the simulation of airflow in the layer near roof-level (Raupach et al., 1980). Usually, however, this layer is not modelled separately, but rather is implicitly included in simulations of the UBL.

Data on wind speed above roof-level is an important input to several practical applications of urban climatology (e.g. such as illustrated in Figure 6) or for wind load calculations. At present such data are usually derived by empirically determined correlations with airfield data or estimated by simple models for urban-rural transformation of wind profiles.

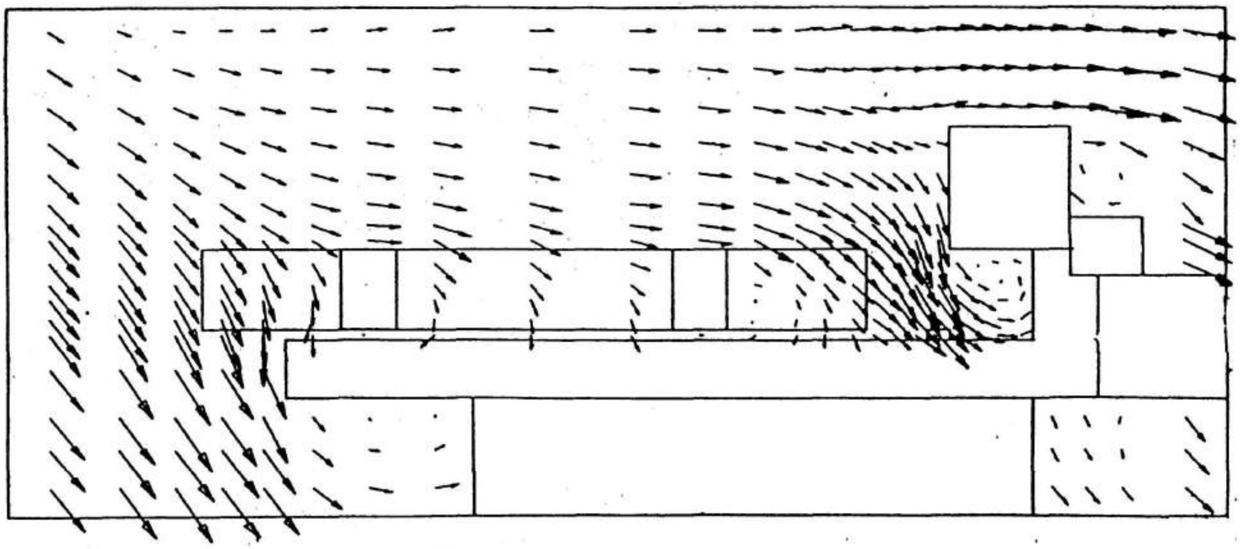

Figure 5. Airflow pattern at 2 m above ground around an office complex as determined by numerical simulation with the PHOENICS model. (One of the buildings is standing on columns, allowing airflow to pass underneath.)

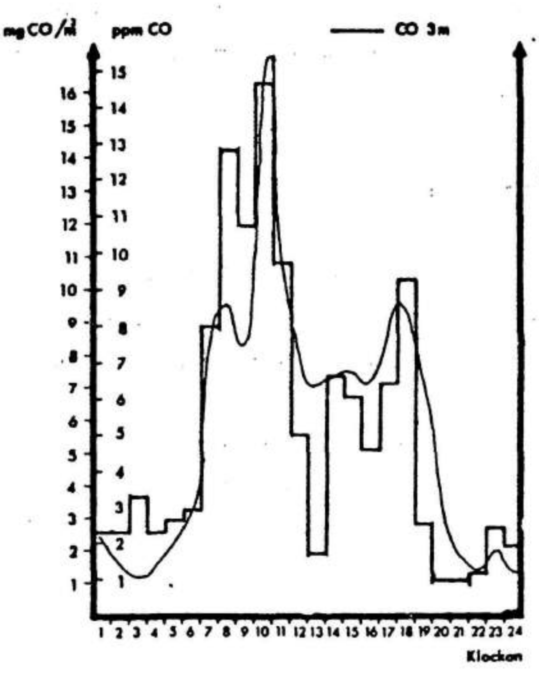

Figure 6. Measured (discontinuous curve) and calculated (continuous curve) data on CO-concentrations 3 m above ground on the west side of a main traffic route in central Stockholm.

The general problem of airflow, turbulent and radiative exchange in the layer closely above tall roughness elements requires both closer theoretical analysis and experimental investigation. In particular, the applicability of surface layer similarity theory, implying the existence of a constant flux layer, needs to be carefully examined.

4.4 Urban Boundary Layer Modelling

In contrast to the urban canopy and wake layers, the UBL has been extensively simulated by numerical modelling. Depending on their purpose such models may be divided into different classes.

Advective models, simulating the downwind growth and thermal structure of a well mixed UBL. The controlling parameters here are urban surface roughness, wind speed, heat input from the urban surface and the upstream rural inversion strength. Such models are used to calculated urban mixing depths and heat island intensity. Reasonable agreement is found in some cases with observations of these quantities during typical heat island situations. There are problems, in particular in assessing values of urban heat input, mainly due to the present uncertainty regarding the turbulent fluxes across the wake layer.

Radiative models, simulating the effects of urban aerosols and gaseous contaminants on radiative heating and cooling of the urban atmosphere. The emphasis here is placed on the formulation and parameterization of equations for solar and infra-red radiative transfer and absorption. There appears to be a certain ambiguity regarding the net radiative effects on temperatures in the UBL and regarding the total (solar plus infra-red) radiation reaching the urban surface. Model verifications are still hampered by the limited amount of experimental data on radiative effects in the UBL. Simulations as well as surface observations have shown, however, that solar radiation may be significantly attenuated in a heavily polluted urban atmosphere.

Dynamic models, simulating both mean flow and turbulence characteristics in the UBL on the basis of the hydrodynamic, thermodynamic and, in some cases, radiation equations. These models may be stationary or time-dependent and include one, two or three spatial dimensions. Surface boundary conditions are usually treated in a rather simplified way by prescribing average values of urban roughness and surface temperatures. The main emphasis is usually placed on the parameterization of turbulence. The approaches used range from simple K-theory for expressing the eddy correlations, to higher-order closure schemes. The number of grid-points and the computer capacity required increases rapidly with increasing complexity of the models.

Radiative and turbulent heat transfer at the surface is usually described by using a surface energy balance model. Fluxes of heat and momentum are often calculated from surface layer similarity theory.

Physical scale modelling of the UBL is less common. Wind tunnel simulations of flow over arrays of heated and unheated roughness elements have been shown to reproduce certain qualitative characteristics in urban-rural transformations of wind and temperature profiles, surface temperature distributions and urban heat island circulations (Sethuraman and Cermak, 1973). Most wind tunnel simulations represent neutrally stratified flows. Only a few very large wind tunnels are equipped to simulate non-adiabatic boundary layers. There are fundamental problems associated with scaling of surface and flow characteristics to obtain kinematic, dynamic and geometric similarity between model and full scale conditions. Complete similarity in all respects is impossible to obtain. Hence, such simulations have to be designed according to their particular purpose.

Experimental verification is a general problem both with numerical and physical modelling of the UBL. Different types of models often produce rather similar results. In spite of the large number of full-scale studies carried out, there are very few data sets available for closer evaluation of the accuracy and predictive power of different approaches.

In spite of the difficulties indicated above, it is probably fair to say that modelling - be it physical, analytical or numerical - of the various portions of the urban atmosphere has many advantages as compared to field investigations. Carefully designed full-scale measurements are indispensable for a deeper scientific understanding of urban impacts on atmospheric processes on different scales as well as for testing of models. Model simulations however offer a much greater flexibility in studying different combinations of urban surface properties and general meteorological (synoptic) conditions. This is particularly important with regard to practical applications of urban climatology, to be dealt with in the following section.

5. APPLICATIONS OF URBAN CLIMATOLOGY

5.1 General

Urban climatology may be defined, in its broadest sense, as the study and prediction of atmospheric conditions in human settlements. These conditions depend on the macroclimatic régime as well as on the regional, local and microscale effects caused by landscape, topography and urbanization, all of which has to be included in descriptions and predictions of urban climates.

Applied urban climatology may be defined as the use of information on climate to predict and control the impact of the urban atmosphere on particular elements of the 'urban system' (humans, buildings, weather sensitive operations).

Five levels can be distinguished for applications of climatology in the planning and design of human settlements:

(a) Regional land-use planning
(b) Urban land-use planning
(c) Urban settlement design
(d) Building design
(e) Building management

The recognition of climatological information as a significant basis for planning decisions at these levels is very different. It appears that this recognition does not depend, in the first place, on the severity of atmospheric impacts but rather on the present ability to control or prevent such impacts. This ability, in turn, depends on the development of predictive methods or models of the relations between climatic inputs and 'system' outputs. Thus, climatological information is extensively used in air pollution control programmes in connection with urban land-use planning and urban settlement design. Frequent applications are also found in building design, in particular with respect to extreme climatic forces. On the other hand, prevention from disasters caused by atmospheric processes is largely overlooked in regional and urban land-use planning. Also, climatic impacts on human health and comfort - other than air pollution - usually have only little influence on settlement design. During the last decade and along with a rapid development of energy conservation in buildings after the oil crisis, the requirements for climatological data for building energy budget calculations have increased significantly. The significance of climate for energy efficient urban planning has attained some attention among planners.

The purpose of the following discussion is to review briefly the situation with respect to the five levels of application, identified above, and to discuss certain associated methodological aspects.

5.2 Regional Land-use Planning

Cities and other human settlements are obviously located in certain preferred types of geographical areas and topographical conditions. The influence of climate is clearly evident on the global scale and, in the case of rural housing, on the local scale. On the regional or mesoscale the climatic influence is probably more indirect as a determinant, in combination with soil quality, for agricultural production. The associated distributions of settlements and population concentrations do not necessarily reflect climatic conditions favourable for human comfort and well being. On the contrary, extensive farming in level country is often associated with rather adverse climatic conditions with strong winds, increasing temperature extremes, dust production and, in cold climates, severe snowdrifts. Such problems have to be overcome by protective measures in local and microscale settlement planning and design.

Topography is a major determinant of climate on the regional scale, in particular with respect to wind, temperature and precipitation. The distribution of rural settlements in hilly areas is clearly influenced by climate.

URBAN CLIMATE METHODS AND DATA

The choice of site is a way to overcome or mitigate adverse climatic conditions. South-facing slopes are usually more attractive than those facing north. Hilltops and valley bottoms are avoided in cold climates due to wind exposure and frost risk respectively.

Topoclimatological mapping is a useful way of assessing various significant climatic determinants (Gol'tsberg, 1969). A relatively new field of applied climatology is the siting of wind energy installations, which has brought about an increased interest in topoclimatology as well as in numerical modelling of flow over complex terrain.

Competition for land and water resources leads to increasing conflicts between urbanization and agriculture. In many cases valuable arable land in areas with favourable climatic conditions is sacrificed to urban development. This has to be compensated by increased agricultural production in the remaining areas, which often requires additional irrigation and use of fertilizers and energy for fuel, drying of grains, etc. Increased regional air pollution further counteracts agricultural production by causing direct damage to crops, vegetables and fruits or by lowering the productivity of soils, which requires additional use of fertilizers, etc.

Extensive and rapidly increasing damage to forests in central and northern Europe during the last three years, most probably as a result of air pollution, is now causing great concern among politicians. In some areas as many as 50% of the trees are now damaged or even dying. Warnings for such consequences were expressed at the UN Conference on the Environment as long ago as 1972 (Anon., 1971).

Much work has been done in developing methods and criteria for rational assessments of climatic conditions necessary, or suitable, for activities in different sectors of society (Givoni, 1969; Koenigsberger et al., 1973; Hooper, 1975; WMO, 1976; Hobbs, 1981; Markus, 1982). These include for example:

- food production
- environmental quality

- transportation
- health and recreation
- energy production
- housing

The vast majority of these studies are concerned with industrialized countries in temperature and cold climates. In recent years studies are also emerging that deal with hot dry and hot humid climates (Koenigsberger et al., 1973; Hooper, 1975; Svard, 1976; Bodoegaard, 1981; Bitan, 1982). In Bodoegaard (1981) climate assessments with regard to housing are presented for different zones in Tanzania. The essential climatic characteristics together with relevant recommendations are summarized for each zone as illustrated in Figure 7.

Cases, where climate assessments have actually been used in regional land use planning are not very well documented in the available literature. It appears, however, that airfields, resorts for health and recreation, major air polluting plants and, lately, wind energy installations are located at least partly on the basis of climatological assessments. Investigations of local climatic modification due to construction of large water reservoirs are sometimes requested by legal authorities as a basis for economic compensation.

The meagre evidence available easily leads to the conclusion that climate is of minor importance in regional planning. However, such a conclusion is not necessarily correct. First of all, arguments and decisions in the planning process are not often publicized, only the final result. Secondly, climatologists may be asked to provide information to the planners but are hardly ever actively involved in the planning process - hence the feedback is poor. Thirdly, trends in population movements, e.g. the migration towards the 'sunbelt' in the USA, seem to indicate that pleasant climatic conditions and low costs for heating of private and commercial buildings may be significant determinants on the national and, possibly, also on the regional scale. Such migration is accompanied by movement and establishment of industries, which in turn further attracts more people. The process is generally unplanned and may even be counteracted by planning authorities. Hence, although new urban developments may be instigated indirectly by climate, they are as yet not located as a result of deliberate climatological analysis.

coastal tropical climate zone

Location: The islands and a strip of land from 20 to 100 km wide along the Indian Ocean.

Altitude: From sea level to about 300 m.

Vegetation: Green and well wooded. Large areas actively induced (agriculature, irrigatin and grazing)

Temperature: Never excessively hot
Annual Mean Max: 29-31°C
Annual Mean Min: 21.5 - 25°C
Diurnal Range: 6.5 - 9.5°C

Humidity: Permanent high
Annual Mean at 1500 hrs 65-75%

Rainfall: Rain may fall at any time of the year
Annual Mean: 750 - 1500 mm
Rainy days: 80-140
In North, two rainy season, one major in April - May and a minor in October - November. In the South one rainy season from December to April.
Driving rain during thunder storms may penetrate openings if facing rain.

Winds: North - East Monsoon: December - March
South - East Monsoon: April - October
Near the sea local wind pattern influenced by sea-land breezes.

COMFORT ASPECTS Combination of high temperature and high humidity causes permanent discomfort. June to September more comfortable due to small temperature drop, less humidity and brisk winds.
Nights offer little relief from the heat of the day.
Complete sun exclusion and maximum ventilation is required.

SITING Locate houses on sites exposed to sea breezes, avoid sheltered sites. Leave trees for shade. Good drainage required for heavy rainfalls. Houses should be widely spaced to allow maximum ventilation in and around building.

BUILDING PLAN House plan should give maximum ventilation, single-banked houses appropriate. Main elevations should face North and South in order to minimize solar gain. Where sea-land breezes are dominant and pronounced, the orientation should be modified in order to achieve max ventilation. Shaded verandahs essential.

STRUCTURE AND MATERIALS Roofs and walls should be light-weight with highly reflective surfaces and emissive to long wave radation. Ceilings are highly desirable for heat and sound insulation. Rusting of C.I.S. and decay of timber shortens life span of roof. Roof overhangs should not be less than 0.6 m, preferably as wide as 1.0 m.

OPENINGS Size: At lest 50% of North and South walls. Opening should give maximum air movement in rooms. Openings should be large, be shaded and have low cill height. Ventilation controll devices such as louvres and shutters may be desirable. Sun shading of walls and openings required. Glazed area should not exceed 20% of the area of the wall. Fly or mosquito screens may be desirable, but will greatly reduce airflow. Screens may be desirable, but will greatly reduce airflow. Screen walls give good permanent ventilation.

Figure 7. Summary of climatic characteristics and associated guidelines for rural housing for the coastal tropical zone, largely below 300 m.a.sl., in Tanzania (Bodoegaard, 1981).

Observational networks are usually not sufficiently dense for regional climate analyses, in particular in regions with complex terrain. Climatological expertise is needed for making interpolations of relevant parameters or to design temporary networks. Here, the use of boundary layer models and remote sensing by radar and satellites opens additional possibilities.

5.3 Urban Land-use Planning

It is probably justifiable to say that climate requires stronger attention in urban than in regional planning. Air pollution is a major concern to most urban planning authorities. Methods for short-term control of urban air pollution levels include operation of monitoring stations for SO_2 and CO in combination with traffic regulation and short-term pollution forecasts. Long-term control and reduction of pollution involves legal restrictions on emissions and fuel usage, zoning of residential and industrial areas, relocation of major traffic routes and major point sources, use of green belts and urban ventilation corridors. All such measures have to be based on statistics of atmospheric parameters such as mixing depth, plume rise and turbulent diffusion characteristics associated with different wind-directions. Numerical modelling of the urban boundary layer with incorporation of diffusion from point sources, line sources or area sources is a widely-used technique.

The influence of climate on urban development is by no means restricted to air pollution problems. Striking differences in traditional urban structure are evident between Scandinavian and Mediterranean cities (Beaujeu-Garnier and Chabot, 1969). The former have wider streets to facilitate clearing of snow. Buildings preferably face south and are well-separated to allow penetration of sunshine at low solar elevations. The latter show a much denser layout with narrow, shaded streets and courtyards surrounded by buildings with thick, heavy walls, all of which helps to moderate the diurnal temperature variation.

Modern downtown areas in middle and low latitude cities often create excessive thermal stress during warm and sunny summer days. This is due to the combination of high building density, high-rise buildings and little or no vegetation. The situation is further aggravated by poor urban ventilation and pollution from cars and buses. Conditions are not only very uncomfortable but may even become dangerous, as demonstrated by increased urban mortality rates during hot spells (Hodge, 1978).

Problems of this kind are of course best avoided at the planning stage by allowing space for parks, greenbelts and open ventilation corridors. Urban renewal, in particular in central areas, also offers such possibilities. However, since the price of land is extremely high in central areas, strong arguments are needed to convince city planners and authorities. This requires methods to establish reliable criteria for human health and comfort and to make statistical evaluations of the frequencies and durations of different urban climatic conditions. Models of the UCL energy balance are needed as a tool for such evaluations.

New residential settlements are often exposed to wind due to their location in open, level areas or on slopes and hilltops. Existing trees and bushes are usually eliminated during the construction stage and it takes a long time for new vegetation to become established. As a result, extremely uncomfortable conditions are often created. Here again, comfort criteria and climatological evaluation on the basis of statistical data and air flow modelling is needed. The statistical base for such evaluations should include data on simultaneous wind speeds, wind directions and temperatures. An example of such composite statistics is shown in Figure 8.

5.4 Urban Settlement Planning

Urban microclimatic conditions are strongly influenced by the grouping, orientation and design of buildings. Many architects and planners have shown strong interest in the possibilities for active and deliberate design which includes the climatic environment. This interest is reinforced in recent years in response to the need for energy conservation and use of active or passive solar heating. There has been an intense development in settlement and building design to achieve lower energy requirements for heating and cooling and, at the same time, to improve indoor as well as outdoor comfort. It appears, however, that this development has taken place largely without the participation of climatologists.

FREKVENSER AV VINDHASTIGHET OCH VINDRIKTNING FOR DYGNET(OVRE VARDE) OCH FÖR DAGEN MELLAN 07-18 (NEDRE VARDE). TALEN I TIONDELS PROMILLE
TEMPERATUREN TILL VANSTER ANGER MEDELVARDET HELA DYGNET, TEMPERATUREN TILL HÖGER MEDELVARDET FÖR DAGEN(C7-18)

STATION: 458 UPPSALA FLYGPLATS　　　month:- 1　　　PERIOD: 1955 - 1975

windspeed ms^{-1}

direction	calm	01-02	03-04	05-06	07-08	09-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26	27-28	29-30	31-32	33-34	35-	sums mean value
LUGNT	1099 561 -9 -8																			1099 561 -9 -8
01-03		174 92 -6 -6	189 98 -6 -6	141 69 -5 -6	49 30 -6 -7	31 19 -7 -7	12 6 -5 -4	6 2 -6 -3	3 1 -5 -4	4 3 -9 -9	1 1 -9 -9	1 -9								610 322 -6 -6
04-06		121 66 -5 -5	137 77 -6 -6	98 56 -7 -6	71 35 -8 -7	32 17 -7 -7	12 11 -8 -8													472 262 -6 -6
07-09		73 41 -4 -4	122 56 -3 -3	91 48 -2 -2	28 21 -3 -3	10 4 -6 -4	2 1 -6 -6		2 -7											329 172 -3 -3
10-12		113 57 -3 -2	176 96 -2 -1	128 70 -2 -1	44 24 -3 -3	19 6 -4 -4	6 4 -4 -5	1 1 -6 -6												488 258 -2 -2
13-15		110 54 -2 -2	148 72 -1 -1	101 63 -1 -1	48 30 -1 -2	7 3 -2 -5	3 3 -1 -1													417 224 -1 -1
16-18		227 114 -4 -4	256 125 -2 -2	193 107 0 0	102 54 0 0	41 28 1 1	20 9 1 1	2 2 0 0	3 3 -3 -3											844 443 -2 -1
19-21		305 160 -8 -8	313 166 -3 -3	312 155 -1 -1	186 94 1 1	67 39 1 1	21 8 1 0	7 1 2 7	3 1 2 -3											1215 624 -3 -3
22-24		417 205 -7 -6	461 266 -4 -4	351 198 0 0	227 135 1 1	113 59 2 2	40 18 3 4	9 5 3 3	1 1 4 4											1619 887 -3 -2
25-27		262 142 -6 -5	239 129 -2 -2	162 99 -1 -1	64 36 0 1	33 13 3 4	6 4 4 3	2 2 4 4												768 425 -3 -2
28-30		224 136 -7 -7	175 88 -4 -4	106 48 -2 -2	44 22 0 -1	21 13 1 1	5 1 0 -3	4 1 4 3	2 6											583 307 -4 -4
31-33		299 175 -8 -8	209 117 -7 -7	166 99 -6 -5	64 35 -6 -5	35 19 -6 -5	13 8 -4 -2	3 1 -1 8	4 3 -5 -3	1 -11										793 456 -7 -7
34-36		212 119 -7 -7	221 114 -7 -6	173 97 -7 -7	81 49 -7 -7	50 32 -6 -7	14 6 -6 -5	7 2 -5 -7	6 4 -7 -5	1 -11	1 1 -8 -8	1 1 -8 -8								763 424 -7 -7
S-DYGN S-DAG MEDELT	1099 561 -9 -8	2538 1359 -6 -6	2646 1404 -4 -4	2021 1112 -2 -2	1009 566 -2 -2	460 251 -1 -1	154 79 -1 -1	40 17 -0 1	23 12 -4 -3	6 3 -9 -9	3 2 -9 -8	1 1 -9 -9								10000 5368

Figure 8. Monthly relative frequencies (1/10 000) of wind speed and direction for the whole day (01-24 hrs, upper value) and for hours between 07-18 (lower value) with corresponding mean temperatures.

Wind, solar radiation and temperature are the most important meteorological elements on this scale. The original data from meteorological stations are, as a rule, not sufficiently representative or detailed to be applied directly. Wind speeds observed at 10 m have to be adjusted both downward, to pedestrian level (∿ 2 m) and, in some cases, upward to roof-level. Global solar radiation needs to be divided into direct and diffuse components, both of which have to be calculated for vertical surfaces with different orientation. Solar radiation networks are, if existing at all, never sufficiently dense - hence there is a strong need for methods to calculate solar radiation parameters indirectly from routine, synoptic observations. Several such methods have been developed in recent years (WMO, 1977; Davies, 1981; Taesler and Andersson, 1984b). Figures 9a, b give an example of such calculations, showing the influence of surface orientation and screening of the horizon on the average daily global irradiation of vertical surfaces.

Temperatures have to be corrected both with regard to regional or local, non-urban differences between the observing station and the building site and, in particular, with regard to the urban heat island effect. Urban climatological modelling, in particular of the UCL, is needed here also.

The combination of wind and temperature determines the energy losses of a building due to heat transmission through walls and roof and air infiltration through cracks and openings. The calculations of both terms require statistical data on wind and temperature in combination (cf. Figure 8). Preferably these statistics should also be locally corrected. The calculation of infiltration losses is strongly dependent on accurate data of wind speed above roof-level and on the wind pressure distributions around the building envelope for different angles of attack. Such data may be determined by wind tunnel simulations (Wiren, 1984) or by numerical modelling or, in some cases, by full-scale measurements. Wind pressure data for different building shapes have been compiled from various sources by the IEA (1984).

In a current project at the SMHI, climate statistics, urban climate modelling and building physics are combined in a computer model (ENLOSS) for calculations of energy losses in buildings. The main purpose is to assess the influence of site selection and local climate in natural and urban surroundings.

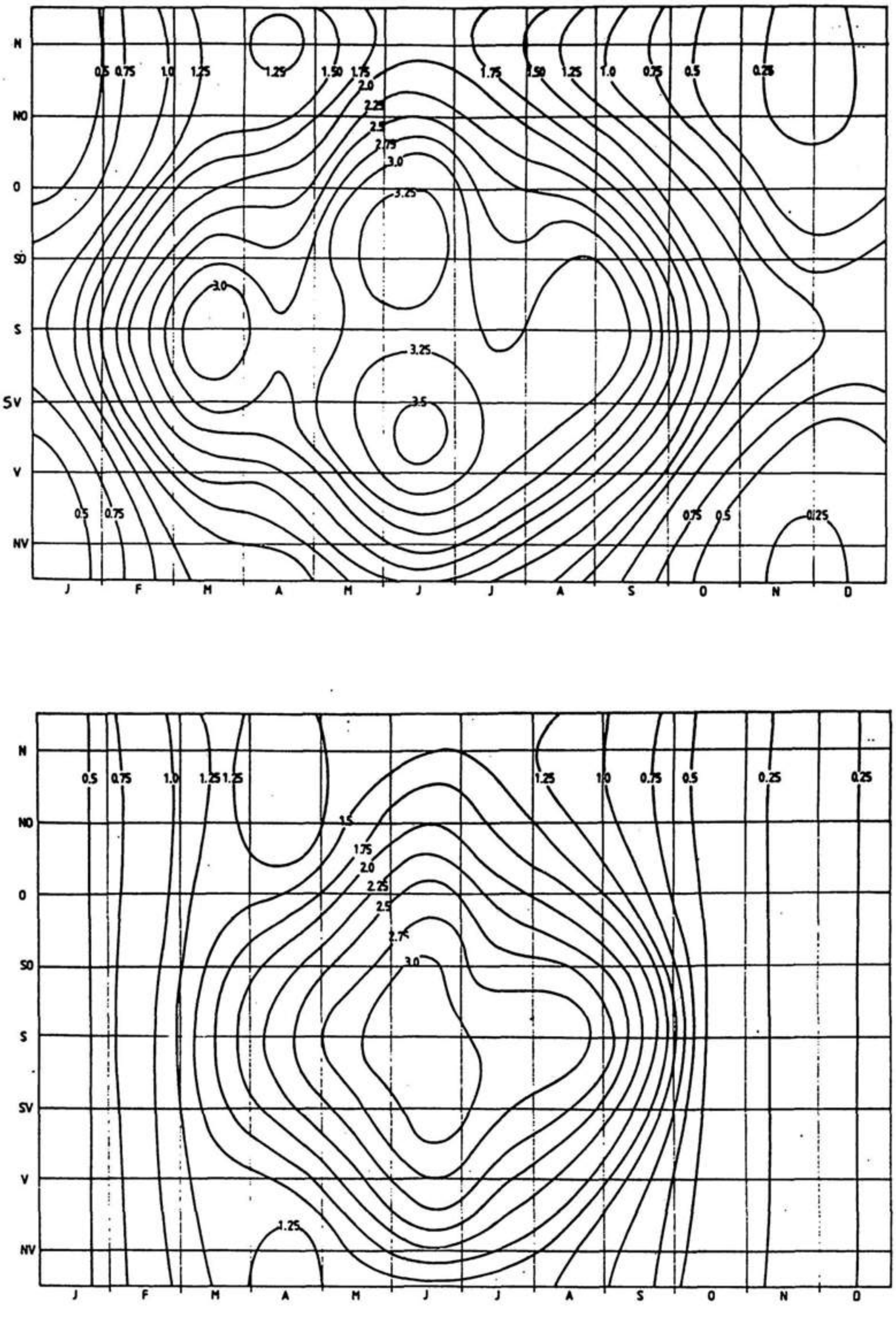

Figure 9a, b. *Daily global irradiation (KWh/m^2) during the year on vertical surfaces facing different compass directions.*
Upper figure free horizon, lower figure 30^o horizontal screening. Mean values 1961-72, calculated from hourly synoptic observations at an airport in southern Sweden.

A standardized building is defined with respect to heat resistance, air tightness, geometrical dimensions and orientation and used as a 'sensor' to probe different local climates. Observations of wind speed and temperature at synoptic stations are corrected by semi-empirical methods to a given site.

Figure 10 shows five different sites selected for such calculations. The calculated average annual heat loss at point 1 was 12% lower than at point 4, and 22% lower than for a site in level, open country, outside the built-up area. These reductions are essentially a result of reduced wind speed due to the rougher built-up area.

By splitting the calculated heat losses according to wind direction the need for wind shelter can be assessed. Contrary to expectations, it was found, in the present case, that cold, northerly winds contribute only little to the annual heat loss. The main losses are associated with the much more frequent westerly and easterly winds.

The calculations have been extended over a larger area, including also an urban area and different topographical conditions. Figure 11 shows the corresponding results, where the influence of the urban heat island is discernible.

Similar methods are being used in some other countries (Markus, 1982; Rauhala, 1983) to assess climatological impacts on heating requirements. It should be possible to develop corresponding methods also for assessments of cooling requirements in hot climates. Access to long-term series of data from meteorological stations is essential in all such applications. It would also be most valuable to run urban meteorological stations in parallel over a few years for verification and calibration of methods for rural-urban corrections.

5.5 Building Design

Applications of climatology to building design are usually referred to as building climatology. It is difficult, however, to make sharp division between these subjects, as may be seen from the above example. Urban climatology is needed to provide corrected data on meteorological parameters for calculations in building design.

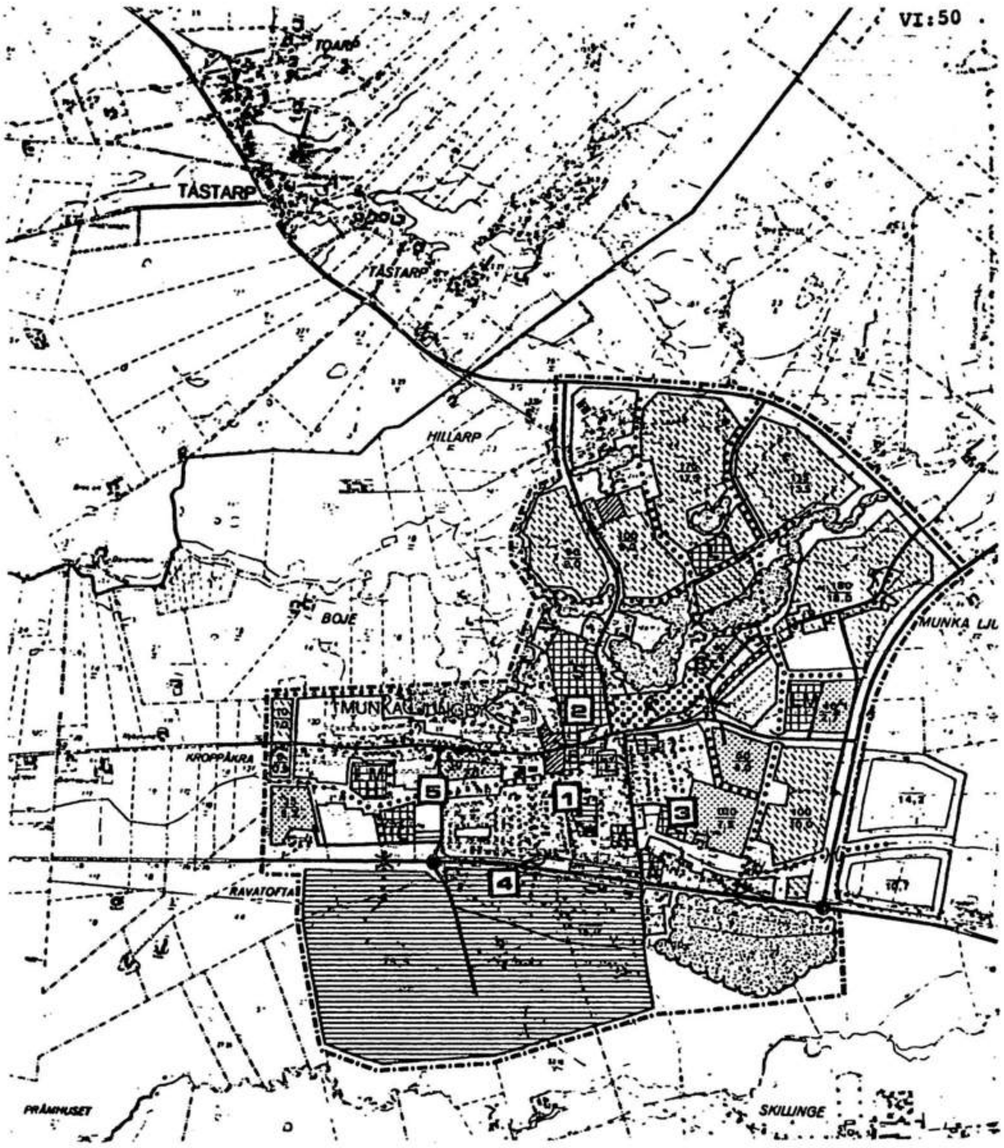

Figure 10. Sites chosen within a small township (Munka Ljungby) in southern Sweden for climatological evaluation of building energy losses as related to local urban environment. The built up area is surrounded by level, open farmland to the east, south and west and by forest and rough topography to the north.

5.6 Building Management

Applications of climatology in building management appear, as yet, to be largely undeveloped. Monthly and annual statistics of heating and cooling degree-days are used, however, as a basis for current follow-up of energy uses. It may be useful to develop similar indices for solar radiation or wind speed or combinations of several parameters.

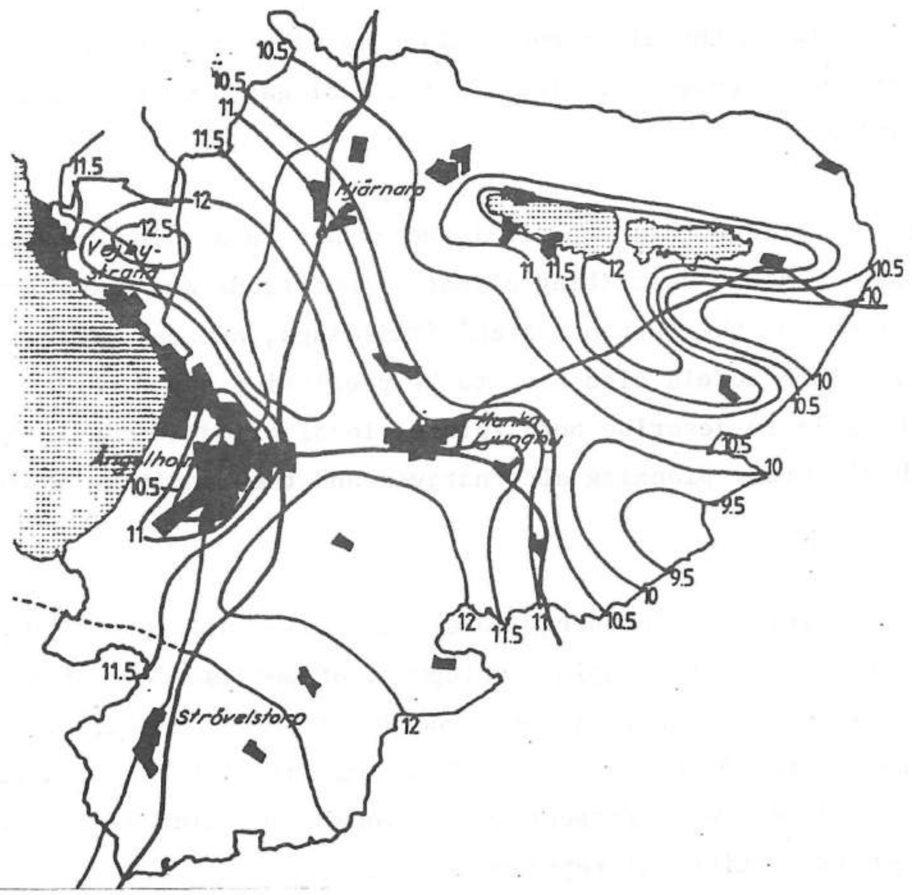

Figure 11. Regional analysis of average (1955-79) annual total heat loss (MWh/y) due to transmission and air infiltration. Calculations include effects due to topography, forest vegetation and urbanization on wind speed and temperature. Values refer to a modern, 1 family house of high quality.

6. CONCLUDING REMARKS

Urban planning is a predictive process which creates future conditions within a framework of given requirements and constraints. The problem is to identify the role of climatology - or rather climate - in this process.

Traditionally, climatological information is given to urban planners in the form of tables, diagrams or maps - all of which give a static description of certain properties of climate. Such data may be relevant in some cases as a basis for defining certain requirements (e.g. for the design of street sewage systems on the basis of extreme value statistics of rainfall). In general, however, the relevance is not obvious since the data are difficult to translate into technical, economical or health- and comfort-related requirements or consequences. This is the real gap between climatology and its application.

In order to bridge this gap, it is necessary to develop integrated 'input-output' models, describing climatic conditions and their impact on various elements of the 'urban system' (buildings, humans, weather sensitive operations). Such models also have to be predictive and discriminating, i.e. they must be able to describe both future, local climatic conditions associated with different planning alternatives and the resulting impacts on the 'system'.

The growing interest in energy conservation in buildings after the oil crisis has brought about a rapid development of models, describing the energy balance of buildings under given or assumed climatic conditions. These may be called 'output'-models. The climatological 'input' is still usually poorly developed both with respect to its local- and microscale accuracy and to its long-term statistical representativity.

The basic challenge for urban climatology is to improve the climatological 'input' by developing methods for accurate local predictions of those climatic parameters, which are relevant to a particular planning aspect. Whenever possible, this should be linked directly with models for 'output'-calculations.

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URBAN CLIMATE MODELS: NATURE, LIMITATIONS AND APPLICATIONS

R. D. Bornstein
Department of Meteorology
San Jose State University, San Jose, CA 95192

1. INTRODUCTION

Atmospheric models serve many useful purposes, from forecasting the weather to the siting of power plants. A potentially important use of such models could be in the planning of urban development so as to create urban climates that are more healthy for urban dwellers.

Mesoscale atmospheric models have recently been reviewed by Atkinson (1981), Pielke (1981), Anthes (1983), and Pechinger (1983). In addition, there have also been reviews of urban climate models by Taylor (1974), Oke (1974, 1979), Landsberg (1981), Bornstein and Oke (1981), and Bennett and Saab (1982).

Following the suggestion of Oke (1976) this paper summarizes atmospheric models of both the microscale climate within the (below roof-level) urban canopy layer and the mesoscale variations within the (above-roof level) urban boundary layer. The basic workings of each type of model is reviewed with respect to assumptions, equations, parameterizations, boundary conditions, numerics, grids, and initial conditions. Also discussed are outputs produced, evaluation techniques, and limitations associated with each type. The role of such models in city planning in general, and in tropical city planning in particular, is evaluated. Finally, possible future developments in urban climate modelling are explored.

2. MODELLING STUDIES

2.1 Canopy layer models

Microscale canopy layer models can be classified as statistical, canyon, or wind tunnel.

2.1.1 Statistical models

Simple regression of urban/rural climatic differences against one or more meteorological parameters is one of the oldest forms of urban modelling (Oke, 1979), e.g. see the work of Goldreich (1974), Unwin and Brown (1975), Conrads (1976), and Hernandez *et al.* (1984).

A more sophisticated statistical model is the harmonic analysis used by Preston-Whyte (1970) to summarize surface temperature distributions in Durban, South Africa. A sophisticated eigenvector analysis was used by Clarke and Peterson (1973) to study the relationship between surface heat island and land-use in St. Louis.

The coefficients of such statistical relationships are different for each city, e.g. Sundborg (1950) found the existing nocturnal urban heat island of Uppsala, Sweden, related various meteorological elements by:

$$\Delta T = 2.8 - 0.10N - 0.38U - 0.02T + 0.03q,$$

where all symbols are defined in Appendix A and where ΔT and T are in degrees Celsius, N is in tenths, U is in m s^{-1}, and q is in gm kg^{-1}. Thus such relationships cannot be used for planning urban development in other locations.

When statistical analysis is used to estimate urban/rural climate differences as a function of city geometry, resulting relationships can be used for planning purposes. For example Oke (1981) showed that maximum urban heat island values ΔT_{max} were related to urban canyon geometry through a sky view factor ψ^*:

$$\Delta T_{max} = 15.27 - 13.884\,\psi^*$$
$$= 7.45 + 3.97\ln(H/W).$$

As shown in Figure 1, the above relationship is valid for (mainly) mid-latitude cities in Australasia, Europe, and North America. It should next be tested against data from tropical cities.

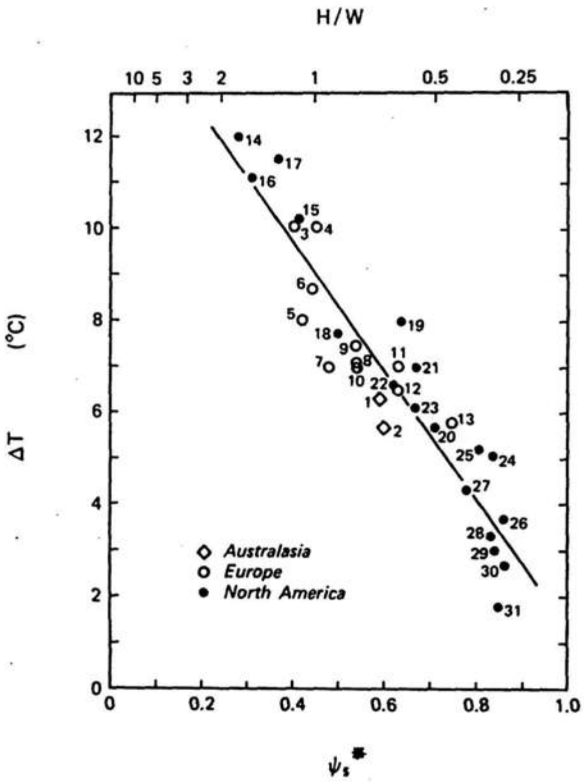

Figure 1. The relationship between maximum heat island intensity observed in a settlement and the canyon sky view factor (from Oke, 1981).

Statistical models generally do not require large computing facilities, but do require good data bases to develop accurate predictor equations. While they can be used to forecast urban climatological parameters, they do not generally provide significant insight into the basic physical processes producing urban climate.

2.1.2 Canyon models

Canyon models generally simulate energy exchanges either around a single building, in a single urban canyon, or for a series of urban canyons. The basic equation for such models is the equation for the energy balance at the earth-air interface, given by Munn (1966) as:

$$Q_F + K^* + L\downarrow - L\uparrow = Q^* + Q_F = Q_G + Q_H + Q_E. \qquad (1)$$

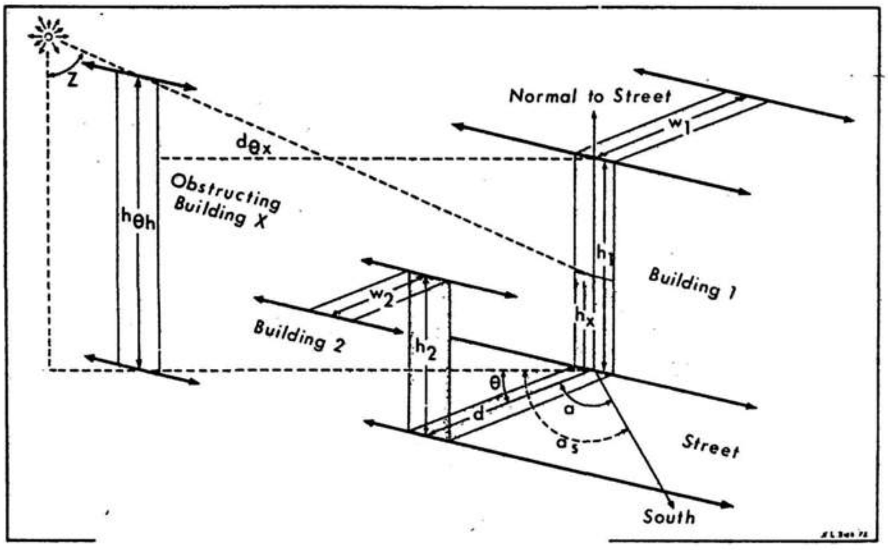

Figure 2. An urban street canyon system characterized by the strip method (from Terjung and O'Rourke, 1980a).

The various canyon models seek to evaluate some or all of the terms in (1), as opposed to simulating resulting meteorological distributions, e.g. see Terjung and Louie (1973, 1974), Unsworth (1975), Nunez (1975), Nunez and Oke (1976, 1977, 1980), Cole (1976 a, b), Arnfield (1976, 1982), and Terjung and O'Rourke (1980 a, b). In the most complex of these models the various terms of (1) are complex sums of terms involving multi-building canyon geometry factors (see Figure 2). For the hypothetical city of Figure 3, Terjung and O'Rourke (1980b) found the complex distribution of summer solar energy shown in Figure 4. Such models should also be applied to urban geometries typical of tropical regions.

Canyon energy exchange models yield important information on microscale variations of the surface energy balance. They also provide estimates of the various urban radiation parameters, e.g. A and ε, needed in the mesoscale urban planetary boundary layer (PBL) models discussed below.

2.1.3 Wind tunnel models

Wind tunnel studies have also provided much insight on flow patterns within the urban canopy layer. Some work deals with effects of single buildings (e.g. Newberry et al., 1973; Isyumov and Davenport, 1975; Penwarden and Wise, 1975), while others concentrate on flows within complex urban canyons (e.g. Cermak et al., 1974; Hoydysh et al., 1975). A discussion of the "similarities" required between real and wind tunnel atmospheres is given below in the section on wind tunnel models of the urban PBL.

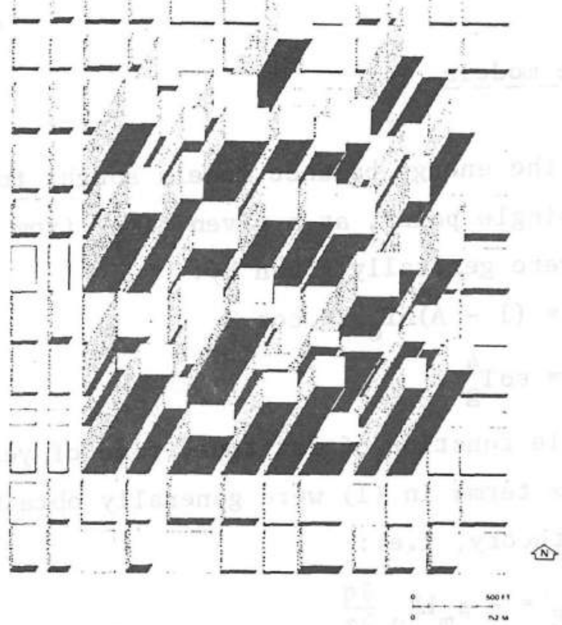

Figure 3. A three-dimensional view of the synthetic city (from Terjung and O'Rourke, 1980a).

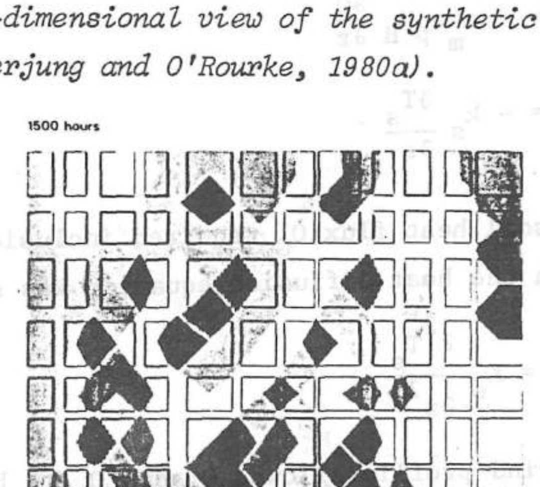

Figure 4. Solar radiation distribution for case of Figure 3. Darker areas receive more radiation (from Terjung and O'Rourke, 1980a).

2.2 Boundary layer models

Mesoscale boundary layer models can be classified as energy balance, advective integral, dynamic differential, or wind tunnel.

2.2.1 Energy balance models

The earliest of the energy balance models sought to predict surface temperature T_g at a single point, at a given time, from solutions to (1). The radiation terms were generally given by:

$$Q^* = (1 - A)\ I_o\ \tau^* \cos Z \tag{2}$$

$$L\uparrow = \varepsilon\sigma T_g^4\ , \tag{3}$$

where cos Z is a simple function of latitude, time of year, and time of day. The non-radiative flux terms in (1) were generally obtained from surface boundary layer (SBL) theory, i.e.:

$$Q_E = -\ \rho_m L K_q \frac{\partial q}{\partial z} \tag{4a}$$

$$Q_H = -\ \rho_m c_p K_H \frac{\partial \theta}{\partial z} \tag{4b}$$

$$Q_G = -\ k_s \frac{\partial T_s}{\partial z}\ . \tag{4c}$$

Evaluation of the soil heat flux Q_G required inclusion in the model of a soil sublayer in which the heat diffusion equation was solved, i.e.,

$$\frac{\partial T_s}{\partial t} = K_s \frac{\partial^2 T_s}{\partial z^2}\ . \tag{5}$$

Use of the logarithmic wind profile allowed Q_E and Q_H to be given as:

$$Q_E = -\ \rho_m L k_o^2\ \frac{\Delta U \Delta q}{(\ln z_2/z_1)} \tag{6}$$

and

$$Q_H = -\ \rho_m c_p k_o^2\ \frac{\Delta U \Delta \theta}{(\ln z_2/z_1)}. \tag{7}$$

When (2), (3), and (5) through (6b) are put into (1), the following equation is obtained:

$$a_1 + a_2T_g + a_3T_g^4 = 0,$$

where the constants a_1 to a_3 are functions of the given surface characteristics (such as ε, k_s, A, I_o, and Q_F) and the given constant meteorological parameters at the top of the SBL (i.e., U, q, and Θ). An iterative process is used to solve for T_q and then Q_H, Q_E, and Q_G can be evaluated.

Such an energy balance model was applied to Sacramento, California, by Myrup (1969a, b) and Myrup and Morgan (1972). The city was divided into 152 squares and a detailed analysis of land usage patterns carried out to obtain the surface characteristics necessary to calculate the energy balance in each of the squares (Table 1). Similar models have been used by Bach (1970), Outcalt (1972a, b), Nappo (1972), and Miller et al. (1972).

The main limitation of these early energy balance models is the lack of feedback between the SBL and the rest of the PBL, i.e. meteorological parameters at the top of the SBL remain constant in time. The models, however, require considerably less computer power than those containing such feedback.

Later one-dimensional energy balance models generally contained two atmospheric layers, i.e., a lower analytical constant flux SBL (of about 50 m in depth) and an upper finite-difference transition layer (of about 2 km in depth). Profiles of Θ, U and q in the SBL are obtained from (4a), (4b), and:

$$\tau = - \rho_m K_M \frac{\Delta U}{\Delta z} , \tag{8}$$

where the K's of (4a), (4b), and (8) are not necessarily equal.

The transition layer equations in a hydrostatic urban PBL over flat homogeneous terrain are:

$$\frac{du}{dt} = fv - \frac{1}{\rho_m} \frac{\partial p}{\partial x} \tag{9}$$

$$\frac{dv}{dt} = - fu - \frac{1}{\rho_m} \frac{\partial p}{\partial y} \tag{10}$$

$$0 = - g - \frac{1}{\rho_m} \frac{\partial p}{\partial z} \tag{11}$$

$$\frac{d\Theta}{dt} = -\frac{1}{\rho_m c_p} \left[\frac{\partial Q^*}{\partial z} - \frac{\partial Q_E}{\partial z}\right] \tag{12}$$

$$\frac{dq}{dt} = -\frac{1}{\rho_m} \frac{\partial E}{\partial z} \tag{13}$$

$$p = \rho RT \tag{14}$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\partial}{\partial z} K_z \frac{\partial}{\partial z} . \tag{15}$$

TABLE 1. *Interface parameters by land-use category (from Myrup and Morgan, 1972).*

	Albedo	Emissivity	Heat Conductivity [cal cm^{-1} s^{-1} $^oC^{-1}$]	Heat Capacity [cal cm^{-3} $^oC^{-1}$]	Wet Fraction	Roughness [cm]
Light-density Residential	.20	.88	.0023	.45	.43	108
Medium-density Residential	.23	.86	.0024	.43	.56	532
Heavy-density Residential	.25	.88	.0022	.40	.43	370
Schools	.15	.90	.0023	.50	.35	41
Shopping	.20	.86	.0022	.42	.04	36
Office	.22	.85	.0025	.45	.13	175
Park	.16	.89	.0030	.58	.93	127
Central Business District	.26	.86	.0024	.42	.07	321
Industrial	.26	.86	.0024	.42	.01	13
Freeway	.30	.80	.0030	.60	.00	4
Open Green	.35	.90	.0006	.30	.05	2
Seasonal Green	.15	.90	.0030	.60	1.00	2
Water	.09	.93	.0014	1.00	1.00	.001

The radiative flux divergence term $\partial Q^*/\partial z$ can be extremely complex, as it can include effects of atmospheric gases and solids on both long- and short-wave radiant fluxes. The horizontal pressure gradient terms in (9) and (10) are generally replaced by constant geostrophic wind components. The basic SBL equations are (4a), (4b) and (8). If a soil layer is included, then (4c) and (5) must also be solved.

Equations (9) through (14) are hereafter referred to as the "basic PBL equations", although not every model retained all of their terms. Finite difference solutions to the basic PBL equations over homogeneous urban surfaces were obtained by Tag (1969), Atwater (1970, 1971 a, b, 1972 a, b), Bergstrom and Viskanta (1972, 1973 a, b, 1974), Lal (1975, 1976), Torrance and Shum (1976), Zdunkowski et al. (1976), Venkatram and Viskanta (1976 a, b, c, 1977), Ackerman et al. (1976), Ackerman (1977), and Dieterle (1979). The last model used the basic PBL equations in the vorticity mode, as will be described below.

The obtaining of finite-difference solutions to the basic PBL equations requires specification of K_z, boundary conditions, as well as establishment of a computational grid and selection of finite-difference schemes. The formulation of K_z can either be first order (dependence only on Reynolds averaged quantities) or second order (dependence on turbulent quantities). All of the models reviewed in this paper, except the final two below, have used first order closure to obtain needed K_z-profiles. Second order formulations require (at the minimum) a new equation for the total turbulent kinetic energy. A review of problems associated with formulating K_z is given by Shir and Bornstein (1977).

Boundary conditions at the top of the model and at the bottom of the soil layer (if included) generally specify constant values, i.e., no effect of surface processes. The temporal variation of T_g is either specified, or predicted from (8) in a manner similar to the earlier models; however, simulation of non-steady PBL profiles allows for time-varying meteorological parameters at the SBL top.

Various finite-difference schemes exist, each with problems that will be discussed below. Initial conditions can consist of (unsmoothed or smoothed) observed profiles or equilibrium model profiles. Observed profiles could contain inconsistencies, e.g., between energy and mass fields, which could cause the model to become unstable, while equilibrium model profiles may be unrealistically simplified. In either case, the extreme PBL forcing associated with the diurnal variations in the surface energy budget should make initial conditions unimportant after relatively few hours of simulated time.

Results generally show one-dimensional PBL models to be fairly accurate in simulating surface fluxes over homogeneous (i.e., generally rural) surfaces (Figure 5). Such models are also used in parametric studies in which single urban parameters (e.g., A, ε, k_s, or Q_F) are systematically varied, e.g. the diurnal variation of Q_F significantly affected predicted New York City (NYC) urban heat island intensities (Figure 6).

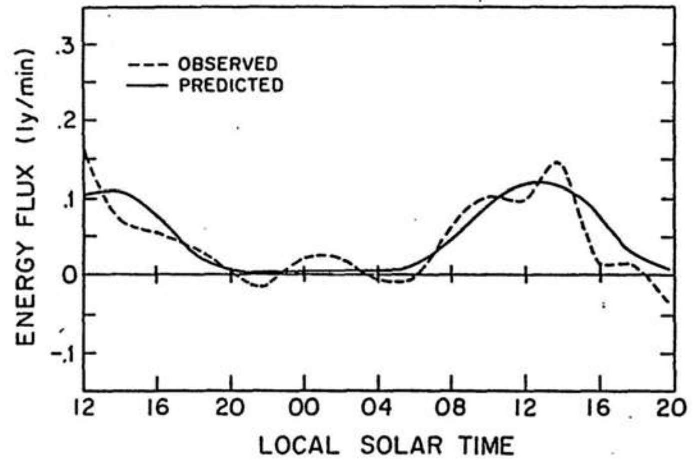

Figure 5. Observed and predicted surface latent heat flux at O'Neill (from Dieterle, 1979).

These models have also generally shown gaseous pollutants (mainly via radiative flux divergence) to produce only small atmospheric and surface temperature changes, except in near calm conditions; however, dense aerosol layers can produce significant atmospheric temperature changes (Figure 7).

In summary, one-dimensional PBL models have been useful in evaluating current and future affects of urbanization on the thermal structure of mid-latitude cities. They could be applied in the same manner for tropical cities; however, Oke (1979) has pointed out that canopy layer effects need to be better incorporated into these models.

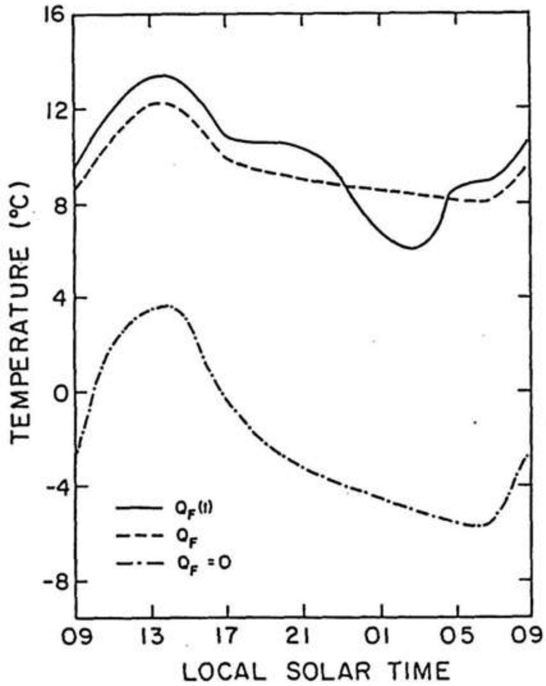

Figure 6. Simulated surface temperature waves for an urban area for the cases of 1) zero, 2) constant, and 3) variable anthropogenic heat flux (from Dieterle, 1979).

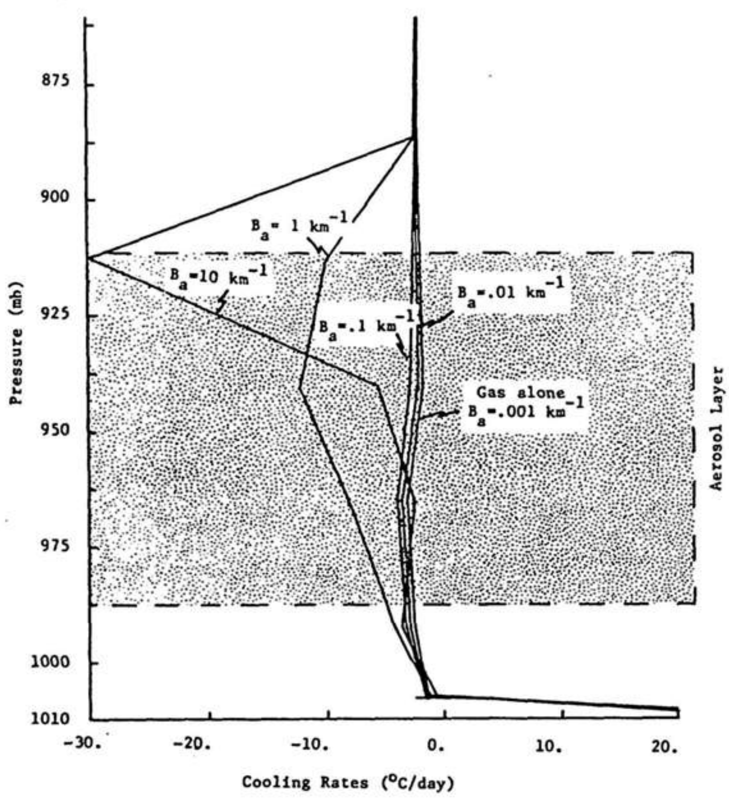

Figure 7. Infrared cooling rates resulting from gaseous and particulate absorption for the Davis night sounding (from Atwater, 1971b).

2.2.2 Advective integral models

The steady-state advective integral model developed by Summers (1964, 1974) predicts the spatial distribution of early morning urban mixing depth (surface to base of first elevated inversion) as Q_F is added to columns of stable rural air passing over an urban area. The spatial distribution of the height of the well-mixed layer h_i, that forms as the rural surface inversion is destroyed from below, is given by:

$$h_i^2 = \frac{2}{\rho_m c_p U_m \alpha} \int_0^x Q_F \, dx. \qquad (16)$$

The spatial distribution of the urban surface temperature excess ΔT is then given by:

$$\Delta T = \alpha \, h_i$$

while the spatial distribution in the mixed layer of any passive contaminant c is:

$$c = \frac{1}{U_m h_i} \int_0^x C \, dx.$$

The model only requires input values of rural lapse rate, mean PBL wind, and spatial distributions of the source term.

The basic model was also used by Kalma (1974), Leahey (1975, 1976), and Clark *et al.* (1984). It produces spatial distributions of mixing depth (Figure 8), surface heat island values, and mixed layer average values of c.

The basic advective integral model was modified by Pasquill (1970) to allow general wind and temperature profiles, but this necessitates evaluation of additional empirical constants. The basic model was also modified by Leahey (1969), who extended its use to areas downwind of a city by the addition of several heat sinks. The new model was used by Leahey and Friend (1971) and Leahey (1972) to study sulphur dioxide distributions in New York City (NYC), where it gave excellent agreement with observed mixing depth values (Figure 9). Non-planar topography was added to the modified model by Henderson-Sellers (1980).

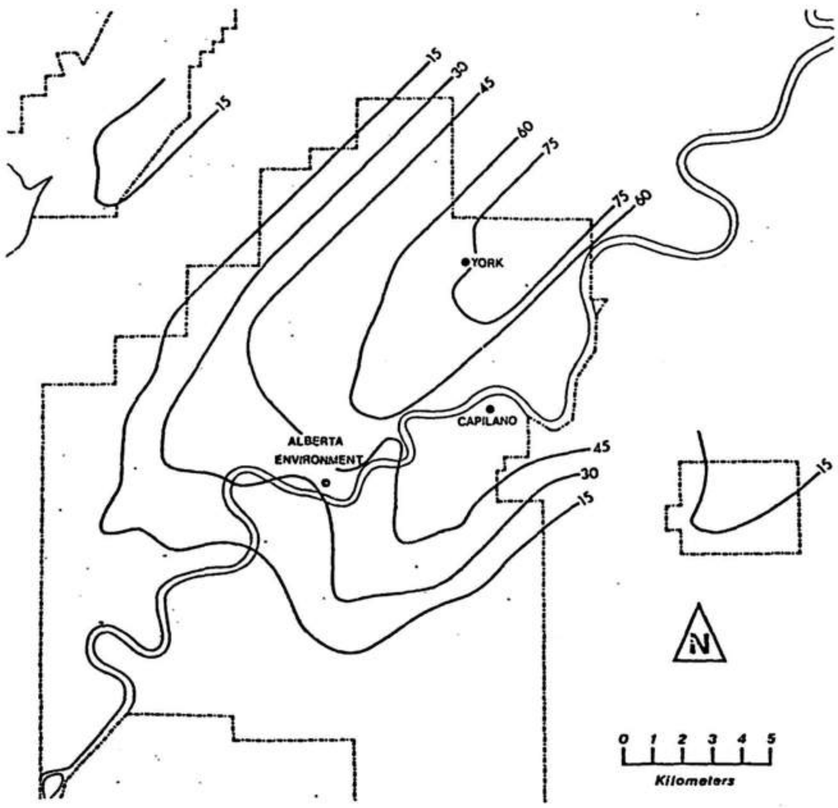

Figure 8. Predicted mixing depths (m) over the city of Edmonton on a day with a SW wind of 2 m s^{-1} (from Leahey, 1975).

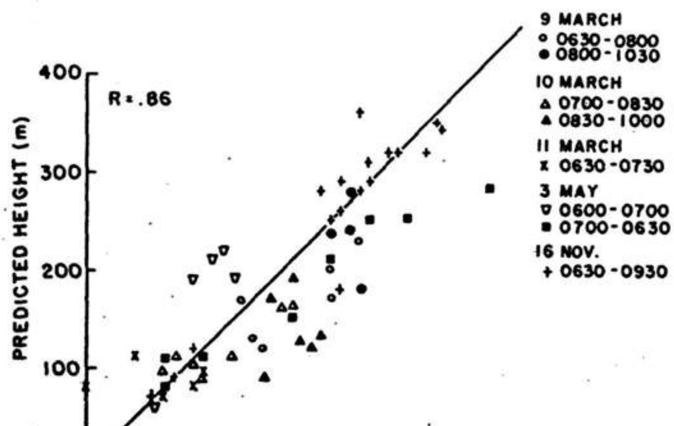

Figure 9. Observed vs predicted depths of the mixing layer (from Leahey and Friend, 1971).

Advective integral models are useful in estimating spatial variations in the effects of urbanization on the nocturnal PBL; they do not require much computer power. For more detailed studies of the nocturnal PBL, and for studies of the daytime urban PBL, it is necessary to use dynamic differential models.

2.2.3 Dynamic differential models

Dynamic models over inhomogeneous terrain, e.g. shoreline valley, or urban areas, obtain solutions to the basic PBL equations; however, (15) is expanded to:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + w\frac{\partial}{\partial z} + \frac{\partial}{\partial x} K_x \frac{\partial}{\partial x} + \frac{\partial}{\partial z} K_z \frac{\partial}{\partial z} \qquad (17)$$

for two-dimensional, slab symmetric cases and to:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} + \frac{\partial}{\partial x} K_x \frac{\partial}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial}{\partial z} \qquad (18)$$

for three-dimensional cases. In addition, the incompressible form of the equation of continuity is generally used to obtain the distribution of w:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \ . \qquad (19)$$

The first solutions to the two-dimensional basic urban PBL equations were analytical solutions to the simplified linearized equations (e.g., Gold, 1956; Findlay and Hirt, 1969; Vukovich, 1971, 1973, 1975; Olfe and Lee, 1971).

The first two-dimensional, finite-difference solution to the basic urban PBL equations was obtained by Delage and Taylor (1970) for urban breeze development in an otherwise calm situation. Similar two-dimensional solutions to the basic urban PBL equations for non-zero regional flows were obtained by McElroy (1971, 1972 a, b, 1973), Wagner and Yu (1972), Yu (1973), Lee and Olfe (1974), Yu and Wagner (1975), and Welch *et al*. (1978).

The two-dimensional basic equations were transformed into the vorticity mode by Yamada and Meroney (1971), Meroney and Yamada (1971, 1972), and Yamada (1972). Their vorticity (i.e., the y-component of the total vorticity) had the form:

$$\zeta = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial z} . \tag{20}$$

The hydrostatic form of ζ was used in the two-dimensional, finite-difference models of Bornstein (1972a, b, 1975), Gutman (1974), Gutman and Torrance (1975), Bornstein and Tam (1977), and Bornstein and Runca (1977):

$$\zeta = \frac{\partial u}{\partial z} , \tag{21}$$

where ζ is predicted from:

$$\frac{d\zeta}{dt} = \frac{-g}{T_m} \frac{\partial T}{\partial x} + f\frac{\partial v}{\partial z} . \tag{22}$$

Equation (22) replaces (9), but the main advantage of the vorticity formulation is elimination of p from the system of equations.

Extension into two-dimensions requires specifications of lateral boundary conditions, horizontal diffusion coefficients, computational grid, and finite-difference advection scheme. The most commonly used lateral boundary condition is that of zero horizontal gradients, i.e. the one-dimensional homogeneous terrain solution. Hydrostatic models only allow one vertical boundary condition on w, i.e. zero w at the surface; however, some models are overspecified as they additionally assume zero w at the model top.

The main use of horizontal diffusion coefficients is as numerical smoothers to remove "computational noise", especially during unstable daytime periods. Some models assume constant horizontal coefficients, while others specify them as functions of the grid spacing and wind shear.

Computational grids can define all parameters at the same grid locations or variables can be staggered, i.e., wind components on cube faces perpendicular to their flow direction so they represent average inflow and outflow rates and thermodynamic quantities at grid volume centres so they represent volume averages. Staggered grids generally give better physical representations to finite-differenced quantities.

Choice of an appropriate finite-difference advection scheme is difficult, as the various schemes can produce non-linear instability, have large numerical diffusion, be non-conservative, and/or be non-transportative (MacCracken and Bornstein, 1977). Some of these problems are very important in certain applications, e.g., non-conservative schemes can produce negative pollutant concentrations.

Results generally show that two-dimensional, finite-difference PBL models are capable of reproducing observed features of the urban PBL. For example, the model of McElroy (1973) accurately simulated the thermal structure of the nocturnal PBL in and around Columbus, Ohio (Figure 10). Likewise, the model of Bornstein (1975) reproduced deceleration due to increased surface roughness at the upwind urban edge, urban heat island-induced maximum wind speed at the downwind urban edge, and weakened near-surface return flow downwind of the city (Figure 11).

Two-dimensional, finite-difference models are better than one-dimensional, finite-difference models, as they include effects of horizontal temperature gradients in producing vertical circulations, as seen in (22), as well as horizontal and vertical advective effects; however, such models are only completely valid for infinitely-long discontinuities, such as long straight shorelines. Since cities are not infinitely long, three-dimensional models are necessary to reproduce some urban meteorological effects, e.g., changes in wind flow direction.

The first three-dimensional heat island model was that of Black et al. (1971), a steady state analytical model of the flow over a heated industrial area in the presence of an imposed wind.

The first three-dimensional, finite-difference urban PBL model was that of Atwater (1974, 1975) and Atwater and Pandolfo (1975). The latter was a simulation of a hypothetical arctic city surrounded by tundra. Results showed stronger arctic summer daytime heat islands than generally found in mid-latitude cities.

A three-dimensional, finite-difference urban PBL model of flow over St. Louis was developed by Vukovich et al. (1976). It reproduced many features of the observed horizontal distributions of urban temperature, horizontal velocity, and vertical velocity (Figure 12). Model sensitivity tests by

Vukovich and Dunn (1978) indicated heat island intensity and boundary layer stability to be the dominant factors in development of heat island circulations.

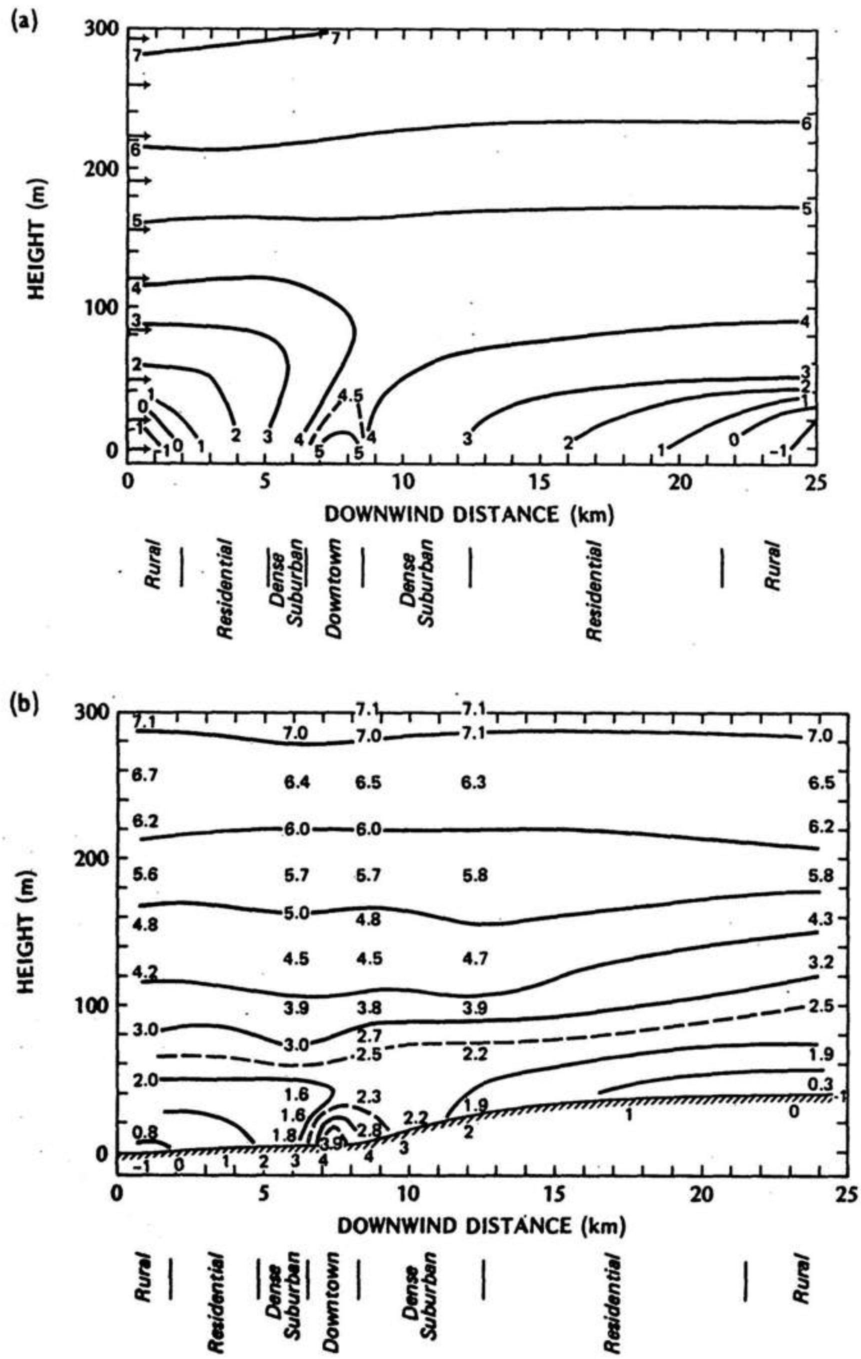

Figure 10. (a) Simulated, and (b) observed temperature structure across Columbus, Ohio near sunrise on March 23, 1969. Arrows on vertical axis of (a) indicate computation heights (from McElroy, 1973).

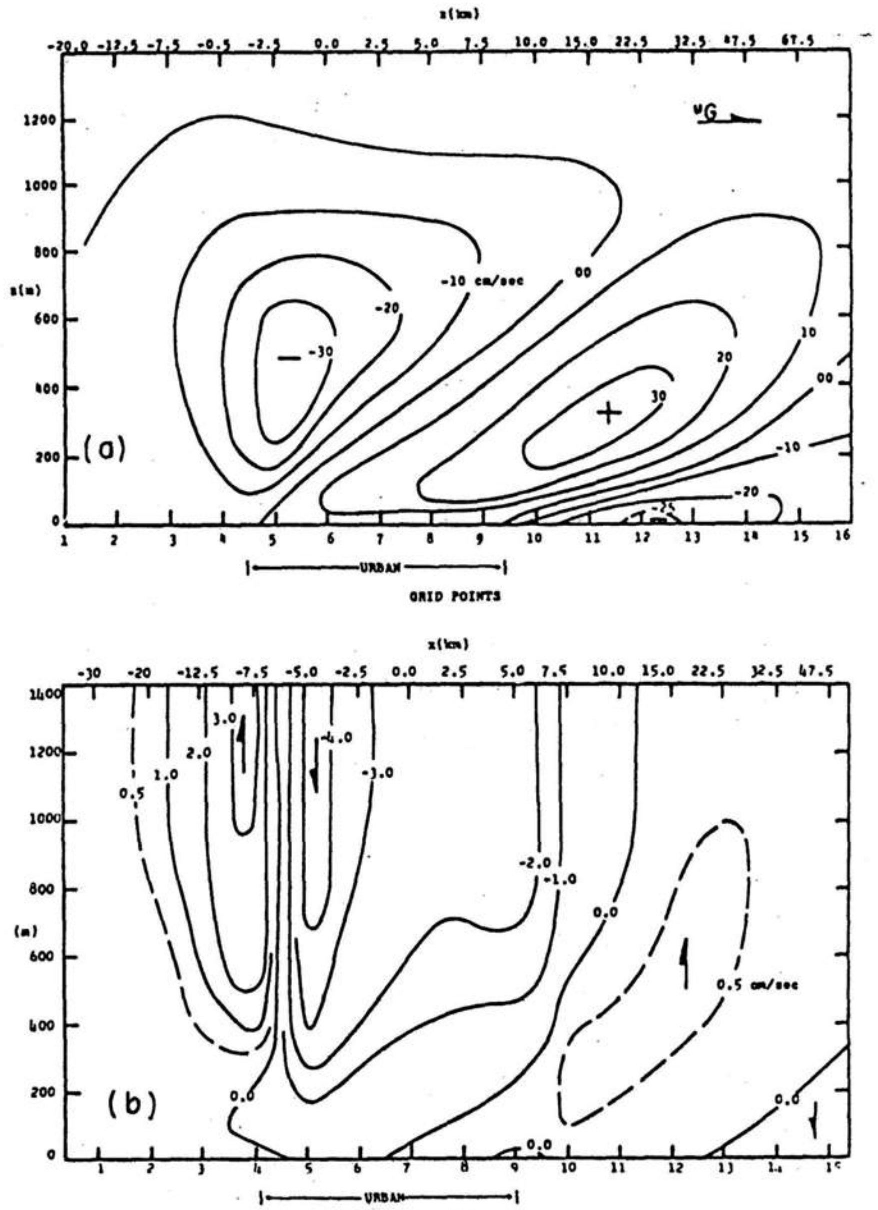

Figure 11. Departures of horizontal (a) and vertical wind field (b) (cm sec^{-1}) from an undisturbed flow during nocturnal conditions over an urban heat island (from Bornstein, 1975).

The model then studied interactions between an intense heat island circulation and ozone distribution (Vukovich et al., 1979). Maximum ozone levels were predicted to occur in the zone of maximum heat island convergence. The model was further tested against four days of METROMEX meteorological data by Vukovich and King (1980). Results showed general agreement with observed meteorological parameters, but the model formulation was not able to accommodate changing synoptic conditions.

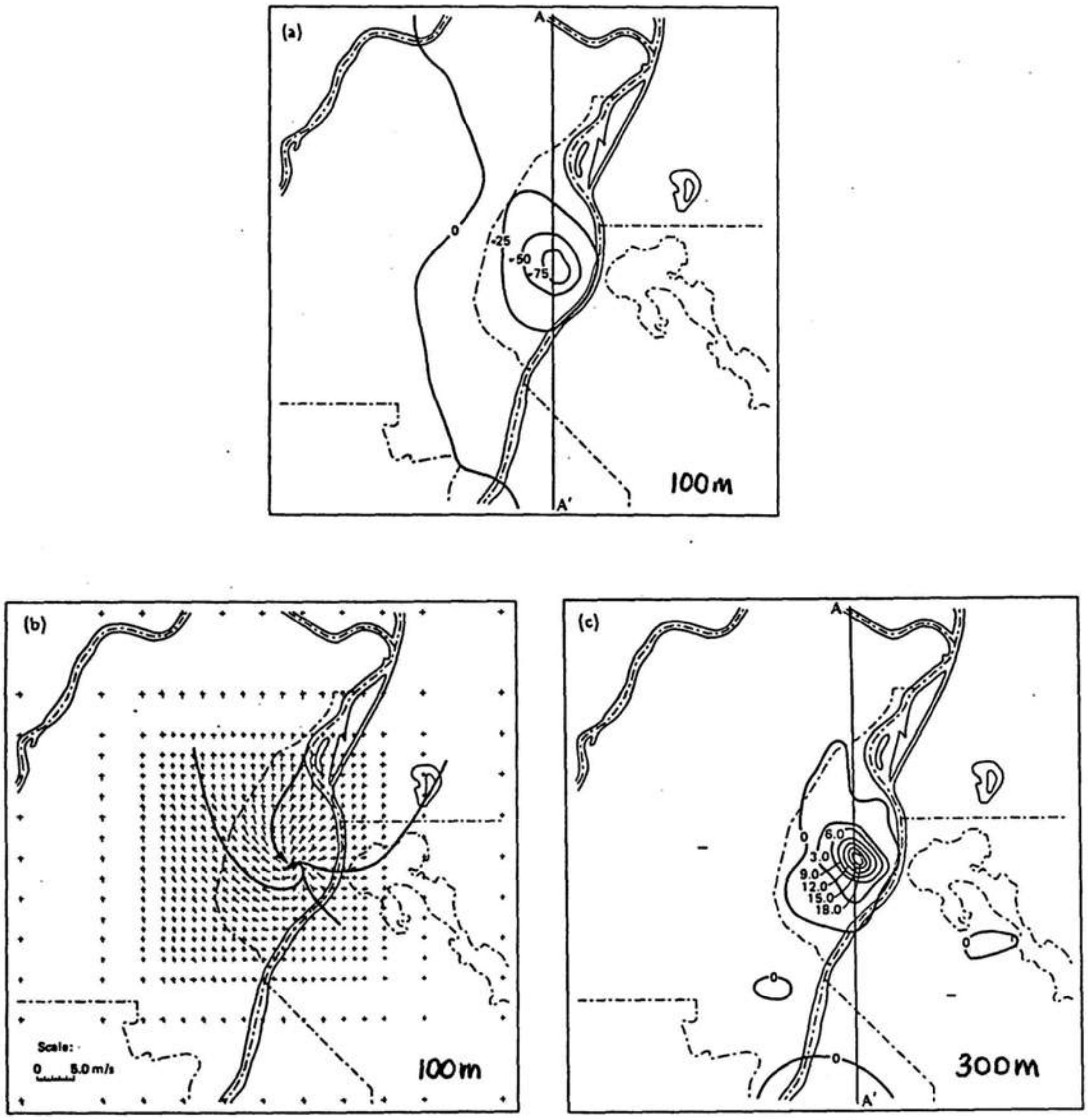

Figure 12. (a) Urban heat island (^{o}C), (b) horizontal flow, and (c) vertical velocity (cm/s) over St. Louis (from Vukovich et al., 1976).

The three-dimensional, finite-difference University of Virginia mesoscale model was used by Hjelmfelt (1980, 1982) to simulate effects of St. Louis on mesoscale airflow. Results were consistent with the hypothesis that observed cloud and precipitation anomalies over St. Louis are related to perturbations in PBL dynamics due to the urban heat island and surface roughness.

Three-dimensional, finite-difference models have also been applied to coastal urban areas to study interactions between urban and coastal mesoscale processes. The primitive equation model of Takano (1983) for the metropolitan Tokyo area utilized a "level 2" second order turbulence closure from Mellor and Yamada (1974) to obtain atmospheric K-profiles. In this formulation K_z-values are related to the x- and y-components of the stress by the following algebraic equation:

$$\frac{\tau_x}{\rho_m}\frac{\partial u}{\partial z} + \frac{\tau_y}{\rho_m}\frac{\partial v}{\partial z} - \frac{g}{T_m}\frac{Q_H}{c_p \rho_m} = \varepsilon^*, \qquad (23)$$

in which shear and buoyancy production of turbulent kinetic energy are equated to molecular dissipation.

The three-dimensional, finite-difference coastal urban PBL model for the NYC area of Bornstein _et al._, (1985) is an expansion of the two-dimensional URBMET vorticity model of Bornstein (1975). It utilizes two hydrostatic vorticities, each of which is predicted from an equation similar to (22). The three velocity components are obtained from two streamfunctions by:

$$u = \partial\psi/\partial z \qquad (24a)$$

$$v = \partial\phi/\partial z \qquad (24b)$$

$$w = -\left(\frac{\partial\psi}{\partial x} + \frac{\partial\phi}{\partial y}\right), \qquad (24c)$$

where the stream functions are related to the predicted vorticities by:

$$\xi = \frac{\partial v}{\partial z} = \frac{\partial^2\phi}{\partial z^2} \qquad (25a)$$

$$\zeta = \frac{\partial u}{\partial z} = \frac{\partial^2\psi}{\partial z^2}\,. \qquad (25b)$$

The model utilizes either a first order or a "level 2.5" second order turbulence closure from Mellor and Yamada (1974) in which K_z-values are related to total turbulent kinetic energy e, predicted by:

$$\frac{de}{dt} = K_M \left(\frac{\partial U}{\partial z}\right)^2 - \frac{g}{T_m} K_H \frac{\partial\theta}{\partial z} - \varepsilon^*. \qquad (26)$$

The model also has a soil sub-layer in which soil temperature and moisture are computed using the model of Santhanam (1980). This allows for simultaneous prediction of surface temperature and moisture from surface heat and moisture balance equations by a double interactive technique.

The model has been applied to NYC. The period of 9 March 1966 was selected for simulation because of a sea breeze frontal passage and because observed SO_2 concentrations were high. In addition, a number of meteorological and concentration analyses had been performed for this day. The simulation began at 1800 EST on the previous day to establish background concentrations and meteorological fields.

The geostrophic wind on this day was specified as northwesterly at 3 m s^{-1}. Simulated surface winds over the city were light (about 1.5 m s^{-1}) and northwesterly until about 1200 EST, when a sea breeze front came onshore bringing southerly winds.

The front moved fast, and by 1400 EST it had passed much of the city (Figure 13). Two hours later it achieved its maximum inland penetration, and the distribution of near surface (37.5 m) winds at this time (Figure 14) shows minimum speeds at the frontal location. The maximum horizontal speed is, as expected, located just offshore.

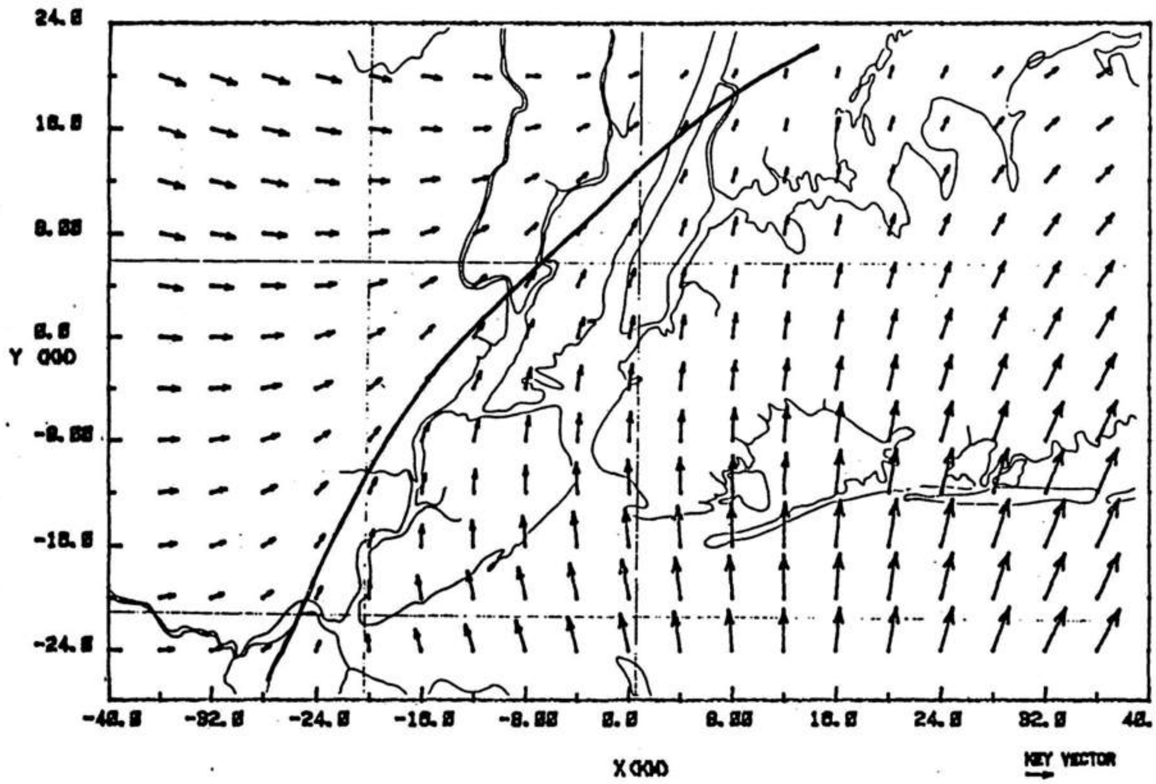

Figure 13. Predicted horizontal wind velocity at 37.5 m at 1400 EST on 9 March 1966. Solid line is sea breeze front and key vector is 1.22 m s^{-1}.

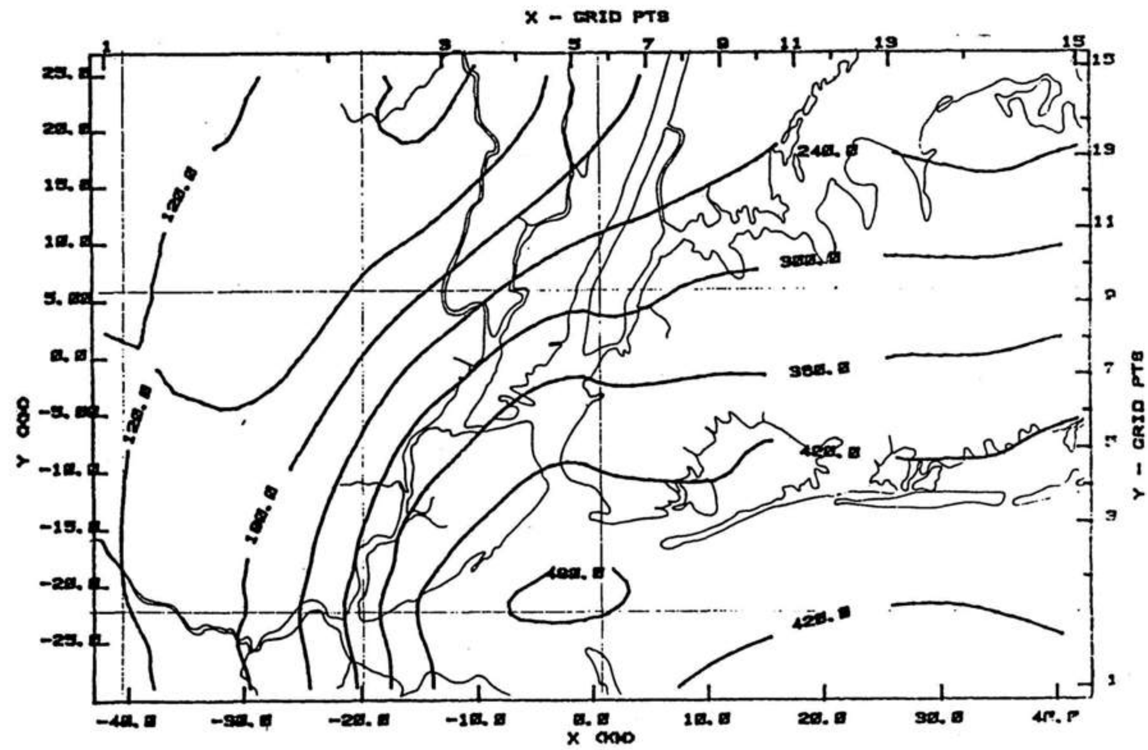

Figure 14. Predicted horizontal wind speed (cm s^{-1}) at 37.5 m at 1600 EST on 9 March 1966.

The spatial distribution of the mesoscale potential temperature perturbation at 1600 LST at a height of 37.5 m (Figure 15) shows a sharp gradient along the coastline. This feature is due to the onshore advection of cool marine air behind the front. This air modifies the predicted surface temperature field via its influence on the surface energy budget.

The figure also shows a slight (few tenths of a degree Celsius) urban heat island over Manhattan (along the 3 K isotherm). This value is typical of the small daytime urban heat island. Finally, the figure shows the warming effects of subsidence over the water region southeast of the city. Surface temperatures over water grid points were held constant in the current simulation; thus the warming in Figure 15 in this region is not due to upward diffusion, but to downward motion associated with the horizontal along-streamline speed-divergence evident in this region in Figure 14.

Comparison with observations showed the PBL model reproducing most of the qualitative features of the observed sea breeze flow on this day; however, the modelled sea breeze front did pass through the area more quickly than was observed.

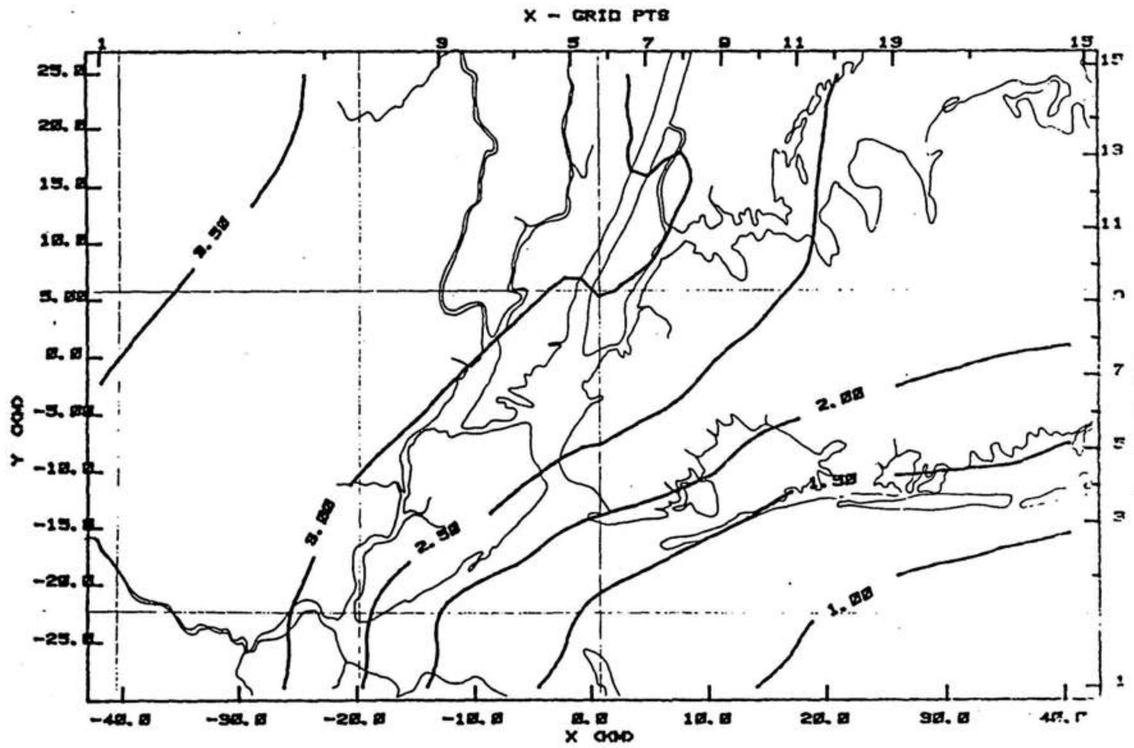

Figure 15. Predicted mesoscale temperature perturbations (K) at 37.5 m at 1600 EST on 9 March 1966.

Post-analysis has identified two reasons for this too rapid movement. The first is the above-mentioned underestimation of the strength of the opposing geostrophic flow. The second is the overestimation of the solar insolation at the top of the PBL, which produced too great a surface horizontal temperature gradient. Future simulations will correct these input errors.

The pre-frontal northwesterly flow produced advection of polluted air to the areas southeast of the high emission regions in Manhattan and the south Bronx (Figure 16). Passage of the sea breeze front decreased surface concentrations in southern coastal NYC locations, as the marine air was initially less polluted than the older urban air (Figure 17).

The marine air became increasingly polluted by urban emissions as the front moved over the city and thus the front brought increasing surface concentrations to the downwind areas on both sides of the Hudson River. By 1800 EST the concentration maximum in mid-Manhattan had been displaced about 7 km to the northwest from its pre-frontal position at 0800 EST. The downwind displacement of the polluted air mass extended throughout the PBL.

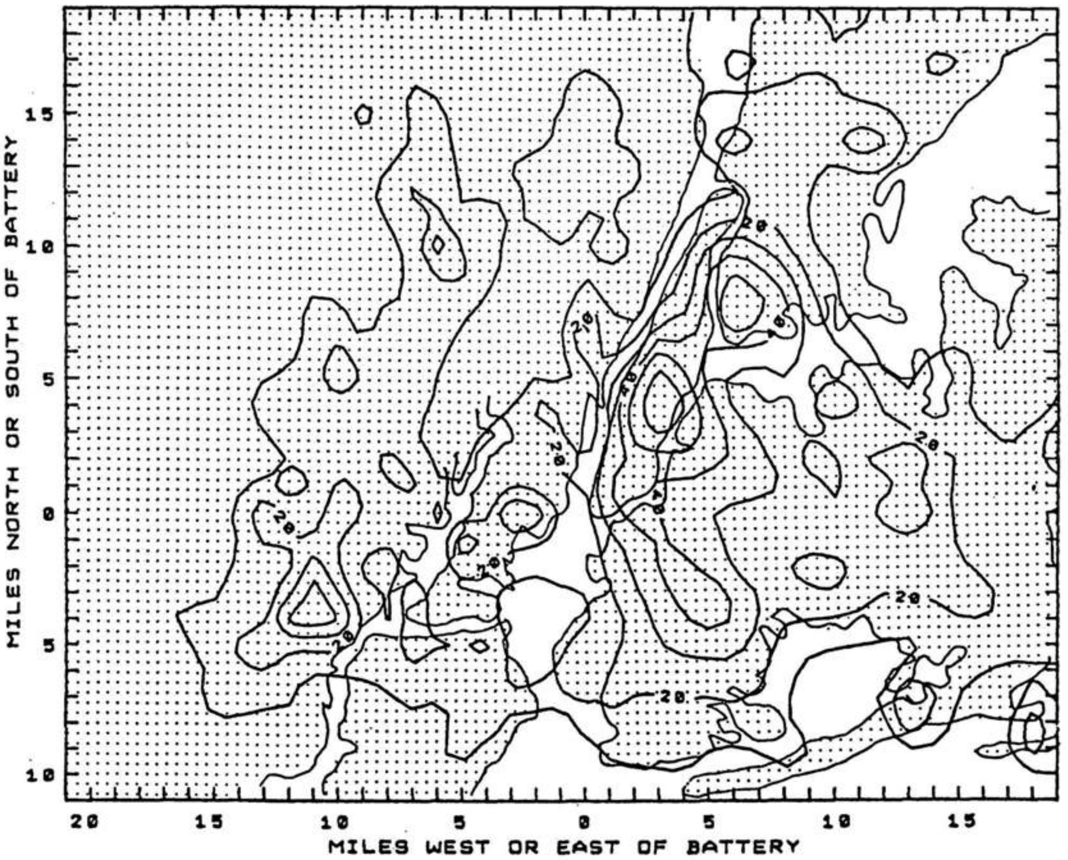

Figure 16. Predicted surface sulphur dioxide concentrations (pphm) at 0800 EST on 9 March 1966.

While three-dimensional, finite-difference models provide better insights into the complex urban meteorological processes than the other numerical models described above, they require the greatest amount of computer power, i.e., they are the most expensive numerical models. There are, however, techniques to reduce these costs, e.g., variable horizontal grid spacings (greatest resolution in areas of maximum interest) allows for fewer grid points.

Use of constant integration time steps Δt throughout an entire simulation is unnecessarily expensive as nighttime stable conditions do not require as small a Δt as do unstable daytime periods. This is true because the process requiring the smallest Δt is vertical diffusion, i.e.,

$$\Delta t = \frac{\Delta z^2}{\partial K_z} , \qquad (27)$$

where K_z is large during unstable periods. Thus Bornstein and Robock (1976) show computational time reduced by use of a Δt which varies with time, and by use of a larger Δt for advection than for diffusion processes. Use of variable vertical grid spacings (minimum spacings near the surface) and use of an analytical SBL also reduce computational grid points.

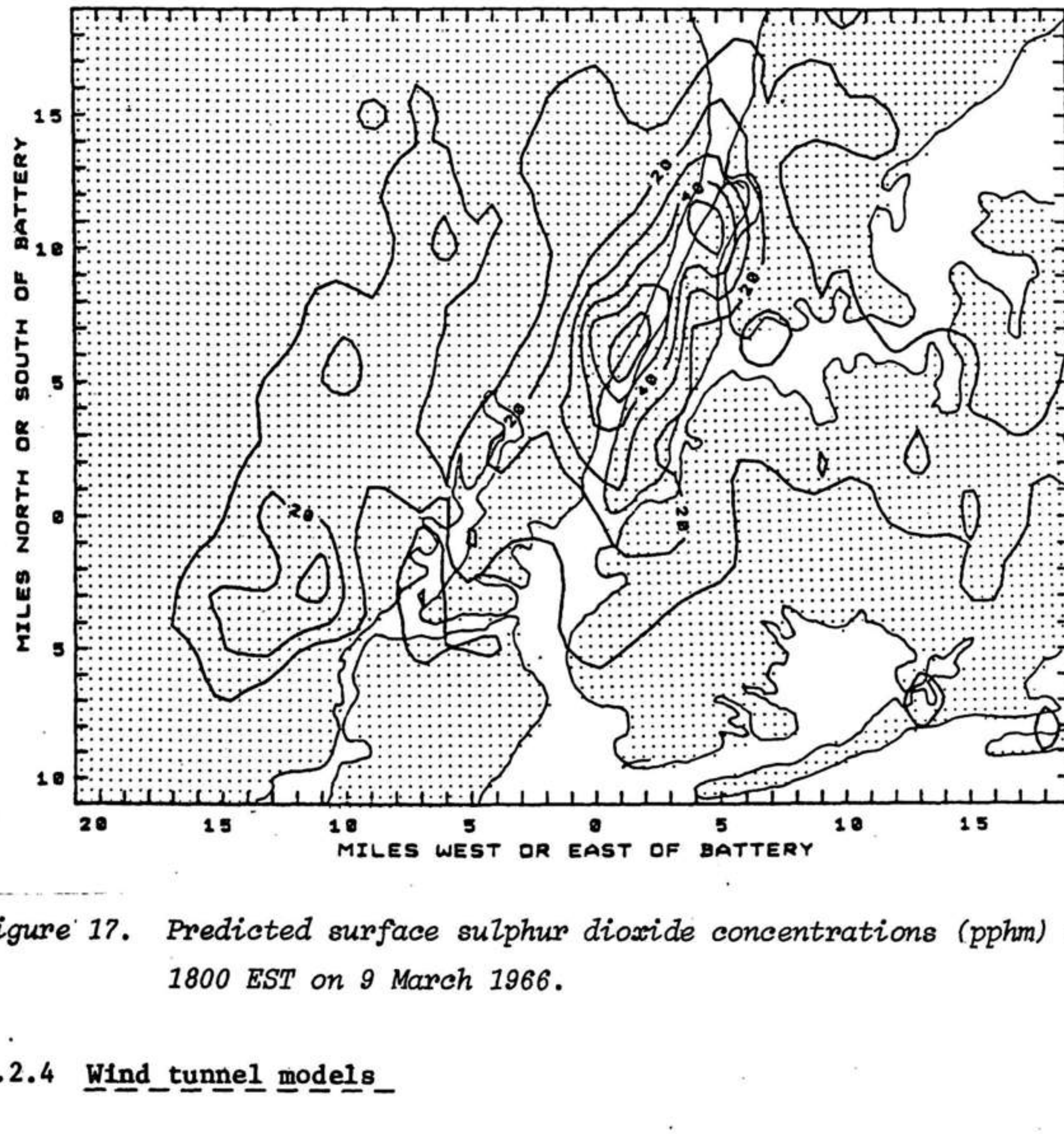

Figure 17. Predicted surface sulphur dioxide concentrations (pphm) at 1800 EST on 9 March 1966.

2.2.4 Wind tunnel models

An early approach to urban boundary layer modelling was the outdoor 1:1000 scale model of Davis (1968) and Davis and Pearson (1970), used to simulate flow over Ft. Wayne, Indiana. Hot wires and roughness elements were embedded in the ground, and measured temperatures to heights of 1.5 m within the model were compared, via Monin-Obukhov parameterization, to observations on a 300 m urban tower. Moderate success was claimed in reproducing stability variations across the urban complex.

Wind tunnel urban PBL simulations with adiabatic layers were carried out by Counihan (1971, 1973, 1975) and Cook (1973, 1974), but the most extensive wind tunnel scale modelling efforts of the urban PBL have been conducted at the Colorado State University. This facility allows stratified boundary layers to be simulated (Yamada and Meroney, 1971; Meroney and Yamada, 1971, 1972; Yamada, 1972; Meroney et al., 1973; SethuRaman, 1973, 1976; Cermak, 1970, 1975; SethuRaman and Cermak, 1974a, b, 1975). Electrical heaters simulate heat island effects and aluminum blocks form street-block patterns. Passive smoke allows flow visualization, while mean wind speed and turbulence are monitored with temperature-compensated hot-wire probes. Many of these studies were carried out in conjunction with two- and three-dimensional finite-difference modelling studies.

Bennett and Saab (1982) describe the new meteorological wind tunnel facilites at the École Centrale de Lyon, the Hochschule der Bunderswehr in München and the National Institute for Environmental Studies in Japan. They also describe the similarities that must be achieved in a wind tunnel, i.e., topography, Reynolds number, Prandtl number, Rossby number, Richardson number, and boundary conditions.

They conclude that wind tunnel simulations are tempting, given the difficulties associated with numerical models; however, they also conclude that wind tunnel modelling has problems associated with achieving the required similarities.

3. CONCLUSION

A review of the classes of urban climate models has been presented for both the urban canopy layer and urban boundary layer. The basic workings of each type of model has been reviewed with respect to assumptions, equations, parameterizations, boundary conditions, numerics, grids, and initial conditions.

The most useful of the numerical urban models, in increasing order of computer power requirements, are the advective integral models, one-dimensional energy balance models, and the two- and three-dimensional dynamic differential models. Wind tunnel scale models for stratified flow situations are also useful by themselves or in conjunction with numerical models.

Although these models are capable of reproducing many of the observed characteristics of urban meteorological fields, certain areas need additional development. One of these is prediction of the evolution of the daytime urban mixing depth, which grows due to convergence of sensible heat, both from below due to thermal convection and from above due to penetrative convection. Recent theoretical advances in predicting $h_i(t)$ have been incorporated into analytical urban PBL models only by Barnum and Rao (1974, 1975) and Carlson and Boland (1978).

Many non-urban, two- and three-dimensional finite-difference PBL models utilize coordinate transformations to simulate topographic effects on mesoscale flows. This technique needs to be incorporated into future urban PBL models so they can be applied to cities with significant topographic features.

Effects of changing synoptic conditions on urban meteorological distributions cannot currently be simulated properly with existing PBL models. One method of dealing with this problem is to utilize time- and/or space-varying upper boundary conditions in the models. These variations can be specified for typical cases (as was done by Reichenbächer and Bornstein, 1979) or can be obtained from output from larger weather forecasting models.

Another weak point of urban PBL models is that they do not fully utilize knowledge gained from urban canopy layer models. Better use of this formation would produce better lower boundary conditions for the PBL models.

Remote sensing information from aircraft and satellites on land-use patterns would also aid in development of better lower boundary conditions for urban PBL models. Utilization of such data has already started, e.g., see the work of Ellefsen *et al.* (1976), Carlson *et al.* (1977, 1981), Dabberdt and Davis (1978), and Goldreich (1984).

Finally, comparison of predicted and observed values is encouraged for an increased confidence in modelling as an urban planning tool. Statistical techniques for model evaluation are becoming more formalized and standardized (Fox, 1981). Such evaluation, of course, requires continued use of existing urban data bases such as the RAPS, METROMEX, and NYC/NYU (Bornstein et al., 1977 a, b) sets. In addition, it requires collection of new data in coordination with the increasing initialization and verification requirements of urban modellers.

The roles of urban models in city planning are many. They include analysis of factors creating existing urban meteorological and climatological patterns. This is accomplished by model simulations carried out with one or more urban characteristics removed or modified within the model, a situation that cannot be duplicated in the real world. In addition, models can be used in planning future urban developments in existing, or even new, cities. Different building materials and/or building configurations can be tested in the computer to help select those which will create a new climate that will be more (and not less) healthy for future urban dwellers.

Application of urban models to tropical regions of the globe will require the collection of the necessary initialization and evaluation meteorological observations. In addition, information will be needed on thermal and radiative properties of tropical anthropogenic and natural surfaces.

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APPENDIX A. List of Symbols

Variables and Constants - Roman alphabet

a_1 to a_3	constants
A	surface albedo
c	contaminant concentration
c_p	specific heat of air at constant pressure
C	contaminant flux
e	turbulent kinetic energy
E	evaporation
f	Coriolis parameter
g	acceleration due to gravity
h_i	height of mixed layer
H	building scale-height
I_o	solar constant
k	conductivity
k_o	von Karman constant
K	diffusivity
K*	net surface solar flux
L	latent heat of vaporization
L↑, L↓	upward and downward directed long-wave radiation, respectively
N	cloudiness
p	pressure
q	specific humidity
Q_E	vertical flux of latent energy
Q_F	anthropogenic heat production
Q_H	convective sensible heat flux
Q_G	vertical soil heat flux
Q*	net radiation
R	Ideal Gas constant
t	time
T	temperature
u, v, w	E-W, N-S, and upward components of velocity, respectively
U	horizontal wind speed
W	building scale-width
x, y, z	E-W, N-S, and vertical coordinates, respectively
Z	solar zenith angle

Variables and Constants - Greek Alphabet

α	stable air potential temperature gradient
ε	emissivity
ε^*	dissipation of turbulent kinetic energy
θ	potential temperature
ξ, ζ	x and y components of hydrostatic vorticity, respectively
ρ	density
σ	Stefan-Boltzmann constant
τ	Reynolds stress
τ^*	transmissivity
ϕ, ψ	x and y components of stream function, respectively
ψ^*	urban sky view factor

Subscripts

$( )_c$	contaminant
$( )_g$	surface
$( )_H$	heat
$( )_m$	PBL average
$( )_{max}$	maximum value
$( )_q$	moisture
$( )_s$	soil
$( )_x$	x-direction
$( )_y$	y-direction
$( )_z$	z-direction

Others

$\Delta( )$	difference

PART B: APPLIED URBAN CLIMATE (PROBLEMS AND SOLUTIONS)

THE PLANNING AND MAINTENANCE OF URBAN SETTLEMENTS TO RESIST EXTREME CLIMATIC FORCES

Ian R. Davis

Disasters and Settlements Unit, Department of Architecture
Oxford Polytechnic, Oxford OX3 OBP, UK

1. THE VULNERABLE URBAN ENVIRONMENT

> 'It is unpleasant for architects to think about hurricanes, earthquakes and fires in relation to our work. Architecture carries with it the idea of permanence which makes designing for disasters seem almost contradictory...'

However, not all designers operating in the man-made environment have adopted such a blinkered approach:

> 'The designers of the great ocean liners were less confused. The ships functioned as national symbols but also were designed to provide transportation, shelter and life support under a broad variety of environmental conditions. Finally, they were designed to sink, at which time the delicately scaled frieze of lifeboats which decorated the superstructure became functional.' (Hartram, 1980)

This paper will attempt to examine how the design and maintenance of the built environment to resist extreme climatic forces can be significantly advanced, so that the design of safe buildings will become as commonplace as the design of every ship to resist the forces of wind and water. This is an urgent concern since the evidence is clear that urban environments are becoming increasingly vulnerable to climatic hazards with millions of lives as well as property and incomes at risk from damage or destruction. So, prior to considering a balanced strategy for risk reduction, it is necessary to briefly consider some of the elements that contribute to the vulnerable urban environment.

CITIES AND EXTREME CLIMATIC FORCES

1.1 Poverty and Vulnerability

By definition, any analysis of urban climatology in tropical areas must include a consideration of the impact of extreme climatic forces. It has been calculated that about 95% of all disaster related deaths occur among two thirds of the World's population that occupy developing countries (Burton et al., 1978). For example, the average Japanese disaster kills 63 people, whilst the average Peruvian death toll is 2,900. The 1974 Hurricane Fifi killed over 4,000 in Honduras whilst only 49 when Darwin, Australia, was devastated in Cyclone Tracy (Timberlake, 1984). These comparisons from a recent press briefing by EARTHSCAN are rather simplistic and fail to explain the reasons for the variations of casualties, and the diverse forms of hazard; however a broad pattern is suggested in the figures which is well substantiated by the available statistics.

1.2 Vulnerability, Population Growth and Urbanisation

Turning to the focus of this conference, statistics are notoriously imprecise as to the exact proportion of these casualties who come from tropical countries but it is certain that the overwhelming majority are in this category. Regarding the urban context, the other major emphasis of this conference, it is less clear how many of these casualties lived in towns or cities. However, given the scale of urbanisation it is becoming increasingly evident that urban areas are now the prime vulnerable context for extreme climatic hazards.

A further factor that results in the creation of the vulnerable environment concerns population growth. Ludo Van Essche, an architect/planner working on the staff of the Office of the United Nations Disaster Relief Co-ordinator (UNDRO), has recently written:

> 'The rapid growth and spread of population in hazardous areas is steadily contributing to the monetary costs of disasters in terms of lives lost and damage to property and investment. Most developing countries double their populations every 20-25 years (assuming national population growth rates of 2-3%) while the urban population in these countries double every 12-15 years (assuming urban growth rates of 4-7%).'

Van Essche then related the population growth to slums and squatter settlements where the rate of expansion is larger than the normal urban rate:

> 'In settlements such as these there is a doubling of population every 5-7 years. Densities are usually very high - up to 100,000 persons per km^2 and more. Even the average densities for urban areas as a whole are high enough to cause concern.' (Van Essche, 1984).

This is a paradoxical situation since prior to 1930 disasters (such as droughts and epidemics) were some of the major regulators of population increase. However, due in part to rapid improvements in medical care these increases are occurring on a worldwide scale, as became apparent in the United Nations World Population Conference in Mexico City in July 1984.

One of the most significant findings of the conference was that the growth in the World population will largely occur in the urban areas of developing countries. Many of the projections of the UN Conference were for cities in areas prone to tropical cyclones and severe flooding (Table 1).

TABLE 1. *Population Projections for six disaster prone cities (Fox, 1984).*

City	Population in 1984	Projected Population in 2025	Extreme Climate Risks
Karachi	7 million	20-30 million	Cyclone
Jakarta	8 million	20-30 million	Cyclone
Calcutta	11 million	20-30 million	Cyclone/Flooding
Delhi	7 million	20-30 million	Flooding
Dacca	3 million	20-30 million	Cyclone/Flooding
Shanghai	12 million	20-30 million	Flooding

Taking two highly disaster prone Developing countries within tropical zones, India is currently projected to expand its current urban population from 180 to 660 million by 2025, whilst the urban population of Indonesia is likely to grow from 35 to 130 million.

The implications of this rapid increase of urban populations in the coming 30 years are that families migrating from rural areas to disaster-prone towns and cities will inevitably be obliged to live on the least favourable land which in many instances will be in unsafe locations such as flood plains, and steep slopes prone to landslides and severe erosion. Thus the vulnerability of populations is closely related to population growth and urbanisation.

1.3 Vulnerability and the Location of Settlements

It has long been apparent that societies live in locations which relate primarily to their economic livelihood, and for poor communities this relationship is critical in terms of their survival. This paper is concerned with vulnerable settlements at risk from flooding, whether river flooding or coastal surges resulting from high winds. It is also concerned with the impact of high winds such as hurricanes, cyclones and typhoons (all of which are the same type of phenomena, but differently named according to varied geographical regions). It does not refer to the much higher intensity tornado-force winds since the forces are too great for effective preventive design of buildings. Accompanying high winds there will inevitably be intense rainfall which frequently results in flooding; thus river and coastal flooding and high winds are closely interconnected hazards.

In considering problems of vulnerability to high winds and flood risk, it becomes apparent that the areas under scrutiny are river valleys, estuaries and coastal belts subject to cyclonic wind forces. Within such areas there will always be very attractive opportunities for work, for example in the river valleys, there will often be the attraction of water supply for field irrigation and domestic uses as well as the advantages of good drainage and fertile soil conditions. In addition, where rivers are navigable the opportunities for communication might be very attractive to residents and the river itself may be a food source; a key economic factor attracting fishing communities to its banks. Then in the case of coastal regions, there are similar opportunities for fishing and coastal trade as well as easy communications, where there is an absence of road or rail links. In estuary regions soil conditions may be very fertile and these are frequently some of the most prosperous agricultural regions within a country. In terms of urban environment it is clear that a large proportion of the World's great cities are either in vulnerable coastal locations, or else on the banks of major rivers subject to periodic flood impact. It has been calculated that 500 million (about 1 out of every 9 people in the world) live in riverine and coastal flood plains.

Over the centuries communities living in such regions have learnt to adapt to the extreme climate forces to some degree, but this adaptation is determined by the frequency of the hazards and also the general economic level of the communities, as to whether they have the financial resources to make changes which might cost them a considerable amount of their limited money. In subsistence economies there may not be surplus to pay for such protection. However, it is apparent that unlike earthquakes (where the return period is normally so infrequent in a given area that adaptation is most unlikely to occur), there is generally some level of adaptation to risk in the case of high winds and flooding. Such adaptation may be rudimentary and there are frequently unrecognized opportunities for the added protection of such settlements.

Returning to the fact that it is the poorest people that are at risk it can be assumed that disasters are a symptom of poverty, or put another way, vulnerability is closely related to the deprivation of communities from the basic resources within industrialised societies. This is an important factor in considering the question of protection of these settlements, since all too frequently the attitude of public authorities, governments and some UN agencies has been to place reliance on multi-million dollar public works projects, such as the building of dams, overflow canals, etc. But these measures are frequently undertaken with a priority concern to protect property rather than lives, and they do not address the problem of literally millions of people living in marginal peri-urban communities who are exposed to climatic risks. Experience has shown that there is much that can be done at lower cost; at community levels for the protection of these people and some of the major areas of opportunity for protective action will be identified here.

1.4 The Impact of Extreme Climatic Forces on Buildings and Settlements

The impact of extreme climate on the built environment is dependent on three key variables:

- Firstly, the severity of the hazard in terms of intensity. This will be closely related to the frequency (or return period) of recurrence.
- Secondly, the spatial distribution and density of population in the affected area.
- Thirdly, the nature and condition of the property exposed to the hazard in terms of settlement location, building configuration and constructional techniques.

Both the second and third variables are closely related to the overall economic level of the area in question.

The techniques of how to plan settlements, and how to design buildings to resist high winds and floods are generally well known and it is not appropriate to cover them in detail in this paper (e.g. See Eaton 1980; UNDRO 1976, 1978a, b, 1979; NBS 1977). However, it is clear that whilst there is a well developed body of usable knowledge on wind resistant construction techniques, there remains, as yet, inadequate coverage of flood resistant building or on post-flood repair or drying-out of buildings. This omission is serious, and forms an important target for research work in the coming decade.

Figure 1 indicates the impact of climatic hazards on various sections of a given community.

SECTORS OF URBAN ENVIRONMENT

CLIMATIC HAZARDS	Buildings and Settlements	Infra-Structure (roads, services, etc.)	The man-facturing economy, Industries, Factories	Loss of Life Potential
High winds	●	◑	●	○
High winds linked to coastal storm surge	●	●	●	●
Flooding: Heavy rainfall	◑	◑	○	○
Slow onset Flooding	◑	◑	◑	◑
Flash Floods	●	●	◑	●
Drought	◑ [1]	○	●	●

Key:
● Major Impact
◑ Partial Impact
○ No Impact

<u>Note</u>:
[1] In Drought situations building needs can be created due to population movements. In addition the lack of natural building materials (i.e. reeds/branches) can have adverse consequences on opportunities for building.

Figure 1. Impact of climatic hazards on various sectors of disaster-prone urban environments.

2. REDUCING RISKS TO THE URBAN ENVIRONMENT FROM EXTREME HAZARDS

2.1 <u>Levels of Protection</u>

The axiom 'Prevention is better than cure' runs through the theme of this conference, and is particularly appropriate for all aspects of pre-disaster planning. In the past fifteen years this has rapidly developed into an extensive body of knowledge with three key terms being used: 'prevention', 'mitigation' and 'preparedness'. Each indicates different types, or levels, of intervention. Few societies are able to contemplate total 'prevention' because it usually involves highly complex and costly measures. The term 'mitigation' embraces a broad spectrum of measures which are essentially protective. 'Preparedness' is a term often used to describe measures adopted in anticipation of a disaster, such as evacuation planning.

These terms may be applied to all sectors, technical or otherwise, and Table 2 indicates some of the measures falling within their respective confines appropriate to settlement planning and building design:

TABLE 2. *Pre-disaster planning.*

Description of Elements in Pre-Disaster Planning	Typical Measures in Building Sector	Effectiveness of Measures
PREVENTION	Totally safe siting and construction of buildings to resist hazard impact, relocation of unsafe settlements.	Extremely expensive in both economic and social terms.
MITIGATION	Design buildings for safe collapse. Accept that damage is inevitable but lessen damage and aim to avoid injuries.	Probably the most realistic aim for all but the wealthiest societies.
PREPAREDNESS	Tie ropes to a building's roof to withstand extreme winds. Evacuate area.	Sensible precautionary activities, but serious damage and losses will nevertheless occur.

It should be emphasized that there is some overlap in the terms and that the measures vary from broad, expensive and far-reaching changes under the 'mitigation' heading to pragmatic *ad hoc* activities under 'preparedness'. Throughout this paper the emphasis is firmly placed on mitigation rather than on Utopian dreams of total prevention, or on the more cosmetic preparedness measures. However, the objectives of mitigation may still seem a little overambitious in the light of the limited resources available in most disaster-prone countries. Therefore, there is a need in any situation to assess the risks and to define the objectives further, establishing the various degree of protection that may be hoped for in given sectors. For example, the Thames Flood Barrier was recently completed at a cost of approximately 1050 million dollars. It was designed to provide protection for the city of London against the impact of surge tides for the next 70 years - after which time it will no longer be adequate for this purpose due to the gradual rise in sea level. Were the costs and the environmental impact not deemed too high, it would have been possible to design and build the barrier to last for at least 150 years.

2.2 Removal or Reduction of Risks?

It is necessary to examine a given disaster-prone urban environment and to map the likely hazards and analyse the vulnerability. Once the risks to the various sectors at the local level have been identified, resources can be deployed in accordance with the priorities that are established. Table 3 indicates some of the measures that may be employed to reduce risks from climatic hazards.

Certain types of building will require particular attention insofar as they are habitually occupied by groups such as children (who are the future resource of any community), which merit special attention. While the loss of a family may be a tragedy for relatives, the loss of a whole class of children will be a major calamity for the entire community. Thus, all buildings of public assembly (mosques, churches, cinemas, etc., and especially schools) need to be designed, and built, to higher safety standards than private dwellings. Even within the poorest countries there will always be adequate money for public authorities to design or strengthen school buildings against extreme hazards.

TABLE 3. *Measures to remove or reduce hazards from various climatic hazards*

CLIMATIC HAZARDS (Descending order of mortality)	% of Total Natural Disasters reported in a given year	Cause of Death	Vulnerability of Houses and Settlements	REMOVAL OF RISK		REDUCTION OF RISK	
				Possible Solution	Major Difficulties	Possible Mitigation Measures	Major Difficulties
Drought	15%	Malnutrition resulting from lack of food/ water/resistance to simple infections	Overall location relative to food/water supply	Maintain supply of staple foodstuffs/ water	Logistics; market prices	Advance warning of crop failures (i.e. market price fluctuations in staple foods)	Resources to monitor drought indicators
Tropical Cyclones	20%	Drowning/ Exposure; injuries sustained when parts of buildings/trees/walls fall on people	Location of settlement adjacent to coastlines	Relocation of communities	Impossible in any general sense (may be possible at local level); location related to occupations and income levels	Cyclone shelters; evacuation policies; shelter breaks; stronger buildings	Economics, logistics, social consequences
Floods	40%	Drowning/ Exposure	Location of settlements on low-lying ground in river basins/ estuaries	Relocation of communities	Impossible in any general sense (may be possible at local level); location related to occupations and income levels	Flood control measures; evacuation policies; stronger buildings	Economics, logistics, social consequences
Other	10%	Various					

Note: The overall total percentage in the above list excludes a 15% figure for Earthquakes which has been omitted since this is obviously not a climatic hazard.

The Aims and Sectors of Mitigation Planning

The main objective of mitigation is to reduce risk to a given community by protecting life and property. Protection of life involves not only preserving the physical well-being of the population, but also reducing the risk of social, psychological and economic deprivation that frequently follows disasters. The concept of poverty, used in this way, includes a wide diversity of elements, from livestock and fruit trees to buildings and cooking utensils. Mitigation planning should also have as an aim the protection and preservation of income, since when this is threatened or eliminated, life itself is clearly at risk.

Planning for risk reduction is a highly complex process that embraces a wide variety of professions, working in various sectors. Figure 2 represents disasters as the meeting place between extreme climatic forces and a vulnerable context.

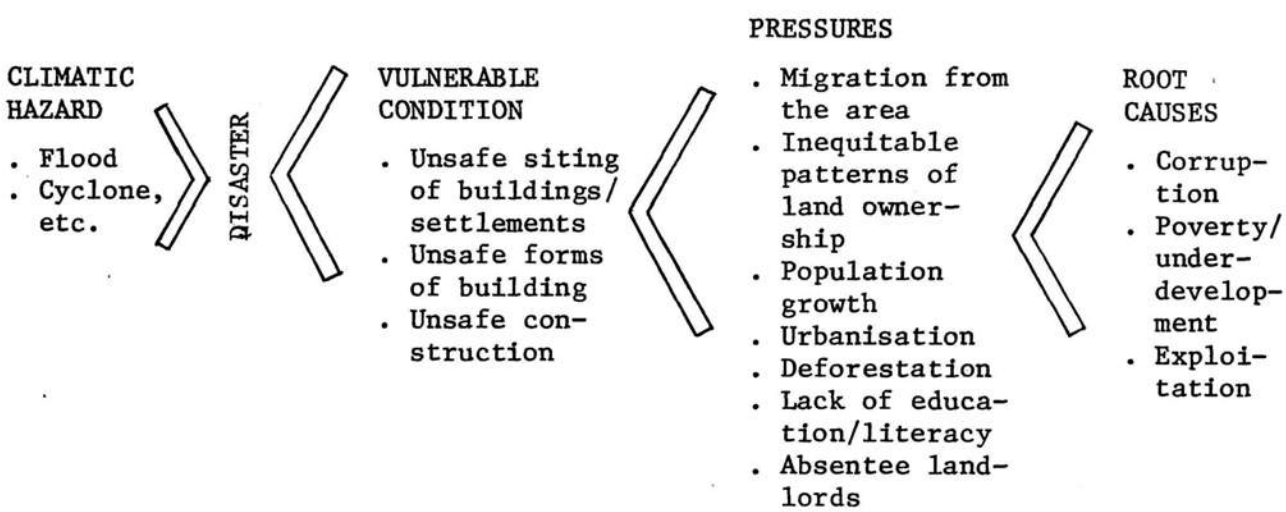

Figure 2. A disaster as the interface between extreme climatic forces and vulnerable conditions.

Activities to address the situation depicted in Figure 2 can occur by focussing on the hazard (i.e. river controls, meteorological warning systems for impending cyclonic winds) and secondly by acting to lessen risks to the vulnerable context (i.e. improved siting and construction of buildings).

The subject is complex and covers a wide range of sectors, professions and the departments or agencies of governments, UN bodies or non-governmental organisations. Some regard disaster mitigation as a subject in its own right, whilst others see it as a developmental issue or as a subject that is essentially climatological, structural, hydrological, architectural, economic or concerning physical planning.

Similarly, the range of professions concerned with the protection of settlements in, for example, a coastal area subject to cyclonic winds, could include: hydrologists, meteorologists, physicists, structural engineers, architects, climatologists and physical planners. However, within any country a minute number of the above are likely to have devoted their specialised energies to the specific area of hazard mitigation.

The subject also overlaps a wide diversity of governmental offices, which might include: Public Works, Water Management, Meteorology, Town Planning, Emergency Planning, Public Health, and Social Affairs. In certain disaster-prone countries such as Jamaica and Ethiopia specific governmental departments have been established to promote disaster mitigation, often acting with appropriate personnel drawn from relevant governmental departments.

The UN system also responds with a diversity of organisations being involved in a region that has suffered a coastal cyclone, or desires protection from future devastation. These could include: The World Meteorological Organisation (WMO), UN Centre for Human Settlements (UNCHS), The Office of United Nations Disaster Relief Co-ordinator (UNDRO), United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP). Certain of these agencies are operational in field activities whilst others are essentially concerned with a co-ordination role. An increasing trend is for various UN agencies to formulate post-disaster joint assessment missions as a prelude to concerted action with one agency being designated by the UN Secretary General as a 'Lead Agency'. An example of this process occurred in January 1984 when UNDP, FAO, UNICEF, WHO, WFP, UNIDO, and UNFPA joined in an UNDRO-led mission to Mozambique following Cyclone Demoina which aggravated a very serious drought situation (UNDRO 1984).

In terms of pre-disaster planning UNDRO has maintained a vital role in this sector since the agency was formed over a decade ago. As a part of this responsibility they have published extensively on disaster mitigation. Currently UNCHS are committed to a work programme that embraces disaster mitigation measures for the protection of buildings and settlements. However, it is clear that the major activity of the UN system in terms of disaster response is as relief assistance rather than mitigation, and this priority reflects the perception of most governments and private voluntary agencies.

Although it is invidious to single out any specific government, private agency, or consulting body that has made particularly important contributions to hazard mitigation related to buildings and settlements, there are certain that stand out from others and merit attention. The US government's Office of Foreign Disaster Assistance (OFDA) have exercised decisive leadership and a strategic role in this field for the last decade. This has resulted in the promotion of conferences and projects to reduce housing vulnerability in a wide variety of countries. Secondly, the Swedish Red Cross deserve attention for their important initiative in publishing a new study: '*Prevention Better than Cure*' (Swedish Red Cross 1984).

Thirdly, all practitioners in this field acknowledge the vital leadership that Fred Cuny and INTERTECT (a US based consultancy organisation specialising in Disaster Planning) have exerted over the past 15 years. In this period they have developed tools for mitigation planning which have been developed into operational programmes in numerous countries: Jamaica, Guatemala, Peru, Soloman Islands and many others (INTERTECT 1981, 1982a, b, c and undated).[1]

In the following sections there will be a summary of the various measures that are necessary to reduce risks. They normally need to be addressed in the following sequence:

- Raising public awareness
- Assessing the risks
- Addressing the hazards
- Devising and implementing appropriate safe planning and building measures
- Developing training and education for various levels
- Statutory provision

These six strategies are fundamental to any policy for reducing risks from extreme hazards. In general statutory provision follows, rather than anticipates, public opinion; the overall approach coming from the bottom up, starting with the raising of public awareness and leading to legislative action.

Raising Public Awareness

This subject will embrace curriculum development for school children, the dissemination of warnings of impending disasters, and media and advertising programmes to alert the public at large to the risks they face and steps they can take to reduce them. The ideal time to instigate such public information/education programmes will always be in the immediate aftermath of a disaster when the public will be sensitive to the issues involved. Many countries, such as Japan and Jamaica have adopted the policy of running drills to test disaster preparedness. These exercises can be very costly when they involve a wide range of public officials, but they can be very effective in developing general awareness of disaster risks.

In terms of school curriculum development there are two obvious opportunities. Firstly, disaster risks can be dealt with on similar lines to road safety education in primary schools. Then for more advanced age groups it is sensible for the subject to be incorporated into appropriate subject curricula such as physics, or geography.

Risk Analysis

On the eastern seaboard of India there are approximately 3,000 kilometres of coastline at risk from cyclonic winds. In certain areas, such as Andhra Pradesh, as many as four cyclones might occur within the annual season. Therefore, communities have responded creatively to this challenge, although their response has not resulted in them permanently evacuating the areas at risk on account of the economic livelihood priorities already noted. In other areas where the return period is less frequent, adaptation might be very slow and it may be extremely difficult in such areas to alert people to the risks that they face. The assumption that short return periods with increased risk will automatically result in a response cannot be assumed and in addition there may be areas which have not had a frequent disaster, where the risks whilst unrecognised may be very great indeed.

This situation results in a need for a detailed examination of the problem. An approach to this will involve 3 inter-related tasks. Firstly, Hazard Mapping where, on an area-by-area basis, studies are made to investigate the specific hazard or hazards to which an area is exposed. This will involve examination of government, meteorological and hydrological data, and local community records, and from this some indication will be formed of the risk from natural hazards in terms of magnitude, location and frequency. In order to map these hazards a monitoring system will need to be established to build up an essential data base.

Following the mapping of hazards, the next process is one of Vulnerability Analysis where an examination is made of the areas that are at risk; this will relate to both property and lives, and will result in the examination of agricultural resources, infrastructure and sites of settlements to determine whether they are at risk from various hazards and also an examination of the construction, form and level of maintenance of the existing building stock. This latter examination will be particularly important for all public buildings and particularly schools, hospitals, police stations and all buildings which are likely to either have multiple occupancy where the risks are going to be dramatically increased. These buildings are likely to be of particular value in dealing with a disaster emergency, with the need for large volumes of protected space, for displaced families and emergency functions.

From these two processes of hazard mapping and vulnerability analysis, the third process is undertaken, entitled Risk Assessment, which quantifies the risks for a given region, and on the basis of this final analysis some understanding can be made as to the relative vulnerability of a region or of a specific house type within a given settlement. This information is crucial in terms of the deployment of resources to address the risks. For example, it might be found that adobe buildings within a given settlement are particularly at risk from flood impact due to erosion, whilst concrete block houses are not at risk and therefore some strengthening programme might be possible for such dwellings. There may also be opportunities for the relocation of particularly vulnerable sections of settlements.

The process of hazard mapping, vulnerability analysis and risk assessment are too frequently regarded as specialised skills only to be undertaken by visiting international experts. However, the reality is that much can be done at a local community level, relying on the knowledge of local people who have experienced disasters during their lifetime. It is possible that with simple instruction a community could establish their own risks with some precision. An additional bonus is that the activity of examining their risks and reporting on them, is in itself an important element in disaster preparedness, since it raises awareness within the community, which may not occur when visiting personnel undertake the task, which all too often results in unimplemented reports residing unattended in the filing tray of government officials who never requested the consultancy in the first instance.

3. A BALANCED PROTECTIVE STRATEGY

The following proposals advocate the need for a four part protective strategy for urban areas at risk from extreme climatic forces. This strategy can be summarised in a rather simplistic and symbolic form as a rectangular medieval fortress with four protective corner bastions, each being dependent on the others (Figure 3).

The four strategies are all interactive. For example LEGISLATION is unlikely to occur unless there is a high level of PUBLIC AWARENESS. Then in turn PHYSICAL MEASURES require financial inputs which will not occur without LEGISLATION. The issue of TRAINING AND EDUCATION is equally dependent on the necessary enabling LEGISLATION that will unlock financial resources from governments. It is also clear that there is a close interaction of TRAINING and PUBLIC AWARENESS, each being mutually interdependent on the other mitigation element. Finally, it is necessary to establish what type of PHYSICAL MEASURES will be needed before effective TRAINING can be instigated to implement such measures.

RAISING PUBLIC AWARENESS

- School children
- Professions
- Public officials
- Political leaders

LEGISLATION

- Bye Laws/Codes of practice
- Land-use planning

TRAINING AND EDUCATION

- Local builders and craftsmen
- Architects and engineers
- Building inspectors

PHYSICAL MEASURES

- Environmental measures
- Safe building design
- Safe location of settlements
- Strengthening unsafe buildings

Figure 3. A balanced strategy for risk reduction.

Experience suggests that to rely on just one of these approaches will be almost certainly doomed to failure, whilst the four part strategy may have some positive impact, particularly if implemented in the aftermath of some disaster which has already alerted public consciousness to the anticipated risks.

3.1 Strategies for Risk Reduction

No. 1 - Raising Public Awareness

In the immediate aftermath of a major disaster there is rarely a problem in raising public awareness of the need for improved buildings to resist subsequent disasters. This public concern is also present within communities where there is a short return period between climatic hazards (such as on the eastern seaboard of India). However, where tropical cyclones are highly infrequent, yet nevertheless devastating when they do occur (such as Sri Lanka), there are generally low levels of public awareness.

Therefore, it is clear that a vital prerequisite of an effective policy for risk reduction is for the public at large to be aware of the hazards they might face and the measures they can take to reduce personal risks or to prepare for disaster.

Ways to achieve this are varied but include the teaching of school children; extension classes within disaster-prone communities; and media campaigns. The information to be imparted will be both general and specific. At a general level there is a need to explain the nature and impact of high winds or flooding. Then at more specific levels the public need to be alerted as to any evacuation plans, as well as advice being offered on how to hold the roof on a house, or how to prevent high winds from entering doors and windows. In addition to such cyclone preparedness measures the public also need to become aware of the opportunities of more fundamental mitigation measures concerning safety aspects of site selection, building configuration and construction techniques.

No. 2 - Legislation

Bye-laws and land-use planning are essential mitigation tools, but it has to be recognised that they have severe limitations when dealing with very poor families. Too often the families are unable to afford the implications of such legislative provision. For example, the bye-laws might prohibit certain kinds of building materials which are the only locally available materials the families can afford. They might also proscribe building on certain floodplains, which are again the only land areas open to marginal communities. Therefore there needs to be some realism in approaching bye-laws for such target groups. Bye-laws clearly relate to middle-class communities who can afford the implications and they also relate to all public and commercial building projects. Another major problem with bye-laws and land-use planning concerns enforcement. Many societies have adopted such statutory provision without having adequate enforcement procedures and inevitably this has resulted in a fairly meaningless set of paper provisions with no teeth. There is clearly no point in enacting bye-laws if they cannot be enforced, or if levels of corruption within the country are so great that any bye-law inspector could be bribed into approving sub-standard construction or the elicit siting of a settlement.

Almost twenty years ago Charles Abrams, in his classic study Man's Struggle for Shelter in an Urbanizing World, identified this limitation with codes, his comments were directed to seismic areas, but they also apply to climatic hazards:

> 'Building codes are of course essential particularly in congested areas subject to earthquakes. Too often the codes are national regulations that do not fit some localities, or they are city codes, which do not embrace the codeless suburbs. The tendency in a number of countries is to copy the complex codes of England, Germany or the United States as well as their zoning or planning laws, though they are irrelevant and though the talents to enforce, construe and adopt them may be completely lacking.' (Abrams 1966).

However, despite these limitations there is no doubt that statutory provision is a crucial element in a broad mitigation strategy, but to have any meaning bye-laws need to be relevant, realistic, enforced and closely related to local conditions including the economic levels of poor families.

No. 3 - Training and Education

This strategy is probably the most neglected element in risk reduction. Training needs to specifically apply to craftsmen and builders in safe construction, but it must be noted that this is not purely to build against high winds or against flood impact, it is to build safely against normal conditions. As building technology changes in many Developing countries, particularly with the introduction of reinforced concrete construction and concrete block technology, many local builders and craftsmen are totally unfamiliar with these techniques, possessing little or minimal knowledge of concrete mixes, cover for steel, or even the amount of steel to be used. To deal with this problem training is needed to assist them in improving building construction and effective siting and infrastructure.

Hazard resistant design principles also need to be taught to architects who all too frequently have left the problem of safety to engineers when many of the problems reside very closely within their own court. For example the shape of a building is particularly pertinent relative to flood and high wind resistance and this configuration is not normally determined by an engineer. Levels of roof pitch are critical factors in areas subject to high wind, and this is clearly an architect's concern, yet even in disaster-prone areas architectural students are rarely taught such matters. Therefore, there is a need for curriculum development within schools of architecture in hazard-prone areas to explore the full design implications both in terms of built form, constructional systems as well as the siting of buildings.

In the consideration of architectural education I have identified four prerequisites and will include them here since they are equally as appropriate to climatic hazards as to the seismic context of the original presentation:

(a) Is there already a general awareness of the processes at work for the production of vernacular architecture, in terms of an understanding of local skills, resources, constraints, and a knowledge of the local building process, and the value systems of a given society?

(b) Does an 'earthquake culture' exist? Have architects come to see the importance of this in terms of the siting and the form and detailed construction of buildings, or is there a 'sidestepping' of the seismic issue, regarding this as a strictly engineering or seismological concern.

(c) Is there an understanding of the linkage between general developmental theory and the provision of the buildings? This will require some basic understanding of such topics as the building of institutions, leadership training, rural development, the economics of families living in marginal situations, and the role of housing within the local economy.

(d) The final prerequisite is the parallel commitment by the research community to this task. This is an essential element since well framed research programmes ultimately provide the 'knowledge base' for professional education. (Davis 1984).

It is also clear that the planning profession require specific guidance on the siting of settlements relative to land-use, and their own education needs to include a great deal of attention to the hazard mapping, vulnerability analysis process that is described above. They also need to understand such basic things as the effect of high winds on a community of buildings and how an overall settlement behaves when subject to such forces. At the present time there is an acute lack of teaching material to give to such groups. The engineering profession has normally been better served in this connection, but as with architects and planners, their skills have normally been confined to engineered structures and have not been applied to the homes of the vast majority of the population. The 95% of the disaster deaths that I referred to earlier indicates the need for a shift of resources down to the level of greatest need.

No. 4 - Physical Measures

Three Contexts for Risk Reduction

Prior to a detailed consideration of various aspects of planning and designing buildings to resist extreme climatic considerations, it is necessary to consider three contexts within which activities can take place. These are: firstly, *Reconstruction* following a major cyclone or severe flooding; secondly, *New* building within a given area; and thirdly, improvement to the safety of *Existing* settlements.

Experience has clearly indicated that by far the easiest of these three contexts to address is *Reconstruction*. In these situations of major disasters there is normally the availability of finance, damage which has to be replaced or repaired, political will, media pressure for rapid action. In addition, there is a public, prepared for the first time to consider change in the aftermath of significant failure. Far too frequently after a major disaster the overall focus of all assisting groups is on rapid reconstruction and recovery rather than on protective actions. A ' phoenix from the ashes' philosophy prevails where the overwhelming concern of everyone is to wipe the slate clean and restore normality. However, the 'normality' that has often been restored is one of acute vulnerability. Therefore, a word of caution is needed to suggest that what might need to be rebuilt is the local building industry, or the local administrative system which have been found faulty in the test of their resources by the extreme hazard impact.

An American city planner, George Nez, once stated that in reconstruction planning you first of all think that 95% of the problems result from the disaster, but slowly as you become aware of the problems, you recognise that possibly all of these problems were residual problems within the community prior to the disaster, and all that the disaster did was to act as a scalpel to expose these areas of weakness. The conclusion he drew from this observation was that it was necessary in reconstruction to address the vulnerable situation which led to the disaster.

Turning to the second context, that of *New Building*, it is clear that the safe siting of buildings will inevitably cost more than normal construction, and this surcharge over normal house construction costs (15-20% at a minimum) is likely to be prohibitively expensive for a family living near to economic subsistence level. In this case there may be alternative possibilities such as training programmes or subsidies. In the case of new building being constructed to safe standards the greatest problem is that in the absence of a 'trigger' of a disaster, there may not be the incentive to design buildings, or site settlements against an assumed or calculated risk, when the last disaster occurred in the memory of the oldest man in the community. This highlights the need for disaster preparedness programmes to be developed at all levels to keep the issue alive and to regard it as part of the daily life of the community.

It is important to recognise that there will be potential conflicts in trying to make a building withstand high winds or floods and normal climatic constraints. For example, to protect a village against cyclonic winds in India, it might be advisable to site the whole village in a circular configuration to allow for the rotating winds to go round the village with shelter breaks being provided in concentric form to deal with the specific problems of wind forces. However, there may be numerous reasons why such a configuration is impractical in terms of normal climatic needs or in terms of kinship groupings, land ownership, settlement traditions and other factors.

Finally, considering the third context, the protection of *Existing Settlements*; this presents an even greater problem of how to implement any programme to either relocate settlements which are particularly at risk, or to strengthen existing houses. It is crucial that this type of programme be undertaken by public authorities for all public buildings and the greatest priority in any community is the protection of public buildings and all places of public assembly. Overwhelmingly the most important of such building types is that of schools, where the future of a community will be spending a large proportion of their time and it is tragic to observe how in many recent disasters, school buildings have been some of the most significant failures in a given area. This may be the result of official ignorance or negligence and a key 'strengthening programme' is necessary to examine such buildings and make certain that they are going to withstand the extreme forces to which they may be subjected. However, the strengthening of low-income houses will probably have to be undertaken at a community level and here the need exists for the development of 'barefoot architects', who can operate in a local situation to advise on simple ways to achieve safe building.

There are no easy solutions to the problems of strengthening buildings, and whilst there are important programmes currently being implemented in such countries as New Zealand and the USA to strengthen buildings against earthquakes, these programmes are operational at higher income levels than poor families who do not regard the matter as sufficiently important for their attention, given their other priorities for economic survival.

The remainder of this section has been broken into two broad areas: firstly a brief consideration of warning systems and environmental measures and secondly, a review of measures that relate to settlement planning and building design.

3.2 Warning Systems and Environmental Measures

Since this paper is specifically concerned with the reduction of risk to the built urban environment, it is not appropriate to enter into detail on the subjects of hazard reduction (such as the building of dykes or bunds, and overflow canals for flood alleviation) or of the monitoring of hazards as a part of warning system (such as satellite monitoring of impending cyclones). Such warning systems and environmental measures have become vital elements in any disaster-prone nation's policy for balanced risk reduction. This is particularly the case in the protection of major urban areas. Table 4 identifies the main measures that have been adopted.

The measures listed in Table 4 are already having a significant impact on the reduction of risks. For example, Bangladesh has now established a detailed satellite cyclone warning system. This will ensure that a cyclone, on the scale of that which devastated Chittagong in 1970, will be detected and monitored throughout its progress to the coastline. The meteorological service then collaborates with an extensive Disaster Warning System linked to a locally organised programme of evacuation planning run in conjunction

TABLE 4. *Alleviation Measures for Climatic Hazards.*

HAZARD	WARNING SYSTEM	ENVIRONMENTAL MEASURES TO ALLEVIATE HAZARD IMPACT (Excluding specific building measures - see Figures 4-6)
River Flooding	Monitoring rainfall in valley, advising on anticipated flood levels for downstream communities.	Two measures are normally adopted: Storage: By means of flood plains emergency storage lakes to attenuate peak discharges. Conveyance: Building up levels and by-pass channels.
Flash River Flooding	The breaking of cables stretched across river valleys by water flow offering very short warnings to downstream communities.	The above are unlikely to offer significant protection against the sudden onslaught of flash flooding.
Coastal Surges	Monitoring by satellite and aircraft surveillance linked to a detailed preparedness plan for community evacuation and protection of property.	Raising up the level of coastal villages at risk. Building sea walls or levees. Excavating emergency conveyance channels to absorb the influx of the surge. Constructing raised earthen mounds for people and their cattle to occupy for the duration of a surge.
Cyclones	As above.	As above with the addition of the planting of trees and shrubs as shelter breaks around settlements, or in a continuous coastal band in areas that are cyclone-prone.

with the Bangladesh Red Crescent.

The major problems of these hazard alleviation measures are threefold:

Firstly, despite the rapid progress in satellite warning systems for impending cyclones, there remain acute problems in the linkages between the various groups involved in disseminating a warning to families at risk. Linked to this problem there are major questions such as whether to evacuate; if so where to take the population (which may number hundreds of thousands) and the acute logistical problems posed by mass evacuation.

Secondly, in the case of flood protection measures such as the building of protective dykes, overflow canals and temporary lakes to absorb excess water, the major problem is that of cost to provide the initial protection, and continual financial and administrative attention to maintain the measures in a state of readiness. In many instances flood levels have increased over the past 20-30 years due to a number of factors, such as deforestation, the canalisation of rivers and the encroachment of flood plains for building purposes. Therefore flood alleviation measures that could readily cope with earlier flood levels are no longer adequate for the task.

Thirdly, it is well known that shelter breaks made from bands of tree planting can play a major protective role in mitigating the impact of a cyclone on settlements. However, the pressures for deforestation apply to such shelter belts. Some imaginative attempts have been made to overcome this problem in certain areas such as the Indian State of Orissa. Here, the government donates trees to families who are then made responsible for their safety and upkeep. These can be fruit trees, providing an added economic incentive to keep the trees.

Whilst shelter breaks can reduce wind damage, the greater risk to lives is that of surge flooding and one of the most effective techniques which has been pursued in India, Bangladesh and South East Asia is to raise the whole level of the village. Many villages could be raised by approximately 1-2 metres, which could make all the difference on survival or extreme devastation from a coastal surge. These programmes can also frequently involve the digging out of fish-ponds which can have a significant aspect on the nutritional levels within the community and also their economic viability. Again guidance is needed on how best to achieve such measures but it is almost certain they are only likely to occur where there is strong local leadership, effective local institutions and a community that is sufficiently united to want to make such provision and take collective action.

To summarise, whilst many of the warning systems and environmental measures noted above require high investment, many can be undertaken at a community level with limited material resources, and detailed guidance is needed at this local level on appropriate measures. Whilst the environmental measures which have been noted above can be highly effective, they must not be seen as a substitute for attention to broad settlement planning and building measures. They are in effect another part of the protective mitigation strategy which now will be considered.

3.3 Measures Related to Settlement Planning and Building Design

3.3.1 The Various Levels of Behavioural Impact from Climatic Design

There is an obvious progressive range of impact, starting at the level of maintaining human comfort, then moving to a concern for health and the preservation of lives - by maintaining human safety.

COMFORT
(Considering a range of physiological issues - skin evaporation, solar glare, avoidance of draughts, etc.)

HEALTH
(Considering various anti-pollution measures, avoidance of dust storms and consequent respiratory ailments)

SAFETY
(Protecting people against bodily or mental injury, and in extreme cases death. To these concerns the protection of buildings and property could be added.)

3.3.2 Linking the fields of Hazard Risk Reduction and Building Climatology

The interaction of buildings and hazards has been extensively studied over the past two decades within three broad camps. Fortunately, effective linkages are now being developed between these groups which comprise scientists concerned with understanding the physical forces of wind and water, secondly geographers and thirdly planners, engineers, architects and climatologists. It may help to identify the range of concern of these three groups.

3.3.3 Planning and Designing for Normal and Extreme Climate Conditions

The emerging discipline of building climatology has been primarily concerned with the 'normal' climate range affecting the site of a given building or settlement. This paper is concerned with the incorporation of measures to respond to extreme climatic conditions in all urban areas prone to such hazards. Three groups with a concern for this subject can be identified.

Scientists concerned with the physical properties of hazards and their impact on the built environment

Physicists in a wide range of countries have explored the impact of high winds. In many countries this has been centred in governmental building research centres, or bureaus of standards. Similarly, hydrologists have built up a body of knowledge on rain and snowfall and consequent flood risk. It is clear that the issue of construction and building siting relative to resistance to high wind forces has been much more closely studied than the parallel issue of water and flood impact on buildings. Initially, the structural engineering profession initiated these developments, but gradually their work has been expanded by architects and planners. Together they have attempted to apply disaster mitigation measures in the three contexts noted above.

CITIES AND EXTREME CLIMATIC FORCES

Geographers concerned with Human Adjustment to Hazards

This group is centred in North America in the Universities of Colorado, Toronto and Clark in Worcester, Massachusetts. Their work has developed a body of knowledge on the mapping of hazards, the analysis of vulnerability and an assessment of risk. In addition to this determination (by quantifiable means) of *actual* risks, they have also explored the *perception* of risk by the community exposed to the relevant hazards.

The Planning and Design Professions

It is not necessary to identify this group since they are well known, including planners, engineers, architects - groups that are involved with the normal process of planning and design.

The key question is whether building climatologists working in areas subject to extreme climatic hazards *incorporate* the broad approach that has been carefully developed by the 'hazard community', or should they *work in parallel* with them?

There are many inter-related questions on this topic as well as a large number of variables which influence any decision. However, there is a powerful argument to suggest that a consideration of climatic impact on buildings has, by definition, to consider both the normal annual climatic cycle as well as abnormal (or extreme) conditions. The reason is that any building should be designed, or any settlement planned, with an awareness of the impact of extreme conditions. A tactical decision might be taken that the risks are so low (due to the infrequency of hazards) that costly mitigation measures are not viable. But such an approach is infinitely more responsible than to design in ignorance of such hazards.

In advocating this approach it may help to clarify the argument if we cite an example of the design of a single building detail for both normal and abnormal climatic conditions.

In many climatic zones, in particular hot humid tropical zones, buildings are designed with verandas. Their purposes are varied and obvious

- to provide shade, to provide a semi-open area protected by insect screens, to funnel prevailing winds through a house for cooling purposes (see Figure 4). Such advice with necessary refinements could easily find its way into an architectural students textbook on climatic design.

However, in areas subject to tropical cyclones the actual detailing of Figure 4 needs modification. The wind forces can collect below the veranda eaves and when added to the negative pressures on the roof caused by the extreme wind speeds (the aeroplane wing syndrome); the *entire* roof of the house could be sucked off (See Figure 5).

The solution to the detail is to provide a separate roof structure for the veranda, with the possible extra measure, where funds permit, of a set of shutter doors to seal it off in the event of an impending cyclone. With the separate roof to the veranda it could be torn off the building without pulling the entire roof structure (See Figure 6).

Thus, a totality of approach is needed, and guidelines for architects and planners on building climatology needs to be expanded to incorporate designing against extreme wind forces or flood conditions, and the impact of abnormally heavy rainfall.

Opportunities for Relocation Planning

There have been many instances where entire communities have been moved in response to the risk of flooding or high winds. For example, Belmopan, the new legislative capital of Belize was built in response to hurricane risk, following Hurricane Hattie in 1956. However, in took many years before the relocated town of Belmopan achieved any satisfactory life of its own and at the present time many people work in the town and yet commute back to the vulnerable town of Belize. Such families accept the risks of the coastal settlements which go with the attractive aspects of living by the sea. Therefore, before relocation is considered as a viable option, it is necessary to consider such 'trade offs' and the severe economic aspects that must be faced. Within any serviced settlement the investment levels in the infrastructure are normally so great that relocation will always be a tremendous drain on the resources of even a wealthy government. In general relocation projects have not achieved their objective, since as in Belmopan many relocated settlements have in fact become established whilst the original town which it was designed to replace continues to flourish.

However, despite these words of caution there may be the possibility of relocating *portions* of settlements which are at particular risk where an alternative site is available.

3.3.4 Urban Development and Metropolitan Planning Issues

Since the focus of this paper concerns urban environments, it is necessary to consider some of the key planning issues for this context. Returning to the initial discussion on vulnerability it is worth noting the various sectors of urban areas that are at risk:

Losses to Individuals and Families

This is likely to concern the loss of property, lands (including topsoil after torrential rainfall), housing, livestock, cash reserves and family incomes. Some of the above list concern agricultural elements but it is clear that within the marginal areas of cities, containing recent migrants from rural areas, some family members will attempt to continue to farm on a greatly reduced scale.

Fred Cuny has observed that losses will "in turn cause an increase in personal debt and create dependence on municipal social services. In its broadest sense, economic losses at the micro-level represent a loss of opportunity, for it often means that individuals and families must redirect their efforts simply to re-acquire what they lost." (Cuny 1984).

Losses at a Community Level

Economic losses necessitate a diversion of scarce resources into rehabilitation and reconstruction. These result in an increase in the public debt, a delay in general development and can retard the extension and expansion of municipal services.

Implications for Urban Developments

As has already been stated climatic hazards may require radical adaptation in building and urban development patterns. Examples

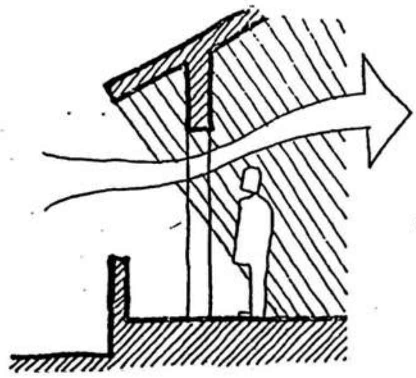

Figure 4. Normal climatic design of veranda in hot/humid tropics. (The roof is designed to provide shade, and wall openings enable cross winds to cool the building interior.)

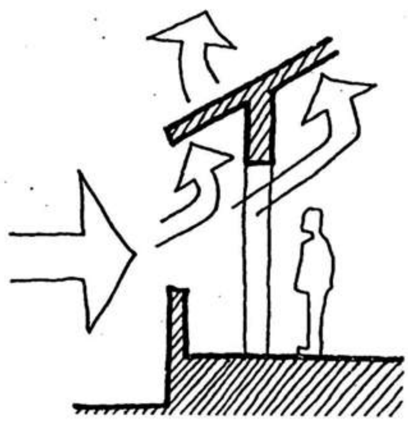

Figure 5. Problem with this design in abnormal high wind conditions. (In extreme conditions the wind forces will enter the house, breaking glass and collecting below the veranda eaves thus pulling the roof off. This is encouraged by negative wind pressure on the roof.)

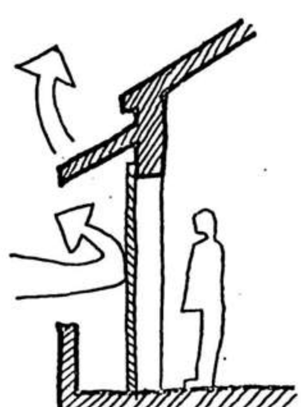

Figure 6. Solution: Design for normal and abnormal climate conditions. (If the veranda roof is separated from the main roof it can be blown off without destroying the house. The opening has been fully shuttered.)

would include the raising of buildings on high plinths or stilts to prevent flood impact. In planning terms 'safe zones' may need to be created.

Urban development can significantly increase the risks. For example, in river estuaries any process of reclaiming land for development purposes can remove vital marshland that can act to provide water storage in the case of flooding. Then in the process of urban development the widespread use of impervious surfaces such as roofs and roads will result in induced risk since there will be additional water run-off.

A key issue will be to site vital 'lifeline' facilities in safe locations and to build them to safe standards. The term 'lifeline' refers to all services and buildings that will serve vital functions after a possible disaster. Thus water, electricity, telephone, sewage and key road systems will all need special protection. In terms of 'lifeline' buildings this will refer to schools, medical facilities, administrative offices, food depots, radio and TV stations, police stations and sewage disposal plants.

The above may seem very obvious, yet it is stated with the experience of disasters where newly built public facilities have failed to survive high wind impact due to ignorance or apathy.

A further consideration concerns the protection of key economic facilities. When factories are destroyed that employ a large percentage of a given population it is clear that their destruction could have potentially devastating consequences for the economic recovery of an entire community. In the 1979 cyclone that devastated Sri Lanka there was extensive destruction of coconut trees. Since it takes ten years to replace these trees before they yield a full crop, the protection of such a vital economic element could justifiably be regarded as a high priority or lifeline facility.

To summarise, urban planners need to recognise that unless they take disaster mitigation planning seriously they can risk the destruction of major sectors of high investment in urban development as well as even more important human losses. And linked to such mitigation planning there will be excellent opportunities for preparedness planning.

4. CONCLUSIONS

Some closing observations are appropriate. Firstly, the community of people who are concerned about these matters is still too small, yet it is encouraging to note the way they are becoming aware of each other's existence to strengthen each other's capacities. Therefore, it is encouraging to note the establishment of a Panel on Risk Reduction in Hazard-Prone Areas, jointly sponsored by the International Disaster Institute and the Intermediate Technology Development Group. I have the privilege of chairing this group at the present time and we have something in the order of 70 members in about 30 countries. We would welcome anyone who is concerned for the protection of settlements against natural hazards to join this group, or the associated inter-American Chapter which was formed in June 1984, to become a part of the network of concerned individuals who share their knowledge and experienee in this field.[2] The Panel, with Virginia Polytechnic (VPI), is organising an International Workshop on the Implementation of Mitigation. This will be held in Kingston, Jamaica, in November 1985 and will be the first meeting on this topic. We are pleased that governments are becoming belatedly aware of the need to refocus their resources away from frequently oversubsidised relief programmes to the neglected mitigation planning sector 'prevention being better than cure!'

A second practical step that could be extremely useful is for anyone working in this field to document their findings, whether these relate to the establishment of training programmes, the development of teaching aids, the instigation of preparedness/mitigation measures applied in the protection or reconstruction of buildings and settlements. In all of these instances detailed case studies need to be documented, which then need to be made available to wide audiences. An international journal 'Disasters' has been established which regularly reports on such matters.[3] In addition there are many other outlets for such information.

To conclude, although many families living in such vulnerable urban settings will have far higher priorities to contend with than the protection against a climatic hazard which rarely occurs, this reality should not obscure the opportunities to reduce the risks they continually face from floods and high winds. For architects and planners there is a powerful challenge to be faced, in John Turner's words:

> 'To work at the ways and means by which they can work effectively with the people they serve' (Turner 1983).

As they become conscious of their social role in meeting the needs (expressed or not) of building users, they will be taking a leading role in the development of policies to result in safer urban development. This presents an immense opportunity to understand and map the hazardous environment (particularly for poor families), and finally to understand what design changes to house forms and siting can be implemented within the economic range of such groups. Experience has clearly shown that any changes that are necessary must meet the acceptance of the occupants or they will stand a real risk of not being applied.

Hopefully, as a result of this vitally important conference, Building Climatologists will expand their range of interests to include hazardous climate conditions, and in so doing to move beyond designing for comfort and health to the protection of communities from abnormal climatic forces. The issues are complex and knowledge is still limited, and as we have seen the design constraints for the protection of poor Third World communities are formidable, yet there can be few greater challenges facing any who are concerned to safeguard lives and property within urban settlements in tropical countries.

ACKNOWLEDGEMENTS

This paper is an expansion of that published in Energy and Buildings, 7, 195-203,1984 and I am grateful for permission to do so. The author is indebted to Fred Cuny for many insights in relation to the content of the section of this paper entitled Urban Development and Metropolitan Planning Issues.

CITIES AND EXTREME CLIMATIC FORCES

NOTES

1. A full listing of INTERTECT publications can be obtained from INTERTECT, Box 10502, Dallas, Texas 75207, USA.

2. Panel on Risk Reduction in Hazard-Prone Areas. Details of membership available from: Chairman, Ian Davis, Disasters and Settlements Unit Department of Architecture, Oxford Polytechnic, Headington, Oxford OX3 OBP, UK.

3. Details of membership in Inter-American Panel (for individuals in Latin, Central and North America and the Caribbean region): Chairman, Fred Krimgold, Research Dean, Virginia Polytechnic Institute, Washington-Alexandria Center, 101 North Columbus Street, Alexandria, Virginia 22314, USA.

   'Disasters' Journal. Editor, Dr. Frances D'Souza, International Disaster Institute, 85 Marylebone High Street, London W1M 3DE, UK.

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LIFE EXPECTANCY IN TROPICAL CLIMATES AND URBANIZATION

W. H. Weihe
Consultant to World Health Organization, Geneva, Switzerland
and
Central Biological Laboratory, University Hospital
University of Zurich, 8091 Zurich, Switzerland

1. INTRODUCTION

Life in urbanized areas and cities is safer for health and richer in possibilities for the individual to improve the quality of life in many ways. As compared to the conditions in rural areas, cities provide more advanced education, a choice for a vast variety of occupations, regular working hours, opportunities for relaxation and recreation, easy mobility and efficient protection from the extreme adverse impacts of the atmospheric factors. The risk for health through the spreading of communicable diseases that arises with high density of population in cities is minimized by a sophisticated infrastructure including clean water distribution systems, sewage and water drainage, power supplies, waste disposal, sanitation of houses and streets, and a concentration of health services, medical professionals and hospitals.

Urbanization has been a slowly growing process in the history of Man's civilization. During recent decades in the less developed countries which are concentrated in the tropical climate belt, towns and cities have become like magnets for the rural population. A large urban migration combined with high reproduction rates and decreasing infant mortality through improved health care has elicited an explosive city growth in almost all developing countries. The population influx is often larger and faster than the required urban planning, extension of municipal administration and organization, and establishment of appropriate health control to catch up with needs. The increasing size of cities itself imposes many problems and there may be a size and density at which their advantages will turn into disadvantages for the population. This can be stated at least for an anticipated increase of climatic heat stress. In densely built-up and inhabitated cities an accumulation of heat leads to heat islands which in tropical climates can be persistent and exceed the limits tolerable for the inhabitants. The protection against such adverse micro-climatic changes within cities is expensive and may be impossible where financial means are not available.

2. DEMOGRAPHY OF CITIES SINCE THE 1950's

The up-to-date data on populations in the World and various regions (Table 1) indicates the lowest growth rate in Europe (0.1% annual rate in Northern Europe) and the highest in Middle America (3.0%) with the highest population density in the Caribbean region (134 persons km^{-2}). After a general increase of reproduction rates worldwide early in the second half of this century they passed a climax in the mid 1970's. Since then, reproduction rates have been on the decline to different extents in the various areas (Figure 1). The data on urban population growth shows a striking difference between more and less developed countries (Table 2). In 1970-1975 the urban growth rate in the more developed countries was 1.7% compared to 3.9% in the less developed countries. The rapidity of city growth was illustrated by one African Minister of Health when he remarked that his capital city increased between 1960 and 1966 from 125,000 to 200,000 inhabitants. Indeed, the recent urban growth rate was the largest in Middle Africa, while the lowest was in Northern Europe where the process of urbanization is at an advanced stage.

The percentage of the total population living in urban areas is on a continuous rise but with a wide variation in the different regions of the World (Table 3). The increase of urban populations compared to total populations is more pronounced in less developed than in more developed regions (Figure 2). The number of cities with over 1 million population is steadily increasing worldwide (Table 4). Estimates up to the year 2000 indicate a rapid growth in number and size of cities. Estimates of growth rates of the city populations separated by size of cities reveals a striking development for the World as well as for the more and less developed regions (Table 5). By the year 2000 the population of large-sized cities (over 4 million) will increase while a stagnation of growth is anticipated for the population of cities with 1 million people or less. The urban population growth will be outstandingly high in the large cities in less developed countries (≥ 4 million) (Figure 3).

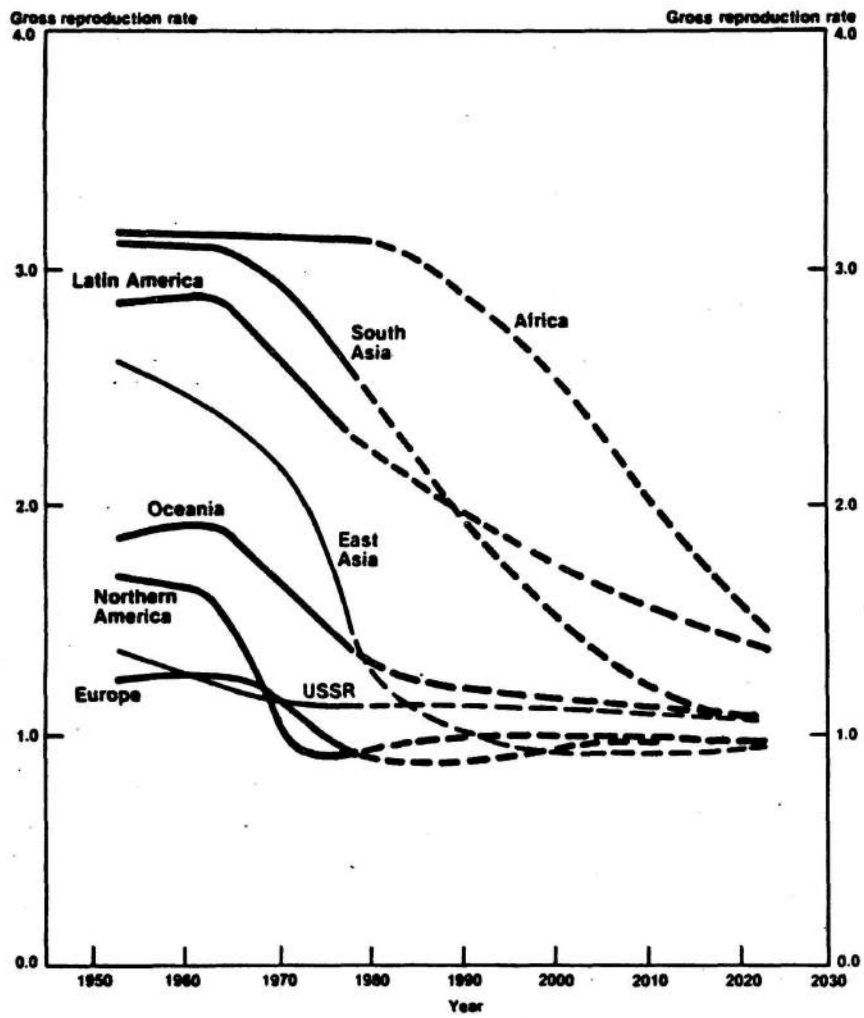

Figure 1. Gross reproduction rate by region, medium variant, 1950-2025, as assessed in 1980. (From United Nations, 1982a).

TABLE 1. *Population, rate of increase, surface area and density of the World and region. (United Nations, 1984).*

Region	Estimates of mid-year population (millions) 1950	1970	1982	Annual rate Population increase 1975-80 (%)	Surface area (km^2)	Density (Population per km^2) 1982
World total	2.525	3.696	4.586	1.7	135.837	34
Africa	220	407	499	2.9	30.330	16
Middle Africa	29	47	56	2.5	6.613	8
Northern America	166	236	253	1.0	21.515	12
Latin America	164	322	382	2.5	20.566	19
Temperate S.A.	25	38	42*	1.3	3.726	11
Tropical S.A.	86	176	210	2.5	14.106	15
Middle America	36	80	98	3.0	2.496	39
Caribbean	17	28	32	1.8	238	134
East Asia	673	1.096	1.205	1.4	11.756	102
South Asia	716	1.256	1.467	2.2	15.820	93
Europe	392	474	487	0.4	4.937	99
Northern Europe	72	82	82	0.1	1.636	50
Southern Europe	109	134	141	0.7	1.315	107

* 1981

TABLE 2. *Urban population and urban average annual growth rates. (United Nations, 1980).*

Region	Urban population (millions) 1970	1980	2000	Urban annual growth (%) 1970-1975	1985-2000
World total	1.368	1.809	3.162	2.8	2.8
More developed region*	687	802	1.010	1.7	1.1
Less developed region**	681	1.008	2.152	3.9	3.7
Africa	81	135	350	5.1	4.6
Middle Africa	10	18	44.	5.7	4.2
Northern America	159	181	234	1.3	1.2
Latin America	162	238	456	3.9	3.1
Temperate S.A.	28	34	45	1.9	1.4
Tropical S.A.	87	135	260	4.4	3.2
Middle America	36	56	124	4.4	3.8
Caribbean	11	16	27	3.5	2.6
East Asia	277	371	634	3.1	2.7
South Asia	255	353	818	4.0	4.2
Europe	302	341	408	1.4	0.9
Northern Europe	65	70	76	0.8	0.4
Southern Europe	72	87	114	2.1	1.3

* Including Northern America, Japan, all regions of Europe, Australia New Zealand and USSR

** Including all regions of Africa, Latin America, China, other East Asia, all regions of South Asia,Malanesia, Micronesia, Polynesia.

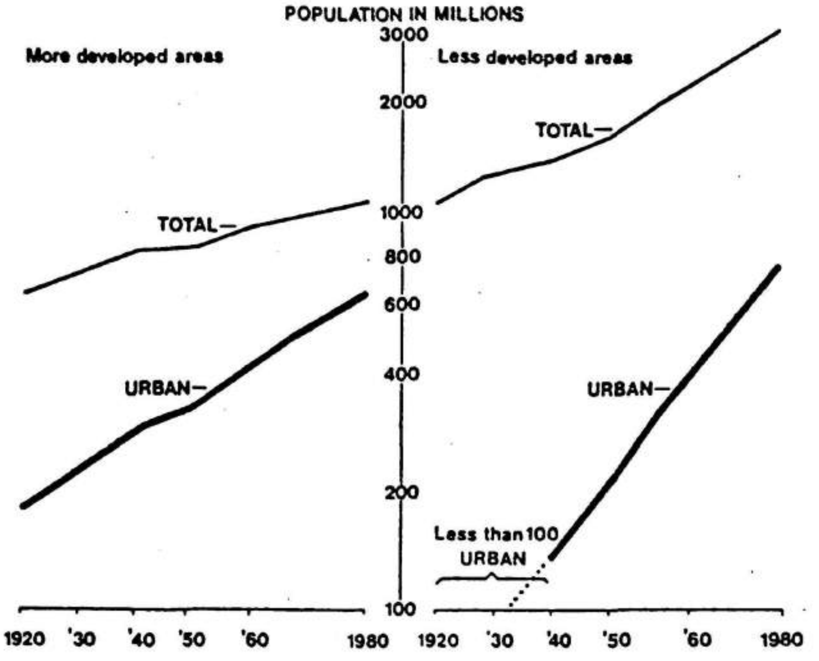

Figure 2. Trends and crude projections of total and urban populations. (From Kleevens, 1972).

TABLE 3. *Proportion of population living in urban areas, 1970-2000. (United Nations, 1982a).*

Region	1970 (%)	1980 (%)	2000 (%)
World total	37.2	41.0	51.0
More developed regions	65.5	70.9	79.4
Less developed regions	25.9	30.7	43.7
Africa	22.8	28.8	42.2
Middle Africa	25.1	34.5	51.5
Northern America	70.4	73.7	80.7
Latin America	57.3	64.7	75.1
Temperate	77.9	82.2	87.8
Tropical	56.2	65.0	76.2
Middle America	53.8	60.7	72.2
Caribbean	44.6	51.2	63.3
East Asia	28.2	32.7	45.1
South Asia	21.2	24.8	37.1
Europe	65.8	70.5	78.4
Northern Europe	81.3	85.0	89.6
Southern Europe	56.2	62.5	72.8

TABLE 4. *Number of cities of a certain minimum size, 1970-2000. (United Nations, 1980).*

Region	1970	1980	2000
World total			
≥ 4 000 000	24	38	82
2 000 000	64	95	192
1 000 000	160	234	440
More developed regions			
≥ 4 000 000	12	15	21
2 000 000	33	40	56
1 000 000	83	110	146
Less developed regions			
≥ 4 000 000	12	23	61
2 000 000	31	55	67
1 000 000	77	124	294

TABLE 5. *Average annual growth rates of city population by minimum city size, 1970-2000. (United Nations, 1980).*

Region	1970-75 (%)	1980-85 (%)	1990-2000 (%)
World total			
≥ 4 000 000	4.81	3.86	4.06
2 000 000	4.72	4.13	3.70
1 000 000	3.78	4.05	3.29
More developed regions			
≥ 4 000 000	2.91	2.00	0.89
2 000 000	2.51	1.48	2.50
1 000 000	2.34	1.89	0.93
Less developed regions			
≥ 4 000 000	7.04	5.19	5.37
2 000 000	7.10	5.31	4.95
1 000 000	5.33	5.64	4.47

The trends in population growth in Figure 2 illustrate that the World population moves towards urbanization. This development is fast in Africa, East and South Asia (Figure 4). In 1980 of 4.4 billion World population 41.1% were in urban areas. In 2025 the United Nations estimates foresee a World population of 8.2 billion of which 65.2% will be urban (Figure 5). Urbanization is simultaneously moving towards mega-cities (Table 6). The number of mega-cities with over 10 million inhabitants will increase from 10 at present to 25 by the year 2000 and 20 of these will be in tropical climates. The size will increase from 10 million in 1950 to 30 million in 2000. The size of such large mega-cities exceeds our present imagination. A striking change in ranking of the 10 largest mega-cities has taken place from 1960 to 1980 (Table 7). London at rank 2 in 1960 was at rank 10 in 1980, while Mexico City at rank 15 in 1960 had risen to rank 3 in 1980 and is expected to be the largest city in the World by 2000. Of the expected 10 largest mega-cities in 2000 six will be in tropical climates.

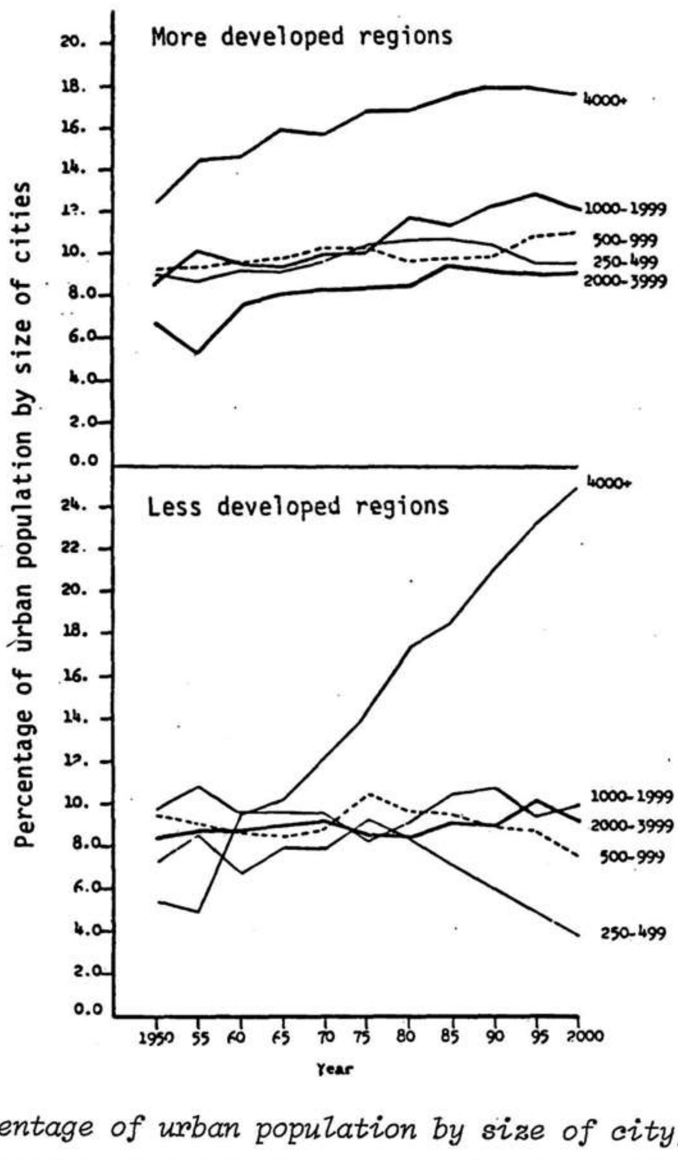

Figure 3. Percentage of urban population by size of city, divided into two categories of level of development. Population size of cities in thousands is indicated on the right. (From United Nations, **1980).**

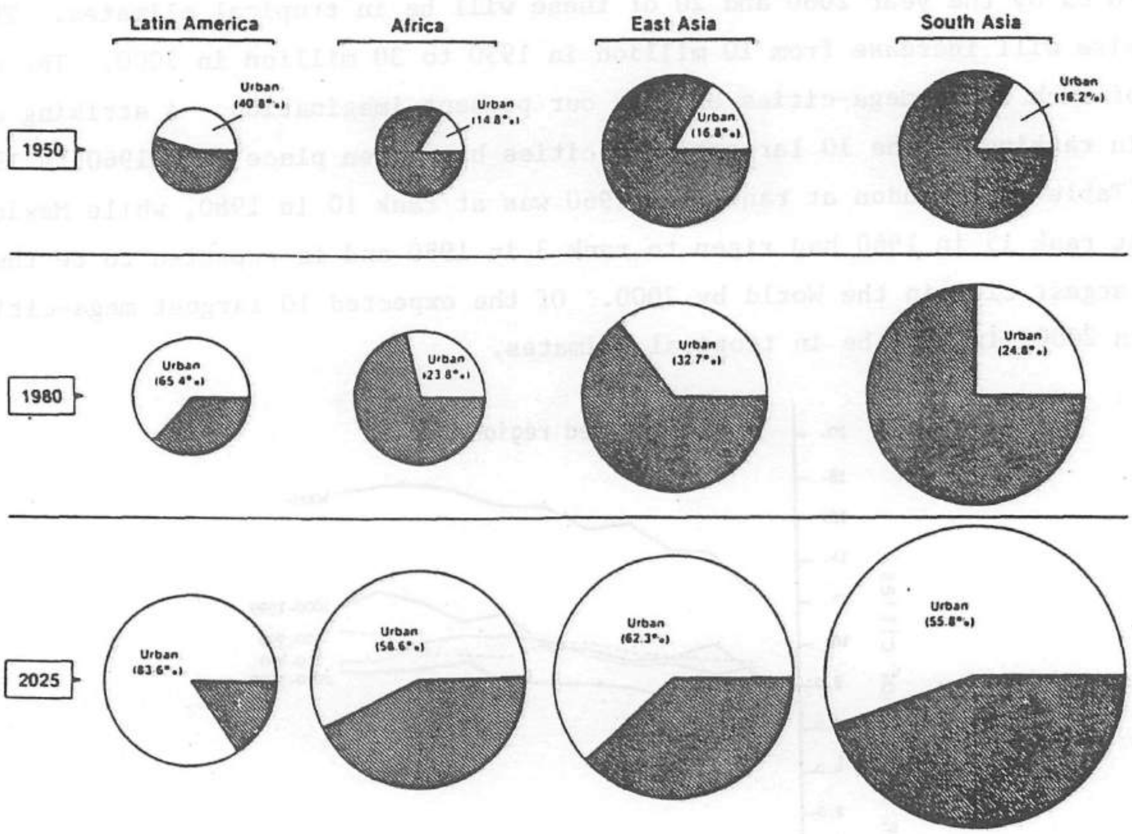

Figure 4. Percentage of the population in urban areas by region, medium variant, 1950, 1980 and 2025. (From United Nations, 1982a).

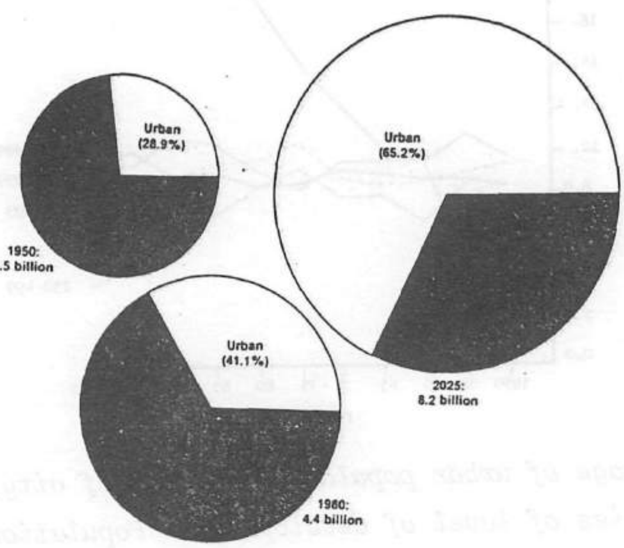

Figure 5. Percentage of World population living in urban areas, medium variant, 1950, 1980 and 2025. (From United Nations, 1982a).

TABLE 6. *Number of mega-cities with 10 million or more inhabitants. (United Nations, 1980).*

Region	1950	1980	2000
World	2	10	25
More developed regions	2	4	5
Less developed regions	0	6	20
Approx.size of world's largest mega-city (million)	10	20	30

TABLE 7. *The World's 10 largest mega-cities, 1960, 1980, 2000. (From United Nations, 1980).*

Agglomeration 1960	Million	Agglomeration 1980	Million	Agglomeration 2000	Million
New York	15.4	New York	20.2	Mexico City	31.0
London	10.7	Tokyo-Yokohama	20.0	Sao Paulo	25.8
Tokyo-Yokohama	10.7	Mexico-City	15.0	Shanghai	23.7
Rhein-Ruhr	8.7	Shanghai	14.3	Tokyo-Yokohama	23.7
Shanghai	7.7	Sao Paulo	13.5	New York-N.E.-N.J.	22.4
Paris	7.2	Los Angeles-Long Beach	11.6	Peking	20.9
Los Angeles-Long Beach	7.1	Peking	11.4	Rio de Janeiro	19.0
Buenos Aires	6.9	Rio de Janeiro	10.7	Greater Bombay	16.8
Chicago	6.5	Buenos Aires	10.1	Calcutta	16.4
Moscow	6.3	London	10.0	Djakarta	15.7

3. MORTALITY LEVELS AND TRENDS

Late in the last century Pearson compared the chances of death on Man's march through life, with a continuous exposure to a succession of marksmen aiming at him with a characteristic spread of hits (Hansluwka et al., 1982). Such hits can be moderate, severe or lethal, depending on the strength and kind of the hit and the strength of Man to resist them. For a population the results of hits are expressed in morbidity and mortality rates. Individual tolerance depends on the constitution and the acquired adaptation. High adaptability and coping capacity are characteristics of Man which provide a remarkable tolerance to the action of environmental stress. However, tolerance varies widely with age and environmental influences and diseases, it is low during infancy, early childhood, advanced and old age, and it is high from early to mid-adulthood. There are vulnerable ages when the resistance and coping capacity are low, and tolerant ages when the resistance and coping capacity are high.

The shape, depth and span of age-specific mortality curves (Figure 7 and 9) of a population in a defined area demonstrate whether there are particular hazards or favourable conditions for certain age groups which can be uncovered by looking into the causes of death. The vulnerability of Man early and late in life is expressed in high, and tolerance in low, mortality rates. Weather and climate are seldom the sole cause of death as in the case of heat stroke due to extreme heat. More important is the contributory stress or aggravating effect of climatic factors on humans with some existing pathology and weakened adaptive capacity. A climatic stress may be harmless or even invigorating for an individual when they are young and tolerant, but fatal in their vulnerable old age, particularly if a predisposing disease exists.

4. THE LATITUDINAL GRADIENT

The UN-WHO joint study "Levels and Trends of Mortality since 1950" (United Nations, 1982b), provides life expectancy data from more developed and less developed countries for a 27-year period from 1950 to 1977 for North America and Europe, Africa, Asia and Latin America. In 37 more developed countries located in cold to warm temperate climates within the 12-year period from 1965-1977 the highest life expectancy for males ranged from 72.7 years in Japan and 71.9 years in Norway to 65.3 years in Portugal and 64 years in the USSR. The corresponding figures for females were 78.0 and 78.1 years in Japan and Norway and 74 and 72.0 years in the USSR and Portugal. The most striking change from around 1950 to the mid-1970's is the disappearance from the list of countries with life expectancies under 64 years of age and the marked separation of life expectancies for the two sexes with a 3 to 10 years longer life expectancy for females than males (Figure 6). For both sexes the highest life expectancies were recorded in the Scandinavian countries and the lowest in the Southern and Eastern European countries and in the USSR. Countries which started with the shortest life expectancy around 1950 showed the highest increase and those which started with the highest life expectancy showed the smallest increase. For comparison in less developed countries of the African continent Algeria, Egypt, Libya and Sudan the life expectancy for the period around 1968 to 1973 ranged for males from 43 years in Sudan to 53 years in Algeria, and for females from 44 years in Sudan to 54 in Algeria and Libya. Life expectancies in Asian countries have been arranged for both sexes combined in three classes of low, medium and high mortality. At the top among the countries with a life expectancy of 60 years and more were Hong Kong (71 years), Singapore (69 years), Kuwait and China (68 years). Countries with a high mortality or low life expectancy of under 50 years were India (48 years), Bangladesh (46 years), Indonesia (47 years). The lowest life expectancies were recorded in Afghanistan (35 years) and Yemen (39 years). The age specific death rates in Sri Lanka illustrate the striking improvements in reducing mortality in a tropical country. The high mortality in the age group 10 to 15 years has declined from 400 in 1945 to 100 in 1970-1972 for males and females alike (Figure 7).

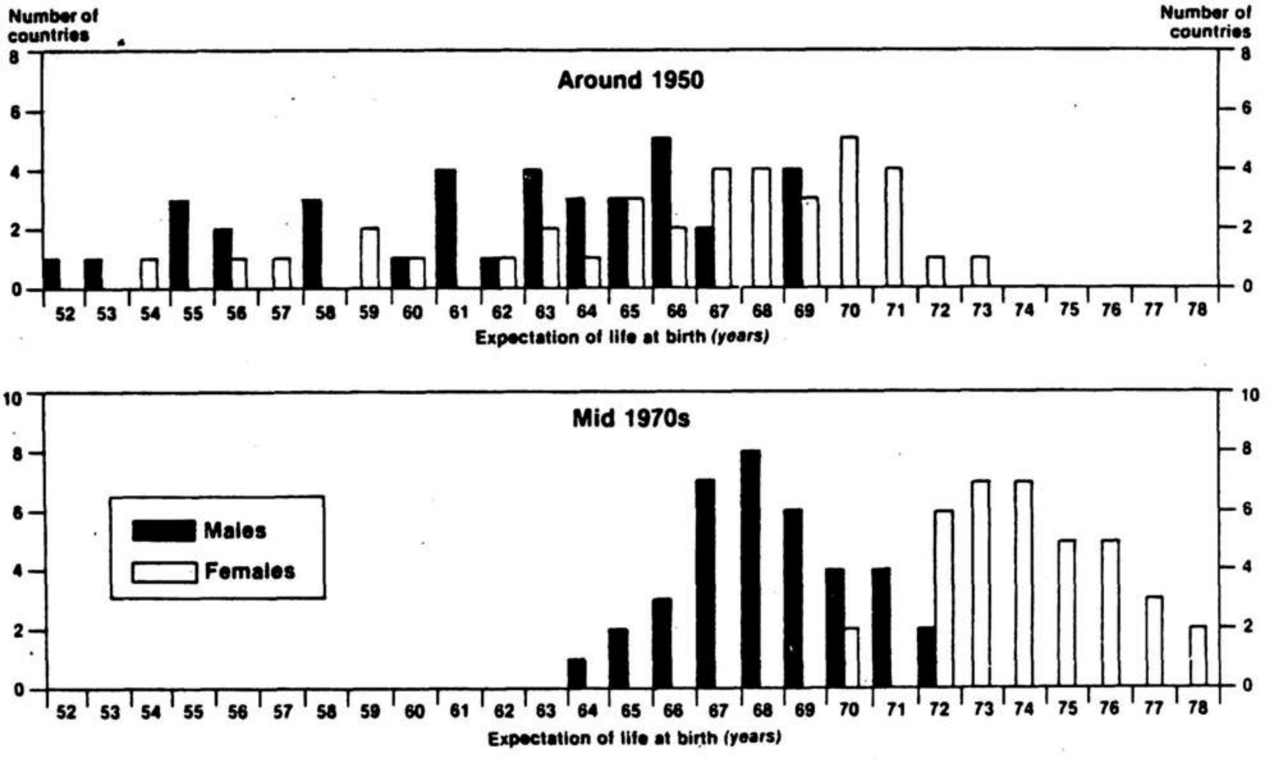

Figure 6. Frequency distribution of expectation of life at birth in 37 more developed countries, males and females, in two periods. (From United Nations, 1982b).

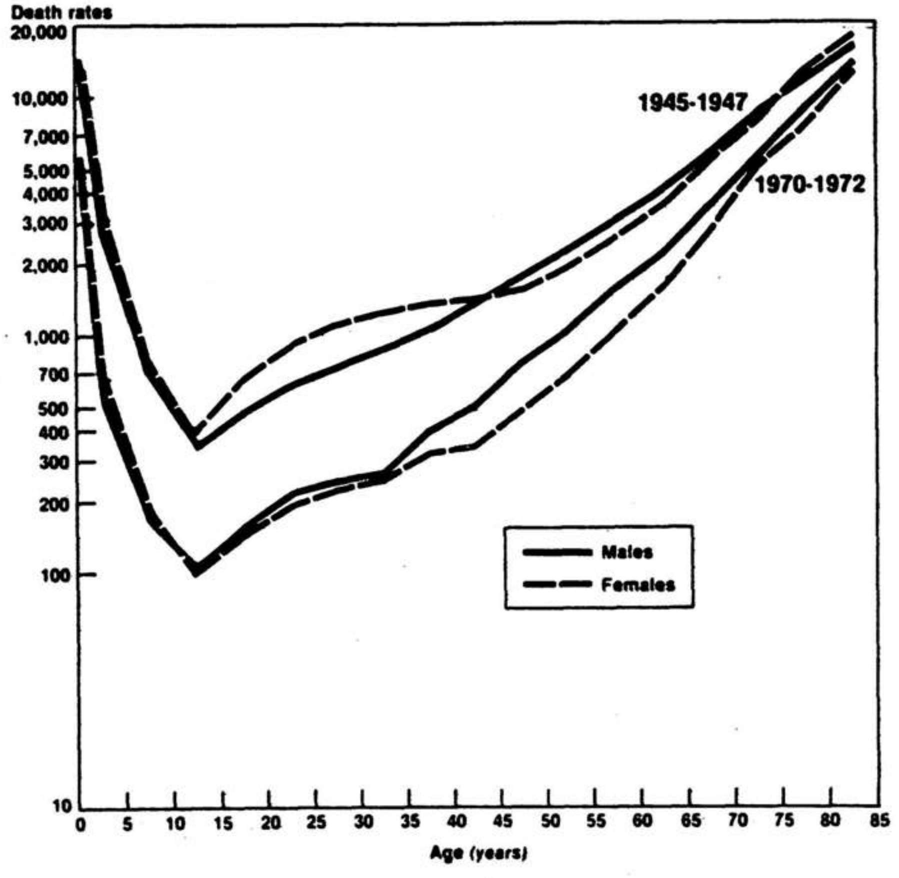

Figure 7. Age-specific death rates, Sri Lanka, 1945-1947 and 1970-1972. Deaths per 100,000 population. (From United Nations, 1982b).

In Latin America the life expectancies in the early 1970's arranged by regions were: Temperate South America 65.4, Caribbean 64.5, Middle America 59.5 and Tropical South America 58.8 years. The region temperate South America included Argentina, Chile, Uruguay, the region tropical South America Bolivia, Brazil, Columbia, Equador, Peru and others (United Nations, 1982b).

The life expectancy data from the more and the less developed countries in temperate and tropical climates reveal that a gradient from high to low latitudes exists. However, in a number of countries in tropical climates long life expectancies are observed which are close to those in the mid-latitudes as in Hong Kong and Singapore, and there are countries with nearly the same climate but large differences in life expectancy, e.g. Kuwait (68 years) and Yemen (38 years).

By and large life expectancies in various regions with tropical and subtropical climates at lower latitudes are moving towards the high levels in regions in temperate climates (Figure 8). But even by the year 2025 the curves are estimated not to have overlapped. This indicates that climate may play a role directly or indirectly in the disparity of life expectancy between regions at higher and lower latitudes.

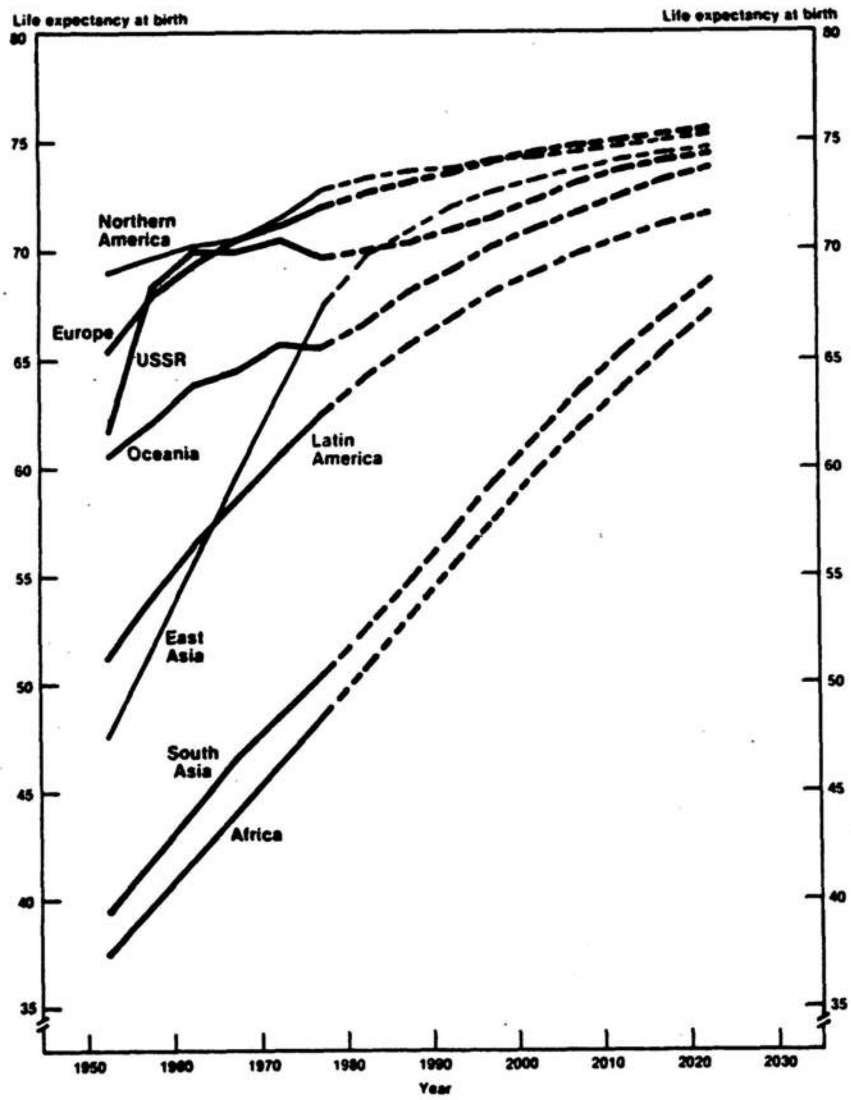

Figure 8. Life expectancy at birth (both sexes) by region, medium variant, 1950-2025, as assessed in 1980. (From United Nations, 1982a).

The demographic trends indicate a rapid increase in size of the higher age groups (45-49, 65-69) in tropical regions with an above average annual population growth (Table 8). The majority of the elderly people will be living in cities where the life expectancy is higher than in rural areas because of better health care.

TABLE 8. *Demographic age structures, both sexes, medium variant, 1950-2000 for 4 selected regions. (United Nations, 1982a).*

Area	Date	Age group (years) 0-4	45-49	65-69
Singapore	1950	165	46	10
	1980	194	109	53
	2000	204	236	87
Mexico	1950	4.635	1.089	379
	1980	11.563	2.270	910
	2000	14.410	4.945	1.687
India	1950	56.079	13.337	8.954
	1980	89.089	28.401	9.450
	2000	106.040	44.740	18.288
China	1950	74.671	28.958	12.065
	1980	98.257	34.099	22.310
	2000	102.618	34.713	34.713

5. THE URBAN-RURAL GRADIENT

Mortality studies in Algeria during the period 1969-1971 demonstrated that "life expectancies were highest in the most urbanized and lowest in the most rural areas". Urban-rural mortality differences are related to density and size of settlement. In 17 states of India in the years 1970 and 1971 infant mortality was lower in urban than in rural communities (Dutta and Kapur, 1982). The urban infant mortality rates ranged from 11 to 134 and the rural ones from 27 to 173 per thousand life births. While on average the infant mortality rate did not change from 1970 to 1978 in rural areas, it declined steadily in urban areas (Table 9). In urban areas of West- and Central-Java and Sumatra mortality declined more rapidly than in the rural hinterlands. For Indonesia during 1970-1974 infant mortality rates were 139, urban 118 and rural 147 per thousand live births. Between 1955 and 1968 a sharp decline in infant mortality for both urban and rural areas was recorded in Thailand which in 1968 was around 25 in urban and 62 per thousand live births in rural communities (United Nations, 1982b). A comparison of the age-specific mortality rates in urban and rural areas of the Republic of China (Figure 9) shows the urban-rural differences as well as the improvement of life expectancy in the young age groups in the period between 1957 to 1975 (Rui-Zhu, 1982).

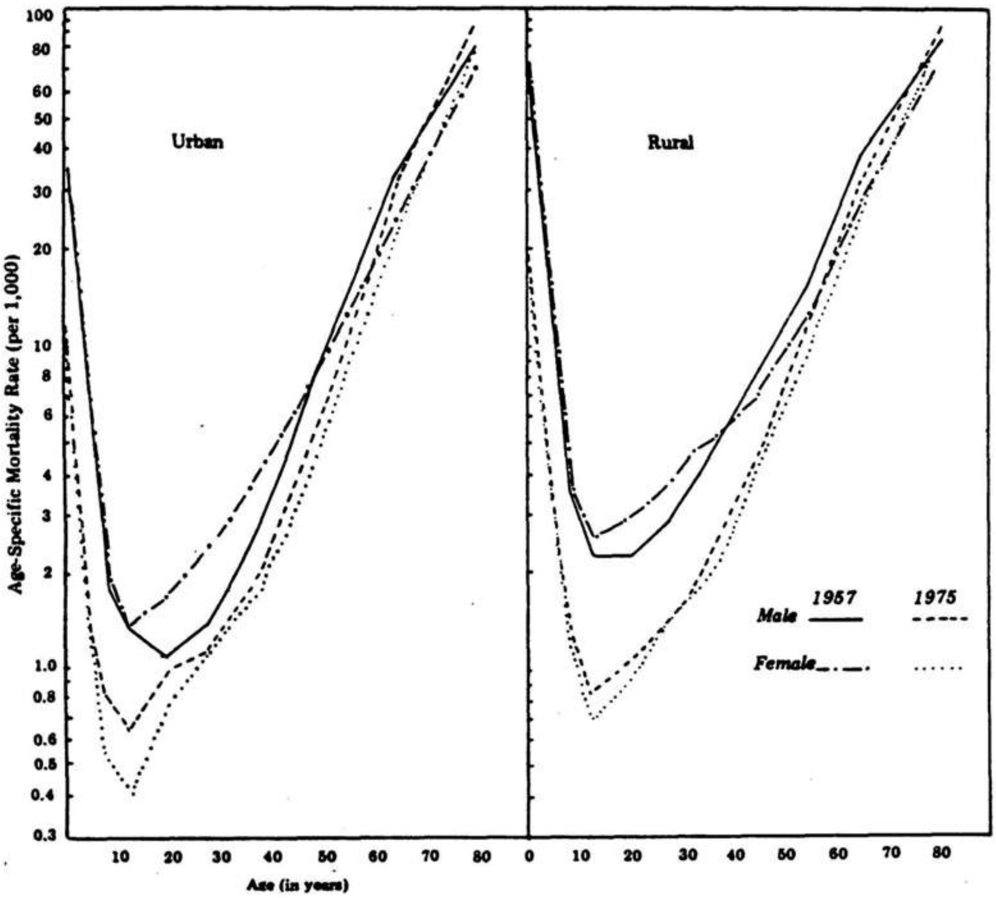

Figure 9. Age-specific death rates in rural and urban areas in China. **(From Ling R.Z., 1981).**

TABLE 9. *Rural-urban infant mortality rates (per 1000 live births), India, 1970-1978. (From Dutta and Kapur, 1982).*

Year	Infant mortality rate rural	urban
1970	136	90
1972	150	85
1976	139	80
1977	142	67
1978	136	70

6. EDUCATION, OCCUPATION, SOCIOECONOMIC AND PUBLIC HEALTH CONDITIONS

There are a few primary determinants by which life expectancy and health in cities are affected. The importance of education of mothers on infant mortality in India from 1970 to 1978 is demonstrated in Table 10. Infant mortality was inversely correlated with the education of mothers. The estimates of infant mortality for some Latin American countries in the period 1970-1974 by educational level of the mother arranged by categories demonstrated that in Bolivia "the mortality level for the lowest educational group is about twice the level for the highest educational group". In contrast to this, in Cuba, mortality levels were least sensitive to the educational level of mothers (United Nations, 1982b).

TABLE 10. *Rural and urban infant mortality rates (per 100 live births) by the level of mother's education and residence, India, 1978. (From Dutta and Kapur, 1982).*

Education level	Rural	Urban
Illiterate	132	81
Literate but below primary	105	59
Primary and above	64	49
Literate and above	90	53

In the USA a strong inverse relationship was found between mortality and degree of education ranging from elementary school to four and more years of college. There is a higher mortality risk for those with a low education level. "That this differential persists into older ages suggests strongly that social and economic differentials play an important role in mortality throughout the life span" (United Nations, 1982b).

In a study in Bangladesh in the years 1974-1977 three levels of occupation were considered, the lowest were agricultural labourers and the highest landowner (D'Souza et al., 1982). In four age groups 1-4, 5-14, 15-44 and 45 years and older the lowest economic groups suffered the highest mortality. In urban areas in the USA manual and service workers showed higher death rate ratios than all other occupational categories.

The economic development of a country is an important determinant of mortality. A negative correlation has been demonstrated between infant mortality and gross national product (GNP), the higher the GNP the lower the infant mortality for the group of more developed countries in 1974. The life expectancy at birth increased correspondingly with the GNP for males and females. This relationship, already noticed in the 1930's, was confirmed again for the 1960's, showing that at a certain national income level the life expectancy reaches a maximum plateau above which no further increase occurs with better provisions for health care through higher income (United Nations, 1982b).

Cities have established high levels of amenities for health control and the most advanced medical services within a country. Urban inhabitants in every country can draw on better health care than the rural population, regardless of level of education, occupation or socio-economic conditions. In India in 1961 there was one physician for every 4,000 persons in urban areas compared to one for every 18,000 people in rural areas. Ten years later in 1971 the relationship urban to rural was 1,500 to 13,000 inhabitants per physician. In Thailand 54% of the physicians and 6% of the population are living in urban areas (Hansluwka and Ruzicka, 1982). In Korea most specialist physicians settle down in city areas with 1,165 people per physician in Seoul city compared to 11,191 people per physician in rural areas (Yang, 1982).

7. CAUSES OF DEATH

In rural and urban areas of China in 1974-1978 cerebrovascular disease, heart diseases and malignant neoplasms were the leading causes of death. In Korea in 1962 and 1972 deaths from cerebrovascular disease, heart diseases and tuberculosis held the first three ranks in mortality, suicide was unchanged at rank 10. Pneumonia and bronchitis dropped from rank 4 in 1962 to rank 8 in 1972, while neoplasms rose from rank 7 to rank 4 (Ruzicka and Hansluwka, 1982). In India between 1958 and 1973 the percent distribution of causes of death from communicable diseases decreased from 65 to 46%. In 32 provinces and 4 regions of Chile spreading from subtropical hot and dry in the north, to subarctic cold and wet in the south, the standardized mortality ratios for

19 cases of death showed a strong relationship with the availability of health services (Haynes, 1983).

TABLE 11. *Causes of death and crude mortality rates per 100,000 population per year in Chile, 1976-1978. (After Haynes, 1983).*

ICD Code*	Cause	Mortality rate	Rank
390-458	Diseases circulatory system	159.1	1
140-209	Malignant neoplasms	100.1	2
460-519	Diseases respiratory system	86.7	3
E800-E999	Accidents, poisoning and violence	73.6	4
780-796	Symptoms and ill-defined conditions	73.1	5
520-577	Diseases digestive system	54.7	6
760-779	Perinatal morbidity and mortality	37.5	7
000-009	Infective and parasitic diseases	33.8	8

* International Classification of Diseases, WHO 1977.

Of the first eight causes of death in Chile (Table 11) mortality from cardiovascular diseases (CVD) was at the first rank, malignant neoplasms were in second position while infective and parasitic diseases were at rank 8. A similar study in Singapore (Kleevens, 1972) in a warm humid climate between 1947 and 1967 showed some remarkable changes in rank order (Table 12). Infective and parasitic diseases at rank 2 in 1947 had moved to rank 8 in 1967, while CVD at rank 6 and neoplasms at rank 10 in 1947 changed to rank 3 and rank 2, respectively in 1967. Accidents, poisonings and violence moved up from rank 7 to rank 6. In Chile (Table 11) these causes of death were at rank 4.

TABLE 12. *Principal causes of deaths, Singapore, 1947-1967, (crude cause-specific mortality rates per 100,000 mid-year population). (From Kleevens, 1972).*

1947	Rank	1967
Symptoms, senility, ill-defined cond.	1	Symptoms, senility, ill-defined cond.
Infective and parasitic diseases	2	Neoplasms
Diseases of the respiratory system	3	Diseases of the circulatory system
Diseases of the digestive system	4	Diseases of the respiratory system
Certain diseases of early infancy	5	Diseases of the nervous system etc.
Diseases of the circulatory system	6	Accidents, poisonings and violence
Accidents, poisonings and violence	7	Certain diseases of early infancy
Allergic, diseases of the blood etc.	8	Infective and parasitic diseases
Diseases of the nervous system etc.	9	Diseases of the digestive system
Neoplasms	10	Allergic, diseases of the blood etc.

In 1975-1977 the three leading causes of death in South and East Asia in 3 out of 4 regions were CVD at the first rank and malignant neoplasms (MN) in 2 regions in the second position (Table 13). Infective and parasitic diseases were at the second rank in 2 regions, that was of equal importance to malignant neoplasms. Accidents, poisoning and violence were at third rank in Japan and Thailand (Ruzicka and Hansluwka, 1982).

TABLE 13. *The three leading causes of death in selected countries of South and East Asia, 1975-1977, all ages. (After Ruzicka and Hansluwka, 1982).*

Country	Rank First	Second	Third
Hong Kong	CVD	MN	RSD
Japan	CVD	MN	APV
Philipines	CVD	IPD	IDV
Thailand	IDV	IPD	APV

CVD = diseases of the circulatory system
IPD = infective and parasitic diseases
MN = malignant neoplasms
RSD = diseases of the respiratory system
IDC = symptoms and ill-defined conditions
APV = accidents, poisonings and violence

The distribution of causes of death in countries in tropical climates has changed to become more like those in the more developed countries of temperate climates (Figure 10). From 1955-1959 to 1970-1974 deaths from cardiovascular diseases rose from 44 to 48% and deaths from malignant neoplasms from 16 to 19%. Mortality from respiratory diseases was around 10% in the particularly vulnerable age groups of very young and very old people of 75 years and older. In an analysis of trends in mortality from cardiovascular diseases in more developed countries from 1950 to the mid-1970's separated for both sexes in 11 of 28 countries male mortality increased, and decreased only in 8 countries. For females the development was more favourable, 20 out of 28 countries recorded consistent declines in female mortality. In Japan, the average decline was 48% in three age groups from 25 to 74 years (United Nations, 1982b). The largest percentage of overall mortality in the tolerant age groups, with a maximum at 20 years of age, was from accidents and violence, and in males higher than in females.

The largest percentage of mortality at the vulnerable ages after about 55 years of age was from cardiovascular diseases. The participation of neoplasms also increased with advanced age with the maximum value between about 50 and 60 years for the two sexes. But while with increasing age the mortality from cardiovascular diseases further increased, the mortality from malignant neoplasms declined in the higher age groups. The percentage mortality from other causes than those particularly designated remained fairly stable over the 20-year period from 1955 to 1974 while the mortality from infectious diseases had fallen strikingly. The same change has also been noticed for data from less developed countries.

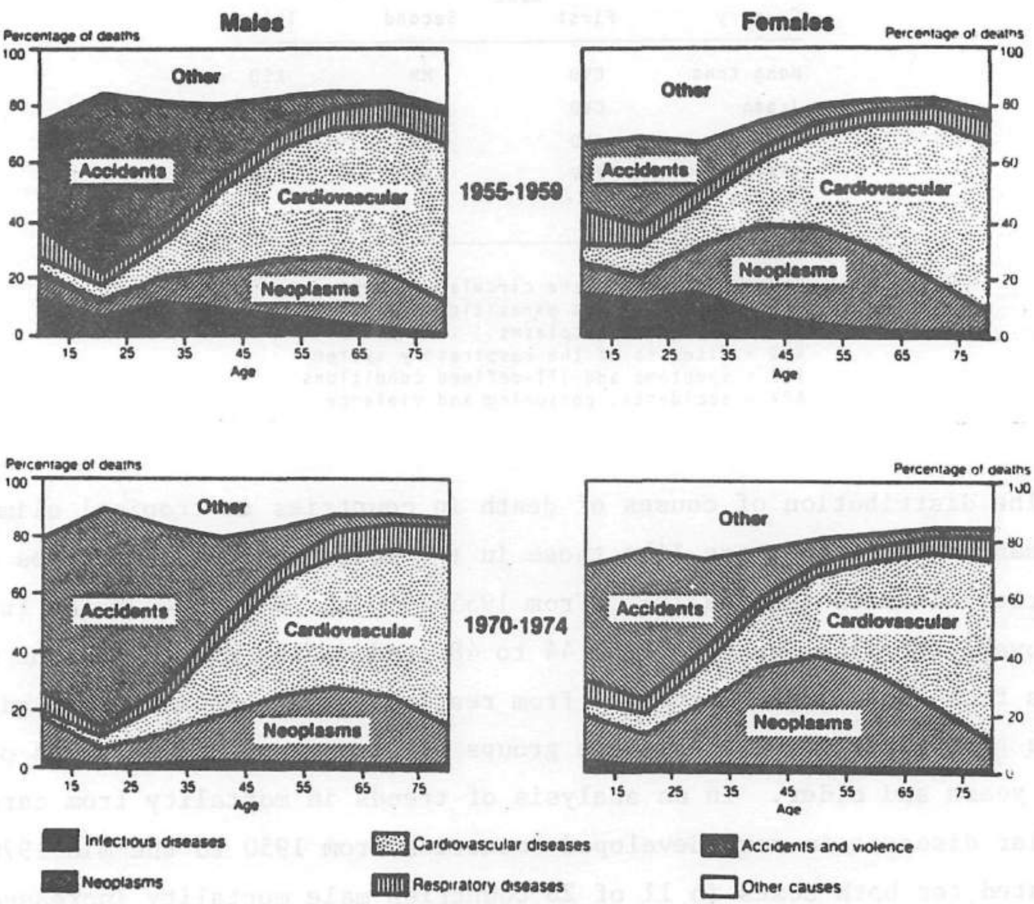

Figure 10. Trends in the percentage distribution of six broad grounds of causes of death to overall mortality by age group and sex, averages for 23 more developed countries, 1955-1959 to 1970-1974. (From United Nations, 1982b).

Of great importance with regard to possible impacts of climate are the age-specific death rates from CVD among adults above 20 years of age (Figure 11). The mortality curves in the mid-1970's averaged for 25 of the more developed countries display a time lag between males and females. The death rate of 200 per 100,000 population for men at the age of around 47.5 years corresponds with that for females 8.5 years later at 56 years of age. This time lag between the sexes narrows progressively with increasing age until it disappears at 85 years and older. These striking differences between the sexes have been mentioned for life expectancy above (Figure 6).

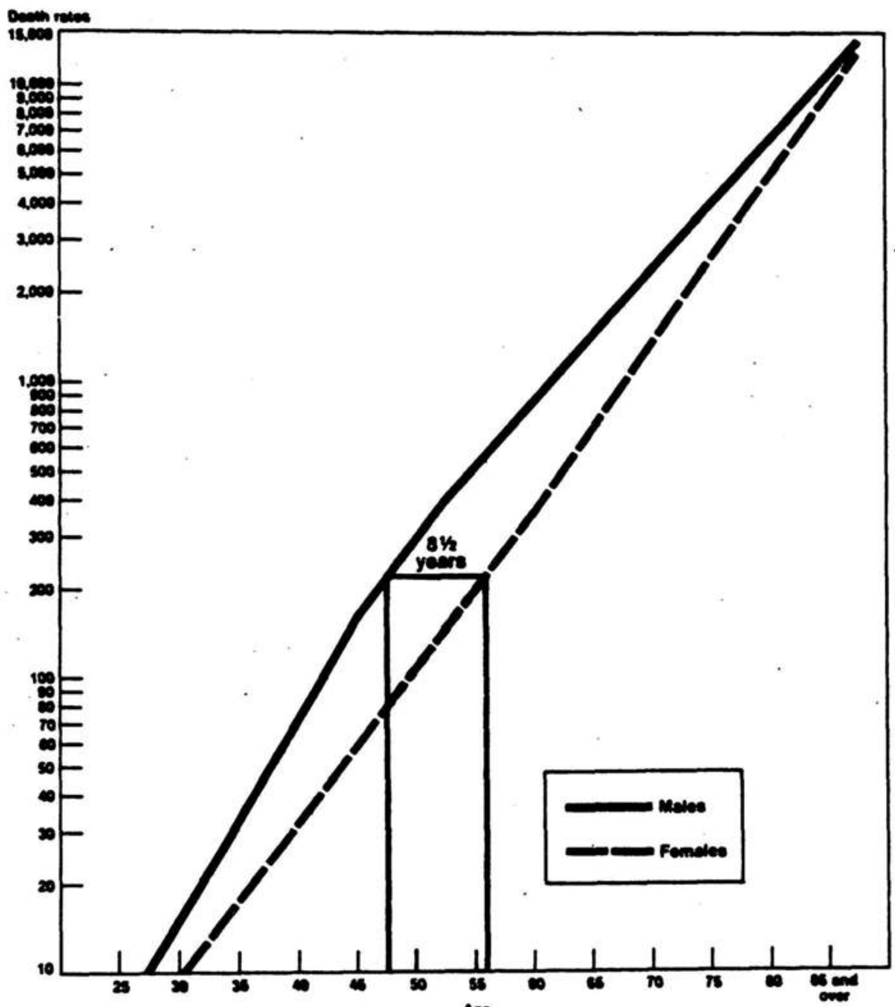

Figure 11. Age-specific death rates from cardiovascular diseases (CDV) among adults, averages for 25 of the more developed countries, mid 1970's. Deaths per 100,000 population. (From United Nations, 1982b).

8. CLIMATE AND CARDIOVASCULAR DISEASES

Sakamoto-Moniyama (1977) has correlated monthly mortality rates from cerebrovascular diseases with mean monthly temperatures for a series of countries. The death index increases linearly as temperature decreases below 24°C mean monthly temperature. Low mean monthly temperatures correspond with high CVD death rates, but at higher mean monthly temperatures mortality rates increase again. Particularly striking was the mortality increase in the hot months in Egypt and Tokyo where the mortality at 26° and 28°C mean monthly temperatures was as high as between 6° and 8°C. The critical mean monthly temperature around which the lowest death rate from CVD in every country appears to lie is at 24°C, above and below this temperature mortality increases. Rogot and Padgett (1976) found low mortality for selected areas in the USA on days with 15.6° to 26.5°C mean temperature as the ideal range.

These large scale observations are supported by local studies on excess mortality from CVD during hot summer months and heat waves. Of 460 cases of heart infarction between 1948 and 1951 in Cairo and Alexandria, 151 cases were from June through August, 85 from September through November and 106 cases from December through February (Avierinos, 1955). The mean monthly temperatures during the June through August summer months were 27.2°C, 28.3°C and 28.9°C compared to 20.0°C in November and 13.3°C in December and January.

During a heat wave from 9 to 14 July 1966 in St. Louis, daily maximum temperatures were between 38.3° and 41.1°C on six consecutive days; night temperatures were 5.0° to 7.5°C higher than in the periods before or afterwards. The weather preceding the heat wave was already considered hot. Between 9-14 July daily mortality rose from the expected 35 deaths per day to 152 deaths for all age groups (Henschel et al., 1969). The increase of excess deaths began on the second day and reached a maximum on the fourth day. No case occurred in the age group 1-19 years, 50% of all cases were in the age group over 65 years. In the period of the heat wave, including the 8 days before and 2 weeks afterwards, the most frequent causes of death were CVD; of the 35% primary heat death, females suffered more than males and the proportion of heat deaths to total deaths was greater for Negroes than Whites. The cases of heat death were not randomly distributed throughout the city area but clustered within the city core inhabited mainly by Negroes with poor housing conditions and overcrowding.

A comparison of the heat-wave deaths in New York with those in St. Louis during July 1966 demonstrated that mortality from all causes increased by 36% in New York and 56% in St. Louis (Schuman, 1972). Predisposing factors were: being over 65 years of age, low income, crowding or poor housing, hypertension, arteriosclerotic, cardiovascular or other circulatory diseases, diabetes or chronic respiratory disease. In the New York heat wave only 6 of 16 major causes of death were elevated above expected levels, 490 of the 1181 cases of excess deaths were from arteriosclerotic heart disease. During the heat waves there was a 138.5% increase of death rate from homicide and reports about clashes with police in the streets. The pediatric deaths of infants under one year of age were controlled during the heat period which suggested that preventive medical and environmental measures were effective, while geriatric deaths were uninfluenced.

The intra-urban variation of heat deaths for St. Louis ranged from -10% and -18% to +260%, +179% and +110%. In a large acreage area of parkland it was +94%, in a concrete area +179% or downtown +141%. The correlation with age composition showed that residents in the low risk area were older than the St. Louis median age of 33.6 years while in the high risk areas residents were somewhat younger. In New York City a low death rate was +10% at Bedford and a very high death rate was +140% at Williamsburg-Greenpoint. Here the age factor was critical with the distinctly younger population in Bedford and a poor older population in Williamsburg-Greenpoint.

Shattuck and Hilferty (1936) reported on mortality from acute heat effects in various parts of the world: "The proportion of deaths from heat in Europe and the British Isles is much smaller than in the United States. Canada has a decidedly smaller proportion of deaths from heat than has the United States. Apparently there are a few deaths from heat in Mexico City, the West Indies or Bermuda. The figures for Central America, for South America, for Africa and Asia permit of no generalization. Some rates are notably low and others outstandingly high. The striking divergences indicate the need for further data from these regions."

From records in national archives they noticed: "The rates for soldiers from the British Isles in India are extraordinarily high whereas those for native soldiers are comparatively low. Deaths from heat are not numerous even among Europeans in the parts of Africa referred to, but it is evident that the Europeans are more susceptible to heat than are the native races."

In an investigation of the relationship between cardiovascular mortality and weather in Memphis, Tennessee, it was observed, "that sudden deaths from arteriosclerotic heart disease may be the ones for which the effect of weather is greatest" (Rogot and Blackwelder, 1970).

The adverse heat effect of city climate as compared to rural climate on mortality rate was reported by Jones et al. (1982) for St. Louis and Kansas City. During the 1980-heat wave, deaths from all causes increased by 57% and 64% respectively in downtown areas, but only 10% in predominantly rural areas of Missouri. One out of 1,000 residents of the two cities was hospitalized or died of heat-related illness. Chiefly affected were the people over 65 years of age, the poor and the non-white. The daily minimum temperature in central Kansas City averaged 4.1°C above that at the suburban airport, demonstrating the nighttime heat stress to which the city population was exposed. The maximum temperature was at 38.9°C on 17 consecutive days and increased on 10 days to 42.2°C.

For European countries similar observations have been reported. The critical temperature seems to be at a lower level. At daily maximum temperatures above 32°C in July 1983 in Rome, Italy, mortality from cardiovascular diseases rose 59% while there was only a small increase of 13% from other causes (MMRW, 1984). During a hot period in the city of Stuttgart, Germany, the mortality among old people increased 30% in the city proper and 15% in the outer regions. The night temperatures inside the city were 18 to 20°C while the air cooled down to 8 to 9°C on the hills which surround the city 200 m higher (Liedermann, 1979). It was pointed out that these conditions reduce the life expectancy of the older population. According to Collins et al. (1981), elderly people over 70 years of age in England have the same preference temperature of 22 to 23°C as young adults but are slow in adjusting to ambient temperature changes due to a higher temperature discrimination threshold.

LIFE EXPECTANCY AND THE TROPICAL CITY

Ellis (1972) has found several relationships from an analysis of mortality from heat aggravated-illness in the USA. Excessive heat was much more lethal than air pollution. Vulnerable groups were the very young and the aged, the sick and the infirm. The leading causes of excess deaths were arteriosclerotic heart disease, respiratory diseases, certain diseases of early infancy, renal disease and influenza. The highest mortality rate was among persons of 65 years of age and older. During repeated heat waves in New York City in 1972 and 1973 it was confirmed that the majority of deaths occurred in persons older than 65 years (Ellis et al., 1975). Deaths from ischaemic heart disease greatly outnumbered those from cerebrovascular events such as stroke on the two days which followed the hottest day of the heat waves. Oechsli and Buechley (1970) reported on excess mortality from heat in Los Angeles in 1939, 1955 and 1963, that maximum temperature below 35°C had little effect on mortality. "Excluding epidemics, the excess mortality in each one of these periods is greater than in any recorded natural disaster in the history of the State of California." The relationship between excess heat and excess mortality for the New York-New Jersey metropolitan area heat wave in July 1966 was (Buechley et al., 1972):

Temperature (°C)	Excess mortality to heat (% of annual means)
32.2	negligible
35.0	27
37.8	75
40.6	200
43.3	546

"Very strong positive relationships appear between temperature measures and logarithm of population density, and a very strong negative relationship between log density and growth in population. Other relationships appear between income, air conditioning and growth but not as strong as those with density."

Following the meteorologist's description of the increase of temperature in the core of cities as heat islands Buechley et al. (1972) introduced the term "urban death island" with reference to the positive correlation between increase of air temperature and increase of excess deaths. On the basis of their equation of the temperature specific mortality ratio (TMR), in which temperature, population density and income levels are considered, they predicted an excess mortality of about 160% for a suburban area and 260% for a core area. They calculated excess deaths from a heat island effect in a city core area for a limit temperature of 39.5°C. An increase of excess deaths was already noticeable at daily temperatures of around 33°C (Clarke and Bach, 1971).

9. HEAT TOLERANCE LEVELS

Tolerance to heat can be assessed as tolerance to temperature alone or to temperature in combination with humidity, wind velocity, and short- and long-wave radiation. In tropical climates the consideration of several factors is required because they form the heat load against which the body has to regulate in order to maintain the heat balance. Many proposals for the combination of several meteorological factors have been suggested which are all classified as indices. The most widely known index is effective temperature, ET, based on subjective reporting of comfort under varying conditions of dry and wet-bulb temperature and air velocity (Chrenko, 1974).

Tolerable and desirable levels of warmth based on effective temperature (ET) have been reported by Ellis (1950; 1953) as follows:

Area	ET (°C)
Comfort zone United Kingdom (winter)	14 - 17.2
Optimum comfort zone USA (summer & winter)	18.9 - 22.8
Optimum comfort zone USA (summer)	20.6 - 22.8
Annual comfort zone Calcutta	20.6 - 24.7
Comfort zone Singapore	22.8 - 25.6
Upper limit comfort zone Iran	25.3
Comfort zone Calcutta (Rao, 1952)	26.9 - 27.6

A critical region of room effective temperatures was found at ET 28.3°C above which the majority of acclimatized men lightly clad will work less accurately and have restless sleep. This ET level corresponds to Ta/Twb values of 32.2°/26.7°C and 35.0°/29.4°C with an air movement of 0.5 m s^{-1}. The values are around the level above which the "death-island" effect begins for weak persons with poor cardiovascular regulation (Buechley *et al.*, 1972). For

Calcutta air temperatures of 30.6-30.7°C were reported to mark the line above which comfort turns into discomfort. This high temperature indicates the remarkable heat tolerance of the inhabitants (Rao, 1952). Auliciems (1982) found group thermal neutrality for climates from all parts of the World to range from 17 to 31°C. Group neutrality is variable due to seasonal acclimatization. This has protecting effects for people in tropical cities as long as their adaptive capacity is not reduced by systemic cardiovascular diseases.

Investigations of urbanized populations in developing countries point to a waxing incidence of alterations of the cardiovascular system. Hypertension is increasing in Africa (Akinkugbe, 1972). The development of hypertension is closely related to urbanization and Westernization because the incidence among rural Africans is low (Isaacson, 1983). Seedat and Reedy (1976) stated that urbanization, obesity and excessive salt intake are predisposing factors of hypertension in African populations. Hypertension is an emerging disease of the urbanized African with further increasing incidence. The majority of patients at Durban, S.A., were between 30 and 50 years old. Ninety percent of African patients suffering from hypertension were from urbanized areas where they had been for at least 5 years.

Heat tolerance levels depend on the length of hours of exposure during a diurnal cycle. As long as there are an equal number of cool night hours after a hot day for restful sleep it is possible to recover from the daytime heat stress and if there are more cool hours at night, higher heat daytime conditions can be tolerated. The balance in the daily cycle of activity-fatigue-recovery is disturbed when recovery from fatigue is hampered by heat during the physiological sleep period at night. The diurnal variation between hot and cool hours during the activity-fatigue-recovery cycle plays a major role in the resistance of individuals with long term cardiovascular diseases or exhaustion. When this is disturbed for one or two days in the event of a heat wave, excess mortality increases (Figure 12) (Clarke, 1972).

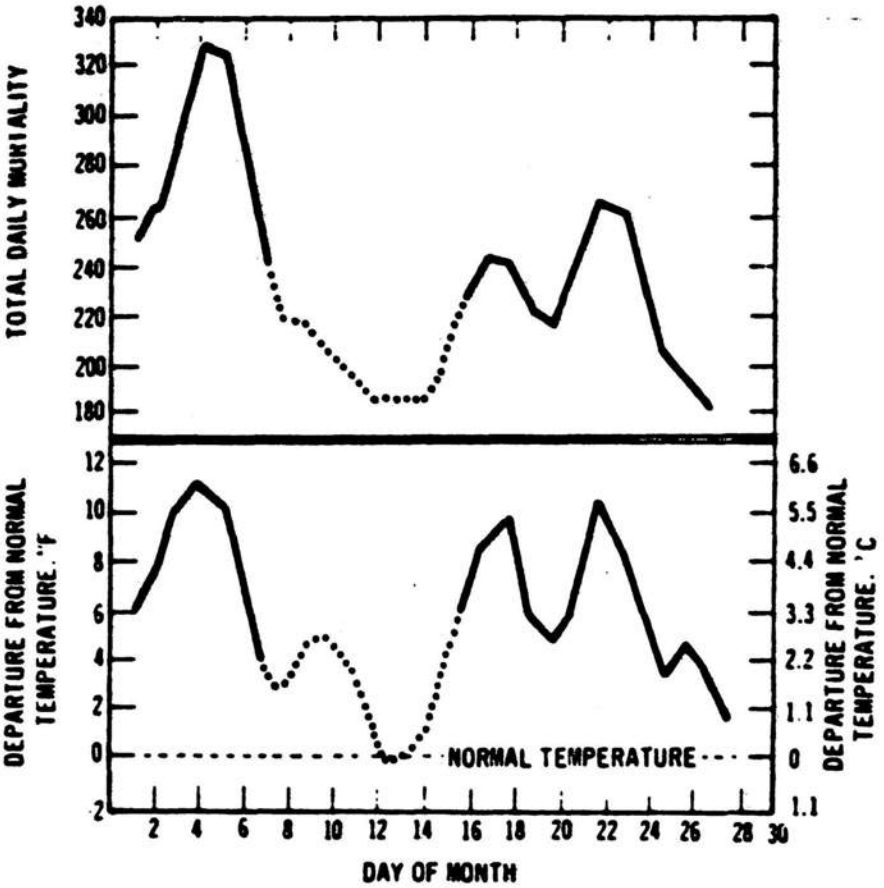

Figure 12. Three-day departures from normal temperatures in Central Park, New York City and 3-day running mean values of total mortality July 1955 in New York City. (From Clarke, 1972).

The total sleeping time (TST) of young men sleeping naked under experimental conditions was longest at neutrality ambient temperature of 29°C. The TST was drastically reduced at ambient temperatures above and below neutrality, and the changes in sleep patterns in the heat mirrored those in the cold (Haskell et al., 1981). During the REM sleep phase (rapid eye movement) the responsiveness of the sweat gland activity and the sensitivity of the regulatory system is at a lower level and there is a widening of the interthreshold zone between heat production and heat dissipation (Libert et al., 1982). During REM sleep the heat tolerance is reduced which is noticed by a faster and greater increase of the heart rate in comparison to SWS (slow wave sleep). The increase of the heart rate indicates heat accumulation in the body before the onset of sweating. With covering the body neutrality of the naked body is lowered to lower temperatures falling well into the range of ambient temperatures of night-time city heat islands.

LIFE EXPECTANCY AND THE TROPICAL CITY

Ethnic differences in climatic tolerance have often been considered. In Malaysia infant mortality for three ethnic groups was high for Malay and Indians and low for Chinese in 1950-1959, and declined up to 1978 steadily in an almost equal proportion (Kit, 1982). Mortality in the first years of life reflects more the health care and socio-economic conditions than adaptation of the individual. The differences between the ethnic groups were the result of quality of nutrition, preventive health measures and living conditions. For adult populations ethnic differences in tolerance to climatic stress have not been verified in any part of the World. When differences appear to be operative further analysis reveals that the state of adaptation and behavioural patterns of the people alleviating or aggravating the climatic situation played a decisive role. The same applies to comparative studies on the temperature tolerance of soldiers moved to another climate as from temperate to tropical climate (Ellis, 1953). Differences between newcomers or immigrants disappear as adaptation and learning on how to deal with the new climate proceed. Differences between races, e.g. Negroes and Whites, in cities are commonly based on available living space, nutrition, occupation, behaviour, and education. Education is a particularly important factor, as it provides the individual with the necessary knowledge to behave reasonably in a given climatic situation.

Physical fitness of Singhalese, Moors, Cylon Tamils and Indian Tamils in Colombo and the country of Sri Lanka was related to differences in the body configuration. Persons in the wet zone of the country had a higher mean fitness index than in the dry zone and in Colombo City (Cullumbine, 1949).

10. CITIES AS HEAT ISLANDS

Heat islands in cities are the result of heat storage in buildings, reduced evaporative heat loss from paved surfaces with quick runoff of water after rain, reduced wind velocities near the ground where people move, and increased long-wave radiation from buildings and pavements (Landsberg, 1970). The relationship between city size and the development of heat islands that form the foundation for death islands is expressed by the data of Table 14. The larger the city area and the population, the greater is the mean urban-rural temperature difference. A comparison of climates in Kansas City with 1.1 million, Topeka with 132,108 and Lawrence with 45,698 inhabitants in 1971-1972 showed that the extent of climate modification in cities closely depends on the magnitude of the urbanized areas (Eagleman, 1974; Oke, 1973). The modifications in the climate were an increase of air temperature, a decrease of relative humidity and increases of comfort index and potential evapotranspiration. Differentials between urban and suburban air temperatures for paved and grass surfaces from 12 to 22 h in Figure 13 demonstrate the reduced cooling of the air over the urban surfaces (Clarke and Bach, 1971). The change in urban and rural temperatures during a complete diurnal cycle in Dallas differed particularly during the night hours (Figure 14). While the maximum temperatures in the early afternoon were equally high for urban and rural areas, the minimum temperatures in the early morning differed by several degrees. In the rural area they fell to those of the range for comfort at rest, while in the city core they remained high, in the discomfort range for man.

TABLE 14. *Comparison of urban heat island and city size. (From Clarke, 1972).*

	San.Francisco	San.Jose	Palo Alto
Population	784.000	101.000	33.000
City area (Km^2)	116.5	38.6	22.2
Density (population/Km^2)	6.730	2.617	1.486
Mean urban-rural difference (°C)	6-7	4-5	2-3
Greatest temperature difference	11.1	8.3	7.0

Differentials in heat to which Man is exposed when living in urban or suburban areas are summarized for 7 indices in Table 15 (Clarke and Bach, 1971). The values for all indices are higher over paved surfaces than over grass and in urban rather than suburban areas. Values of Hr and Hc indicate the heat gained (positive) or lost (negative) by the body. The greatest body heat loss was in the evening hours at the suburban grass site.

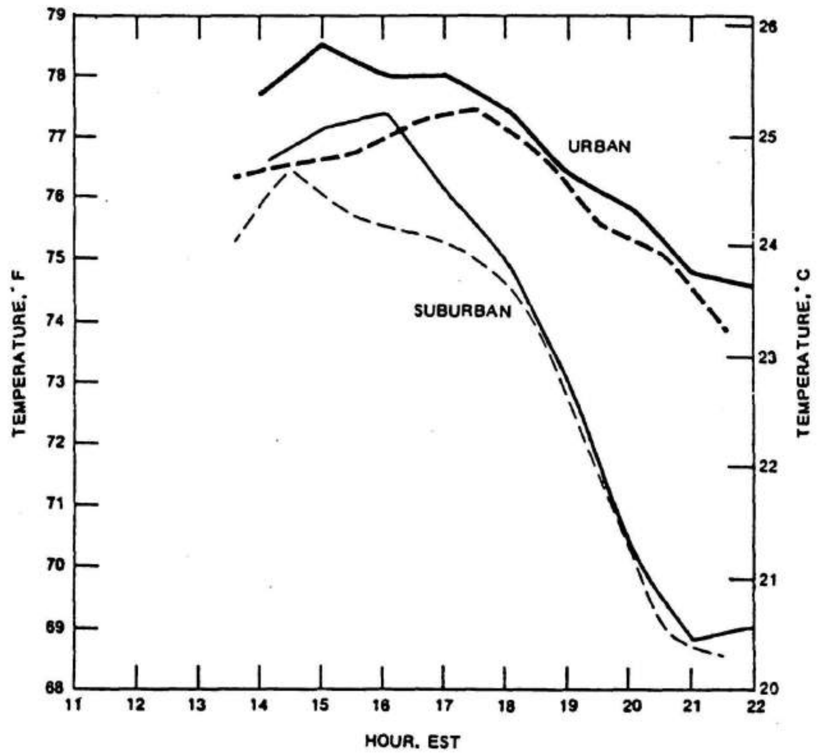

Figure 13. Mean variation of effective temperature over paved (solid lines) and grass (dotted lines) surfaces at urban and suburban sites in Cincinnati City and at a suburban home 27 km east of the city. (From Clarke and Bach, 1971).

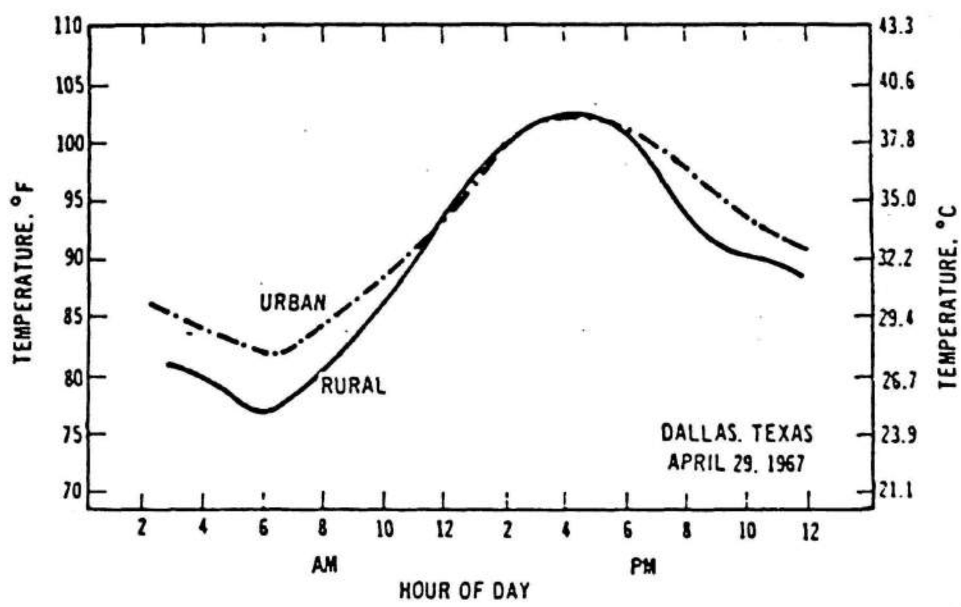

Figure 14. Diurnal variation of rural and urban temperatures. (From Clarke, 1972).

TABLE 15. *Mean values of thermal indices, August 1969, Cincinnati, Ohio. (After Clarke and Bach, 1971).*

Index	14:00 - 15:30 h				20:30 - 22:00 h			
	Urban		Suburban		Urban		Suburban	
	Paved	Grass	Paved	Grass	Paved	Grass	Paved	Grass
ET (°C)	25.6	24.8	24.9	24.5	23.7	23.0	20.5	20.4
CET (°C)	24.8	23.7	24.5	23.8	23.2	23.1	20.3	19.9
CEGT (°C)	28.6	26.3	29.6	28.0	23.6	23.2	19.9	18.9
WBGT (°C)	26.2	24.4	26.9	25.3	22.4	22.2	19.4	19.3
DI (°C)	25.6	24.7	24.8	24.3	23.7	23.6	20.8	19.4
H_r (Btu/hr)	817	470	1042	835	-185	-251	-446	-528
H_c (Btu/hr)	-112	-162	-110	-169	-179	-158	-136	-198
Total	705	308	932	666	-364	-409	-582	-726

ET = effective temperature, $0.4\,(T_a + T_{wb}) + 4.8$
CET = corrected effective temperature, $T_a + T_{wb} + v$
CEGT = corrected effective globe temperature, $T_a + T_g + \ddot{v}$
WBGT = wet bulb globe temperature, $0.7\,T_{wb} + 0.2\,T_b + 0.1\,T_a$
DI = distress index, $0.4\,/T_a + T_{wb}\,) + 15$
H_r = radiant heat exchange (H_r 17.5 ($\bar{T}_r$ - 95), °F
H_c = concective heat exchange ($H_c = 0{,}756\ v^{0.6}\ (T_a - 95)$, °F

In Singapore, located near the equator, where the mean monthly temperatures vary little throughout the year, changes in effective temperatures have been recorded from changes of relative humidity and wind. The acceptable level of ET 24.4°C at Singapore Airport is exceeded during April and May while at Changhi Airport a more comfortable climate is found than in central Singapore because of the availability of wind for cooling (Stephenson, 1963).

For Mexico during 1959-1963 Jauregui and Soto (1967) demonstrated that the tolerable level of the distress index at 48 was exceeded at 14 h as well as at 07 h in Acapulco for almost all months of the year, while the level of discomfort was never reached in Mexico City. This was at a time when the rapid growth of the city began. The city has the advantage of the location at 2300 m elevation where the decrease of temperature with altitude is already effective. It remains to be seen to what extent the favourable temperature conditions still exist after the city has grown even further.

11. CITIES AS DEATH ISLANDS

Cities in tropical climates can easily turn into death islands when they are too large, dense, with short distances between buildings and little green land. Taking 35°C as the upper critical temperature for heat-aggravated death to occur, the vulnerable age groups of the population of Calcutta where the mean monthly maximum temperature is 36.1°C (Table 7) will be particularly endangered. The more so as the incidence of cardiovascular diseases from urbanization increases. Critical situations will arise in other future mega-cities such as Shanghai, Bombay and Djakarta. Tolerable temperatures during the day and night can be readily exceeded so that inhabitants will succumb when weakened from systemic diseases such as those of the cardiovascular system, or when performing heavy physical work continuously, or excessive eating or exercise, when overclothed, crowded and without facilities for providing cooling, such as bathing, showers, ventilators or air conditioning. Elderly people are particularly prone to untimely death due to their reduced capacity to cope with heat. This is expressed in the increasing mortality rates from CVD in the age groups 55 to 64 years and older **(Figure 10).** The death toll will rise further as populations in tropical cities grow older (Table 8). With higher life expectancies for young age groups as a result of the elimination of mortality from infective and parasitic diseases with the improved health control within cities, the percentage death rates from CVD will increase.

The second important cause of death in cities may well be malignant neoplasms aggravated by toxic substances in the stagnant air in cities, polluted with volatile irritants and toxic compounds from the rising use of modern building and household materials, motor vehicle and industrial exhausts. Where the ventilation over an urban area is inadequate so that the polluted air is not regularly replaced by clean air the acceptable daily quantities of irritants are soon exceeded, reaching intolerable toxic concentrations. This may promote the incidence of malignant neoplasms and allergic diseases from hypersensitivity to air pollutants.

A further adverse effect of growing tropical cities to be anticipated is the effect of heat on homicide and suicide aggravated by an increased consumption of alcohol (Ellis <u>et al.</u>, 1980) among the younger age groups between 20 and 45 years. This has been reported from various cities including the 12 cities of the PAHO study (1967).

12. DISEASES DIRECTLY AND INDIRECTLY AFFECTED BY CLIMATE

Diseases of direct impact of heat (ICD 992) namely heat stroke, heat collapse and heat exhaustion are preventable through the appropriate behaviour and removing affected persons to cool premises for treatment. Cardiovascular diseases are directly aggravated by climate while most malignant neoplasms are not. An indirect effect of climate may occur where carcinogens in polluted air over cities reach toxic concentrations over long periods. Skin carcinoma is aggravated directly by exposure to UVB radiation. UVA and B radiation intensity is high in tropical climates, especially at elevations of 1500 to 2500 m where many cities in the tropics are located, such as Mexico City at 2300 m. Native inhabitants are aware of the dangers of sunburn. They are naturally protected against the skin damage by a dense melanin layer in the skin and have learned to avoid exposure by proper clothing and behaviour. Ultraviolet radiation exposure is required by Man for the formation of Vitamin D. Lack of this vitamin in children leads to rickets. Rickets in tropical climates are observed when infants and children are kept indoors in poorly lighted dwellings as is still customary in parts of Ethiopia. Cases of rickets have been reported recently from Mexico City since the UV intensity has decreased due to absorption by air pollution.

Respiratory diseases are indirectly aggravated by pollutants in the air. A direct effect of warm dry or warm humid air is of minor importance as long as there is no major pulmonary infection such as tuberculosis. Tuberculosis morbidity can be high in cities among poor people living under crowded conditions in slums. But such endemic areas can easily be put under health control to avoid its spread.

Diseases of the gastrointestinal system, and gastric and duodenal ulcers have often been related to climate and weather. An aggravating effect of heat and UV exposure cannot be excluded but such effects are often in conjunction with other stress factors. Infections of the intestinal tract are indirectly facilitated because the temperatures of the fluid media in tropical climates favour the viability of causative parasites, e.g. amoeba and enteroviruses.

Water and sewage control and sanitary installations in houses effectively serve to avoid the development and spread of these infections and such control can be carried out more easily in cities than in rural areas.

There are no non-communicable diseases of major importance that are only found in tropical climates. True tropical diseases are communicable diseases, caused by parasites and transmitted by arthropods and other species as vectors. The reproduction and life of these arthropods is climate dependent, therefore, diseases are only found endemic in the areas inhabited by the vector insects. Examples are the Aedes species for yellow fever, Anopheles species for malaria, Similium species for onchocerciasis, Glossina for African trypanosomiasis, Triatoma species for American trypanosomiasis or Chagas disease and aquatic snails for schistosomiasis. Onchocerciasis which was originally limited to Africa, has now been observed in Mexico after it was carried over from Africa to Latin America, supposedly by infected colonial troops. These diseases can be effectively controlled within cities and suburban areas. Anopheles species breed inside houses, ponds and small waterholes under conditions which are common in city slums with improper or non-existent drainage and hygienic facilities. Great efforts are required to keep Anopheles populations down. An eradication of malaria has been highly successful in large tropical areas and this will be continued through mutual effort.

13 PREVENTIVE MEASURES AGAINST ADVERSE EFFECTS OF CITIES IN TROPICAL CLIMATES

Preventive measures, including the eradication of communicable diseases, are specific problems of environmental health that have been considered for large metropolitan areas on an international basis for some time (WHO, 1965; Martin, 1977). The standards for health and comfort of dwellings in different climates apply to rural and urban living alike with some modification (Goromosov, 1968; Senn, 1979). Air conditioning of buildings might be required in factories and offices where heat conditions are such that they suppress occupational performance. The gain in working efficiency may be outweighed by the loss of adaptation of the workers, with less resistance to heat in the uncontrolled room climate of private houses. Cooling of buildings is expensive and the energy required for it contributes to the heat load in the city core. Simpler conventional means such as air ventilators seem more advisable because they produce less heat and do not interfere with human adaptation. The placing of city hospitals in areas where natural cooling is provided is a simple method of saving expenses for air conditioning. The thermal comfort of patients in hospital wards provides a good standard for recommendations on tolerable conditions of the vulnerable age groups (Smith and Rae, 1977). For healthy persons in the working age group complex indices, which consider the major meteorological factors contributing to the build up of heat islands in cities, might prove to be useful for future planning of city layouts (Jendritzky and Nübler, 1981).

Lee (1975) has listed threats and failures of housing in cities. "High dependency upon the supply of energy, creation of heat islands in city cores, development of urban agglomeration and social unrest, interpersonal competition for available interior space, dangers from household chemicals and medicaments, climatic deconditioning of occupants, increasing economic constraints".

Cities offer the most chances for the individual to improve the quality of their life but this is only possible through the concentration of housing, business, industrial production, trade, transport systems, schools and universities. The release of energy and pollutants from the concentration of human activities in a limited space produces a variety of problems when the two principal factors are ignored: the limits of human adaptability and the variation of natural climate. Where extreme natural heat conditions exist, Man's adaptability is periodically or continuously strained to near its limits. Any artificial modification of the climate to further the extreme features will exhaust the adaptation reserve and show up as failures of Man. This is the case in the rapidly growing cities in tropical climates. They can be seen as a gigantic experiment in human adaptability under conditions of increasing restraint. This could happen in the past because of the blind belief of Man in his inexhaustible adaptive capacity and the omission of a thorough recording of the effects of modern cities on his health, rather than his purse. Prevention of future harm to Man's health in cities in tropical climates will have to begin with properly large sample statistics on morbidity and mortality to establish relationships such as between regional heat and death from cardiovascular diseases. At this time it can already be stated that the causal remedy for Man's productivity and health will be to stop the creation of heat islands through an immediate joint action of city planners, architects and medical health officers, meteorologists and politicians.

14. CONCLUSIONS

Urbanization dates far back in the cultural history of Man. It was an attempt to protect his life from environmental and political hazards, to increase and expand his skills and extend his life expectancy and well-being. Today he can point to remarkable results for populations in temperate climates. The efforts are now being enforced and largely copied for populations living in climates where heat is prevalent. The build-up of heat islands inside cities that may be favoured in temperate climates, becomes a threat in tropical climates because temperatures may rise to levels, particularly during the night, which exceed the tolerable limits required for recuperation. Simultaneously, the city's inhabitants are stressed by the host of other factors typical of life in cities, such as noise, traffic, public transportation, crowding, and air pollution. There are indications that the early development of cardiovascular ailments is accelerated by urbanization which reduces the adaptability of the people to cope with heat.

The large scale urbanization underway in tropical climates has initiated a vicious cycle. On the one hand the life expectancy of the inhabitants has increased through successful actions against communicable diseases and improving nutrition; on the other hand cities have produced conditions which further the development of cardiovascular diseases that weaken the resistance to heat. Massing of buildings and release of anthropogenic heat lead to unnatural heat loads for city dwellers. This may curtail previous achievements and eventually reduce the prospects for life expectancy and well-being.

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HUMAN COMFORT IN THE URBAN TROPICS

Luis Sanchez de Carmona
Consultant to World Health Organization, Geneva, Switzerland
and

1. INTRODUCTION

The study of human comfort in cities situated in the tropics must begin with an analysis of the factors dictating thermal and climatic well-being. Lack of thermal comfort assumes very different proportions depending on whether the settlement is rural or urban, and in the latter case, on the specific type of settlement.

In rural settlements, the scale of construction does not give rise to great mesoclimatic changes which could undermine natural conditions. Moreover, traditional building techniques which have been perfected over long ages persist in rural areas. This usually ensures a certain suitability to the physical environment and to local climate in particular. Despite this, the use of traditional techniques does not of itself solve current problems of eco-design in rural areas, since these techniques frequently date from by-gone stages in the development of the means of production or from a structural division of labour which may no longer prevail today.

The problem is more compelling in urban settlements especially those which have sprung up recently. There are many reasons why present-day conurbations situated within the intertropical zone are proving unsuitable for habitation, and bioclimatic dysfunction is doubtless one. Despite its considerable impact on inhabitants' well-being, the problem of bioclimatic unsuitability is usually unknown to the agents who currently develop urban environments. As so often happens, it does not arise with equal intensity in all social contexts. The ruling classes locate their homes in the leafiest, best-aired areas, which are generally the least polluted by industry or by natural, seasonal phenomena such as dust. Moreover they were, at least up to the present, in a position to bear both the initial and operational costs of hardware capable of redressing adverse local bioclimatic conditions. The fact that optimal locations might mean building on rocky, stony or steep ground is not an insurmountable hurdle.

At the other end of the urban social scale lie the provisional communities. Provisional settlements, be they rural or urban, comprise what is known as the "unstructured sector" developing outside the realm of conventional market rules. For instance, it is estimated that the unstructured sector represents up to 60% of the dwellings built in Latin America. While here the physical environment is deteriorating to a much greater extent than in the structured sector, other even more pressing problems arise, such as the lack of basic services, the safety hazard posed by unstable ground, the high cost of tiny dwellings and living conditions which do not meet the most rudimentary of health requirements.

Ecodesign, and bioclimatology in particular, seek to check outmoded trends which are still to be found in professional contemporary design. Examples include the isolation of a development site from its immediate environment, not taking local conditions into account, relying on complicated hardware to make living conditions bearable and the exclusion of occupant involvement in the control of local environmental conditions.

Without losing sight of these aspects of well-being in cities situated in tropical climates, largely in developing countries, this study focusses on thermal comfort. Both physiological and psychological factors will be considered; only general reference will be made to physiological and behavioural adaptation since it is very difficult to be specific about adaptation in the urban tropics.

As to comfort standards in cities situated in the tropics, the effects of urban growth will be analysed first with respect to the climate and then to human comfort. Existing measurements are being mainly made in cities outside the tropics but the findings may be applied to cities in the tropics by careful transposition.

In connection with factors endangering comfort, a short section will deal with environmental pollution, a factor which threatens the well-being of all urban populations, not just those of cities in the tropics.

The final section of this paper will deal with specific possibilities and measures for improving thermal comfort in the urban humid tropics. The approach recommended is based on designs and projects which will make it possible to control the climate by using the elements of nature (wind, solar radiation, vegetation and so on) and avoid the use of mechanical and technology-intensive devices, because they involve costly hardware which consumes large amounts of energy.

In view of its regard for ecology, this approach is known as ecodesign and ecotechnique. It is based on appropriate use of the natural, technological and human resources of the tropics. In this way, evaluation, measurement, analysis and solutions can be applied to the problems of human comfort in the urban tropics.

2. HUMAN COMFORT

A multidisciplinary approach is essential when tackling the subject of human comfort in the urban tropics. The factors to be studied have facets ranging from purely physical to anthropological and cultural considerations. The analysis of physical occurrences and states of mind - to which the former are related - requires the alternating and often allied involvement of disciplines deriving from both the natural sciences and the humanities.

The ultimate goal pursued by these studies could be defined as the attainment of maximum comfort for the inhabitants of human settlements, compatible with their stage of productive development and using a minimum of resources.

The concept of comfort goes beyond the mere absence of well-known climatic dysfunction; however, it can be defined in the narrower sense of "thermal comfort".

Reactions to a specific climatic situation vary substantially from one individal to the next. Among the major factors one could cite are physique, age, diet, degree of nourishment and cultural influences.

Man has gradually come to rule the Earth thanks to his amazing ability to adapt to change, and to climatic change in particular. Despite this, it is imperative to point out the biological limits to this ability.

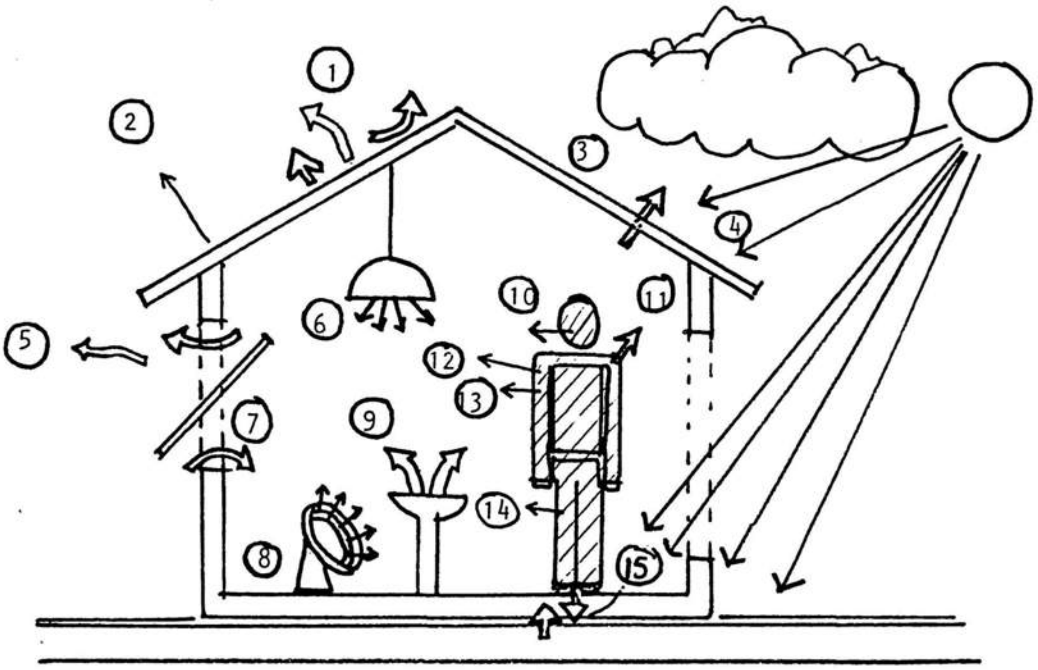
2.1 Temperature and heat levels

The human body is a homeothermal system: in order to function properly it must maintain a constant internal temperature of about $37^{o}C$, whatever the heat conditions in its immediate environment. This temperature is not uniform: skin temperature is lower than body temperature, and that of the fingers and toes is lower than that of the trunk. Average skin temperature can be assumed to be $35^{o}C$. Blood circulation goes a long way to keeping the temperature uniform inside the body. The human body could be likened to a thermal machine whose inputs are water, oxygen and chemical energy (food) in general - together with a certain amount of heat supplied by the environment - and which, in certain conditions, produces mechanical energy (muscular activity) and heat. The internal biochemical processes generate what is called "metabolic heat".

This metabolic heat, which is produced even while muscular activity is slowed to a minimum, must of course be dissipated; if it were not, the body's temperature would rise above the narrow limits for its proper functioning. Muscular activity increases the amount of metabolic heat which has to be dispersed to a considerable extent. The body's thermodynamic yield (percentage of received energy which it converts into mechanical energy) ranges from 20% to 25%.

One can easily comprehend that the main biothermal problem in hot regions is dispersion of the metabolic heat produced by the body in a comfortable and efficient manner.

2.2 Heat exchange between Man and the city



1. Convection (Roof-Air)
2. Heating-System Dispersion
3. Conduction
4. Indirect Radiation
5. Ventilation
6. Heat Radiation
7. Filtration
8. Heat Radiation
9. Evaporation of Water
10. Respiration
11. Heat Radiation
12. Evaporation
13. Sweating
14. Convection (Skin-Air)
15. Conduction

Figure 1. Heat balance between Man and his environment **(Source Hernandez, 1984).**

Although of differing and fluctuating magnitudes, all the usual mechanisms for transmitting heat are at work in the interaction of the human body and its environment (Figure 1):

(a) Conduction - The skin, through physical contact with its immediate environment (air, clothing, ground and furniture), can either gain or lose heat, depending on whether its temperature is lower or higher than the contacted surface.

(b) Convection - Air which has been warmed or cooled by the skin is set in motion by its increased or decreased density, giving rise to convection.
(c) Radiation - The skin radiates heat at infrared wavelengths. The environment is a source of radiation for the body: either "short" waves (solar radiation) or "long" waves (ground and sky radiation). An energy exchange in the form of radiation thus takes place between the skin and even its distant environment. The average person is generally unaware of, or misunderstands, this phenomenon: we can feel "cold" or "hot" even when the ambient air temperature remains within the conventional limits of the comfort zone, depending on whether surfaces close to us are very cold (negative radiation balance for the body) or hot (positive radiation balance for the body). Heat transmission in the form of radiation does not require any physical contact whatsoever in order to take place.
(d) Evaporation - When the relative humidity of the ambient air is below 100%, heat loss occurs because latent heat is involved in evaporation of sweat on the skin surface, as well as through moistening of the air during its passage through the lungs.

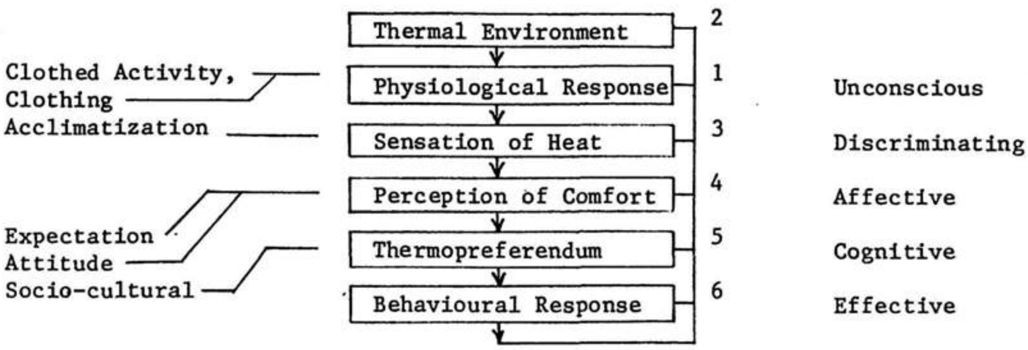
The heat balance between the human body and its environment can be expressed in the following way:

$$Q_M \pm Q_G \pm Q_H \pm Q^* - Q_E = 0$$

where Q_M is the heat produced by the human metabolism per unit of time, Q_G, Q_H and Q^* are the heat gained or lost by the body through conduction, convection and radiation, respectively, and Q_E is the heat continually lost by the body through evaporation.

2.3 Thermoregulation

The possibilities for behavioural thermoregulation include: mere movement towards areas where natural climatic conditions are less adverse; design and manufacture of objects which make up a "material culture", some of which are basically intended for bioclimatic control (e.g. clothing and buildings) and, general management of the environment so as to transform it and make it more conducive to human activity. Individual control over activity itself constitutes one of the major mechanisms of heat regulation, since, as has been seen, "metabolic heat" depends directly on the type of work being carried out (Figure 2).



The feedback cycle shows short- and long-term responses, such as:

1. Changing clothes.
2. Changing the thermal environment: opening windows, switching on radiator.
3. Slight acclimatization change.
4. Change in habits.
5. Cultural changes in lifestyles.

Figure 2. Psycho-physiological thermoregulation model showing perception and response levels **(source Szokolay, 1984).**

The human body is able to regulate heat in specific ways, based on fluctuations in the conditions of exchange between the skin (and the respiratory membranes) and the environment. The skin carries out a very large set of functions, including that of dissipating metabolic heat. This dissipation is partially checked by the heat energy absorbed by the skin from its environment. The skin receives endogenous energy largely by means of the blood circulation. Blood, which is mainly composed of water, has a high specific heat (very close to that of water: $4.2 Jg^{-1} {}^{o}C^{-1}$) and acts as a vehicle for transporting chemical energy (nutrients) and heat (from the core to the periphery). Physiological thermoregulation mechanisms are involuntary and include: sweating, constriction/ dilation of blood vessels, changes in respiration, involuntary muscle activity, changes in appetite and heart rate.

2.4 Variables creating thermal discomfort

The subjective sensation of heat or cold depends on how intensely thermoregulation processes are working, and these in turn are dictated by a limited number of microclimatic variables. Scientific knowledge of these correlations dates from relatively recent times. Up to the late 19th century, for instance, it was believed that thermal discomfort felt by people crowded together in a closed room was due to an alleged concentration of toxic gases produced by the people themselves. The chemical composition of inhaled air, and not its physical state, was blamed exclusively for discomfort.

The foundations of actual understanding of the variables affecting comfort were laid by British doctors such as Sir Leonard Hill at the beginning of the 20th century. The relevance of the field of study obeyed historical imperatives: the British "establishment" had a vested interest in improving the productivity of workers who provided the aching backbone of a far-flung empire: miners confined in suffocating galleries; textile workers in mills where humidity was kept artificially high to prevent the thread becoming brittle; stokers aboard ships plying tropical waters; farm workers harvesting cotton in blistering heat and so on. Based on experiments, some of which dated from the 18th century, three fundamental microclimatic variables were established: the air (and radiant) temperature, the relative humidity and air motion.

2.5 Adapting to the climate

"Acclimatization" is the set of long-term adaptations affecting all organisms which inhabit a basically stable climate. Biothermal processes vary from one organism to the next.

Even today, not enough experiments are being conducted to find out more about acclimatization. Only too often, it is presumed to be non-existent, and biothermal research is carried out on the false assumption that human physiology behaves in a standard, universal way. It has been scientifically proved that basal metabolism rises considerably through acclimatization to cold. Paradoxically, when an individual accustomed to a temperate climate is subjected to continuous heat, their basal metabolism, too, at first rises and then tapers off. The sparse data available for studying thermal comfort usually stem from experiments carried out on subjects who have been acclimatized to temperate environments in the industrialized countries. In the context of the tropics, these findings should be treated with caution. A racist approach has been adopted to try to work out a correlation between an individual's biothermal behaviour and their racial origins. In the past, pseudo-scientific manipulation was used in an attempt to demonstrate that blacks were much better suited to work in the tropics than were Europeans. More serious studies had to acknowledge that individuals of different "races" are capable of achieving identical physical and intellectual productivity. Differences, where they exist, are attributable to upbringing and acclimatization.

Two major approaches to research into bioclimatic control can be perceived. The first focusses on the concept of "thermal comfort". This concept is defined statistically, based on the range of variation of basic factors and their correlations. The studies comprising this approach usually deal with the needs of lightly-clad individuals who are either at rest or performing sedentary work. One common feature of quantitative approaches to the concept of "thermal comfort" is their simplicity of expression. It is easy to understand that the work of air-conditioning engineers forms the basis of this knowledge and that the typical problem everyone tries to solve is one of ensuring an "acceptable" climate for tertiary-sector workers as a whole, at least insofar as easily quantifiable variables enter the picture.

The second approach focusses on the concept of thermal stress or discomfort. The aim here is to define and quantify this stress objectively, by establishing a relationship between physiological events and basic variables using empirical formulae amenable to verification through experiment. These formulae are often elaborate and unwieldy when it comes to expressing and using them; their aim is to establish models of objective physiological functioning which can lead to forecasts.

This second approach seeks to study the biothermal behaviour of individuals confronted with extreme climatic situations either due to the intensity of their activity or the climatic variables of their environment. The social experience underlying this approach is ergonomics, which involves variants depending on whether the scope is civilian or military. The classic problem to be solved is forecasting an individual's resistance and productivity when subjected to adverse climatic conditions.

While the first approach emphasizes the subjective aspect of comfort (forecasting how certain persons will "feel"), the second stresses objective physical circumstances (forecasting what will occur physiologically, outside the realm of the mind).

Both approaches have led to the study of heat defence mechanisms. The fight against cold does not seem to worry researchers much, to the extent that there are obvious, effective and easily-applied solutions: increased physical exercise, causing greater production of metabolic heat, and heavier clothing, thus limiting heat loss. Moreover, since time immemorial Man has known that any kind of combustion yields heat. A mere fire can work a pleasant change on adverse microclimatic conditions, whereas the deliberate production of cold was a very recent, and even today still very costly, human achievement.

Current knowledge of bioclimatic circumstances is still rather sketchy and poorly integrated. Although we profit from the objective findings of the above-mentioned trends in research, at the same time we have to transcend the social experience on which they are based. Our scope is not restricted to air-conditioning a conventional office building or assessing a battalion's chances of operating in a desert.

3. THERMAL COMFORT INDICES

3.1 Physiological indices

A large number of indices have been proposed, and are in use, to estimate and characterize the physiological state of comfort. Some of the more common and important ones include the concept of "Dry" Exchange and the Required Evaporation, Evaporative Capacity, the Heat Stress Index, and the Sweat Index. For detailed information on these and other measures of comfort the reader is referred to Olgyay (1963), Givoni and Berner-Nir (1967), Fanger (1972) and Givoni (1976).

3.2 Psychological indices

These studies have been geared towards experiments and empirical ascertainment of the bioclimatic conditions which an individual, wearing ordinary clothes and performing light work, would describe as "comfortable". As was noted earlier, the implicit goal of this research seems to have been increasingly defined as that of achieving the lowest heat stress possible for workers in temperate regions' tertiary sectors. The "clothing" and "metabolic rate" variables are therefore eliminated (it is taken for granted that dress is standard and that work is of a light office variety).

Concepts and techniques include the Effective Temperature Index, the Comfort Zone, and Bioclimatic Charts. Here again the reader is referred to Olgyay (1963), Fanger (1972) and Givoni (1976).

3.3 Physiological and behavioural adaptation

Adaptation is almost by definition an outcome of biological success. It implies that the organism is capable of functioning efficiently and reproducing its own kind under prevailing conditions. However, the concepts of adaptation formulated by biologists are inadequate when it comes to applying them to human situations.

The ordinary biologist usually defines "adaptation" in Darwinian terms. For him, the term connotes a state of fitness in relation to a given environment, enabling the species to grow in numbers and take root in new territory. From this standpoint, Man is particularly well-adapted to life in highly urbanized, industrialized society; the urban population is constantly growing and gradually carrying its way of life to the four corners of the Earth. Admittedly, modern Man is increasingly prey to chronic disorders resulting from his lifestyle, and in all likelihood, technological advances do not contribute significantly to his happiness; however, from a purely biological standpoint, these shortcomings of modern life are of minor importance. The chronic disorders which are an essential feature of today's civilization affect people most in their later adult life, once reproduction has taken place and their contribution to social and economic development has been made. The question of happiness becomes important only when attention shifts from purely biological matters to the much more complex issues of human values. Therefore, when we apply the concept of adaptation to Man, we should use different criteria from those used in the field of general biology.

Physiologists and psychologists attribute a broader meaning to the word "adaptation" than that associated with the Darwinian theory of population, but they still do not take the rich complexity of human life into account. In their view, a response bears the mark of adaptation when it promotes homeostasis, by using metabolic, hormonal or mental processes meant to correct the disturbing effects of ambient forces on the body and mind. Although it is obvious that these adaptation responses contribute to the organism's well-being at the time they occur, they unfortunately produce side-effects which are harmful later.

Man has been successful as a biological species because he is adaptable. He can hunt or till the earth, ingest meat or vegetables, live in the mountains or at the seaside, isolate himself or be part of a team and live in a democratic or totalitarian State.

On the other hand, history shows that societies which thrived in former times, owing to their high degree of specialization, rapidly declined when conditions changed. A highly-specialized society is seldom adaptable. Cultural homogeneity and social regimentation originating in the increasing monotony of a technological society, coupled with the standardized patterns of mass education and communication, make it more and more difficult to exploit the biological wealth of our species to the utmost. These circumstances may pose a threat to the survival of civilization. We must avoid uniformity of both the environment and behaviour and strive to diversify our surroundings. The results may entail a certain loss in efficiency, but the most important aim is to provide the myriad repositories required for nursing the seedlings which now lie latent in the heart of Man. Diversification of the social environment constitutes a fundamental aspect of functionalism, whether it is a matter of planning cities, designing houses or organizing life itself.

In a course of action of this kind, it is essential to recognize that Man may achieve a certain degree of adaptation even in extremely adverse conditions; the ultimate negative effects of such conditions are at times disguised, as in the case of adaptation to polluted air.

As demonstrated by everyday events, Man sometimes brings himself to accept treeless boulevards, starless skies, tasteless food and life without fragrant flowers, the song of birds, the joy of spring days or the vibrance of autumn. The loss of these avenues of pleasure does not have any apparent adverse effects on a person's physical well-being, or on his ability to play an effective role in the economy. Indeed, most of his working life tends to be spent increasingly in standardized rooms, offices and industrial plants, since this makes it more convenient to maintain premises and students are less easily distracted.

Little or nothing is known of the effect on Man of such an outright denial of the natural stimuli with which he developed as a species. Air, water, earth and fire are not merely mixtures of chemicals and physical forces; they are influences which have shaped human life and, in all likelihood, created profound human needs that are not about to change in the foreseeable future. The pathetic weekend exodus to beaches and countryside, along with fireplaces in overheated city flats, prove the persistence of biological yearnings which Man developed in his evolutionary ascent. Just as the most domesticated dogs and spoiled cats still behave in many ways like creatures of the wild, so modern Man exhibits many of the traits and needs of the Old Stone-Age hunter and New Stone-Age farmer.

The great undertaking which adaptation responses represent, for better or for worse, outlines the urgency of formulating techniques for analysing environmental problems, not only as static, "here and now" phenomena, but also their dynamic ramifications for the future.

In both the environmental and social sciences, the development of methods for studying dynamic systems is imperative, for patterns of biological and mental responses are changing just as rapidly as their social counterparts.

Environmental developments neither occur nor operate in a social vacuum. They can only fulfil their aim of greater health and happiness if they are geared to the needs and resources of society, as well as to the special conditions created by the overall environment. It is typical that these aspects should be in an ongoing state of transformation. Be it a large estate or a city park, a slow-paced country road or a multi-lane thoroughfare, a city square or a national park, a hamlet or a city, a suburb or a satellite community, the environment should constantly evolve in response to changing human needs and aspirations. The idea of an optimal environment is unrealistic, because it implies an aesthetic conception of the biological and social nature of Man. Planning for the future demands an ecological attitude which entails evolving transformation and ongoing, creative human activity.

4. URBAN COMFORT LEVELS IN THE TROPICS

4.1 Effects of Urban Growth on the Climate

Cities differ from the country not only in temperature, but also in all other climatic aspects. Climate here is taken to mean the net result of multiple, interrelated variables, including temperature, water vapour in the atmosphere, wind speed, amount of solar radiation and amount of precipitation. Often, the fact that these variables do not normally vary in the same way within a city as they do in the open, surrounding countryside can be measured directly as differences in temperature, humidity, precipitation, mist and wind speed between the city and its environs. This difference is also visible in urban phenomena such as persistent smog, premature blooming of plants and longer frost-free periods.

Cities themselves are the cause of these differences. Their compact masses of buildings and pavement obviously constitute a marked departure from the natural landscape, and their inhabitants' activities are a sizeable source of heat. All these factors taken together explain five basic influences which differentiate a city's climate from that of the surrounding area:

(a) Artificial transformation of the ground surface - The materials making up urban surfaces differ from those of the natural landscape, they may have higher heat capacities and be better conductors. The mean albedo may also undergo changes going from country to city. The shape of the urban surface also differs sharply from that of the countryside: broadly speaking it is "rougher", leading to greater friction between winds and local surfaces. The outer surfaces of buildings act as reflectors and radiators which, in concert, amplify the effects of incident radiation. The differentiating effect of this urban factor in relation to the countryside is heightened when the Sun is low in the sky: the countryside offers very few vertical surfaces.

(b) Urban drainage systems usually carry away precipitation falling on the city in short order. Natural seepage of moisture into the ground is thereby prevented or lessened. Mean urban evaporation and transpiration are often low in comparison with those of adjacent rural areas.

(c) Increased air pollution - Urban activity generates smoke, gases and dust which pollute the atmosphere. On the one hand, these substances suspended in the atmosphere reduce the amount of sunlight which reaches the surface; on the other, they hinder free transmission of ground radiation into space.

(d) Local generation of heat energy - Cities are sources of technologically-produced heat: from industry, motor vehicles and certain infrastructures. In medium and high latitude cities home-heating is also important.

4.2 Effects of Urban Air Pollution

Air pollution ought to be considered a costly and unpleasant consequence of present-day industrialization and urbanization. The question now being raised is whether pollution is a serious public health hazard.

The foremost places where its effects are felt are body surfaces in direct contact with the air: the skin, largely protected by clothing, and the respiratory tract, which is totally unprotected. Evidence has been found of increased bronchial and lung illnesses: especially bronchitis and emphysema. However, it cannot be ascertained in either legal or medical terms that any pollutant is directly to blame for bronchitis, emphysema or other bronchial and lung disorders.

If pollution actually has an impact on public health, then this fact has to show up among a substantial portion of the population. Its effect on individuals, however, is not unduly noticeable. Fortunately, deadly fogs such as those which descended on the Meuse Valley (Belgium) in 1930, Donora (Pennsylvania) in 1948 and London in 1952, are few and far between. In these three cases the higher death rate mainly affected the elderly, along with those who were afflicted with lung disorders.

Most pollutants enter the atmosphere as a result of combustion. Although the inhabitants of present-day cities seldom, if ever, use their fireplaces, everyday life depends in a large measure on combustion. Clean, efficient electric radiators rely ultimately on the heat released by coal combustion, just as televisions do. In most cities rubbish is burned, often twice, in backyards and public dumping grounds. Automobiles are veritable burners on wheels when their motors are running and also plague the environment when no longer used. In a word, the energy we use is produced by combustion, and most of our refuse ends up in an incinerator.

The end products of complete combustion are water and carbon dioxide which alone are not unduly harmful in the amounts produced in cities. However, neither fuels nor rubbish generally undergo complete combustion, and an endless variety of chemical substances is spewed out into the air. One product of combustion is smoke, which is partially composed of solid particles perceptible by the senses; their aggregates are either soot or ash. The process of combustion also generates invisible chemicals which may represent a greater health hazard.

Although sufficient factual knowledge of air pollution exists, this same understanding is lacking when it comes to considering effects on public health.

For reasons connected with the nature and progression of the disease, it has not been possible to establish death statistics for bronchitis and emphysema, although it would seem that both diseases are on the rise. This is insufficient, however, to demonstrate that the incidence of pulmonary disorders increases with pollution. An objective researcher has to seek the relationship between cause and effect; for that matter, ministries of

Public Health need greater proof to justify the social cost of pollution control measures.

Other findings suggest that there is, in fact, a relationship between urban air pollution and the incidence of bronchial and lung diseases. They refer to the link between tobacco and certain types of lung cancer. It is a known fact that these forms of cancer are less prevalent in rural areas. In the country, smoking is less common than in cities, since cigarettes represent a constant fire hazard for farmers. If the effect of polluted city air on smokers is to be circumscribed in accurate figures, then the working data should bear on smokers who have moved from city to country.

Controlling environmental pollution, be it in air, water or food, poses a colossal problem. Present-day pollution is not the work of a handful of malicious individuals or even of our neighbours' dirty habits, as might have been the case 50 years ago. Current pollution is produced by the "no Man's land" of highly industrialized society. Pollution control measures affect the intricate mosaic of society at large.

5. THERMOREGULATORY MEASURES TO SUIT THE URBAN TROPICS

5.1 Standard Design Criteria

Bioclimatic design is based on analysis of meteorological factors, which means that architecture must both preserve physical, functional and aesthetic aspects and meet the needs of comfort and economy. Furthermore, the bioclimatic design approach aims primarily to create an environment of comfort for the community by utilizing natural air-conditioning systems in an attempt to economize non-renewable energy resources to the utmost and capitalize on "alternative natural energy" sources.

Bearing in mind that bioclimatic architecture consists in planning and building with regard for the interaction of meteorological factors and construction, so that the latter itself regulates matter and energy exchanges with the environment and sets the conditions creating a feeling of thermal comfort among people, the following guidelines have been drawn up for bioclimatic design (see Figures 3 to 5 and Tables 1 and 2).

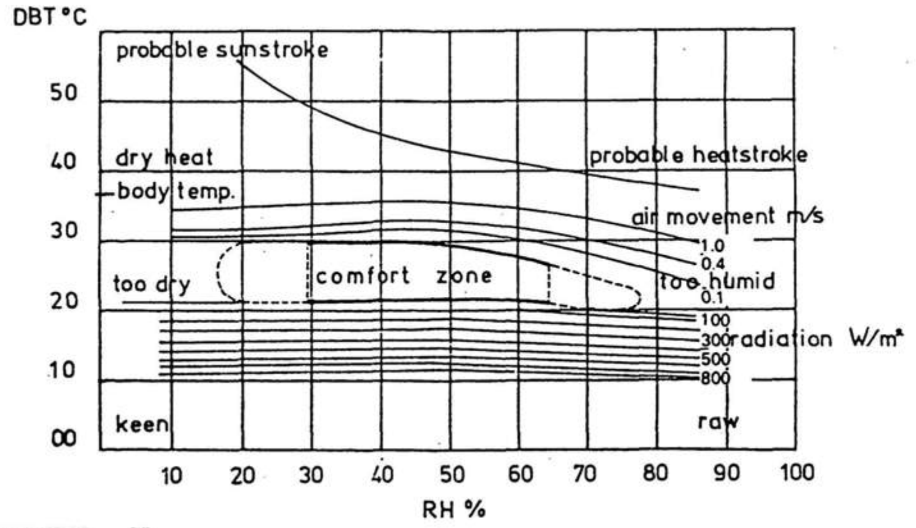
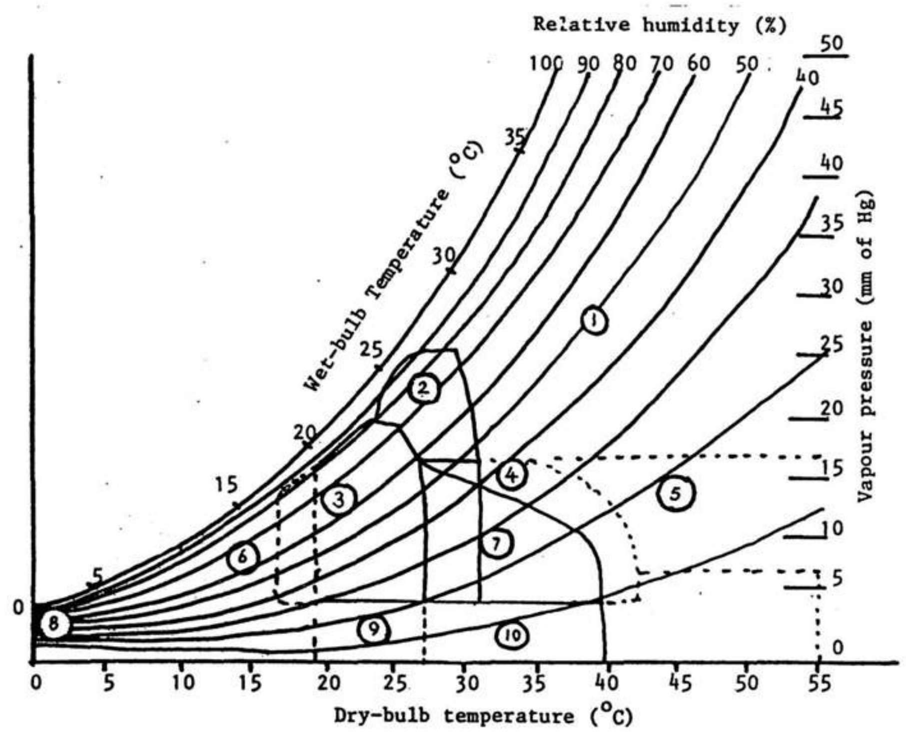
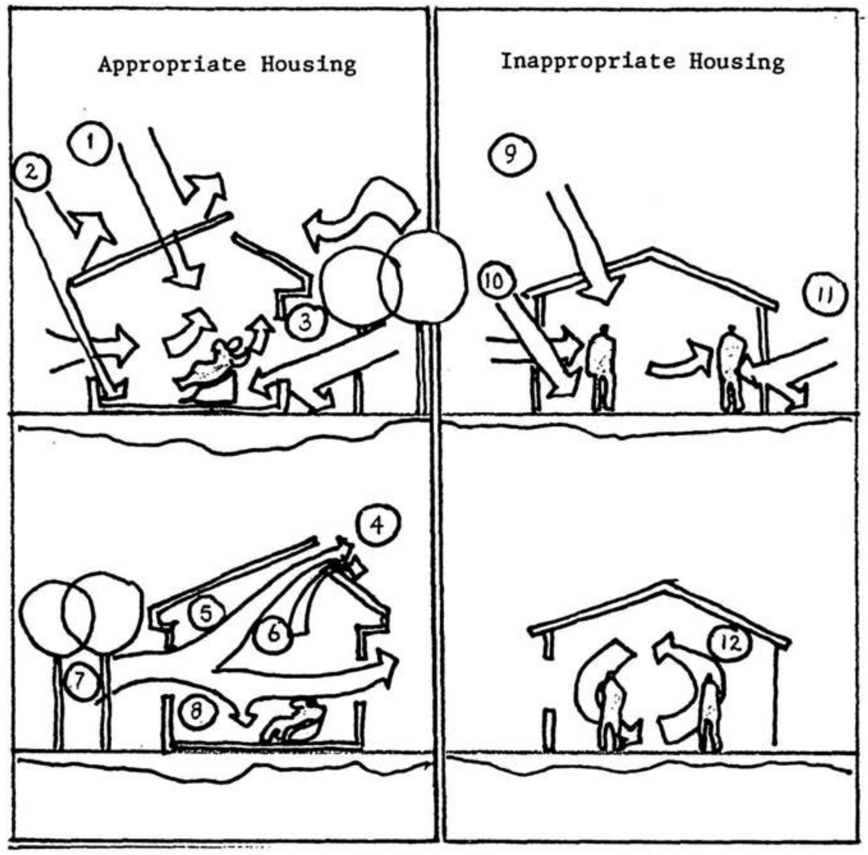


Figure 3. Bioclimatic Chart. Defines a comfort zone in terms of dry-bulb air temperature and relative humidity. Additional lines show how this zone can be moved upwards by air movement and lowered by increased radiation.



1. Conventional dehumidification
2. Natural or mechanical ventilation
3. Human thermal comfort zone
4. Night-time Infrared Radiation in Underground Construction
5. Air-conditioned by conventional means
6. Conventional or passive heating
7. Thermal inertia
8. Conventional heating
9. Humidification
10. Evaporative cooling

Figure 4. Bioclimatic Control in Buildings **(Source Hernandez, 1984).**



1. Radiation via roof
2. Window radiation
3. Conduction via walls
4. Hot air
5. Convection
6. Natural ventilation
7. Fresh cool air
8. Cool air
9. Roof radiation
10. Radiation via window
11. Conduction via walls
12. Hot air

Figure 5. Bioclimatic Design and Materials (Source Ceballos Lescurain, 1984).

TABLE 1. *Design Strategy for Cooling Rooms in the Tropics.*

Comfort Variable	Cooling Option	Design Strategy
Air temperature	Control of heating	Shaded
	Natural ventilation	Tempered Structure
	Radiation decrease	Thermal Insulation
	Conduction decrease	Night-time Radiation
	Humidification	Air Exchange
	Induced ventilation	Thermal Chimney
	Microclimate	Retaining Wall
		Direct Solar Radiation
		Greenhouse
		Cooling by Evaporation
		Vegetation
Air Motion	Induced ventilation	Thermal Chimney
		Retaining Wall
		Direct Solar Radiation
		Greenhouse
		Air Exchange
		Subdivision of Space
Humidity	Humidification	Cooling by Evaporation
	Dehumidification	Drying
	Microclimate	Air Exchange
		Vegetation
Radiant temperature	Control of heating	Shaded
	Natural ventilation	Tempered Structure
	Induced ventilation	Thermal Insulation
	Radiation decrease	Air Flow
	Conduction decrease	Thermal Chimney
	Microclimate	Retaining Wall
		Direct Solar Radiation
		Greenhouse
		Vegetation

Source: Cook (1984).

TABLE 2. *Standard Specifications Suggested for Dwellings in Hot Climates.*

1. INSULATION	
Roofs	R = 3.5 (18) min
Outer Walls S/E/W	R = 2.0 (10) min
N/Adjoining	R = 1.0 (5) min
Inner Walls	*R = 1.0 (5) min
Cooling Ducts	*R = 2.0 (10) min
2. SHADING	
S/E/W Eaves	60 cm min
S/E/W Windows	Reduct. of 60% min vs. 3 mm light-colour glass
N Windows	Max. surface vs. wall 12%
	*Roof C/R = 2.0 (10)
3. PAINT	
Roofs	Very light colour and reflective
Outer Walls	Light colour
4. SEALING	
Windows	*Yes
Doors	*Yes, and close door and vent
Lattices and Vents	*Hermetic (even on fireplaces and elsewhere)
5. SECTIONALIZATION	*Yes
6. EQUIPMENT	
Central Ventilator	
Evaporative Cooler	With pump control for areas with high relative humidity
Window Cooling	EER = min
Central Cooling	EER = min
7. LIGHTING	*Fluorescent in kitchen, living-room and master bedroom

Notes: *If cooling equipment or 200V hook-up are used.

R-Heat resistance coefficient in metric units ($^{o}C\ m^{2}W^{-1}$) (English measurement in brackets)

EER - Energy Efficiency Ratio

Source: Diego Muñoz (1984)

Bioclimatic design should:

. provide greater comfort by making the structure suit the local physical environment including daily and seasonal changes.
. thoroughly apply passive air-conditioning systems to the envisaged structure.
. utilize building materials in the most suitable and rational way.
. set architectural and urban design standards in line with the climatic features and sunlight of the region.
. develop passive air-conditioning systems to provide greater ambient physiological comfort.
. provide structures, designed in accordance with bioclimatic recommendations, capable of themselves regulating ideal heat levels for occupant comfort.

The following research has been proposed for proceeding methodologically in design work:

. analysis of climatological characteristics - studying the country's various regions, ascertaining their geographical location and climate and obtaining appropriate climatological data.
. analysis of bioclimatic characteristics - obtaining temperature and humidity levels; plot graphs of the mean, maximum and minimum monthly values for each place to ascertain whether they fall inside or outside the "thermal comfort" zone.
. analysis of insolation characteristics - determination of the sunlight levels on different planes at the geographical latitude of the selected place to obtain the solar energy impinging on the horizontal, east/west and north/south planes. The Sun's position can also be located and referred to in any season or moment of the year using a solar graph.
. analysis of special events - consider the climatological impact of specific occurrences: days with and without appreciable rain; cloudless, variable and overcast days; days with dew, hail, frost, electrical storms, fog and snow. This information helps one understand the overriding conditions of the environment in each place throughout the year.

Five standard design criteria have been grouped together (see Tables 3, 4, 5):

TABLE 3. *Urban and Architectural Design Criteria - HOT, WET CLIMATE.*

URBAN DESIGN	<u>Choice of Site</u> Elevated land facing prevailing winds, especially on hilltops. Northern and eastern slopes recommended as they receive less radiation. <u>Layout</u> Street system should be laid out along western axis, so that all lots are well-exposed to north wind. Layout should facilitate water run-off towards low-lying areas. Avoid wet and flood-prone low-lying areas. <u>Structure</u> Emphasis on spacing or scattering of dwellings, i.e. low density recommended. Propose large lots. <u>Outdoor Areas</u> Should be well-ventilated and shaded. Minimum distances from dwellings to equipment and services. Urban walkways ought to be shaded. <u>Landscape</u> Land is usually rolling. Scenic walkways should be provided facing the sea. In locations without view of sea or mountains, vegetation should be included in urban design. <u>Vegetation</u> Abundant vegetation. Shade trees with high canopies so as not to obstruct breezes. No bushes near dwellings to divert or brake wind. Careful with land on dunes: uprooting trees allows wind to shift dune to other side.
ARCHITECTURAL DESIGN	<u>Dwelling Type</u> Open, insulated housing recommended, facing favourable winds and directions. Should be built slightly off ground owing to wetness. Where possible, build more than one level. <u>Floor Plan</u> Dwelling should consist of separate parts since outdoor conditions are usually comfortable when shaded. Living and eating should therefore be linked closely with outdoors, as should cooking and washing which can also be done in open air. <u>Orientation</u> Dwellings should predominantly face north or northeast. Protection of west side where solar radiation is intense in summer. Cut down on sunlight from south. Cross-ventilation indispensable. <u>Shape</u> Dwellings should be longest in most favourable direction. <u>Interior</u> Interior areas should be shaded and ventilated. Preferably large, high areas, which can be subdivided by opaque, mobile screens. Materials should resist moisture and the elements. Provide for a safe place as shelter from hurricanes. <u>Colours</u> Light, pastel colours best as they are reflective and prevent dazzling. Should be used inside and out.

Source: Bazant (1983).

TABLE 4. *Urban and Architectural Design Criteria - HOT, DRY CLIMATE.*

URBAN DESIGN	**Choice of Site** Land sloping east and southeast in low-lying areas where cool air flow is comfortable. Avoid valley floors with little air circulation. Mountain shadow useful in obstructing undesirable winds. **Layout** Street system should be laid out along northeast axis to protect from intense western solar radiation and cold north winds. **Structure** Provide for clustering of dwellings to create inner courtyard environments sheltered by thatching and trees. Dwellings should be very close together to avoid heat gain by reducing surfaces exposed to solar radiation. Strive for medium density. **Outdoor Areas** Dwellings should be near services, connected by shaded walkways. Avoid extensive paved surfaces which transmit and accumulate heat. Try to provide for bodies of water. **Landscape** Views of mountains, if any, should be incorporated in urban design. When land is flat, provide for inner views. **Vegetation** When vegetation is sparse, reforest with species suited to climate. Lawns and bushes should be able to absorb radiation and retain evaporation, while providing shade.
ARCHITECTURAL DESIGN	**Dwelling Type** Very compact, two-storey dwellings minimally exposed to sunlight are recommended, in strings or clusters. Tall buildings should be massive. **Floor Plan** Aim is heat loss (in summer) rather than heat gain in winter. Dwellings should therefore be closed, near one another and surrounded by green areas to provide evaporative cooling. Ceilings can be high. Heat-generating areas (kitchens, bathrooms) should be separate from other areas. **Orientation** Dwellings should face west and southwest to provide a good solar radiation balance. Cross-ventilation recommended in summer. **Shape** Compact shapes recommended, slightly longer along northeast axis. Housing shape should allow minimal exposure to sunlight. **Interior** Indoor space arrangement should provide amplitude and cooling effects. Areas ought to have depth to cool and check fierce outdoor heat. Connect interior to sheltered patio and garden. **Colour** Light colours have high solar reflection index and should be used extensively. Dark colours ought to be used to absorb heat in winter.

TABLE 5. *Urban and Architectural Design Criteria - HOT, SEMI-HUMID CLIMATE.*

URBAN DESIGN	Choice of Site	Select land sloping north or east; avoid sites sloping west and south. Try to use elevated areas which are cooler. Sites are prone to erosion if vegetation is removed.
	Layout	Street system should be laid out along eastern and western axes. Protection against strong cyclone winds on land near seaside. Layout ought to provide easy water run-off, along with its collection and storage in low-lying areas.
	Structure	Use thatching or unbroken facades facing west, and strive for utmost contact with outdoors when conditions are favourable to east. Provide for small clusters of dwellings of low or medium density.
	Outdoor Areas	Allow for short distances between dwellings and public services. Walkways should be shaded and paved with low heat-retention materials.
	Landscape	Sea an attractive feature which should be incorporated in scenic routes and views. When site is mountainous, mountains should be integrated into urban landscape.
ARCHITECTURAL DESIGN	Dwelling Type	Semi-compact construction. Unbroken facade facing unfavourable direction and open facing favourable one. Small clusters and strings of houses desirable.
	Floor Plan	Partially-closed dwelling, open facing pleasant views and winds. Only one storey should be built to avoid heat gain. Some areas may exceed 2.30 m in height.
	Orientation	Exposure to north and east; closed-off on west side, south side sheltered.
	Shape	Dwelling may be rectangular with short side closed-off facing west or southwest and long side facing east or northwest.
	Interior	Properly-oriented areas may be of slight depth, since less appropriately-oriented areas require greater depth to avoid solar radiation. Cross-ventilation indispensable.
	Colour	Preference given to light colours as they are more reflective, especially on facades exposed to intense sunlight. Medium and darker colours - more absorbent - may be used on facades exposed to lesser degree.

Source: Bazant (1983).

- Urban Planning Guidelines:
  - shape of lots, layout and orientation of blocks
  - optimal orientation of dwellings
  - pedestrian access specifications
  - lateral appurtenances
- Building Plan Guidelines:
  - configuration
  - facade design or best alternative
  - roof type
  - best location of service areas
  - height from floor to ceiling
- Solar Projection and Enhancement Devices:
  - natural protection outside
  - inner courtyard
  - skylights
  - eaves
  - balconies
  - porches
  - vertical blinds
- Windows and Openings:
  - main and rear facades
  - lateral facades
  - ventilation
- Procedures and Materials:
  - roofing and thermal insulation
  - walls and thermal insulation
  - exterior colours and texture
  - auxiliary air-conditioning equipment
  - location of clothes-cupboards

In hot, humid climates, ventilation constitutes the best means of ensuring biothermal comfort. A clear understanding of local breezes and their potential microclimatic variants is indispensable. Making use of natural breezes tends to be more effective than any type of thermal draught that could be installed.

Buildings should be highly permeable, allowing air to be channelled into the interior. If due attention is paid to the conditions under which air enters and escapes from every nook and cranny, indoor circulation may be achieved in the lower areas used by the occupants. Cross-ventilation may require a mere cross-type layout. If desired effects are to be obtained, the spacing of buildings must be treated with special care, so that none of them casts a "wind shadow" on the others. This requirement may reduce a settlement's density. In hot, humid regions, dwellings have traditionally been of the single-family variety and are well spaced. Nevertheless, it is quite feasible to condition the air of a multi-family dwelling so as to achieve satisfactory indoor ventilation, although few studies or experiments have been carried out on this matter.

Outdoor spaces should be designed so that the air stream passing through them to windward of each building is not unnecessarily overheated, thereby nullifying its beneficial effect.

The interiors typical of this kind of climate have traditionally included high ceilings (often exceeding 3 metres in height). Recent studies have demonstrated that this feature reduces economy without contributing appreciably to improved bioclimatic conditions. When a ceiling fan is used, however, the overhead space may have to be increased substantially so as to ensure a minimum of 2.2 m between the fan blades and the floor.

It is often stated that very light construction is the only appropriate type for hot, wet climates and that, as a result, the usually low diurnal temperature variation does not require great thermal inertia as a correction factor. The universal applicability of this principle is now being challenged; in some cases, it has been found that the radiant night-time cooling of a correctly-located structure possessing great thermal inertia suffices to reduce the indoor day-time mean radiant temperature (that given by a globe thermometer), thereby alleviating the heat burden somewhat.

The greater the average number of cloudless nights, the more effective is this process.

COMFORT IN THE URBAN TROPICS

In all cases, structures must be protected to the utmost from direct, intense solar radiation occurring at times of light cloud cover. This protection should be extended to the area immediately outside. Traditional devices such as verandahs, wide eaves and covered porches can meet this need without posing an obstacle to breezes; at the same time, they protect against downpours, the heaviest of which should be taken into account when deciding upon slopes and drainage.

The finish on surfaces directly exposed to the elements should ideally be very reflective. This is a particularly important requirement in the case of roofing, which is subjected to direct and/or diffuse solar radiation. Double-layer roofing offers advantages, provided the space between the layers is ventilated effectively. The outer layer sharply reduces the radiation reaching the second layer, thereby limiting the temperature of the space between them. Although outdoor vegetation plays a welcome role by providing shade, foliage must be regulated so as not to obstruct breezes.

Interior areas which generate the greatest amount of heat and humidity (e.g. kitchens) should be properly located and afforded both better ventilation and special circulation. The designer should take into account the high heat stress suffered by occupants in these regions, which raises the overriding need to control production of metabolic heat (i.e. physical work) by avoiding layouts requiring needless effort. Space design in these climates is a delicate undertaking, and functions should ideally be separated so as to ensure that each operates fully. As to the view of the outdoors, it should be remembered that in these regions the sky is usually dazzlingly bright, even when it is overcast.

Thermal comfort is perhaps the first and foremost theme in making the tropical habitat suit the needs of Man. Thermal comfort is defined as the equilibrium point between human body temperature and ambient temperature, enabling a person to perform ordinary activities in satisfactory conditions. In the wet tropics, thermal comfort is afforded by indoor temperatures and relative humidity enabling the body to dissipate its excess heat. This heat loss takes place through the evaporation of sweat deposited on the skin, and heat convection towards the air mass or any other surrounding medium. Thermal comfort is generally afforded by temperatures in the 22-25°C range and a relative humidity of 50 to 60%.

In the wet tropics the air is constantly laden with water vapour, so that its absorption capacity is greatly limited. If it were feasible, the air mass would therefore have to be constantly replaced by increasing its circulation speed and drying it. The most common way of achieving such a result is conditioning the air by using electrical and mechanical devices.

Nevertheless, the use of devices of this kind is not recommended in these regions, owing to the sheer size of the population and the social and economic circumstances of its members. Moreover, using air-cooling devices means consuming conventional energy, which could profoundly affect the economy and ecology of the region.

The replacement of hardware such as electrical and mechanical air-conditioning devices by the application of a new ecological rationale, in the architectural and urban design of human settlements, should be seen as a goal in the search for techniques suited to human settlement in the tropics. Traditional architecture, both within the region and abroad, offers simple ways of controlling the climate, methods which spur on the search for "software": appropriate, low-cost techniques for the enhancement of thermal comfort in human settlements.

Control of three natural elements - insolation, ventilation and precipitation - can be achieved through simple design innovations, based on certain considerations peculiar to each element.

5.1.1 Control of Insolation (see Figures 6, 7, 8 and 9):

Solar radiation is one of the factors exerting the greatest influence on thermal comfort. The heating of surfaces exposed to the Sun's rays is, of course, the most direct cause of rises in temperature. When these surfaces are the roofs and walls of buildings, the heat absorbed is transmitted into the interior. Moreover, when the ground is covered with hard materials, it reflects ambient heat onto buildings, thereby increasing the ambient temperature. Finally, clouds also reflect sunlight and prolong its thermal effects beyond the hours of greatest exposure.

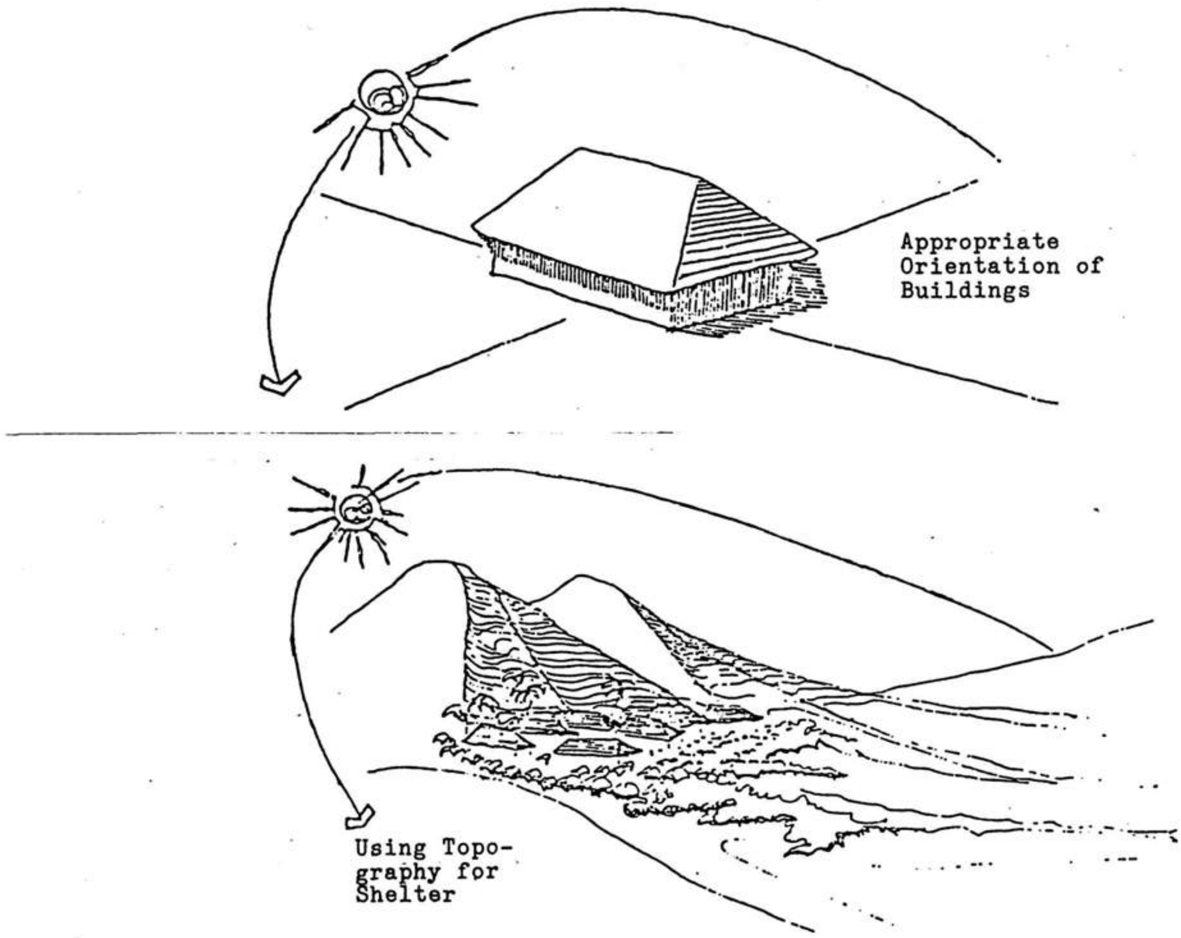


Figure 6. Alignments for Controlling Insolation (Source CEPAL/PNUMA/SAHOP, 1980).

Given the foregoing, the suitable orientation of buildings so as to protect them from direct sunlight is clearly one of the primary requirements for reducing the effects of incident solar radiation; effects that are so welcome in other climes. Since the region under study is situated within the tropics, the Sun is said to be "high"; it moves on an east-west course with a slight inclination towards the south or north, depending on how far the station is away from the Equator.

North- and south-facing slopes of elevated areas receive less solar radiation owing to the Sun's motion and declination; for this reason, they are favourable as sites for settlements. If these locations do not benefit from the wind, then this latter factor should take precedence.

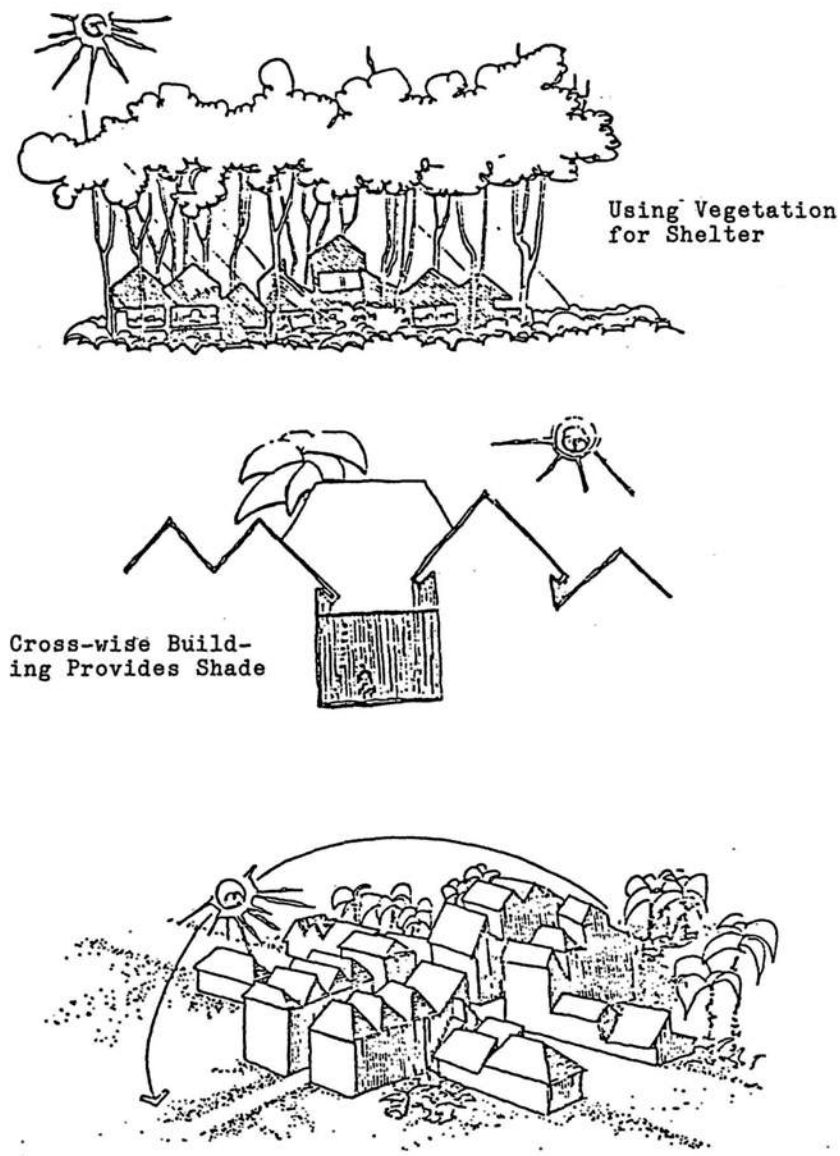


Figure 7. Generating Shade **(Source CEPAL/PNUMA/SAHOP, 1980).**

Vegetation, especially the tall variety, provides a natural means of sheltering buildings from prolonged sunlight. Streets and walkways can be sheltered using the shade afforded by buildings or eaves and porches. This interlocking of buildings can provide a means of enlarging shaded areas where there is traffic, especially pedestrian traffic. For outdoor sites where people have to remain for relatively prolonged periods (e.g. bus stops), trees or roofing designed for this purpose could be used.

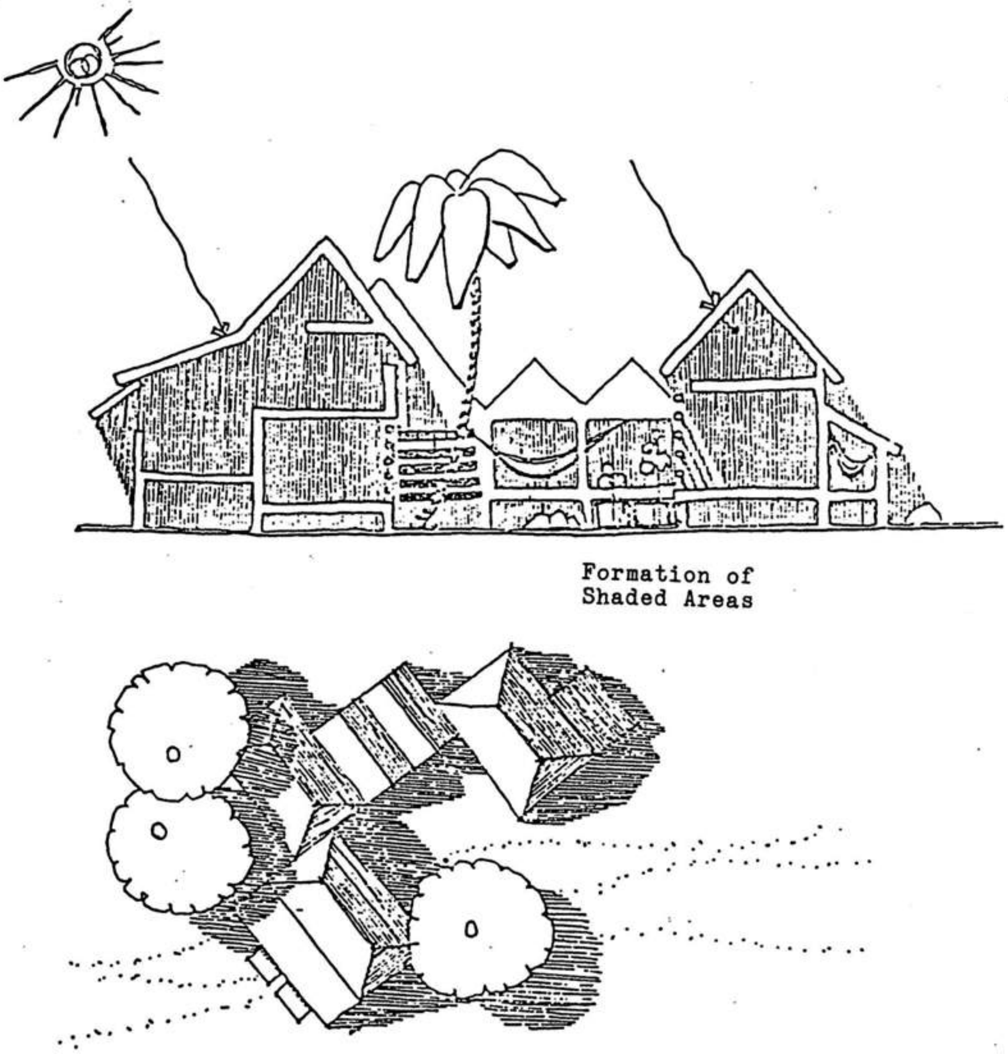


Figure 8. Generating Shade **(Source CEPAL/PNUMA/SAHOP, 1980).**

To reduce heat gain in a settlement, the overall relief of the rooftops should be jagged and predominantly pitched. In this way, at any time of day there would be surfaces either in shade or not receiving direct sunlight. This is not the case when flat or only slightly sloping roofs are used. That is why it is also useful to arrange buildings in such a way that they shade one another as well as open spaces.

It is very important that vegetation be used to shade areas set aside for vehicle parking. These areas are notorious heat reflectors, contributing greatly to rises in the ambient temperature of settlements. If the natural shelter afforded by trees is coupled with the use of non-reflective and variegated materials for paving streets and car-parks, a settlement's mean temperature can be perceptibly reduced.

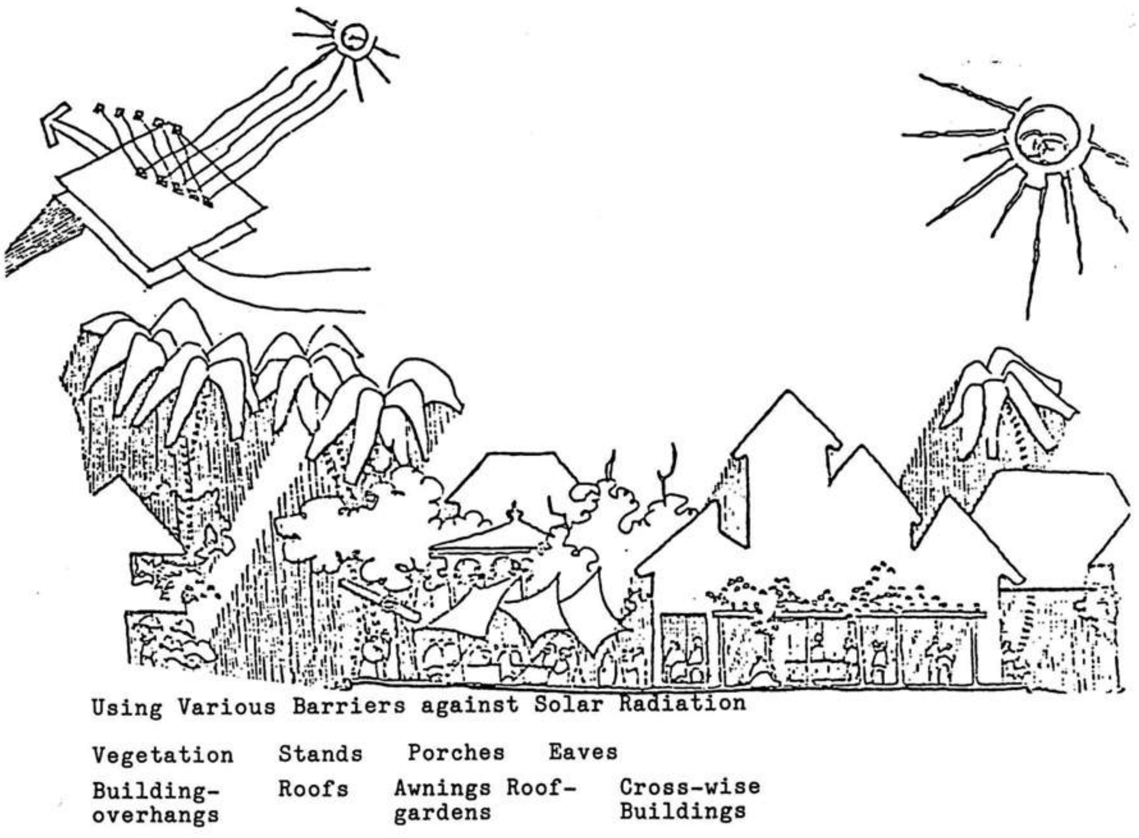


Figure 9. Protection against Solar Radiation (Source CEPAL/PNUMA/SAHOP, 1980).

The predominance of the sun as a source of heat generation outlines the extraordinary importance held by the roofs of buildings in the wet tropics. Roofs are clearly the most important element when it comes to adapting dwellings to a hot, wet, tropical climate. Their role of providing shelter from the Sun's rays and the rain can be typified by the image of a parasol or umbrella, which protects a space where shade, ventilation and shelter from a torrid Sun must be ensured. These conditions require the covering to be waterproof, to reflect heat from solar radiation or absorb it without transmitting it to lower levels and, lastly, to afford visor-like protection against the brilliant arch of the sky so characteristic of the wet tropics.

This function has been traditionally served by the "palapa" in the tropical regions of Mexico. A very tall, comparatively stout structure with a steeply-pitched roof of woven palm leaves, it meets the above-mentioned specifications fairly adequately. Indeed, the palapa's shape allows hot air to escape from its upper structure, while at the same time creating an insulating cushion which stabilizes the temperature and affords protection against both rain and blistering heat.

COMFORT IN THE URBAN TROPICS

A large space covered by a lightweight roof, beneath which family life can be organized around sheltered, open areas in close contact with nature, ought to be - even today - a model fitting the specific needs of middle- and lower-income town-dwellers who cannot avail themselves of modern electrical and mechanical air-cooling devices and who have to cluster together in units of relatively high density.

The concept of a lightweight, waterproof roof, insulating against heat and protruding well beyond its support beams, should be maintained as a design principle. A roof of this type should be supported by a series of columns or porticos, apart from the walls or partitions. It must be flexible enough to support hurricane winds, seismic movements and strong downpours, while at the same time protecting the occupants' privacy.

As for the covering itself, the use of palm leaves or any other non-compact material may offer an appropriate solution within certain limits. The basic requirement is the roof's pitch which must be very steep, making water-proofing unnecessary in view of the quick run-off. When this is not possible, the possibility of using waterproof materials which are poor heat conductors should be explored. Roof-tiles or shingles are such materials, but - here again - they are not sufficiently mass-produced for widespread use, and new ceramic products factories have to be built.

While awaiting development of these new industries in the region, imported products might have to be used. In this case, the design would have to provide for air spaces acting as thermal insulation. If these spaces were open to wind circulation, the insulating effect would be enhanced. Climatic conditions in the wet tropics clearly dictate the need for wide roofs, making it mandatory to think in terms of the entire structure rather than isolated units. With this in mind, roofing must be conceived in terms of standard modules which could be combined, so as to extend covered spaces continually.

Incorporating more complex technology such as steel or plastics can only be regarded as longer-range solutions. Priority should therefore be granted to the potential of organic substances, baked earth and certain readily available manufactured materials.

In setting priorities, regard should be given to the possibility of borrowing technology derived through experience in the area or in places where economic and environmental conditions are similar. For example, there exists a curious technique for building baked-mud arches. The arch consists of a bamboo (otate) and reed-grass cradling, which is covered with successive layers of clay mud and chopped grass poly leaves. Once the mud has dried, the cradling is set alight and completely burned with the help of firewood, thereby baking and stabilizing the arch.

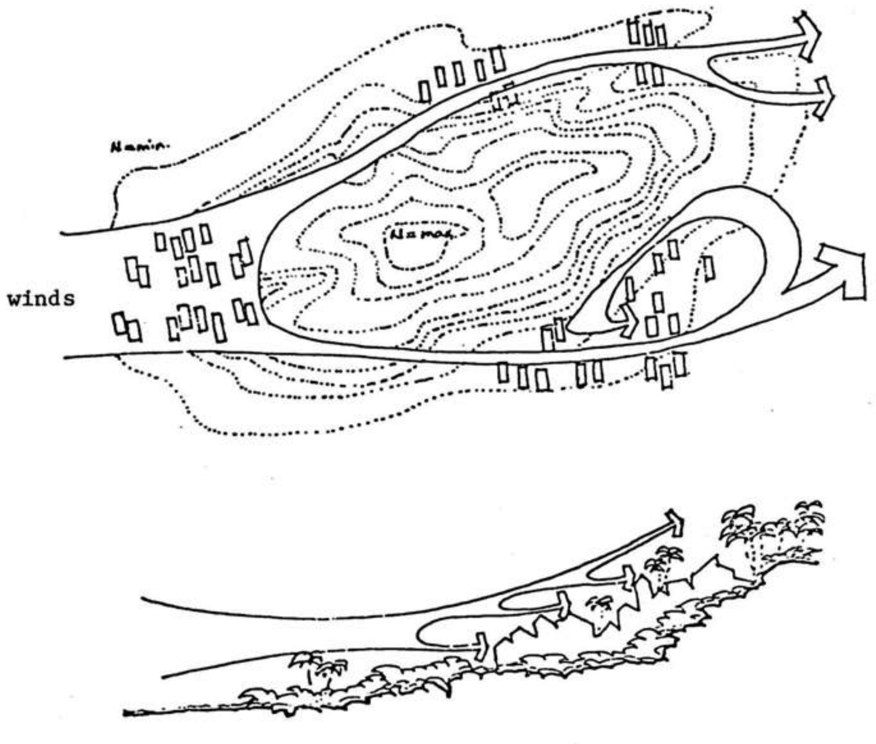


Figure 10. Generation of ventilation **(Source CEPAL/PNUMA/SAHOP, 1980).**

5.1.2 Control of Cross-Ventilation (Figures 10 to 14)

Taking advantage of natural draughts is the primary prerequisite for increasing Nature's capacity to absorb excessive heat generated by the human body. The general layout of the settlement, together with building design and selection of materials, can reduce a tropical climate's adverse effects, while natural ventilation can be stimulated by applying certain principles of fluid dynamics, thereby replacing technology based on appliances and conventional energy.

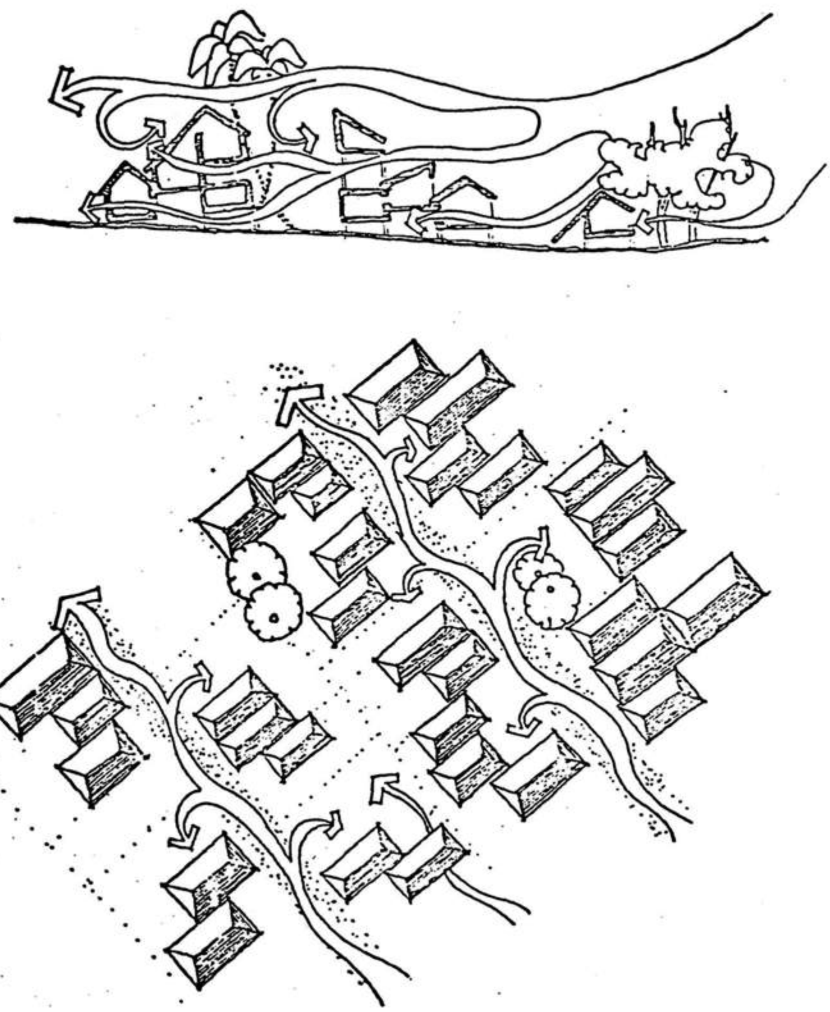


Figure 11. Generation of ventilation **(Source CEPAL/PNUMA/SAHOP, 1980).**

It can further be demonstrated that "channelling" air is one of the most effective processes in ecodesign and that air flows can be generated artificially, by using temperature differences which either already exist or can be created in various parts of the settlement, as the Arabs have done in the dry tropics. It should be recalled that in early Spanish colonies, decrees provided that streets in hot climates should be narrow, so as to create air flows and afford shade.

The natural arrangement of buildings in the wet tropics would seem to tend towards a certain amount of scattering, so as not to obstruct incident prevailing winds. However, economic and social imperatives dictate that cities must become more concentrated, making it necessary to increase the density to reduce the cost of public services and achieve required social cohesiveness.

Channelling air flows helps distribute them over the settlement as a whole and even increase their circulation speed. Yet this necessarily implies integral designing of entire settlements large enough to ensure the application of the above-mentioned principles. To a certain extent, channelling air requires somewhat denser construction.

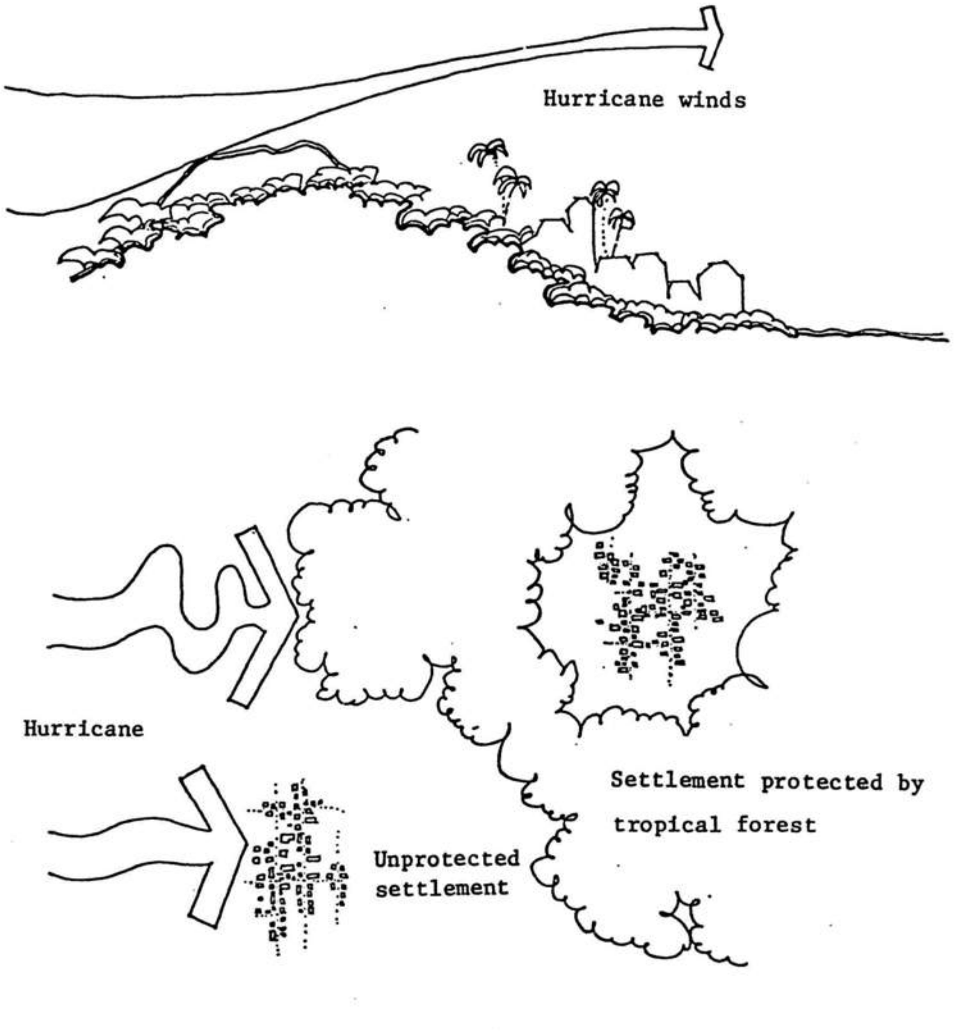


Figure 12. Protection from hurricane-force winds (Source CEPAL/PNUMA/SAHOP, 1980).

Public areas, streets and squares should be sheltered from direct sunlight and built on a scale which reduces walking distances. Generally speaking, the large, open areas so frequent in temperate countries are not recommended in the tropics. Streets, especially those closed to automobile traffic, should always be sheltered, as was the standard during colonial times.

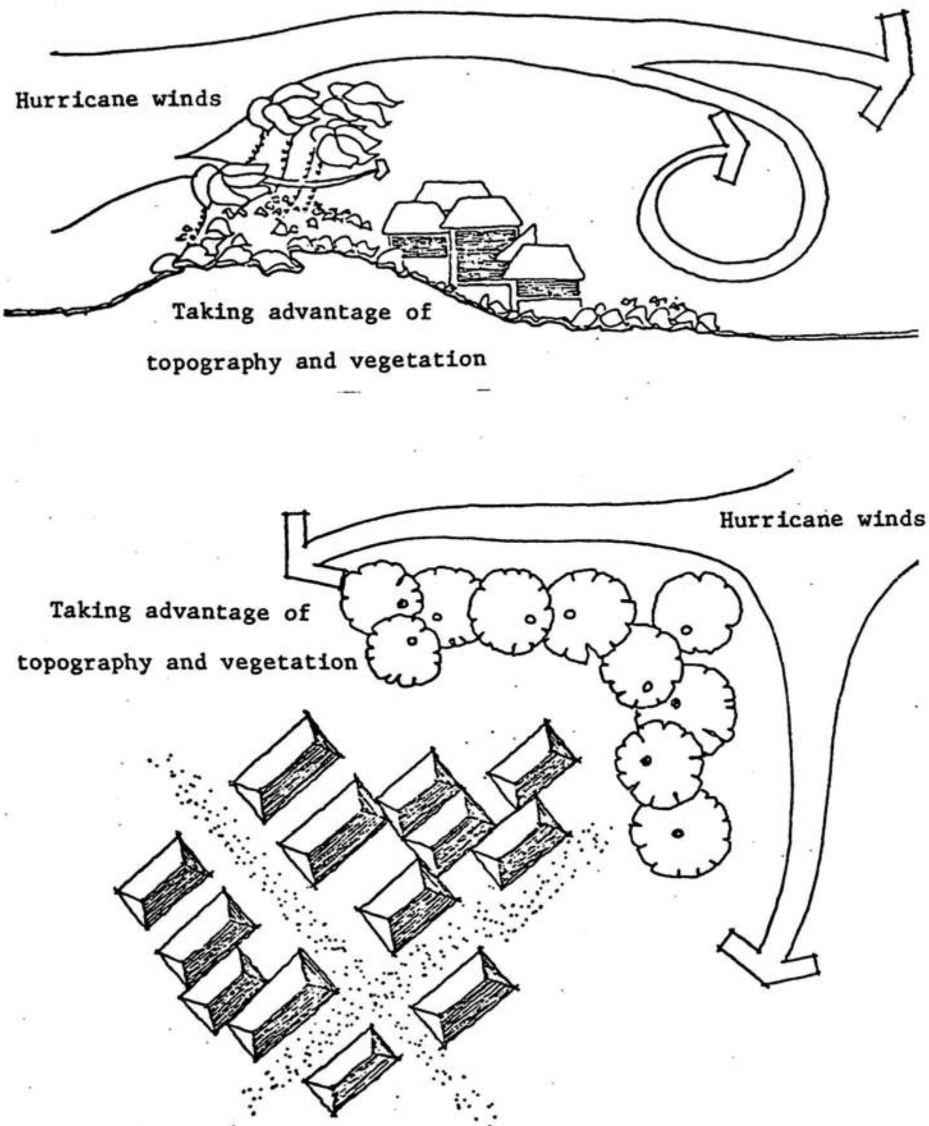


Figure 13. Protection from hurricane-force winds (Source CEPAL/PNUMA/SAHOP, 1980).

It is essential to create urban areas which are shaded and, as far as possible, include air streams which flow through the entire urban network, injecting or absorbing cool or warm air around public buildings. A city as a whole should be a system in which public and private areas, be they built-up or open, fit as interdependent and inseparable elements into an ensemble. The channelling of winds should be treated as an essential principle in the ecodesign of human settlements in the wet tropics.

More than in other latitudes, urban areas in the wet tropics have to be endowed with suitable vegetation, which ought to be as abundant as possible.

Paved surfaces should be kept to a minimum to avoid overheating through absorption and reflection of light and heat. Trees should have a high, leafy canopy so as not to hinder air circulation near the ground; for the same reason, low vegetation should be kept separate from buildings. Breezes should ideally originate in shaded meadows where they are cooled by the mass of vegetation. Buildings ought to be fairly long to facilitate cross-circulation; in other words, rooms should be arranged in a single row or cross-shape in order to allow the air to flow freely, something which is difficult to achieve when air has to travel from one room to the next. Optimal ventilation can be attained by locating settlements in elevated areas on windward slopes. Wherever possible, settlements should be located on hillsides, even when their slopes are not at right angles to the prevailing wind. In such cases, winds from other directions can cause welcome countercurrents and eddies.

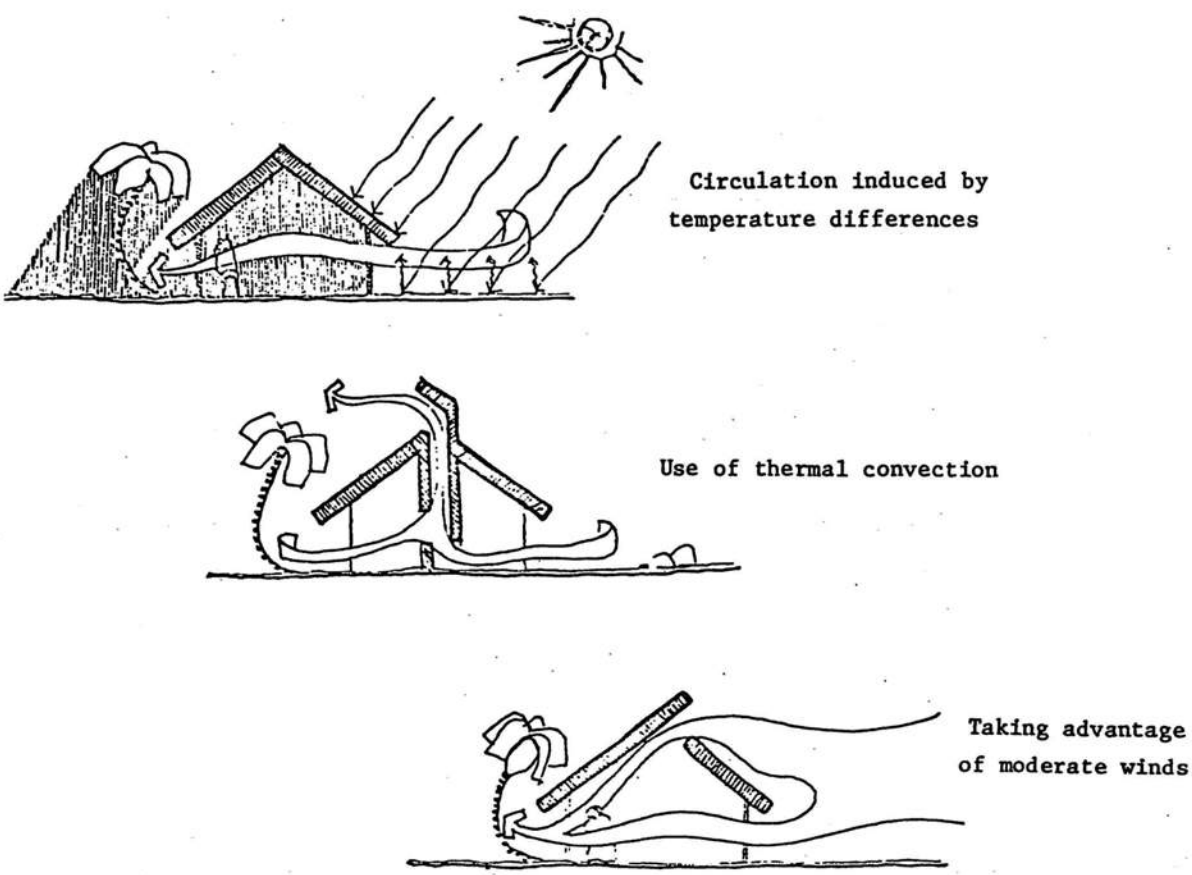


Figure 14. Generation of air currents **(Source CEPAL/PNUMA/SAHOP, 1980).**

The longest thoroughfares should be oriented in the direction of the prevailing winds. If they are narrow in a funnel wind speed will be increased. On the other hand, if streets conveying air flows, open onto wider areas, wind speed will be reduced and moderate turbulence created.

Similar effects can be produced inside buildings by arranging outlet openings, corridors and stairs properly. For isolated buildings, it is important to remember that openings facing prevailing winds ought to be relatively small to increase the air velocity. If the relief created by a set of rooftops is uneven, turbulence will be created at this height, thereby stirring up the mass of hot air in amongst the buildings.

Should it be necessary to build structures substantially taller than their neighbours by and large, empty spaces can be left for the air to flow around them, thus diminishing their tendency to act as windbreaks.

Whenever the settlement's net density is low enough, buildings and vegetation ought to be arranged so that air currents and countercurrents are generated, along with slight turbulence in open areas intended for the public, in streets and squares reserved for private use and even patios and walkways.

5.1.3 Control via Apertures and Barriers

While the function of walls in the dry tropics is to provide thermal insulation (above and beyond their structural role), their specific purpose in the wet tropics is to ensure occupant privacy and to shelter properly. The separation of structural and protective roles is facilitated by using lightweight materials. These should afford air circulation, with the help of lightweight cellular elements acting as filtering screens. Uninterrupted, heavy walls, which have to be built as protection against hurricane winds, are an exception.

The use of load-bearing walls has been introduced in the region as a result of indiscriminate importing of foreign techniques. This clashes with practices nurtured by experience which are still observed in the region. Nevertheless, the quantitative and qualitative changes dictated by the scale of future settlements make it necessary to search for new materials and designs, at once ensuring mass production and satisfying the environmental requirements of the wet tropics.

In the design and construction of future settlements, walls should continue to act as filtering screens, in contrast to their role as structural supports. They ought to allow air to flow freely while, at the same time, ensuring the privacy of family activities and work requiring separation and safety. Here, any type of material capable of operating like a venetian blind should be used. These materials need to reflect light and heat and be resistant to rain, humidity, sunlight and corrosion by airborne agents. Roof-overhangs together with the use of chemical compounds, are among the most appropriate ways of protecting screen-walls against the elements (Figure 15).

The following are some of the primary techniques now available for achieving the conditions mentioned:

Vegetation Screens:

- Bamboo (otate) split lengthwise, with the round, shinier side facing outwards for better reflection of light. Bamboo screens can be combined with palm leaves or fixed bundles of straw to afford better visual protection, although this reduces wind flow (Figure 16).
- Wooden planks placed upright or crosswise, leaving slits for air flow while providing a visual barrier.

  Since both materials are subjected to sunlight and humidity-induced rotting, they must be treated. Their life-span is short (roughly six years).
- The bajareque or enjarre is a traditional building material, consisting of reed-grass on wood held in place by river-rattan, to which a mixture of clay and chopped grass poly (a local gramineous plant) is applied. Although the resulting material has a relatively short life-span, the wall can easily be renovated simply by removing the mixture (while checking the state of the reinforcement material and anchorings), then wetting and repacking it. With this technique, it is also easy to choose locations for apertures. Durability can be enhanced by fortifying the mixture and protecting it with compounds which are resistant to saltpetre-laden water.

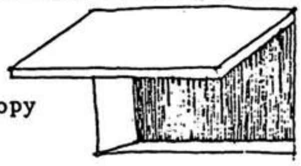
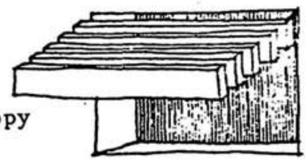
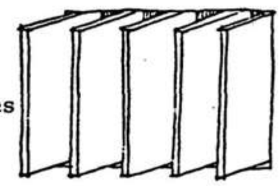
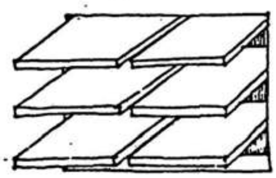
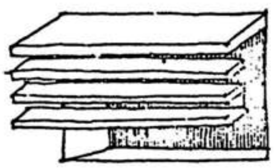
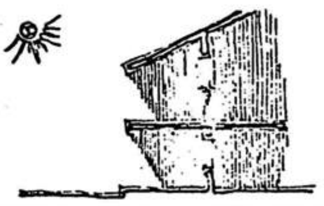
Type of Control		Reduction of external heat	Efficiency of cross-ventilation	Lighting control	Average efficiency of control
		(IN PERCENT)			
Concrete canopy		70 - 80	80 - 100	45	70
Slatted canopy		85	80 - 100	77	84
Vertical louvres		70 - 80	10 - 50	45 - 65	54
Horizontal louvres		70 - 80	45 - 50	45 - 70	53
Suspended louvres		80 - 85	80 - 100	70 - 80	82
Verandas		75 - 80	80 - 100	40	69

Figure 15. Comparative analysis of various ways of controlling the entry of heat through windows **(Source CEPAL/PNUMA/SAHOP, 1980).**

Overhangs should be as wide as possible, since all facades exposed to sunlight must be protected - particularly those facing west. The general layout should be uncluttered and flexible, with open, shaded passages allowing air to flow freely. The use of removable partitions can help achieve this effect. There is no reason why indoor environments should be closed off, for much of life can be spent comfortably in the open air, provided there is shade and protection from insects. Indoor/outdoor separation is less strict than in colder climates or the dry tropics, where dwellings must be insulated from the exterior. Special care should be taken to ventilate areas generating heat and humidity or intended for storage.

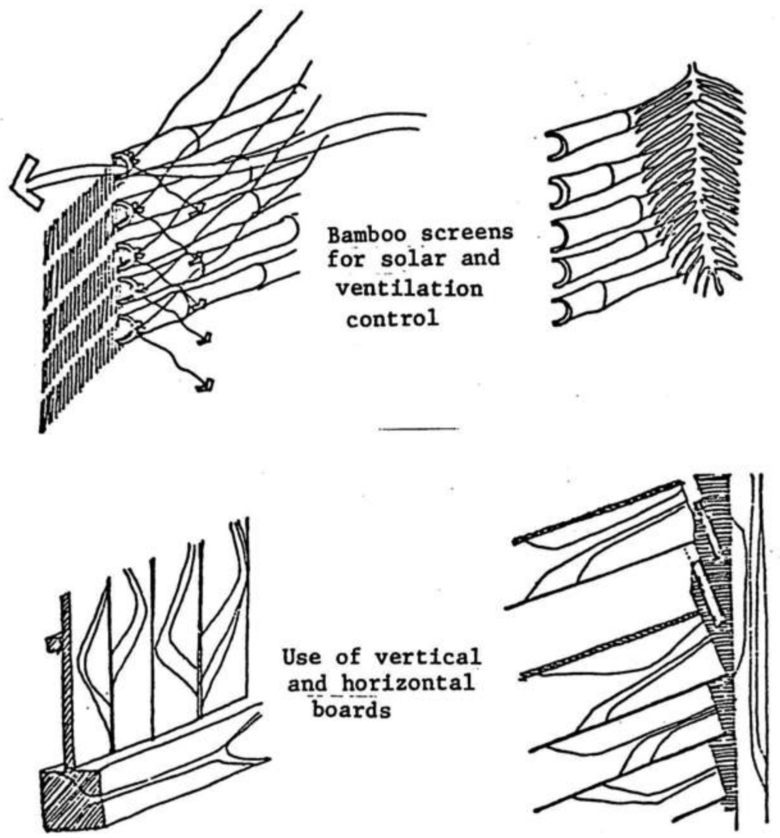


Figure 16. Vegetation screens (Source CEPAL/PNUMA/SAHOP, 1980).

Dwellings ought to be oriented in such a way that they keep incident solar radiation to a minimum while capturing breezes whenever possible. A 10% error in any direction is admissible; despite this, anything concerning orientation ought to be decided only after checking a solar map indicating direction and angles of solar radiation at different times of the year.

The advantages of cross-ventilation have already been reiterated; however, in order for it to be effective, certain requirements must be met. First of all, one must bear in mind that an indoor air stream's location depends on its inlet, while its velocity (and thus its volume) depend on its outlet. It is important to point out that, contrary to popular belief, the largest apertures should not be located in facades facing the prevailing wind. If the apertures giving access to wind are smaller than those allowing it to escape, then air speed will increase in accordance with Venturi's principle (fluid velocity increases as a section is constricted).

When conventional windows are used, inlets should be located in the lower part of the walls facing outdoor breezes, and outlets in the upper part of the opposite walls, so as to produce diagonal flows inside. In order to avoid low-pressure areas (e.g. of hot air, which tends to accumulate near the ceiling) outlets should be built into the upper part of the roof.

A good design principle is to keep illumination and ventilation functions separate, as there is no reason why they should have to be derived from the same materials. There is no practical need for glass doors and windows in the tropics (unless large amounts of dust are suspended in the air). Using glass makes construction needlessly expensive and reduces air circulation; moreover, when glass is directly exposed to the Sun's rays, it radiates heat and raises the indoor temperature considerably.

As far as possible, doors should allow the passage of air even when they are closed. Perforated materials or slats are quite commonly used and effective, their main drawback being their relatively high cost. It is recommended that, in any event, at least the lower part of doors be venetianed and that doorways be extended to the ceiling and fitted with slats.

It should not be forgotten that the natural direction of air flow is modified by an urban layout and that, as a rule, the velocity in city areas is reduced to about one third of that in the open countryside.

Properly used, air circulation can replenish interior air many times over. The volume of air in circulation can be estimated according to the following formula:

$$V = 3150\ Av$$

where V is the volume of circulating air (ft^3), A is the total area of the inlets (ft^2) and v is the incident wind velocity (mph). When the angle of incidence is less than 90° the volume is reduced, and the difference can be estimated by applying the coefficient 0.5 when the angle of incidence approaches 45°. When screens are used to protect apertures from insects velocity is again reduced. Here, reduction can reach 60% in the case of a fine-mesh screen (applying a new reduction coefficient of 0.5 usually suffices).

Often, taking advantage of natural conditions is not enough; they can be enhanced through architectural design by applying certain principles of physics mentioned earlier. These principles are applied mainly to create air pressure differences, change the direction of air flows and avoid formation of low-pressure areas which have a braking effect on velocity, thus reducing the amount of air in circulation. The principles can be applied through a wide variety of designs, which can themselves be combined in different ways to suit every circumstance and requirement.

One of the most common ways of applying the principle of thermal draught is by building vertical ducts or chimneys wherein air is accelerated and can syphon off air from the interior. In other instances, indoor-outdoor air pressure differences can be used to draw air through horizontal ducts, especially in multi-storey buildings, producing similar air-renewal effects.

In order to increase outdoor air pressure around single-family dwellings, the age-old principle of elevating the structure may be used. This avoids the layer of reduced velocity near the surface due to friction with the ground and low vegetation. Savings can also be made despite the greater cost of the structure, because the need to level the site is eliminated.

In addition to the principles of physics referred to, it is also possible and certainly recommended to "treat" the often hot air entering dwellings, especially in urban areas. There is no reason why processes of this kind should mean using mechanical equipment. In some areas in Iran, for example, spontaneous architecture has produced an ingenious air-cooling system, equivalent in its results to a mechanical air conditioner. Similar effects may be derived from outdoor terraces, beneficial for two other reasons; they actually make it possible to bring down the temperature of the outdoor air by placing it in contact with a mass of cool air. The same result can be obtained by providing cool surfaces or elements (water or vegetation) which act on the intermediate area between the wind's direction and its inlets in dwellings (cf. traditional Mediterranean patios comprising fountains and gardens).

Finally, it should be noted that temperature control measures can affect air circulation, especially when they take the form of barriers placed in windows and wall apertures to restrict sunlight.

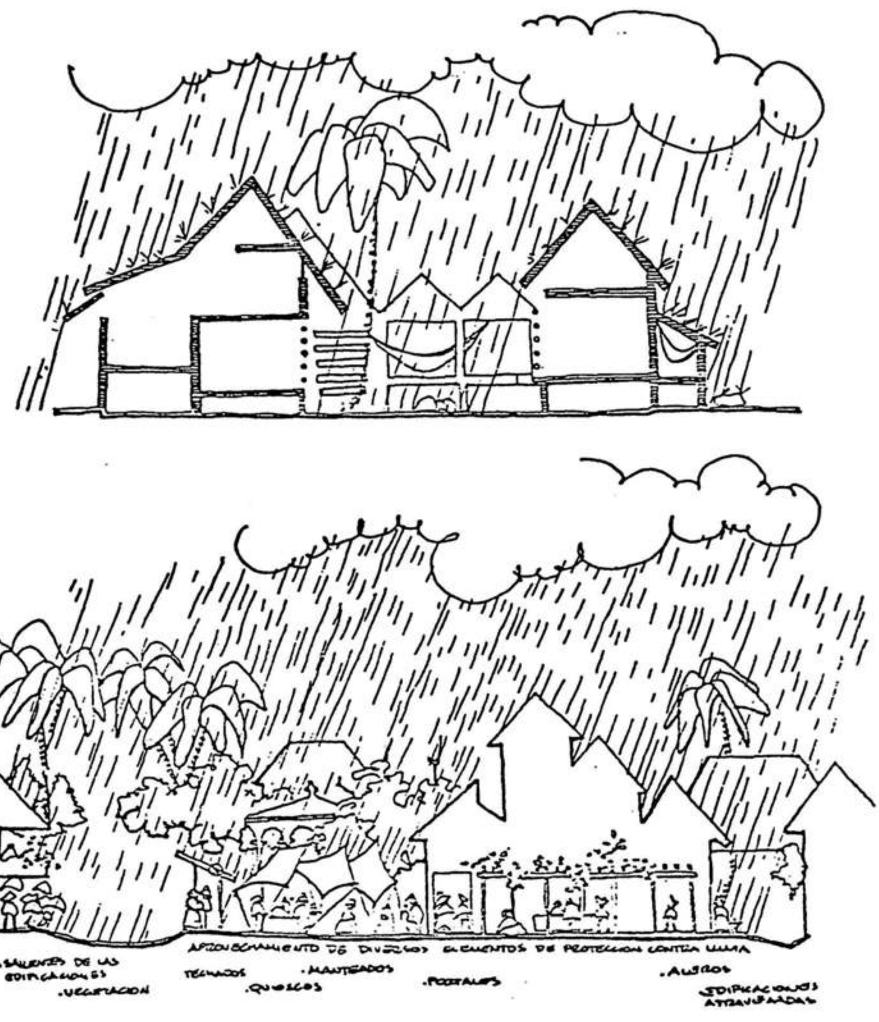


Figure 17. Protection from rain (Source CEPAL/PNUMA/SAHOP, 1980).

5.1.4 Control of Rain and Humidity (Figures 17 and 18)

Rain ranks third among the natural elements which have a decisive impact in the wet tropics and therefore shapes all types of ecodesign. Floods, wet ground and high relative humidity are the most obvious consequences of tropical precipitation, which is possibly the most important differentiating factor with respect to other climates.

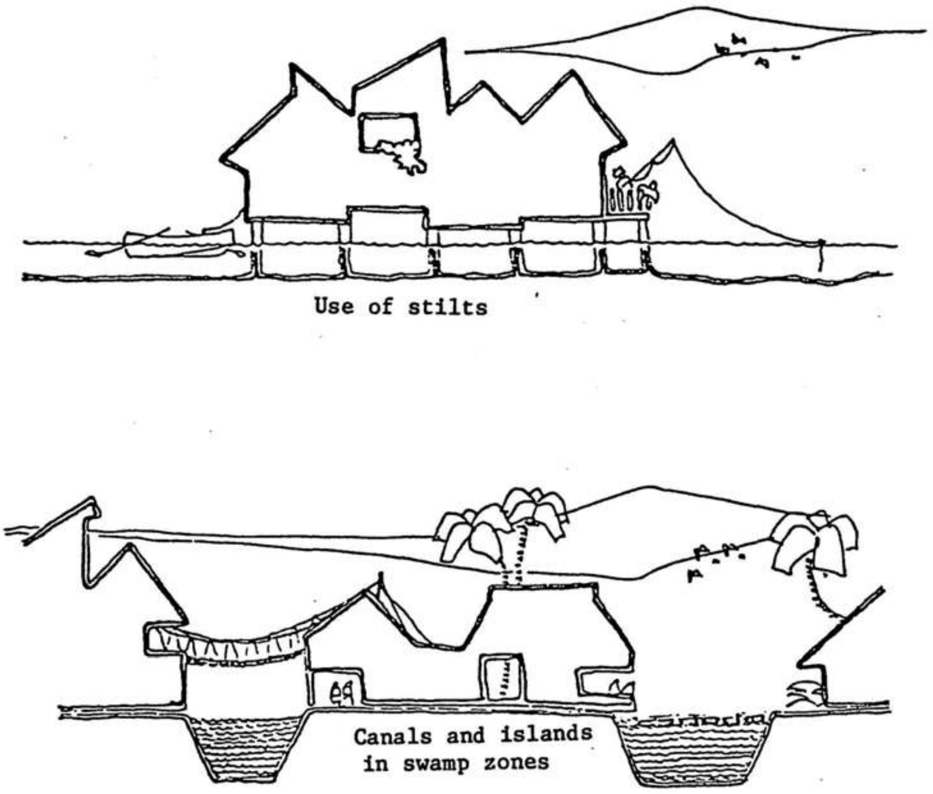


Figure 18. Protection from humidity (Source CEPAL/PNUMA/SAHOP, 1980).

In riverine flatlands there is a high risk of flooding, especially during the seasons of heaviest rainfall. Rivers easily overflow their shallow beds, while natural seepage into the ground is restricted by saturation of the subsoil. Locating settlements on only gently-sloping land is obviously ill-advised; hence their frequent siting on hillsides.

There are certain drawbacks in choosing sloping land, however, which can be avoided by adopting appropriate techniques. The use of heavy machinery in preparing sites for habitation destroys vegetation, levels the natural slope and destroys the soil structure. All this increases run-off, which plugs up drains in the low-lying areas of settlements. Floods caused in this manner are exacerbated by the loss of absorbent surfaces, resulting from the use of unbroken pavement and total occupancy of the ground by buildings.

As far as protection against tropical rains is concerned, whatever a settlement's location with respect to topography, ecodesign should specifically aim to create the conditions required for human activities needing shelter from rain. Protection from rain generally imposes design requirements very similar to those needed for protection against sunlight, and the materials used in each instance are practically the same.

The heavy rains so typical of the wet tropics have a great impact on roadways. In extreme cases, streets become genuine canals, preventing pedestrian and vehicle traffic during downpours. Streets should and must be designed using techniques different from those prevalent in other climates. Despite this, the general trend shows no sign of departing from imported patterns. Even more sadly, it marks a step backward in relation to building codes in colonial times. These codes provided for pedestrian shelter by means of eaves and covered walkways, features which long became part of city life and were subsequently neglected. Streets nowadays are generally paved with unbroken asphalt. This technique prevents rainwater being absorbed, creating one of the causes of flooding. In addition, the colour, texture and composition of asphalt are conducive to high absorption of heat, which is released when the temperature falls in the evening, making it difficult to cool the environment.

As a matter of principle, unbroken, rigid pavement preventing seepage into the subsoil ought to be banned. Streets should be surfaced with coarse, porous material having a low heat absorption index. Brick, concrete (blocks) and even wood (from species not otherwise used in construction) afford good possibilities as components in paving streets, public squares and private courtyards. The advantage of using brick lies in the abundance of clay in many tropical regions and the potential economic gains from producing it on nearly any scale.

New paving materials and techniques should be studied, especially where raw materials are available locally.

In summary, paving materials are of the utmost importance in that they must allow rainwater to seep into the subsoil, facilitate drainage and absorb as much of the heat generated by solar radiation and vehicle traffic as possible.

When pavement is impermeable and unbroken, the subsoil is insulated from the environment and receives only the heat transmitted from the pavement by convection. This is why porous materials are recommended. They can be spaced out to allow rain water to filter downwards, while at the same time cooling the subsoil.

Rain can also be beneficial, leading designers to adopt a different attitude. It may be used to supply a city with water. Generally speaking, rainwater is a resource which comes free of impurities (except when there is air pollution) and can be stored for later use. In some areas sufficient quantities could be stocked to meet the household needs of a population. Practical methods of collecting rainwater should therefore be investigated, perhaps including underground tanks and storage basins; these would amount to a modern-day version of the Maya cenote*. Alternatively, tanks might be built into roofs, allowing the water to flow simply by gravitational force. Here, however, structural problems might arise which would have to be given due consideration.

Rainwater cannot be recommended for all uses. Its suitability for drinking needs to be tested in each case. The availability of proper collection, storage and distribution techniques should also be dealt with at the same time in the design and planning stage of a settlement. This type of water supply nevertheless has considerable potential and could offer comparative advantages over other supply techniques, especially in the case of relatively self-sufficient settlement modules.

The logical result of the technical recommendations made in the preceding pages would be their implementation, not only because they complement one another, but also because the delineation of settlement modules is a prerequisite in facilitating the planning of human settlements in the wet tropics.

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*Translator's note: A "cenote" is a deposit of water found in America, generally at a great depth in the centre of a cavern.

There are obvious advantages in having relatively independent units grouped together to form modules. The component parts of such modules (dwellings, complementary structures and basic services) could then provide mutual benefits.

A reciprocal interrelationship of this kind is not only economical; it arises from the benefits of those environmental conditions which are possible only in communities of a certain size. The aim is to imagine and design artificial micro-habitats which can later be integrated into larger settlements, optimizing their relationship to the environment under prevailing conditions in the wet tropics.

The following are noteworthy design features which could be integrated in a single conceptual, physical unit:

- the harnessing and channelling of air streams, perhaps including cooling and dehumidification by non-mechanical means;
- complete protection from solar radiation and rain;
- the use of rainwater; and
- the evacuation of waste water.

The design criteria which ought to be applied would have to include the potential economies of scale of an integrated plan. For instance, the maximum capacity of septic tanks for waste water could provide a starting point in deciding on the optimum scale for a settlement module.

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URBAN HYDROLOGY IN THE TROPICS : PROBLEMS, SOLUTIONS, DATA COLLECTION AND ANALYSIS

Thomas Dunne
Department of Geological Sciences
University of Washington, Seattle, WA 98195 USA

1. STATEMENT OF PROBLEMS

Modifications of the land surface during urbanization change the type or magnitude of runoff processes. The major change in runoff processes results from covering parts of the catchment with impervious roofs, sidewalks, roads, and parking lots, and from drastically lowering the infiltration capacity of soils exposed and packed down on construction sites and unpaved roads and tracks. As a result, the volume and rate of overland flow are increased, or overland flow is introduced into areas which formerly contributed only low volumes of relatively slow subsurface flow.

Paved and packed surfaces are smoothed, so that the speed of overland flow is increased. Drainage density is increased and overland flow paths are shortened as gutters, drains, and storm sewers are laid in the urbanized area to convey runoff rapidly to stream channels. Natural stream channels are often straightened, deepened, or lined with concrete to make them hydraulically smoother to increase the speed with which the flood wave is transmitted downstream, so that even without an increase in runoff volume, the peak discharge rate would be increased. The land-surface modifications are summarized in Figure 1, and their effects on the stream hydrograph are illustrated in Figure 2.

Temporary storage of floodwaters in large artificial channels, in detention ponds, artificial lakes, or behind obstructions such as highway embankments and under-sized culverts, may decrease flood peaks in some urbanized basins. Diversion of stormflow out of the basin may accomplish the same result. However, in most cities, flood peaks are increased by urbanization, and the effects are greatest, relative to the undisturbed condition, in small basins and in smaller flood-producing storms. In the largest storms, most of the landscape generates runoff whether it is urbanized or not, whereas in smaller rainstorms, the contributing area may constitute only a small fraction (<10%) of the undisturbed drainage basin, and may be increased severalfold by the introduction of artificial impervious areas. The effects are also greatest relative to natural conditions, in small basins, because they may be entirely urbanized and lack storage areas such as broad floodplains where water may pond to modulate flood peaks.

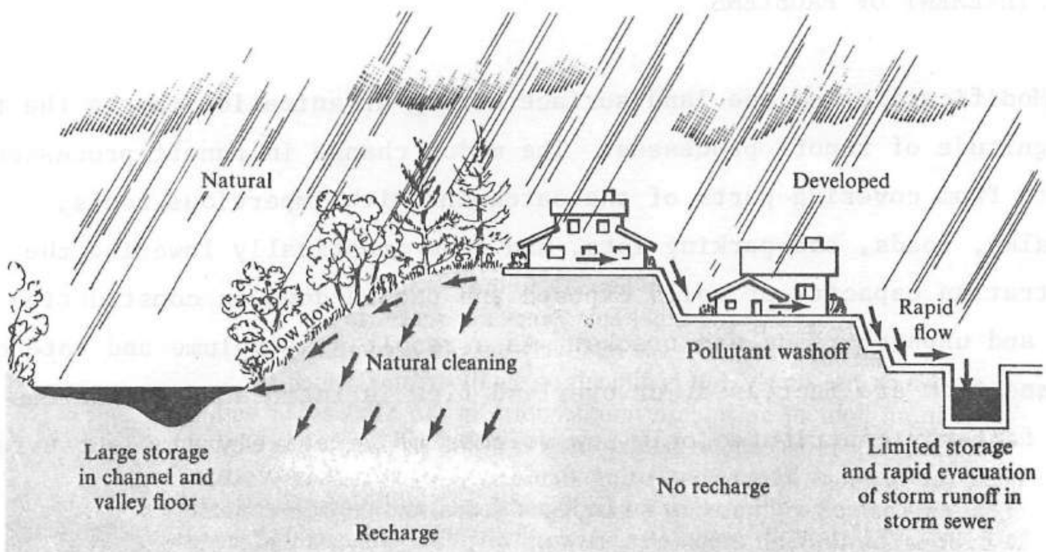

Figure 1. Schematic representation of the problems to be managed in the control of urban storm runoff. (Source: Dunne and Leopold, Water in Environmental Planning, Copyright W.H. Freeman Co., 1978).

The increased peak flows cause overbank flooding, stream channel erosion, undermining of bridges and other structures, or overtaxing of sewer systems. Traffic is disrupted, homes and businesses damaged, and in severe cases, such as the recent floods in Mexico City, lives are lost. The problem is often exacerbated by deposition within natural and artificial channels and reservoirs of sediment eroded from construction sites and roadways. Much of the storm runoff is contaminated with sediment, feces, oil, and other chemicals, which pollute surface water sources and spread disease.

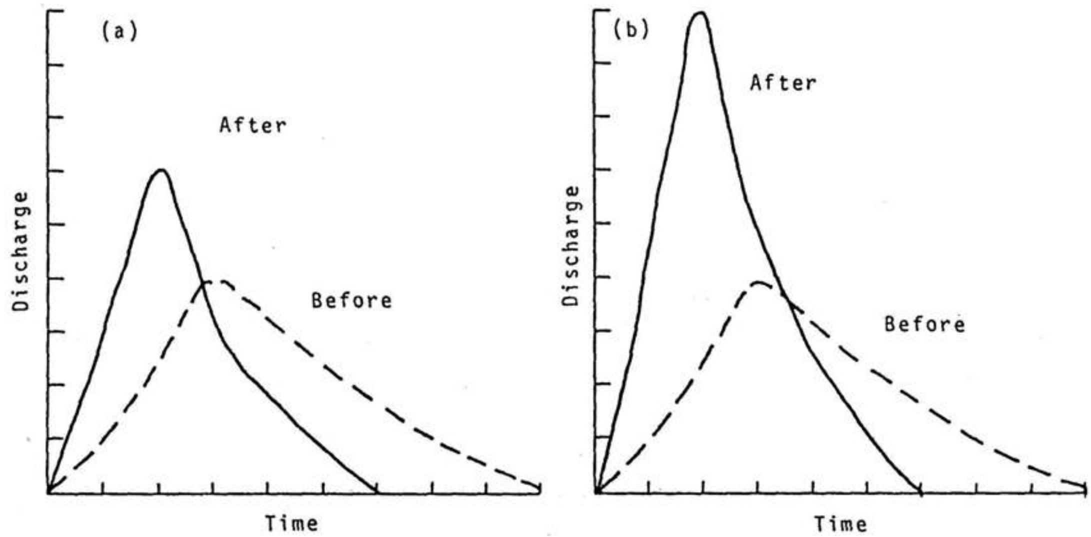

Figure 2. (a) Effect on the flood hydrograph of increasing the speed of runoff without increasing its volume; (b) Effect on the flood hydrograph of increasing both the speed and volume of runoff.

The increase in storm runoff is accompanied by a decrease in the amount of water entering the soil in urban areas. Some of the soil water would have evaporated back to the atmosphere under natural conditions, and a portion of the infiltrated water still does so in the city. However, the amount of evaporation from urban landscapes is being studied in a rigorous and systematic way in only a few places, such as Moscow (L'vovich and Chernogayeva, 1977) and Vancouver (Kalanda et al., 1980; Grimmond, 1983), and it is impossible to generalize yet about its importance in tropical cities. The unevaporated surplus contributes either to subsurface storm runoff from shallow, perched saturated layers in soils with an impeding horizon, or to slower, dry-weather flow through deeper bodies of groundwater. In most cities it is difficult to predict the effects of urbanization on each of these flow paths, because of the great spatial heterogeneity of the urbanized landscape and the possibility that intense recharge of the groundwater can occur locally where water is ponded or sewer pipes break. However, the net effect of urbanization on the water balance of the phreatic zone beneath most cities is to lower the water table and decrease dry-weather flow. Pluhowski (1969) documented an example of decreased baseflow after urbanization on Long Island. In cities such as Nairobi, Mexico City, and Los Angeles, which cover useful aquifers, these trends are dramatically aggravated by the pumping of groundwater for municipal and industrial use.

In many tropical cities, storm drainage problems are extreme for a variety of reasons. First, rainstorms are often intense. Second, urban growth is frequently rapid and uncontrolled, so that neither time nor resources are available for planning to mitigate the storm runoff problem. The problem becomes particularly acute when a city spreads from a lowland into the surrounding hills. Uncontrolled storm runoff overtaxes the (originally adequate) storm-sewer system of the flatter downtown area, which is frequently inundated. Examples of such developments can be seen in Barcelona, Spain, and in Rio de Janeiro and Teresopolis, Brazil. Third, the impact of sediment deposited in drains and natural channels can be particularly severe because of the highly erosive rainstorms of some tropical regions and the widespread unpaved, heavily-used roads and poorly-designed construction sites.

Important difficulties face the hydrologist in predicting the effect of urbanization or in designing measures to alleviate the urban runoff problem in tropical cities. Records of rainfall intensity and of runoff from rural or urban basins are usually sparse and short. Because uncontrolled urbanization is spreading rapidly, it is difficult to predict, or even to obtain up-to-date information on, its extent and nature. However, the hydrologic processes that are disrupted by urbanization are quite well-understood, and are similar in the tropics and in temperate regions, where they have been studied in detail. Many of the materials and designs used in urbanization are common to both regions. Thus, to an extent that is unusual in rural hydrology, it is possible to transfer concepts and measured parameters from temperate urban areas to tropical cities.

In this paper I will review the types of strategies that have been developed for reducing peak discharge rates from small, urban drainage basins. Then, I will summarize the kinds of data collection and analysis that are necessary for providing the numerical values on which to base both the generalized predictions, needed at the planning stage of urban development for anticipating storm-drainage problems and for comparing the effects of various control strategies, and the detailed computations needed at the design stage. My emphasis will be on simple measurements and analytical techniques in the belief that these are the only ones which can be used as quickly as is necessary and with the limited resources available for urban hydrology in most tropical cities. Although the techniques are simple, their results for small areas and open-channel flow problems are no less precise than those of the current generation of complex, expensive methods. However, the latter do have a role to play in the design or improvement of large networks of channels, sewer pipes, and control structures, serving large, heterogeneous urban landscapes. These networks are usually designed and constructed by specialized engineering firms. Examples of the methods used with a heavy bias toward engineering practice in the United States, are reviewed in the publication edited by Yen (1982).

A primary message of this paper is the need for hydrologists and engineers from tropical cities to make some simple field measurements which can guide, check, and be used to alter the application of methods developed in other regions where climate, building design, and urban layout may be different. These measurements must be made with cheap, simple, and vandal-proof instrumentation.

The paper will deal with hydrological problems generated within the urban area, and not with those originating upstream. Thus, I will not discuss another common hydrological hazard in cities: that of the encroachment of buildings into flood-prone areas of the landscape. This problem and the nature of hydrological analyses required for its amelioration are described by Dunne and Leopold (1978, Chaps. 10 and 11). Nor will the paper deal, except in passing, with the effects of urbanization on groundwater or with issues of water chemistry and microbiology which are the focus of much modern research on urban runoff. An introduction to this topic is given by Roesner (1982).

2. FLOOD CONTROL IN SMALL URBAN CATCHMENTS

The range of solutions available for reducing flood peaks in urban catchments involves either reversing the hydrologic changes described above or compensating for them by temporarily holding water on or below the land surface and releasing it slowly to a stream channel or to the groundwater. The technology of urban storm drainage is evolving rapidly, and new techniques are continually being developed. Engineers and hydrologists concerned with the problem need to update their knowledge of the subject frequently, through reading journals or reviews such as those by Wright-McLoughlin (1969), Hittman Associates (1974), and Kibler (1982a). The following will give only a brief indication of the types of storm runoff control now being used. At all stages of planning and design, however, it is important to exercise anticipation and common sense, rather than simply installing structures because they appear in a handbook. For example, if holding urban runoff in a detention basin near the outlet of a basin (Figure 3) will cause the maximum contributions from upstream and downstream to coincide, it is better to handle the runoff from the lower part of the basin by some other means (perhaps by not detaining it at all). This is not a general rule, but only an illustration of how a problem can be aggravated with the best of intentions, unless a thorough hydrologic analysis is conducted. One way of addressing this problem would be to measure or compute flood hydrographs from the larger undisturbed area and from the smaller urban area with various forms of storm runoff control, and to compare their timing at the basin outlet.

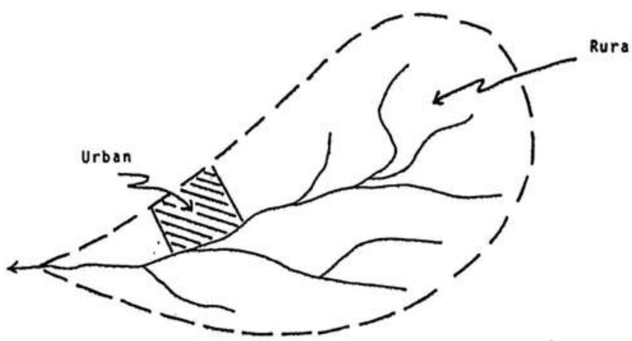

Figure 3. Detention of storm runoff from an urban area in the lower part of the drainage basin may cause that runoff to enter the main channel at the same time as runoff from the upstream, rural part of the basin.

Strategies for reducing the impact of urbanization on flood runoff deal with one or both of the effects illustrated in Figure 2. The amount of storm runoff may be reduced, or the runoff may be delayed and flows from various sources may be rendered asynchronous.

2.1 Methods of Reducing Storm Runoff Volumes

The most obvious method of reducing runoff is to maintain the original infiltration capacity on the largest possible area within the urban landscape. This involves retaining as much of the natural vegetation and permeable topsoil as possible, which requires careful clearing and grading of land. Often, all vegetation and topsoil are removed from a site simply for convenience, and at the end of construction costly attempts are made to re-establish or import topsoil and vegetation cover. Careful survey of the site and a rational construction plan can reduce some of these costs as well as runoff and sedimentation problems. After construction, it is necessary to protect the vegetation of the urban areas from woodfuel harvest, and to promote the planting of covers that are effective in maintaining high infiltration capacities and in protecting against soil erosion. It is less useful to plant species that are not resistant to trampling damage, uncontrolled pruning, or which (like many eucalypts) are allelopathic and render soil on the forest floor bare and erodible. There lies in this problem fruitful ground for more cooperation between foresters and drainage-control engineers than one sees in most countries.

Figure 4. Porous pavement (Source: Dunne and Leopold, Water in Environmental Planning, Copyright W.H. Freeman Co., 1978).

Large portions of the urban landscape are either surfaced with artificial materials or are subject to such heavy pedestrian or vehicular traffic that they will not sustain a vegetation cover. Portions of heavily-used pedestrian areas can be surfaced with porous pavement (Figure 4), which consists of open-grated concrete pavers. Soil is laid and seeded with grass in the spaces within the pavement to promote infiltration. The installation is successful, of course, only where the climate and traffic allow the grass cover to survive, and where the subsoil is permeable enough to allow drainage of a significant portion of the rain infiltrated during each wet season. Unfortunately, in many tropical cities neither of these conditions is met, and the cost of installing porous pavement does not always justify the benefits. Some clay-rich tropical soils also swell or weaken dramatically when they absorb water and this effect may disrupt the surface or building foundations. Furthermore, some artificial building materials and materials for surfacing roads and parking lots weaken and deteriorate when they absorb water. Any plan to increase the infiltration of rainwater should include a review of the suitability of local soils and building materials.

2.2 Methods of Delaying Storm Runoff

Some methods of delaying storm runoff involve keeping the storm runoff at or near the land surface and simply increasing the time over which it drains into stream channels. Others involve diverting a portion of the storm runoff to slower groundwater during the storage period.

Because most of the storm runoff originates on impervious surfaces, one obvious method of runoff control is to retain water on rooftops, parking lots, and similar areas, although not on roadways where it becomes a hazard to traffic. Many new commercial, industrial, and administrative buildings are designed to hold several centimetres of water on their roofs. The roof drains are equipped with collars and flow constrictors designed to release the water slowly (at rates of 5-10 mm h^{-1}) to some ground installation for further detention or to a stream channel. Rooftop storage is not suitable for most of the lightly constructed, smaller buildings in tropical cities; it requires careful design, stout construction, and some safe means of draining rainfalls larger than the design depth.

Parking lots and pedestrian areas can also be designed to store several centimetres of water by means of curbs and berms, if the surfacing materials are sufficiently impermeable or resistant to deterioration when wet.

Since the ponding is rare and temporary, this is a cheap means of providing large volumes of storage on easily-controlled land without unduly disrupting its primary use. On sloping land, terraces and berms can also be used to detain water and to spread it onto adjacent, more permeable areas.

Runoff from rooftops, parking lots, and streets can be diverted to various kinds of trenches, pits, ponds, and underground tanks for temporary storage. For example, the runoff can be intercepted by gravel-filled trenches aligned along contours (Figure 5a). If the surrounding soil is adequately permeable, these trenches will regain their storage capacity between storms; if not, they can be equipped with a perforated drain tile set at the base of the gravel (Figure 5b). However, such trenches cannot long maintain their capacity if large amounts of fine sediment are washed into them.

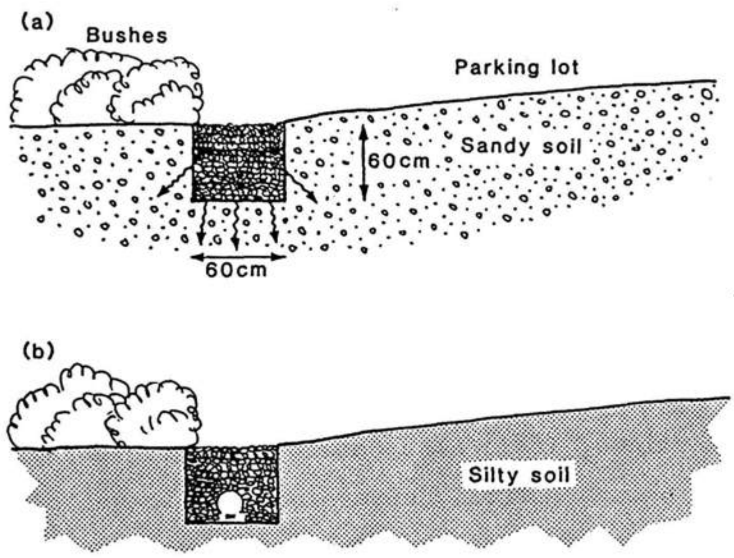

Figure 5. Trenches for intercepting, storing, and infiltrating surface runoff.

Runoff can be diverted to metal or concrete tanks installed below ground (Figure 6). At low rainfall intensities, the runoff is directed into drains and flows directly to the stream channel. At higher runoff rates, flow out of the drain is restricted to a chosen maximum value, and the excess runoff is backed-up and stored in a large tank under the developed site. After the rainstorm, water continues to drain slowly from the tank through its permeable base and through the drain. The capacity of the flow constrictor and the volume of the tank can be adjusted to keep peak runoff rates after development to a level smaller than or equal to those before urbanization for storms of a chosen frequency. As with rooftop and trench storage, installation of these underground tanks can be made the responsibility of the land developer as a condition of receiving the building permit. The difficulties of using such small-scale solutions are in ensuring that they are adequately designed, properly installed and maintained, and that they do not aggravate the problem of runoff timing portrayed in Figure 3. There is no simple solution to this last problem other than relying on the individual design engineer to make a reasonable estimate or measurement of the timing of flows from the upstream area and to design the local system accordingly.

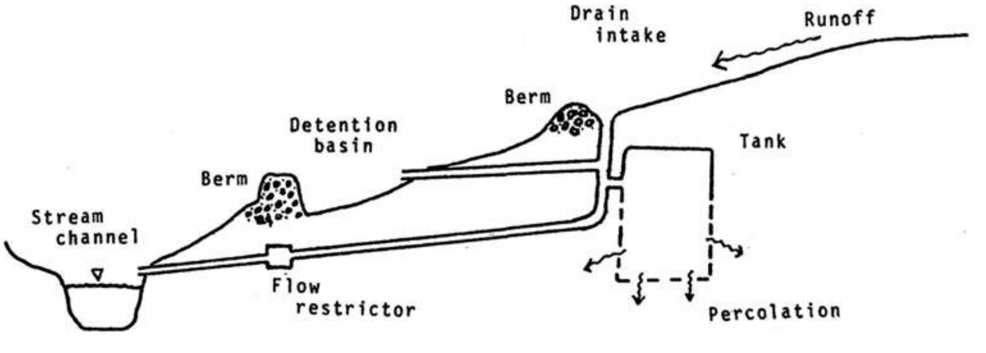

Figure 6. A typical underground storage system installed below a small urban development.

If land pressure allows, it is also possible to divert storm runoff to surface pits, which occupy natural depressions or excavations. Typical examples of such basins vary in area from 0.1 to 10 hectares and have storage capacities of 5000-50,000m^3. If the substance is a deep, permeable, unsaturated sand or gravel, most of this storage capacity may lie below a pipe outlet and the water will drain to the groundwater within a few days. However, if as in much of the tropics, the city is built upon clay-rich soils or on bedrock, there is no significant infiltration, and the pipe outlet must be placed low enough to drain all of the required volume in order to restore the capacity of the pit. Maps of the surface geology of urban areas, and discussion with geologists, geomorphologists, or soil scientists would assist the drainage-control engineer in locating permeable zones, such as sandy river terraces or other permeable geological formations where seepage from pits would reduce storm runoff without contaminating useful groundwater.

If the surface layers are not adequately permeable, an infiltration well with a diameter of 1 to 3m and a radial pattern of distributary pipes could recharge water from the storage basin to a deeper, permeable formation. Peterson and Hargis (1973) described an example of injection from 4 wells in a detention basin serving a 162-ha residential neighbourhood on permeable volcanic rocks in Hawaii. The surrounding detention basin had a volume of 76,000m^3 and was designed to control the 10-year flood. The polluted urban runoff was isolated from a shallow aquifer by casing the upper 40m of the wells. However, the high cost of such a strategy and the favourable geological conditions which it requires limit its usefulness to special situations. More commonly useful in the tropics is temporary storage in depressions which later drain through a pipe. Health considerations may even require the prompt drainage of such facilities in tropical cities.

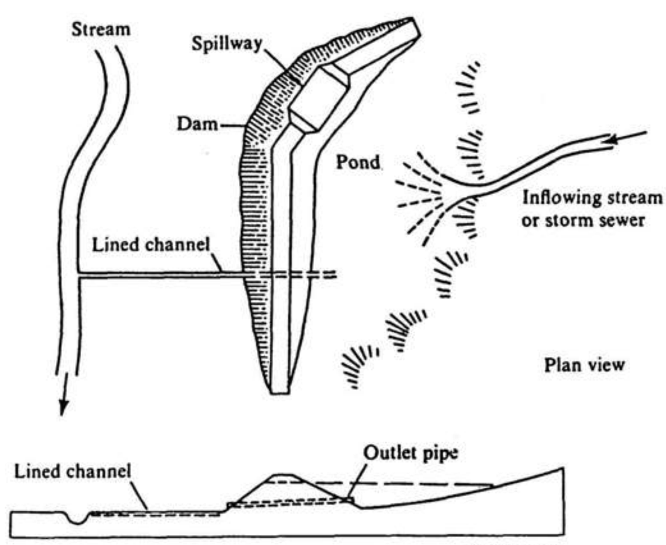

Figure 7. A small detention dam with a pipe outlet for the slow release of stormwater and a spillway for passing extreme flood peaks safely. (Source: Dunne and Leopold, Water in Environmental Planning, Copyright W.H. Freeman Co., 1978).

Where topography is suitable and dyking is possible, small dams can be built to provide floodwater detention basins (Figure 7) larger than those described above. The dam must be equipped with a narrow outlet pipe or weir, which allow water to drain out slowly after the storm, and a spillway to convey water safely over the dam if the capacity of the basin is overtaxed. The purpose of such a detention structure is to store a sufficient volume of water to reduce the peak discharge from short, intense rainstorms to pre-urbanization levels (Figure 8). This aim can be achieved by proper choice of the height of the dam (which determines the maximum potential volume of storage for the particular topography of the site) and the geometry of the outlet (which determines the discharge rate for a given water elevation). The effect of these detention basins on peak flows diminishes rapidly downstream of the dam as the contributing area increases and the volume of runoff stored constitutes a decreasing proportion of the total runoff. Although they are effective, if properly designed, such detention basins are costly to install, and they occupy valuable urban land. However, this land lies in the flood-prone valley floor and is not permanently inundated. It may be used for grazing and recreation between storms. In some cities, the design of detention basins takes advantage of natural lakes, but the resulting impact on water quality is usually bad as sediment and other pollutants tend to fill and eutrophy the lake. The design aspects of detention basins are reviewed by Whipple et al., (1983).

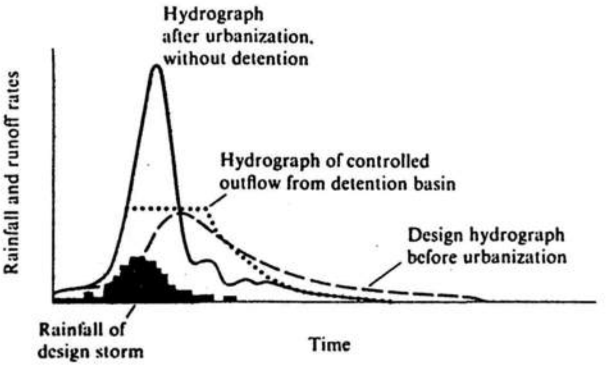

Figure 8. Storage requirement for a detention basin designed to keep flood peaks from an urban basin down to rural levels. The shaded area represents the volume of storage required. (Source: Dunne and Leopold, Water in Water Environmental Planning, Copyright W.H. Freeman Co., 1978).

3. METHODS OF RUNOFF PREDICTION

In the planning and design of storm runoff control systems, it is necessary to predict the volume, peak discharge, and timing of urban runoff under a range of circumstances. This is required in order to evaluate the consequences of installing various control measures and of doing nothing. Most techniques of runoff prediction are extensions of those developed earlier for rural areas and some require first that runoff be predicted for the basin in its original rural state. The techniques are described extensively in various textbooks and manuals, such as those of the American Society of Civil Engineers (1972), Dunne and Leopold (1978), and Kibler (1982a). In this paper I will refer only to the most commonly used and simplest techniques. More complex methods, which portray the hydraulics and spatial patterns of runoff processes, require too much data for routine application in tropical cities. Such methods are reviewed by Dendrou (1982), Torno (1982) and Yen (1982).

3.1 Rational Runoff Formula

The rational method predicts peak discharge rates from data on basin area, rainfall intensity, and land surface characteristics, using the formula:

$$Q_p = 0.28CIA$$

where Q_p is the peak discharge in $m^3\ s^{-1}$, I is the rainfall intensity in mm hr^{-1}(usually chosen from some design consideration), A is the basin area in km^2, and C is a coefficient chosen to reflect the proportion of rainfall that is converted to storm runoff. Although the method is widely criticized, it is also widely and successfully used, even by its critics. It is often hidden in complex computer models. The formula is useful for basins smaller than about 100 hectares. which can reasonably be expected to approach equilibrium between rainfall and runoff in a short, intense storm. The basis of the formula and considerations necessary for its application in rural and urban areas are described with worked examples by Jens and McPherson (1964), Dunne and Leopold (1978, pp. 298-305), and Kibler (1982b). It is useful for the design of culverts and channels draining small urban areas, where peak flows are needed. With the addition of some easily developed assumptions about the average shapes of hydrographs in the region, the method can also be used to define hydrographs for the design of small detention dams. Extension of the method to tropical cities requires only that drainage areas be measured (which is not necessarily straightforward in cities, where surface channels or subsurface pipes may transfer runoff across basin boundaries); that short-period rainfall intensities be measured; and that values of C obtained from other regions and urban styles be checked and modified for tropical conditions through the simultaneous measurement of rainfall intensities and peak runoff rates in small basins.

3.2 Probability Analysis of Floods

If flows have been recorded in a basin with a more-or-less constant degree of urbanization, it is possible to analyze the probabilities of a certain discharge being equalled or exceeded within a year or longer period. Such information is the basis of much engineering design of channels, bridges, and other structures. The concepts, methods, and limitations of probability analysis are reviewed in any textbook on hydrology. It is also common to combine data from all gauging stations in a region by some means of multivariate analysis to provide a method of estimating the probabilities of flood peaks at ungauged sites in the region (e.g. Benson, 1962, 1964; Rantz, 1971; Wong, 1963).

The flow records from most urban basins are neither long enough nor stationary enough for probability analysis. The most common method of applying probability analysis to urban runoff is first to define flood frequencies for the rural condition and then to increase the peak flow of a given frequency by an amount that is related to the amount of impervious area or the proportion of the area drained by artificial channels (e.g. Figure 9). Early examples from the work of Carter (1961), Leopold (1968), Anderson (1970), and Rantz (1971) are summarized by Dunne and Leopold (1978, pp. 324-329). These early, simple methods provide models of what might be accomplished in tropical cities after a few years of measurement. Less useful as models for the tropics are multivariate analyses of flow records of uneven quality from large areas (e.g. Sauer et al., 1983). Such analyses depend upon the slow, expensive accumulation of massive amounts of data, requiring much subjective judgment for their interpretation. The nature of the flow data and of some of the controlling variables preclude the use of very rigorous statistical methods, and the prediction errors are as high as those from simpler methods.

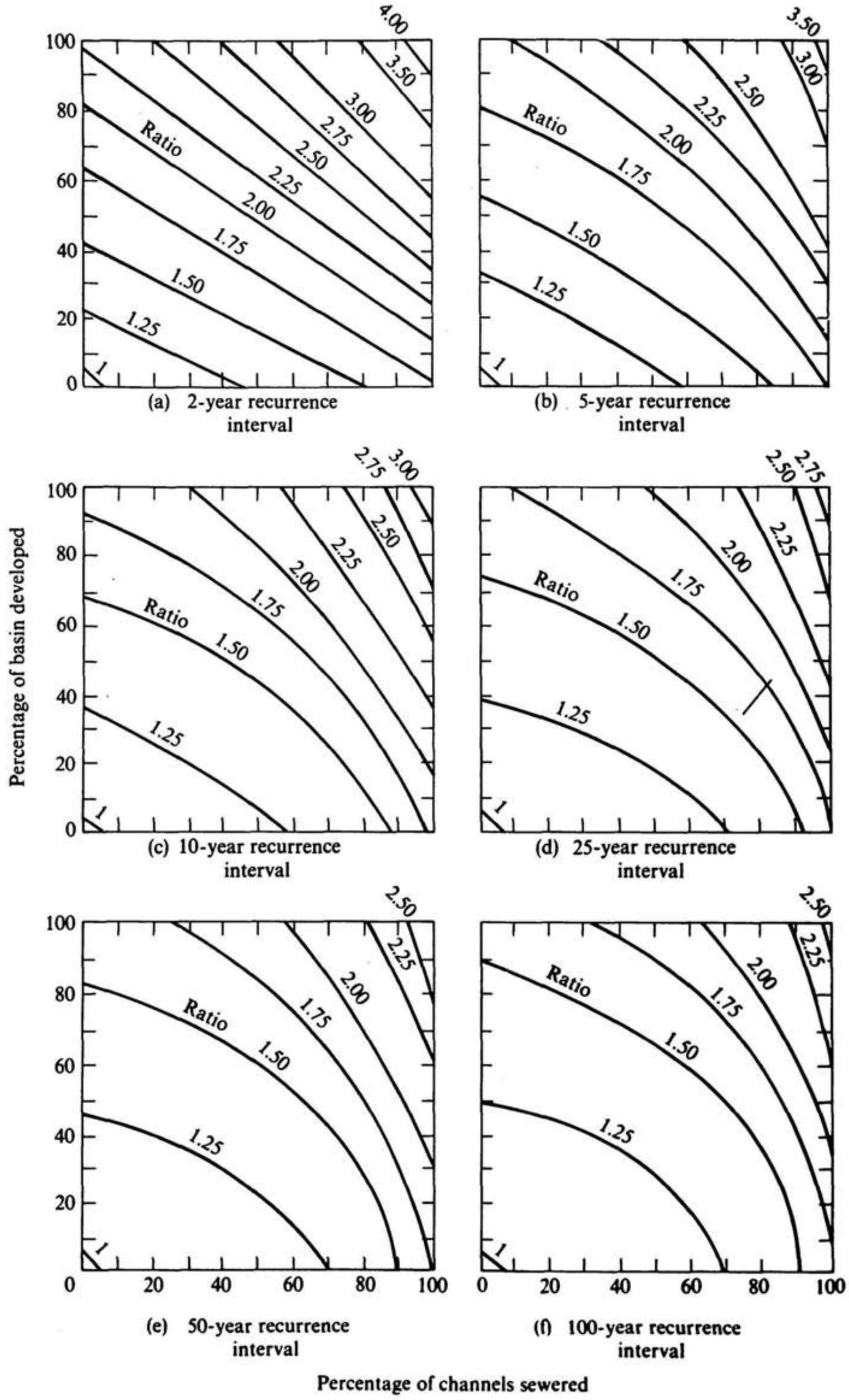

Figure 9. Ratios of peak discharges for urban basins to those for rural basins for floods of various recurrence intervals. Development of 100% of the basin is roughly equivalent to 50% of the area being impervious (Source: Rantz, 1971).

3.3 Unit Hydrograph

The unit hydrograph for a drainage basin defines the time distribution of a unit depth of runoff (e.g. 1mm or 1cm) generated by a rainstorm of fairly uniform intensity occurring within a period of time, which depends upon the area of the basin and is found by trial and error. The concept, though approximate, is useful because many of the basin characteristics, such as size, shape, and channel gradient, which affect the timing of runoff (i.e. the shape of the flood hydrograph) are constant from storm to storm. This is particularly true in urban basins. Use of a unit hydrograph for runoff prediction is based on the assumption that the shape of the hydrograph thus remains constant from storm to storm, so that there exists a linear relationship between the volume of storm runoff generated and the discharge at any time. This approximation allows the ordinates of the unit hydrograph to be multiplied by the ratio between the depth of runoff generated in the predicted storm and the unit depth of runoff under the unit hydrograph (Figure 10).

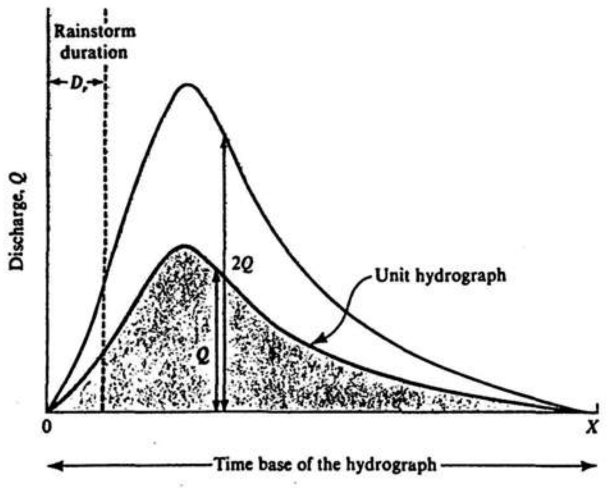

Figure 10. A one-centimetre unit hydrograph (shaded) and a hydrograph consisting of 2 cm of runoff, obtained by doubling the ordinates of the unit hydrograph. (Source: Dunne and Leopold, Water in Environmental Planning, Copyright W.H. Freeman Co., 1978).

There are many important, but simple, methodological issues to be addressed in constructing unit hydrographs from field measurements of rainfall intensity and runoff, but they are beyond the scope of this paper. They are discussed by Wang and Wu (1972), and by Reid and Dunne (1984). Once unit hydrographs have been established for a sample of basins, parameters of the shape (e.g. peak discharge, time to peak discharge, duration of storm runoff) can be correlated with physical characteristics of the basin. The resulting regression equations can be used to generate synthetic unit hydrographs for ungauged basins in which the necessary physical characteristics have been measured. Snyder (1938) introduced the concept of a synthetic unit hydrograph for rural basins, and it was developed into a widely used tool for small basins by the U.S. Soil Conservation Service (1972). Espey et al. (1966), Rantz (1971), and Hall (1977) have developed unit hydrographs and their synthetic counterparts for urban basins. The procedures, methods of checking them by simple field measurements, and worked examples are provided by Dunne and Leopold (1978, pp. 329-350) and by Kibler (1982b).

3.4 Prediction of Storm Runoff Volume and Timing

In the design of flood detention structures or in preliminary identification of those portions of a drainage basin which are likely to produce most of the storm runoff after urbanization, it is commonly useful to predict volumes of storm runoff in chosen design storms. This can be accomplished through local correlations, if measurements of rainfall and runoff are available.

Another technique for estimating runoff volumes involves subtracting from rainfall an index of the total amount of water abstracted from the storm runoff process by interception, evaporation, and infiltration (Aron, 1982). The conceptual analyses of these abstractions are usually too detailed to represent our knowledge of the physics and spatial complexity of the processes. Most of the analyses are based on data from rural landscapes with poorly conceived extensions to urban areas where they create an illusion of understanding. For example, the use of infiltration equations in heterogeneous urban areas constitutes little more than a technique for providing two or three free parameters which can be adjusted during calibration of runoff models against rainfall and runoff data. It is simpler and clearer to obtain a few local measurements of rainfall and runoff volumes and to develop from these a summary "lumped" index of abstractions, such as the Φ-index, which is defined as the average rate of abstraction during a storm (Aron, 1982; Kibler, 1982b, p. 122). Rantz (1971) extended the method to urban basins.

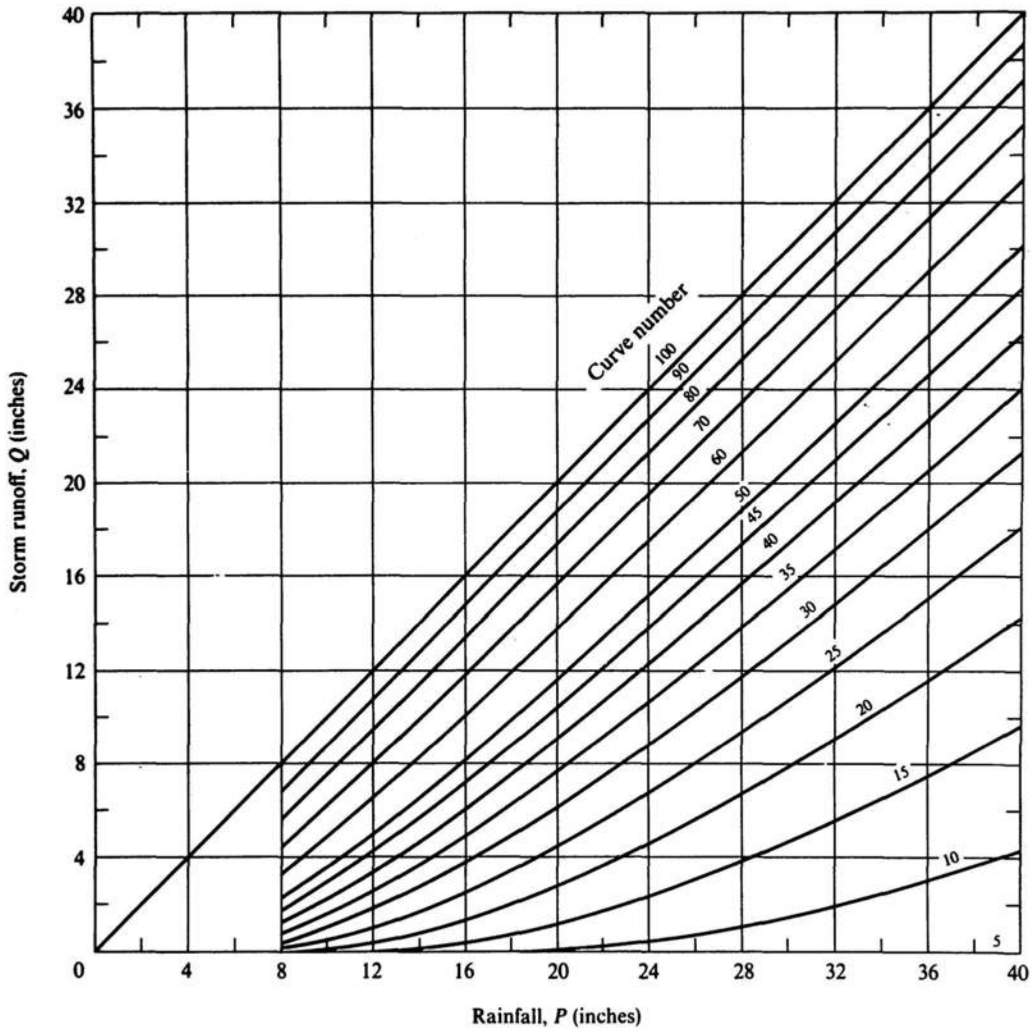

Figure 11. Chart for estimating the volume of storm runoff from total rainfall for various soil-cover complexes indicated by curve numbers. (Source: U.S. Soil Conservation Service, 1972).

A third useful method of predicting runoff volumes as well as the entire hydrograph is the U.S. Soil Conservation (1972) method of using curve numbers, (Figure 11), which are empirical indices of the hydrologic response of soil and vegetation covers, developed from runoff records in small basins in the United States. As such, the values may need to be modified on the basis of tropical measurements, but they represent a good starting point on which to base preliminary calculations as well as analyses of runoff records. The method has been extended recently to urban areas, where the curve number, and hence the volume of runoff per unit of rainfall increase with the extent of impervious cover (Figure 12). If the entire hydrograph is needed, the hydrologist may use a dimensionless unit hydrograph such as the one shown in Figure 13 to distribute runoff during the storm. The maximum value on the mass curve is the computed runoff volume and the slope of the mass curve at any time indicates the discharge. Kibler (1982a) and the original publications (U.S. Soil Conservation Service, 1972; 1975), present more details, and Dunne and Leopold (1978, pp. 339-340) emphasize the need for, and simplicity of making, a few field measurements to check and modify local application of these methods.

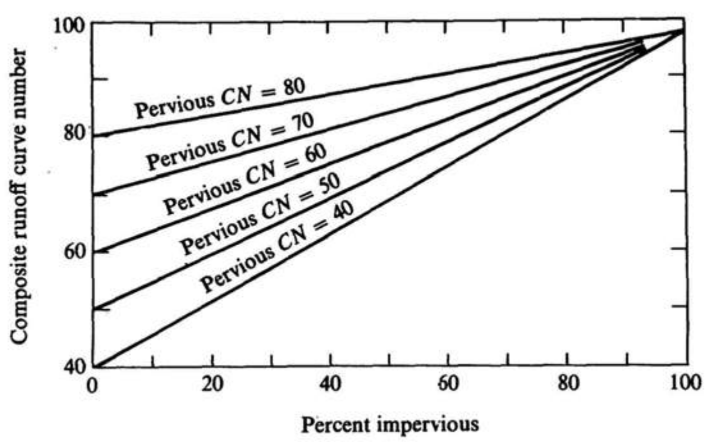

Figure 12. Composite runoff curve numbers for combinations of impervious area and curve number for the remaining unpaved area. (Source: U.S. Soil Conservation Service, 1975).

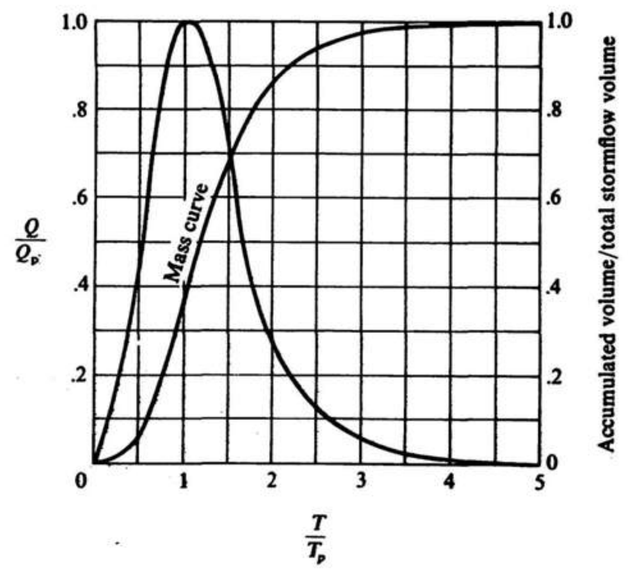

Figure 13. Dimensionless unit hydrograph and mass curve of storm runoff, based on averaged hydrographs from representative small drainage basins, Q_p and T_p are discharge and time of peak flow, respectively. (Source: U.S. Soil Conservation Service, 1972).

3.5 Flood Routing

A frequent task in urban hydrology involves assessment of the value of delaying storm runoff by diverting it through natural lakes, ponds, or bogs or by constructing small dams, as described above. It may also be necessary to examine the effect of some alteration of the land surface or of storage on the flood hydrograph downstream. These tasks require the consideration of how storage in a lake, channel, or floodplain affect the timing and shape of the flood wave. The procedures developed for this purpose are known collectively as flood routing, and there are two types of procedures: hydraulic routing and hydrologic routing. The former is required for complex or expensive projects, including networks of storm sewers, when one wishes to define the water elevation, pressure, velocity or area inundated at many places in a network of flows. The methods require large quantities of data and of computation, and are beyond the scope of this paper.

Hydrologic routing is simpler and can be computed quickly by hand on the basis of a few specifications or a few field measurements. It provides discharge hydrographs at a few chosen points, and therefore water elevation and open-channel flow velocities can be determined also in a straightforward manner. The principles underlying hydrologic routing are: the continuity of mass (i.e. inflow to a reservoir or channel reach minus outflow equals the change in storage in some time interval), and that there is a relationship between storage volume and outflow (in the reservoir case) or between storage and both inflow and outflow (in the channel case). This latter relationship must be defined on the basis of engineering design of some structure of known hydraulic characteristics and by field measurements of water elevation and discharge. The details of computation are described by Dunne and Leopold (1978, pp. 350-363), Viessman et al. (1977), and other hydrological textbooks. A typical result is shown in Figure 14, which emphasizes how the designer's choice of an outlet geometry for a detention basin influences the degree to which a flood hydrograph is diminished during storage. Other worked examples are given in hydrological texts.

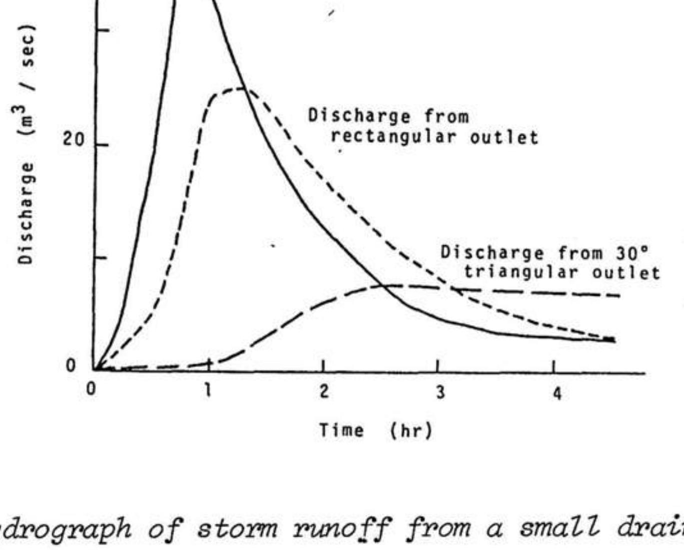

Figure 14. Hydrograph of storm runoff from a small drainage basin entering a detention basin with vertical sides and a water-surface area of 4 hectares, and the resulting outflow hydrograph from (a) a rectangular, sharp-crested weir, 10 m wide and (b) a 30° triangular weir.

4. FIELD MEASUREMENTS

One frequently hears two complaints about the conduct of hydrology in the tropics: that there are no or few local measurements, and that prediction methods developed for temperate regions are applied to tropical conditions in an inappropriate manner or with the use of empirical coefficients that have been evaluated only in the temperate zone. The solution to both of these problems is to conduct an intelligently-designed, simple, and cheap program of field measurements, and to analyze and use the resulting data. This proposition is particularly tractable in a tropical urban environment.

In developing countries several excuses are often given for the lack of fieldwork. There is no petrol for travel. There is no money for per diem expenses. There is no equipment. However, many useful field measurements can be made for urban hydrology near home or office, or at sites accessible by public transportation. Most of the necessary field measurements can be made with equipment that can be purchased from the petty cash in any office budget. Useful measurements of the hydrologically important characteristics of urban land use (types of urban areas, percent of area that is impervious, density and gradient of natural and artificial channels, etc.) can be made on aerial photographs that are available in any country, using the large numbers of underemployed technicians who populate many agency offices. The major stumbling block in such a programme is the dearth of scientific and technical leadership at an active level in the relevant agencies. There is a need for hydrologists who can decide on what should be measured, can take personnel into the field and show them how to make simple hydrological measurements, and can explain to them what to do with the results. All of the computations described above, which are the basis of most planning and design for stormwater control, can be made by hand. The absence of a computer is no reason for a lack of hydrological analysis.

The hydrologic data most commonly needed in urban stormwater control are rainfall intensity measured over short time periods, storm runoff, and the hydrologically important characteristics of the urban area.

4.1 Rainfall Intensity

The rainfall-intensity régime to which an urban stormwater-control system will be subjected is poorly known because there are few automatic rain gauges in most cities. Records at these stations are usually short and discontinuous because of equipment failures or lack of servicing. Many recording instruments allow discrimination of time intervals only to 15 minutes, whereas for the analysis of runoff from small urban areas (about 1-100 hectares), 1- to 5-minute rainstorm intensities are usually needed (Wang and Wu, 1972).

The problem of measuring rainfall and of establishing networks of gauges has been reviewed in many other publications, including those of WMO. Therefore, I will not review the subject here, except to say that there is much to be gained from adding cheap, simple, manual methods to the more sophisticated and expensive technology used by most meteorological agencies for measuring rainfall intensity. For example, work crews in urban areas could be supplied with transparent plastic rain gauges and instructed to read the accumulated rainfall in them at 5-minute intervals when their work is interrupted by a storm. They could note the time, location, and the rate of rainfall accumulation. Technicians, school teachers and pupils could do the same at their offices and homes. These results would be fragmentary, of course, but they could be assembled by an urban climatologist or hydrologist to add detail to the pattern of large rainstorms defined from the relatively small number of stationary gauges in the official network. Over a period of years, large storms would be sampled, and hydrologists would have a base for establishing: isohyetal maps of important storms in which large spatial anomalies occurred in the runoff; elevation-intensity relationships; depth-area curves; ratios between maximum rainfall intensities measured in the official network and the maximum point rainfall in the urban area or the average value over 1, 10, or 100 sq. km; and typical mass curves for short storms. There is also much to be learned from surveys of rainfall collected in non-standard containers, such as buckets and troughs during major rainstorms. For this purpose, it is important to empty the office of all technical personnel during or immediately after a large storm, so that they might search the urban area for potential sources of rainfall data (as well as flood marks which could be surveyed later to determine peak flood discharges). Such data are only valuable if they are compiled and continually analyzed as they accumulate. Literature which may suggest various useful forms of analysis are reviewed by Gilman (1964) and by Dunne and Leopold (1978, pp. 56-72).

A strategy for increasing the availability of useful rainfall intensity data in tropical cities might include the following actions. First, the needed types of intensity data should be summarized. Second, some automatic gauges should be purchased and placed in a few strategic locations, attention being paid to the reason for placement at the particular sites, to regular checking and maintenance of the instrument, and to a plan for reducing and analyzing the resulting data. Third, a large number of simple non-recording gauges should be purchased or made, and dispensed to work crews, hydrologists and other personnel who work and live at various places in the city so that they might visually record short-period rainfall intensities. Fourth, these fragmentary data should also be compiled and analyzed soon after collection.

Over a long-period of time the data base will grow sufficiently for standard intensity-duration-frequency analysis. Longer records of 6-, 12-, and 24-hour totals, which may be available from major weather stations, can also be rendered more useful for urban hydrology when a few short-period intensities become available to indicate typical ratios between shorter and longer maximum intensities in a storm. Hershfield (1977), Hershfield and Wilson (1958) and Reich (1963) make suggestions for ways of extending the usefulness of such records. Even in the short term, the data accumulated will become directly useful for planning and design. A long rainfall record is not necessary, for example, in the evaluation of C-values for the Rational Runoff Formula or for the Unit Hydrograph procedure. Reid and Dunne (1984) used visual observations of rainfall accumulated in a plastic cylinder together with simultaneous gauging of culvert outflow using a bucket and a watch to define unit hydrographs from various types of road surfaces. It was necessary to measure the values in only a few surface storms in order to define the unit hydrograph well.

4.2 Runoff

There are also many technical manuals which outline the instruments useful for measuring and recording flow and water-surface elevation in small streams. With these instruments, it is possible to make a continuous record of stream discharge, or intermittent visual records, or to record only the peak elevation of runoff during a specified period. It is possible to collect such data at a natural cross-section of stream channel or where the shape of the cross-section is artificially controlled by a concrete weir, bridge support, or culvert. It is usually possible to make more precise measurements at controlled cross-sections, but if one is interested mainly in high flows, measurements at natural cross-sections are usually of adequate precision for the analytical and prediction techniques for which they form the basis.

Several important points should be kept in mind when it is decided to invest resources in obtaining flow records as a basis for prediction and design in urban hydrology. First, the purpose of the measurements should be clear. If, for example, a probability analysis of peak flows is required, then it is necessary only to install cheap, vandal-proof crest-stage gauges, which record peak water-surface elevation, and to calibrate each channel cross-section so that elevation values can be converted to discharge. On the other hand, if a unit hydrograph study is required, it is necessary to have continuous records or at least frequent visual observations of water-surface elevation at a staff gauge on the stream bank. Second, it is necessary to gauge appropriate representative basins, rather than basins which are conveniently located or chosen more-or-less at random. Third, a gauging site must be selected which has no backwater problems, complex geometry, or other characteristic that would cause large measurement errors. Fourth, it is necessary to promote good measurement procedures. For example, since runoff responds so quickly to rainfall in urban areas, it is necessary to record both quantities precisely by checking the synchroneity of clocks on recorders or those of observers. It is also necessary to check recorders frequently and to maintain them in good working condition. Fifth, technical personnel should visit and take care of instruments during floods. They should check that instruments are working and should fill gaps by visual observations in cases of failure. High discharges should be measured directly with a current meter to define the upper portion of the stage-discharge rating curve. If the flood has already receded, flood marks should be surveyed and peak discharge computed by the slope-area method (Chow, 1959; Dalrymple and Benson, 1967). Finally, the flow data from large storms should be compiled promptly and analyzed together with the associated rainfall records.

When planning a measurement programme and when analyzing its results, it is important to realize that in many basins undergoing urbanization, the hydrological conditions are changing rapidly. Therefore, it is necessary to obtain quickly a few records of storms at various stages of urbanization and to document the hydrologic condition of the basin at each stage. It is not appropriate to analyze the probability of flows on the basis of a record collected during this non-stationary period.

4.3 Drainage Basin Characteristics

In most tropical cities, the best record of land-use is aerial photography, which has been repeated several times during the past 40 years. The increased future use of infra-red photography will facilitate the discrimination of vegetation on soil-covered areas and unvegetated impervious areas. With the aid of a simple stereoscope and aerial photographs, it is possible to make preliminary maps of basin perimeters, which must then be checked on the ground because artificial channels or pipes may transfer stormwater across drainage divides. Aerial photographs can also be used for producing urban land-use maps, which classify areas on the basis of their hydrologic characteristics. The map units should be based on the local range of hydrologically important characteristics, and might include some variants of the following land-surface types: commercial; industrial; bare construction sites; high-, medium-, and low-density residential areas (defined according to the number of dwellings per hectare); agriculture, forest, etc. Such maps are useful for choosing representative measurement sites and for extending results from them to the whole urban area. Aerial photographs can also be used for measuring parameters such as the proportion of the land surface that is impervious, the length and area of roads and tracks, or the extent of artificial channels.

For most hydrological purposes, it is neither necessary nor possible to wait for the results of citywide or national mapping projects. The hydrologist can usually make the necessary measurements quickly and cheaply from available data sources. However, for forecasting the long-term hydrological consequences of city growth, it may be necessary to couple measurements of hydrologically important land-use characteristics with some model or plan which predicts the spatial pattern of urban growth and its interaction with local topographic and climatic conditions.

5. CONCLUSION

The most significant water-related issue in most tropical cities is the control and safe disposal of storm runoff. The processes by which urbanization increases storm runoff are understood under most circumstances. Various strategies for reducing or delaying storm runoff have been developed, but their usefulness varies with local conditions. The technology of runoff control is still evolving rapidly. For small urban areas, the technology is simple to design and construct. Elaborate citywide networks of storm sewers, with loops, over-pressured segments, diversions, and complex outfalls are difficult to design and construct, and are usually installed by large, specialized engineering firms, using methods reviewed in Yen (1982).

The basis of any plan for controlling urban storm runoff must be a programme for measuring and analyzing data on rainfall intensity, runoff, and the hydrologically relevant aspects of urban land use. Some suggestions for such a programme, together with simple methods of analysis and prediction, are reviewed above.

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ENERGY RELATED ISSUES

John K. Page
Emeritus Professor of Building Science
University of Sheffield, Sheffield S10 2TN, UK

1. INTRODUCTION

Urban climatologists, for the most part have not so far perceived the key contribution they can make to effective energy planning of cities. This is partly because they approach the problems descriptively as climatologists rather than operationally as decision makers. The object of planning is to achieve a better outcome than would have resulted otherwise, by making appropriate land-use decisions backed by appropriate environmental policies. The real demand is for climatic engineering based on climatic science, and not simply to carry out climatic science studies.

The climate, through its impacts of heat and cold on individuals, creates major demands for energy in human settlements. Climate is also a valuable energy resource in its own right, capable of supplying very considerable amounts of natural energy, which, by proper planning, may be harnessed for human use. The daylighting of buildings is one often forgotten example.

The various individual activities are interlinked spatially by transport systems, whose waste products need to be removed from the urban environment in ways that do not impinge harmfully on the health of individuals or damage the broader ecosystem within which they live. The industrial systems, often in tropical countries inefficiently using energy resources, add to the pollution load. The wind is a key natural energy resource, which assists in achieving a less hazardous dissipation of the wide range of pollutants created by human urban activity, as well as inducing natural ventilation through individual buildings. It is important that the dissipation of hazardous wastes does not form part of the natural ventilation system of any building. The energy problem has therefore to be viewed three-dimensionally, taking full account of the vector characteristics of weather.

The goal is therefore the clean-air energy-conserving city which takes maximum advantage of natural climatic resources to supply energy and which simultaneously makes it possible to reduce the demands for energy by relating energy conservation measures to urban climate. Minimizing the need to burn fossil fuel supplies minimizes atmospheric pollution at the same time, Page (1980).

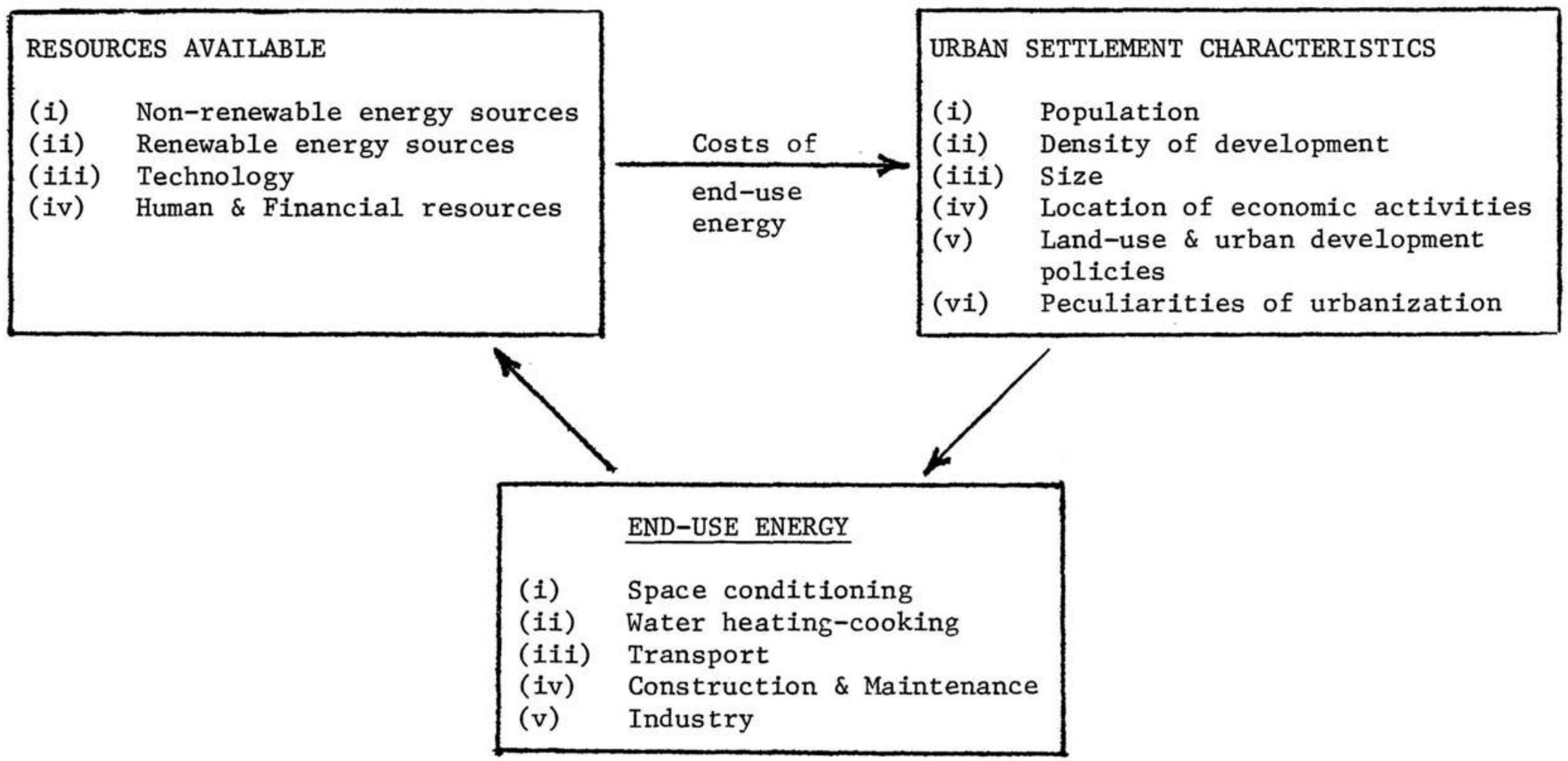
The human need for adequate internal energy in the form of suitably prepared palatable safe food, adds another demand for adequate external energy to prepare it. Safe food storage, especially important in hot tropical countries, adds a further key energy demand. Food preparation is often a major source of atmospheric pollution in tropical cities, as it is carried out on very inefficient wood burning stoves. People tend to overlook that the summation of millions of apparently small activities can produce a major impact.

The system being discussed here has been well set out diagramatically by Rao and Carella (1980) in Figure 1.

2. PATTERNS OF ENERGY CONSUMPTION IN TROPICAL CITIES

It is not easy to establish patterns of energy consumption for tropical countries due to the unsatisfactory statistics available, especially for the poorer sections of the community. A key factor is often the failure to include firewood and charcoal in the official figures. The consequence is that the reported figures for domestic energy consumption are usually too low, especially in all year round hot climates, where the main domestic demand is for fuel for cooking and hot water. The importance of fuelwood

Figure 1.


RESOURCES AVAILABLE
(i) Non-renewable energy sources
(ii) Renewable energy sources
(iii) Technology
(iv) Human & Financial resources
Costs of
end-use
energy
URBAN SETTLEMENT CHARACTERISTICS
(i) Population
(ii) Density of development
(iii) Size
(iv) Location of economic activities
(v) Land-use & urban development policies
(vi) Peculiarities of urbanization
END-USE ENERGY
(i) Space conditioning
(ii) Water heating-cooking
(iii) Transport
(iv) Construction & Maintenance
(v) Industry

and charcoal was carefully considered at the UN Conference on New and Renewable Sources of Energy at Nairobi held in 1984 (Report of the Technical Panel on Fuelwood and Charcoal (1981)).

While the majority of the population would welcome air conditioning, it is simply not an affordable luxury for most inhabitants of tropical cities at the present time. The majority have to accept discomfort, because they cannot afford the alternative. In a hot climate high thermal discomfort leads to lassitude, in contrast to cold climates where thermal discomfort tends to promote physical activity. The economic costs of thermal discomfort which are the consequence of the low economic productivity associated with lassitude, are very serious in many tropical countries. High priority therefore needs to be given to further research and development of natural cooling techniques which offer the prospect of greater economy than the complex mechanical systems currently used. Reference should be made to the new report of the *Ad Hoc* Expert Group Meeting on The Use of Solar Energy and Natural Cooling in the Design of Buildings in Developing Countries, held in Nairobi, Kenya, in September 1984 at UNCHS (Habitat) (UNCHS, 1984).

3. IMPORTANCE OF BIOCLIMATIC ANALYSIS IN URBAN ENERGY STUDIES

An important starting point in considering urban design from the point of view of energy conservation in tropical climates is detailed bioclimatic analysis to establish the nature of the thermal stresses encountered in any area, and also the patterns in time of these stresses. Such analysis identifies the directions of climatic modifications needed in urban design and the nature of the measures needed to conserve energy by appropriate building design. The main cause of stress in tropical cities is by definition heat, but it is important to be able to assess in combination the influence of dry-bulb temperature and humidity at different times of day and night at different seasons. Milne and Givoni (1979) have, for example, developed a way of plotting data onto a standard psychrometric chart, supplemented by energy option overlays to identify the building design options open in any specific climate to achieve comfort without resort to air conditioning equipment.

The UNCHS Report of the *Ad Hoc* Group, already mentioned, has attempted to classify solar building and natural cooling opportunities against a simple classification of prevailing climatic conditions. The appropriate solutions potentially open need to be identified before any detailed attempts are made to harness climate to energy conservation design.

The analysis techniques so far developed have tended to concentrate on the specific building. Wider techniques of a similar objective nature need to be developed to assist in the urban planning process.

4. ENERGY ANALYSIS OF URBAN CLIMATES

The contribution of climate to urban energy balances can be analysed in three inter-related modes:-

- climate as an energy supply source
- climate as a key influence on energy demands
- climate as a critical resource for dispersing the pollutants produced as a consequence of matching energy supplies to energy demands using fossil fuels

If one maximizes energy supplies from the external environment, one can supply a significant proportion of the energy demand without recourse to fossil fuels. This, if realistic and appropriate solutions are found, will offer both economic and environmental benefits. The key discipline required is a capacity to prepare adequate energy audits for different energy-using activities, so sound solutions can be separated from unsound. The concept of energy utilization targets can help distinguish good designs from less satisfactory designs in any specific climate. The rapid fall in the price of microcomputers is beginning to provide powerful tools of analysis using colloquial programs, usable by non-experts with ease. It is important that developing countries take advantage of these new technologies, and it is encouraging that WMO is taking a new initiative in this area. The new techniques allow the user to explore the solution field for himself, which is much more effective than attempting to find the solution through a third party. Furthermore the solutions can usually be presented graphically as well as numerically, which can assist considerably in identifying relationships with the three-dimensional world of physical planning (WMO, 1983).

5. NATURAL CLIMATIC RESOURCES AVAILABLE TO REDUCE FOSSIL FUEL DEMANDS

Table 1 classifies the natural climatic resources which may be used to reduce the amount of fossil fuels used in cities. It is easy to forget the traditional uses of such resources, for daylighting, natural ventilation, & night time cooling. The role of landscape in tropical cities is not simply to provide visual amenity, but also to modify climate to improve human comfort.

TABLE 1. *Natural climatic resources that may be used with appropriate preplanning to supply some of the energy needs of urban complexes.*

RESOURCE	USE	ENERGETIC ECONOMIES
Solar Energy	daylight	most economic use
	passive heating	
	active heating	
	active cooling & dehumidification	least economic use
Wind energy	natural ventilation	most economic use
	external surface cooling	
	wind power water pumping	
	wind power electricity	least economic use
Nighttime outgoing long wave	cooling by air drainage from adjacent higher surfaces	most economic use
	surface cooling of courtyards and open spaces sheltered from wind	
	nighttime surface cooling of buildings	least economic use
Precipitation	latent heat cooling	most economic use
	- through fountains & springs	
	- through plant evapo-transpiration	
	-through creating large bodies of water	least economic use

Four main resources are identified, solar energy, wind energy, nighttime out-going long-wave radiation (an important source of cooling), and precipitation, which provides the basic resource for evaporative cooling, both by direct means and through botanical evapotranspiration. The main applications of each resource are arranged in order of relative economic effectiveness for each source of supply. Meteorological aspects of solar energy and wind energy have been well discussed in the two WMO publications produced for the U.N. Nairobi Conference on New and Renewable Sources of Energy (WMO, 1981a, 1981b).

Less systematic discussion has so far been given to the other two resources which are so important for the cooling of tropical cities. A useful preliminary account of the role of night-time long-wave radiation may be found in the new report of the UNCHS Report of the *Ad Hoc* Expert Group Meeting on the Use of Solar Energy and Natural Cooling in the Design of Buildings in Developing Countries (UNCHS, 1984). This area certainly requires more active attention at the building level. However the critical role of the radiative cooling of inclined terrain in determining the local climate of cities is often overlooked in urban climatology. The practical effects have so far been little explored in tropical cities, but its impact can be very great, for example, in Caracas. Such cold air drainage is an important resource for reducing the need for night-time air conditioning in tropical cities.

The role of water as a source of evaporative cooling was certainly well understood in historic cultures like Iran. The historic approaches have been well documented by Bahadori (Bahadori, 1979, 1984). Landscape must be considered as a critical energy saving resource in tropical areas, providing not only shade and heat dissipation at the canopy level, but also significant cooling as a consequence of the evapotranspiration. Botanists and agricultural scientists have an important advisory role to play in operational urban climatology in tropical cities. Much research in agriculture is relevant in the city sector as well.

The relative importance for the four main natural resources can only be determined by detailed local analysis, which must include the bioclimatic analysis already mentioned. Table 2 sets out the main factors promoting the use of these natural resources in any particular climate. The most important unsolved problem is how to achieve dehumidification economically in hot humid regions, where radiative cooling is relatively ineffective. In such climates wind remains the crucial natural resource, and its blocking a social crime.

TABLE 2. *Factors promoting use of various natural climatic resources.*

Solar Energy	Low cloudiness Clean atmosphere - absence of pollution Favourable orientation of buildings & streets Terrain slope favourable Reflective ground cover Absence of terrain obstruction
Wind Energy	High basic windiness Open planning Absence of excessive wind barriers & trees Exposed terrain Height, both above ground level & above general terrain level
Nighttime Long Wave Radiation for Cooling	Clear night time skies Low relative humidities Terrain suitable form for useful air drainage Absence of obstructions blocking flow Low wind speeds
Precipitation for Evaporative Cooling	Adequate rainfall Ground suitable for surface or underground storage Controlled wind circulation to retain cooled air Relative humidities not excessive

6. CLIMATIC PLANNING AND THE REDUCTION OF ENERGY DEMANDS

6.1 Cold Seasons

Climate plays a key role in the creation of energy demands for space heating. The discomfort caused by cold is only important in high level tropical cities. Cold at night is common at higher altitudes and needs to be planned for.

Table 3 outlines the factors to be considered in successful cold weather design to reduce the demands for energy in buildings. Control of excessive wind flow rates is especially important, when standards of construction are low, as the amount of air infiltration is so high. In such conditions, the heat island effect confers positive benefits, and cold air drainage on still cold nights can adversely affect low lying terrain. Considerable advantages accrue if the warmth of the day can be stored to offset the cold of the night.

TABLE 3. *Urban planning in relation to control of energy demands of urban climates-cold seasons.*

1. Maximise passive solar gains by appropriate orientation
2. Provide shelter from cold winds, especially to reduce excessive ventilation
3. Avoid or block adverse air drainage from higher colder terrain
4. Provide good drainage of surface water to avoid dampness
5. Maximise advantage of urban heat island effect by controlling wind flow by aerodynamic drag
6. Pedestrian movement in the sun and out of the wind, wherever possible.

6.2 Hot Dry Seasons

The energy demands in hot dry climates mainly arise from the need to reduce the indoor air temperatures. Table 4 sets out the basic design objectives to reduce energy demands in such climates. The strength of the solar radiation implies special attention should be given to making it easy to shade buildings. This is facilitated by making the long-axis face north/ south. The use of evaporative cooling in courtyards helps reduce temperatures during the day. Wind flow is best restricted to moderate levels. At night the outgoing radiation provides a powerful source of cooling. The heat island effect is not helpful, and attempts should be made to dissipate it. Air drainage offers an important tool. Solar analysis is critical. Shading is favoured by relatively high densities.

6.3 Hot Humid Climates

Table 5 sets out the techniques for energy conservation in hot humid climates. Shading is again important, but the shading techniques have to be different because of the strong need for natural ventilation. As trees grow easily in such climates, they provide an economic way of combining shading and some cooling by evapotranspiration. Night-time net long-wave radiation loss is often low, due to the low cloud base and high humidity, so air drainage is less strong. The most important asset is the wind, so aerodynamic planning is a key factor determining the extent to which acceptable comfort can be achieved without air conditioning. The wind analysis is thus the most important factor. Again the heat island effect is not helpful. In these situations the wind offers the best chance of dissipation.

TABLE 4. *Urban climatic planning in relation to control of demands for energy: Hot seasons - Dry climates.*

Hot seasons - Humid climates

1. Minimize solar impacts on building surfaces by appropriate site orientation
2. Facilitate the provision of external shading by providing adequate space for tree planting
3. Maximize air flow characteristics of urban areas using appropriate building form
4. Avoid high densities of multistoried buildings
5. Reduce urban heat island effects by dispersing solar energy at the tree top canopy level, and encouraging good air movement below
6. Remove excessive soil surface water to control relative humidity.

TABLE 5. *Urban planning in relation to control of demands for energy: Hot seasons - Humid climates.*

Hot seasons - Dry climates

1. Minimize solar impacts on building surfaces by appropriate site orientation
2. Use high ceilings with small high windows to provide good daylight with small openings
3. Facilitate external shading by appropriate site orientation
4. Where water resources allow, provide trees for shading and fountains in wind controlled environments
5. Make good use of lower night time temperatures and high outgoing long wave radiation by promoting nighttime cold air drainage from cooler adjacent terrain
6. Reflect incoming heat at roof level and shade streets to reduce heat island effects
7. Use air drainage to break up urban heat island.

7. SEASONAL STORAGE OF COOLNESS

Two main practical techniques of seasonal energy storage may be identified:

- Storage of energy in the ground,
- Storage of energy in the water resource.

The ground, at a relatively shallow depth has a stable temperature close to the annual mean temperature. The ground in a tropical climate with a big inter-seasonal range, therefore, can be used as a source of coolness in hot weather, either by integrating the building partly into the ground, or by setting up a suitable heat transfer system to transfer cold to the ground in cool weather and to extract it from the ground in hot weather into the building.

Any large body of water also heats and cools slowly, so another approach is to use the stored water resource as a source of coolness - this is especially possible with underground aquifers. In some areas, for example Iran, water was traditionally transported underground from the nearby mountains by aquifers running long distances underground. The water at source was cold and further evaporation took place in aquifers, so a long range of supply of cool water was created. The issues have been well reviewed by Bahadori (1979, 1984) and summarized in the UNCHS Habitat Report (1984).

Such techniques however are less successful in the hot humid tropics, partly because the annual range of temperature is small and partly because the water table is usually high.

8. TRANSPORTATION AND ENERGY USE

A significant proportion of the energy use in tropical cities is used in transportation. There are ways in which this energy use could be reduced:-

- by making cities more compact
- by making private vehicles smaller and more energy efficient

- by intermixing spatially, residence and places of work
- by making work from home more possible using information technology techniques
- by replacing private transportation by public transportation.

The first way is usually not acceptable on environmental grounds. The fourth way currently requires too much investment. The fifth way is often contested by the individual. In the long run, we may see the solar cell battery-charged commuter car as the economic, pollution-free, solution, but unfortunately that day is some way off.

In the short run, we must see the car as a significant pollutor and plan climatically to systematically cope with its pollution.

The physical form of the highway system requires careful climatic consideration, especially in view of the significant effect of motorway embankments on urban wind flow patterns and on urban air drainage patterns. The need to disperse motor vehicles fumes makes it desirable to avoid canyon-like streets, so the wind can achieve some pollution dispersion. The appropriate physical form of the motorway system must be thought through to reconcile transport interests, and environmental interests which make these detailed impacts through the climatically-driven pollution transport processes in the atmosphere. We must plan climatically to make the best of the worst features of present transportation systems.

9. TECHNIQUES OF URBAN CLIMATIC ENERGY ANALYSIS

Table 6 sets out some of the techniques of analysis of specific meteorological facts of urban climate, linked with energy provision and conservation. Meteorologists will note some of the investigational techniques are not those used by conventional meteorologists. The microcomputer with graphics facilities is an extremely powerful tool for handling many practical urban problems simply in a way that matches the drawing board design techniques used by designers. An exception is the prediction of urban wind flows, where there are no acceptable techniques other than those based on dynamic flow studies in wind tunnels. Aerial infra-red photography is a very powerful tool for analysing air drainage phenomena. While the costs of such techniques may appear high, the actual costs are trivial compared with the daily energy costs of even the poorest tropical cities.

TABLE 6. *Techniques for handling climatic aspects of urban energetic problems.*

1. Solar geometry and shading	Solar charts, microcomputer graphics
2. Solar radiation	Microcomputer and mainframe programs for slope radiation analysis linked with local observations of global and diffuse horizontal radiation.
3. Wind	. Computer analysis of directional characteristics of wind records at different times of day in different seasons in relation to temperature. . Wind tunnels linked to general terrain models. . Wind tunnels linked to local models of the urban environment.
4. Long-wave radiation and air drainage + night cooling	. Microcomputer models cross-linked with temperature and humidity. . Infra-red photography from aeroplanes at night, preferably linked with long-wave radiation observations.
5. Precipitation and evaporation loading	. Hydrological analysis in relation to urban landscape water demands. . Analysis of climatic characteristics of inter-seasonal water stores.
6. Thermal demands	. Heating degree days . Cooling degree days

Table 7 sets out some of the classes of spatial analysis of urban complexes which can be usefully carried out, as part of the process of urban climatic planning to ensure that better urban conditions are achieved at lower energy costs. The various studies need to be overlaid to produce a land-use plan to guide urban energy policy.

TABLE 7. *Typical subjects of urban climatic energy analyses.*

Overall terrain analysis	Identification of wind flow characteristics, air drainage characteristics, solar overshading by hills, precipitation differentials
Orientation analysis	Identification of preferred orientation of buildings and streets
Built area/open space area analysis	Identification of patterns of layout to promote good air flow and tempered air
Daylight and ventilation analysis	Identification of desirable patterns of density to promote adequate daylight and ventilation
Open space and landscape analysis	Relating open space to widen wind and air drainage pathways. Mitigation of urban heat island effects
Site analysis	Identification of optimum patterns of site use to conserve the energy needed to operate buildings on specific sites
Transportation analysis	Exploration of effects of transport routes on urban climates, especially blocking effects on air drainage
Natural energy resource analysis	Identification of areas most suitable for:- . Harnessing solar energy . Wind energy . Good natural ventilation . Creation of desirable air drainage patterns . Water storage in optimal climatic locations . Climatic modification through evapotranspiration by plants

10. CONCLUSION

It would appear by appropriate climatic planning that significant savings in energy running costs of tropical cities could be achieved. Additional benefits would result from the increased comfort of people, both at work and at home. Air pollution levels would be reduced as the joint consequence of better use of natural climatic energy resources, and the improved conservation of energy made possible by the climatic modification, consequent on planning properly for climate. Consideration of the actual nature of the terrain, its modification by transport systems, by the clusters of buildings, in relation to landscape policy will be needed, implying inter-disciplinary collaboration on a significant scale between urban climatologists and other professions.

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THE INTRODUCTION OF CLIMATOLOGY INTO THE ADMINISTRATION AND DEVELOPMENT OF PLANNING IN THE CITY OF STUTTGART

J. Baumüller

Department of Climatology in the Office for Chemical Analyses, 7000 Stuttgart 1, Federal Republic of Germany

1. INTRODUCTION

The reciprocal effects between climate, air pollution and city planning have been known for a long time. Their combination leads to what we know as "Stadtklima" (Kratzer, 1937) or "urban climate". The problem is an old one, for example in the year 61 AD Seneca said: "When I left the heavy air of Rome and the stench of the smoking chimneys, the flow of soot and the pestilential steam from them then I feel a change of my good health". (Griffiths, 1976).

However in the Federal Republic of Germany it wasn't until the year 1976 that the Law for Planning and Building made it a requirement to see climate and air as important factors in planning. Since this time it has been necessary to take the atmospheric environment into consideration in the development plan of a city.

The change of the skyline which takes place in the building of a city influences the interaction between the ground and the atmosphere in a three-dimensional way. This is an important point of view because planners mainly think in two dimensions.

2. THE DEPARTMENT OF CLIMATOLOGY

Earlier than other cities Stuttgart began to involve municipal climatologists in urban planning. This can be traced back to the fact that the air quality of Stuttgart is not very good. This is because the city lies in a basin and the mean wind velocity is only about 2 m s^{-1} and temperature inversions occur frequently.

CLIMATE AND PLANNING IN STUTTGART

In the year 1699, when the buildings in Stuttgart were usually only one storey high, it was proposed that they should be raised to two storeys. Members of the Council were against this plan, because they said that such high houses diminish the flow of fresh, cold air in the city basin and that an increase in illness and disease would be the result. You can imagine that these warnings were not very successful because like many of its surrounding cities, Stuttgart is today a great industrial centre in the Federal Republic of Germany, and there are now buildings in the city with many more than one storey.

In 1951, recognizing the problems of air pollution climatology, an office for Urban Climate (integrated in the Chemical Office of the city) was established in Stuttgart. Today, the following people work in this section for urban climate:

- 3 meteorologists
- 1 physicist
- 1 engineer
- 3 engineering associates
- 1 secretary
- 1 driver

It is a municipal institution, so activities are limited to within the borders of Stuttgart, where about 570,000 people live. The main fields of study are climate, air pollution and noise. The special role of this department was outlined by an earlier minister for planning the Ravens area in a television show called "Planning as a factor in environmental protection". Further, the activities of the Department of Climatology were the object of a film with the title "Urban development and urban climate using the example of Stuttgart". This film was a contribution to the UN-Conference "Habitat" in Vancouver in 1976. The development of this department from two members in 1951 to the ten members of today, shows the great importance accorded to environmental protection in connection with the rapid technical and economic development of industry in Stuttgart.

The department's activities have been very many-sided, and we have had to solve many problems about air quality, urban climate and planning.

Figure 1 shows the range of interaction with other municipal offices. Notice that more than 50% of our work is together with the city planning office.

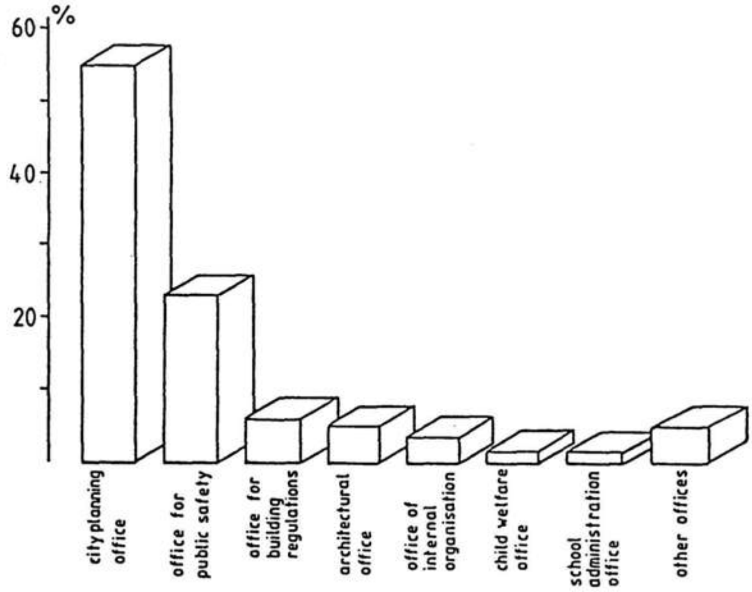

Figure 1. Activities conducted by the Department of Climatology for other municipal offices.

It has been increasingly necessary to get detailed values about both the air pollution conditions in Stuttgart, and also about the meteorological parameters. This requires buying expensive instruments, including an automated station for air quality control and a mobile measuring station. The maintenance of all the instruments is conducted by our own personnel.

A great advantage in our work is that our activities cover not only climate but also air pollution concerns. It is important to mention that we not only plan and carry out measurements, we also interpret the results and give advice to the planners, based upon these results.

3. EXAMPLES OF MEASUREMENTS AND RESULTS

As in other big cities one can find the urban heat island effect in Stuttgart (Figure 2). The differences in temperature between the city-centre and the surrounding countryside is about 6-7 degrees Celsius and is in good accordance with the formula of Oke (1973) represented in Figure 3. Note that this diagram also includes the results of measurements in small cities in Germany from the work of Danzeisen (1983).

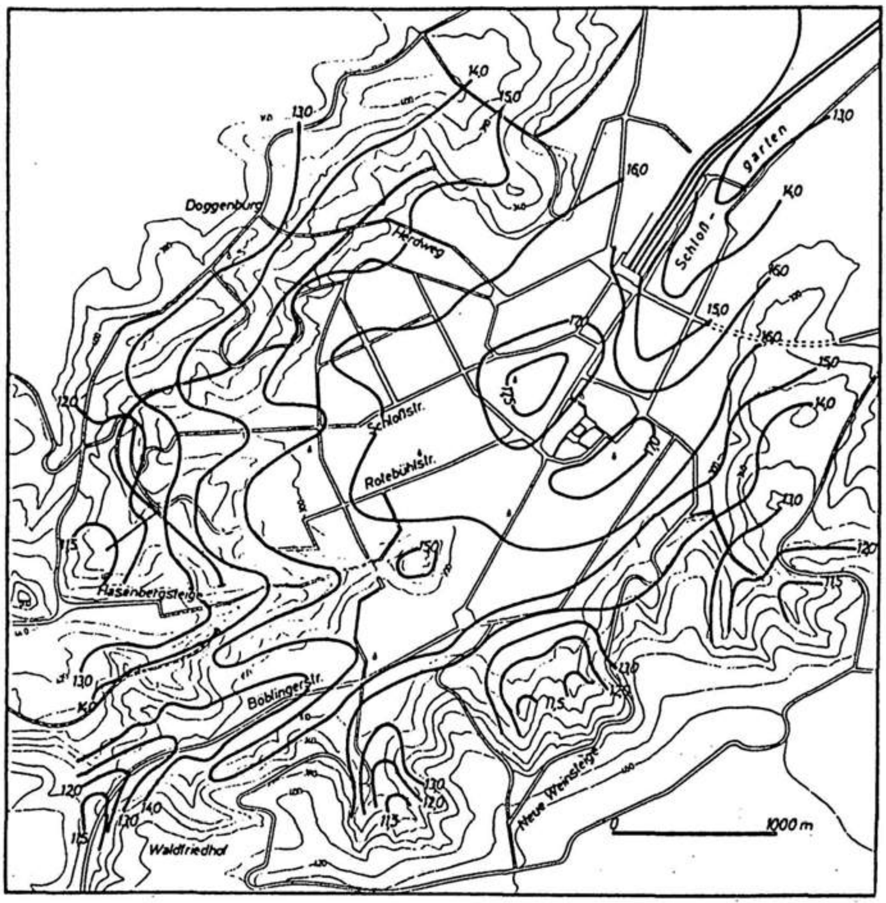

Figure 2. Isolines of air temperature in Stuttgart, 21.8.1965, 6.00 a.m. (Hamm, 1969).

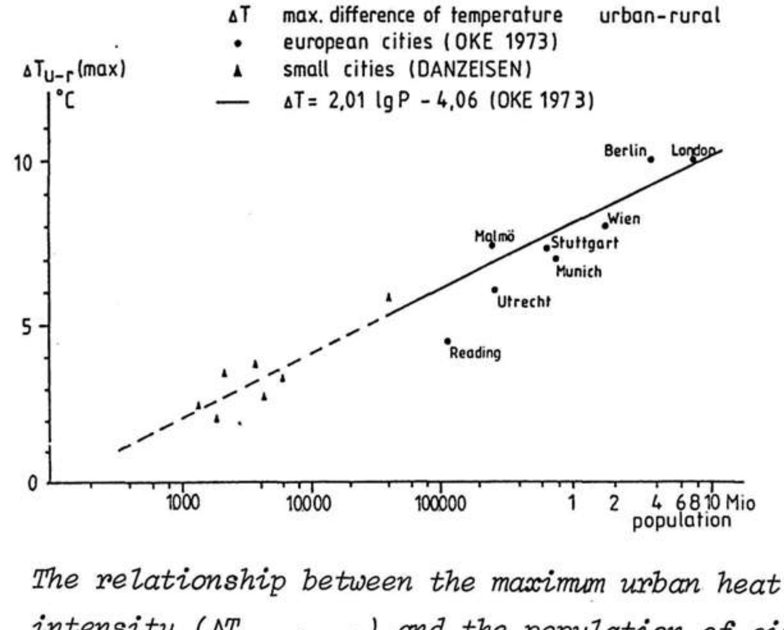

Figure 3. The relationship between the maximum urban heat island intensity ($\Delta T_{u-r(max)}$) and the population of cities in Europe (Oke, 1973) as extended by Danzeisen (1983).

The demand for detailed data was the reason why in 1976 infrared pictures by remote sensing were made to show the contrast between the countryside and the city. Although these pictures only show the surface temperature the measurements were very helpful in constructing the new Development Plan of Stuttgart. Together with other methods and some experience on climatology it was possible to use these thermal pictures to discern regions with cold air lakes and cold air flows.

Good knowledge about air movement, especially cold air flow, can also be obtained using the simple method of observing smoke drift from smoke cartridges. For example it can be used to assess the effect of a building as an obstacle in an important cold air flow to the city centre.

The damage of trees better known in Germany as "Waldsterben" was the reason infrared pictures were taken in 1983. It allowed the registration of all damaged trees in the city. The interpretation of these data will be conducted by the Office of Horticulture. We have the job of discovering whether any direct interaction with air pollution elements is evident.

The air pollution in a city is strongly dependent on the wind. Strong winds enhance dilution whereas weak winds allow pollution accumulation. The persistence of weak wind situations has an especially detrimental influence on air pollution. Therefore it is important to use statistical methods to calculate from measured data how often extreme wind situations will be found. Figure 4 is an example which shows that the persistence of weak winds for longer than 6 days only occurs once every 10 years (Höschele, 1984). This is in good agreement with the frequency of severe smog episodes in the southern part of Germany.

In addition to the wind velocity the height of inversions has a strong influence on air pollution concentrations. This is made clear in Figure 5. Inversions in the lower boundary layer, up to a height of about 300m, produce high SO_2 concentrations but they decrease again at 300m-400m. A second maximum can be seen at 700m. This characteristic profile is a hint that two main emission heights for SO_2 are evident in the city. It is our desire to reduce SO_2 by the prohibition of coal and oil for house heating. This is possible through a so-called Antiburning Act, and also by reducing the SO_2 and NO_2 outputs from stacks by washing the waste gases. Prohibition of coal and oil for house heating has been included in 150 local plans of the Stuttgart region. By installing heating with natural gas as the fuel we had reduced the SO_2 emissions in Stuttgart by more than 1000 tons per year.

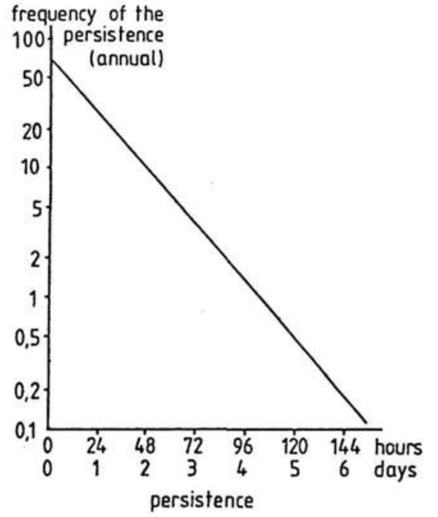

Figure 4. Frequency of the persistence of weak winds (below 1.5 m s^{-1}) in the "Oberrheintal" area, 1978-1982 (Höschele, 1984).

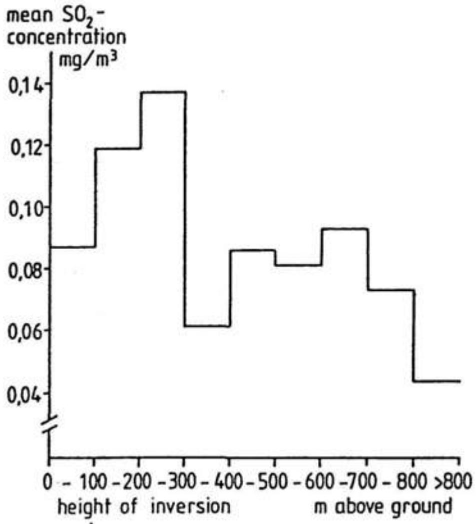

Figure 5. Dependence of SO_2 concentrations on the height of the inversion in Stuttgart.

Another great problem, not only in Stuttgart but all over the world, is air pollution from cars. In streets, for example, more than 90% of the air pollution comes from the exhaust of cars and it is urgent that emissions from this source should be diminished quickly. While the SO_2 concentration is a good tracer for winter smog situations in high latitude regions, ozone indicates another type of smog often called "Los Angeles smog". The generation of this smog is strongly influenced by solar radiation (e.g. Figure 6). Whilst on a sunny day in summer ozone increases soon after sunrise and NO breaks down we see another picture when the sky is covered with clouds. Ozone now is low. This photochemical smog isn't only a problem of cities at low latitudes but also of cities in Germany at about 50 degrees of latitude. In summer we find values of about 200 ppb of ozone over some hours. To diminish this kind of smog it it necessary to decrease the output of NO_2 and CH.

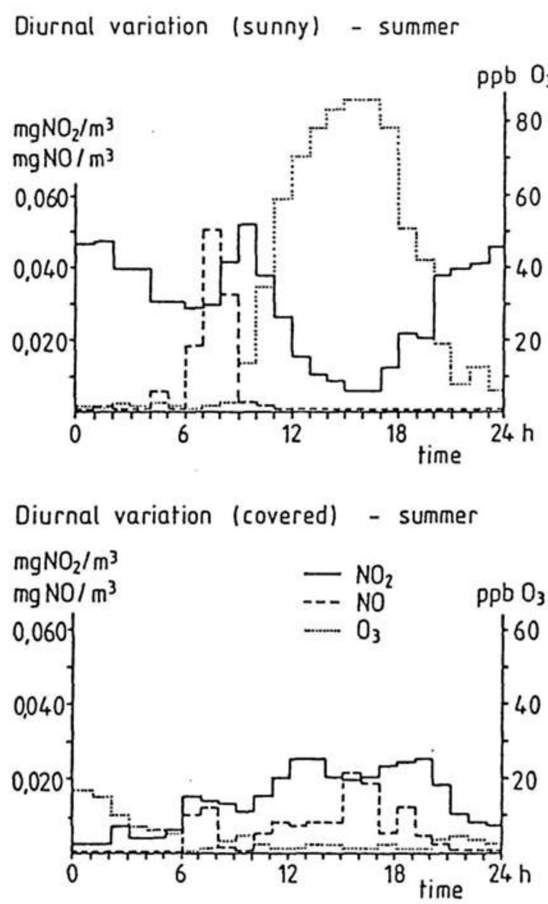

Figure 6. Diurnal variation of NO, NO_2 and O_3 on a sunny and a cloudy (overcast) day in Stuttgart.

To reduce the air pollution in streets it is possible to plan the direction of the streets in accordance with the main wind direction. Figure 7 shows the dependence of air pollution in a street canyon in relation to different wind directions above the roofs (Leisen, 1982). The highest values on the lee-side occur when the wind blows at right angles to the street. Knowing these effects, which can be simulated well in a wind tunnel (right side of the Figure 7), the streets can be planned in a manner so as to reduce air pollution by providing good diffusion in the street.

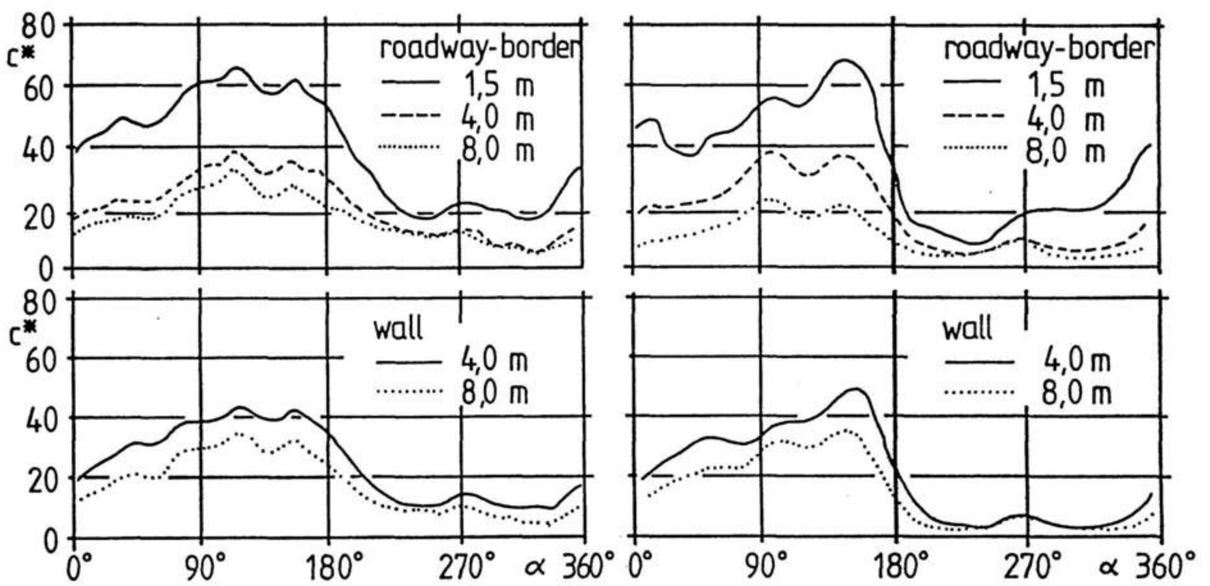

Figure 7. Normalized air pollution concentrations (C) at different heights in a street canyon as a function of the wind direction (above the roof). Left panel - field observations; right panel - wind tunnel data.*

In another approach it is possible to calculate the air pollution near a street with a relatively simple model for a line-source:

$$C = \frac{Q}{\bar{u}\sqrt{2\pi}\ \sigma_z} \left(\exp.\left[-\frac{(z-H)^2}{2\ \sigma_z^2}\right] + \exp.\left[-\frac{(z+H)^2}{2\ \sigma_z^2}\right]\right)$$

where C = the concentration of the air pollutant, Q = the rate of emissions, u = the mean wind velocity, H = the height of the emission source, and σ = a diffusion-parameter. The calculations are primarily based on the number of cars and their emission-rates and are good enough to say at what distance it is safe to build dwelling-houses so that air pollution quality standards are not exceeded.

4. PUBLIC RELATIONS

The Department for Climatology tries to make all results of its investigations available. Therefore we edit our own series of communications. In these communications it is possible to find all the facts necessary to understand the measurements and conclusions.

Some years ago we mounted a large exhibition in the town hall on the subject of urban climate and air pollution in Stuttgart, and it was very successful.

Many people in Stuttgart who see the problems of air pollution and urban climate visit our office to get advice or to lodge a protest against some planned or existing emission sources. Today it is fair to say that in Stuttgart there exists a good consciousness in respect of these problems by the people.

5. CONCLUSION

The fact that the urban climate of Stuttgart is acceptable is thanks to an order issued by the Lord Mayor of Stuttgart in 1951, that climatologists must be consulted by all municipal agencies whose actions can affect the city's climate.

The Department of Climatology is a part of the main Department for Public Safety and Environmental Protection and not of the Department for City Planning. This is important to mention, because in this way it is possible for the work to be more independent. Our activities can be compared with those of an independent expert. Unfortunately there is no universal rule to apply to get a good urban climate. Therefore it is necessary to take into account all functions of planning and see that their sum does not become negative.

The Law for Planning and Building in Germany gives us the possibility of influencing the way to build on, in order to take into account climatological concerns.

Stuttgart's practices can very well serve as a model for other cities in the Federal Republic of Germany and elsewhere. This kind of awareness of climatological needs is rather the exception than the rule. Great efforts are necessary to keep urban climates satisfactory and the air clean. Let us make such efforts!

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PROBLEMS OF DESIGN FOR CITIES IN THE TROPICS

H. E. Landsberg
Institute for Physical Science and Technology
University of Maryland, College Park, MD. 20742

1. TROPICAL CITIES AND CLIMATE

Urban design and the urban fabric should be in harmony with the local climatic conditions. Certainly indigenous dwellings and settlements fulfilled this condition, but modern cities in many respects deviate from this concept. This is particularly true for the metropolitan areas of the tropics.

Socio-economic and demographic problems are at the base of the problem. For this reason a quick assessment of the facts will illuminate the difficulties facing the city planners of the tropical belt. At present 118 nations and territories lie fully or partially within the land areas enclosed in the zone between the Tropics. About 1.7×10^9 people live in this zone, or about 38% of the World's population. The latest projections of the World Bank estimate that this population figure will increase by about 50% at the end of the century. It is also the region encompassing many developing countries with high birth rates. Presently about 170×10^6 or 10% of the tropical population live in metropolitan areas with populations of 1 million or more each. Table 1 gives a list of these human agglomerates. In most of them the density of settlement is very high. An example is Bombay, India, where 175,000 persons are packed into one km^2. The size distribution is shown in Figure 1. It is also notable that among the 53 localities listed 31 or 58% are situated at the coast. This fact has a number of major climatic implications to be discussed later. Another fact is that a majority of the cities are in regions governed by the seasonal monsoonal atmospheric circulations, with pronounced dry and wet seasons (Figure 2). The annual rainfall figures shown in Table 1 also show that many of the megalopolitan tropical cities have large amounts of rain, but there are exceptions. There are a few that lie in arid zones.

TABLE 1. *Tropical Metropolitan Areas with ≥ 1 Million Inhabitants*

	Central City	Country	Population (x 10^6)	Annual Rainfall (mm, rounded)
C	Abidjan	Ivory Coast	1.6	1980
C	Accra	Ghana	1.0	790 +
	Addis Ababa	Ethiopia	1.2	1070
C	Ahmadabad	India	1.7	820 +
C	Bandung	Indonesia	1.7	1900
C	Bangkok	Thailand	5.2	1440 +
	Belo Horizonte	Brazil	2.4	1060 +
	Bogota	Colombia	4.3	1470 +
C	Bombay	India	8.2	2080 +
	Brazilia	Brazil	1.1	1560
C	Calcutta	India	9.1	1600 +
C	Caracas	Venezuela	3.0	840 +
C	Chittagong	Bangladesh	1.1	2730 +
	Dacca	Bangladesh	3.0	2010 +
	Delhi/New Delhi	India	5.2	670 +
C	Fortaleza	Brazil	1.3	1370 +
*	Giza	Egypt	1.3	60
	Guadalajara	Mexico	2.3	900 +
	Guangzhu	China	2.9	1720
	Guatemala City	Guatemala	1.6	1310 +
C	Guayaquil	Ecuador	1.1	1100
C	Hanoi	Vietnam	2.6	1800 +
	Harbin	China	3.0	580
C	Havana	Cuba	2.0	1230
C	Ho-Chi Min City	Vietnam	3.4	1980 +
C	Hongkong		5.1	2270
C	Jakarta	Indonesia	6.5	1800 +
*	Johannesburg	S. Africa	1.3	710
C *	Karachi	Pakistan	8.6	200 +
	Kinshasa	Zaire	2.2	1390 +
C	Kuala Lumpur	Malaysia	1.0	2410
C	Lagos	Nigeria	1.7	1830 +
C	Lima	Peru	4.9	50
C	Madras	India	4.3	1210
C	Manila	Philippines	5.5	2070
	Mazatlan	Mexico	2.1	810
	Mexico City	Mexico	14.0	750 +
*	Monterrey	Mexico	1.9	580
	Nanking	China	2.4	1320 +
	Nova Iquacu	Brazil	1.1	n.a.
C *	Porto Alegre	Brazil	2.3	1330
	Quezon City	Philippines	1.0	n.a.
C	Rangoon	Burma	2.7	2620 +
C	Recife	Brazil	2.3	1610 +
	Rio de Janeiro	Brazil	5.1	1080 +
*	Riyadh	Saudi Arabia	1.3	150
C	Salvador	Brazil	1.8	1900
C	San Juan	Puerto Rico (U.S.)	1.1	1630
C	Santo Domingo	Dominican Republic	1.0	1420
	São Paulo	Brazil	8.3	1430
C	Singapore		2.4	2420
C	Surabaya	Indonesia	2.4	1780
C	Taipei	Taiwan	3.5	2180 +

Sources: National Geographic Atlas of the World, 5th edition, Washington, D.C., 1981, and World Weather Records.

Footnotes:

C - indicates coastal city.

*Areas * outside the Tropics but below 30° latitude and have tropical climates.

+Rainfall shows a very pronounced annual (monsoonal) variation.

Obviously the cities in the wet and the dry zones present radically different planning problems.

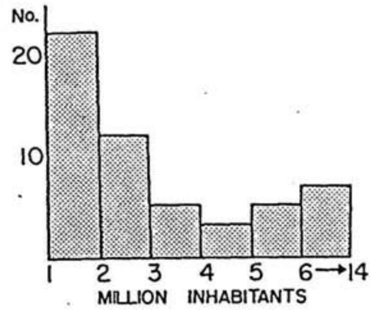

Figure 1. Number of metropolitan areas in the Tropics with > 1 million inhabitants.

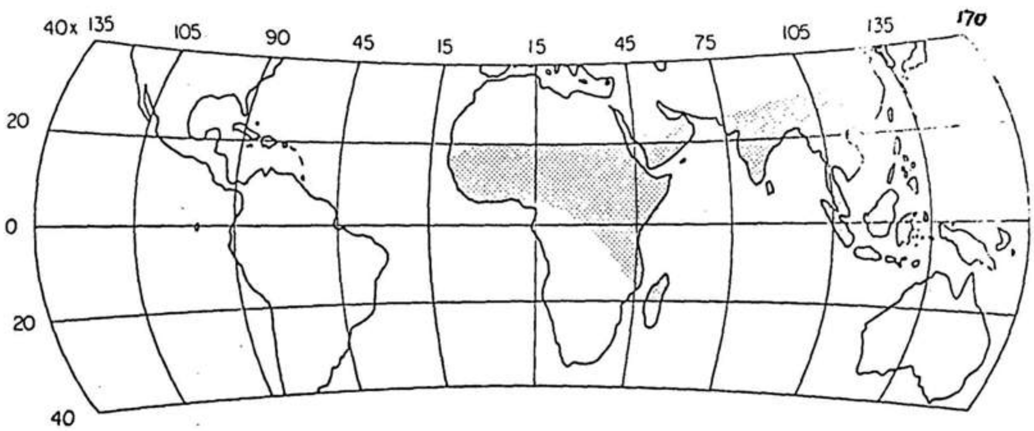

Figure 2. Monsoon-affected land areas (adapted from Ramage, 1971).

The present conditions look formidable enough but a look into the future indicates that they will become further aggravated. Every prognosis indicates that the trend for migration of people to the cities will continue. Fewer persons will be engaged in farming and employment opportunities will tend to be in the manufacturing and service sectors of the economies. Current estimates project that even in developing countries more than half the population will live in urban areas. Anyone who has visited the cities in the tropics learns quickly that planning entered only marginally into lay-out and growth patterns of the urban areas. And climatic planning seems to have been virtually non-existent. One cannot blame the current generation for this. A lot is an evil inheritance from earlier colonial days. When the first colonists occupied tropical lands, often at strategic harbour locations, they transplanted housing construction and urban design of their home countries to the new shores. These were usually quite unsuitable for the tropical climates, except that they offered rain protection. Even presently European and American architectural structures dominate the metropolitan areas of the globe.

Climatically, besides the seasonally large amounts of rainfall in the majority of tropical metropolitan areas, a few other important climatic characteristics need to be noted. One is the very small annual temperature range, which in the inner tropics is generally less than 5°C (Figure 3).

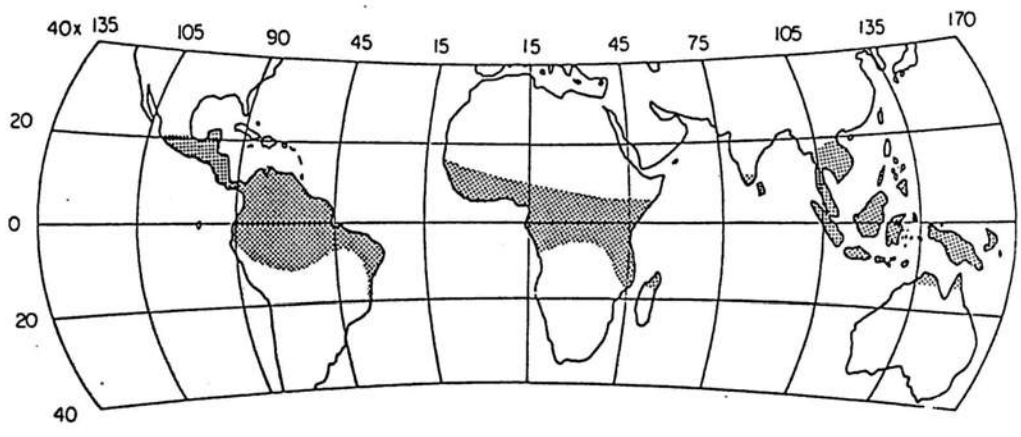

Figure 3. Areas with annual temperature range (warmest-coldest month) of <5°C.

Exceptions are the somewhat higher-latitude monsoonal areas, for example in India. In many of the non-desert localities in the tropics the diurnal range is larger than the annual range. In the coastal areas tropical storms, often with very high wind speeds, are frequent occurrences (Figure 4). Their tracks carry them often to extratropical latitudes, where they are among the most damaging weather events. Independently, thunderstorms have their highest frequencies in the moist tropics (Figure 5). In some tropical areas the yearly cloud-to-ground lightning density has been estimated at 10 km^{-2}. Because of the high elevation of the Sun, solar radiation is also a climatic element of great importance in the tropics. The incoming energy has its highest values in the dry tropics and subtropics (Figure 6). Thus many climatic factors and their geographical distribution must enter the process of planning for settlements. This applies to the tropical areas no less than for higher latitude zones.

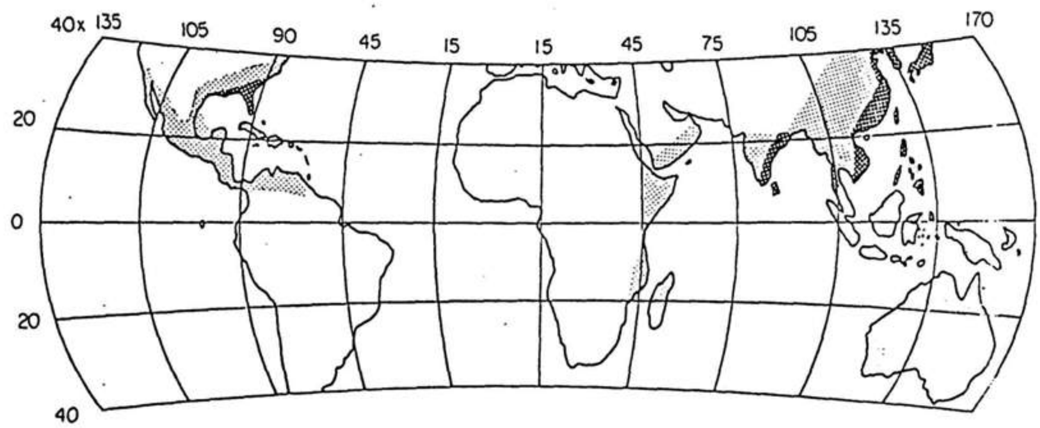

Figure 4. Coastal areas affected by tropical storms

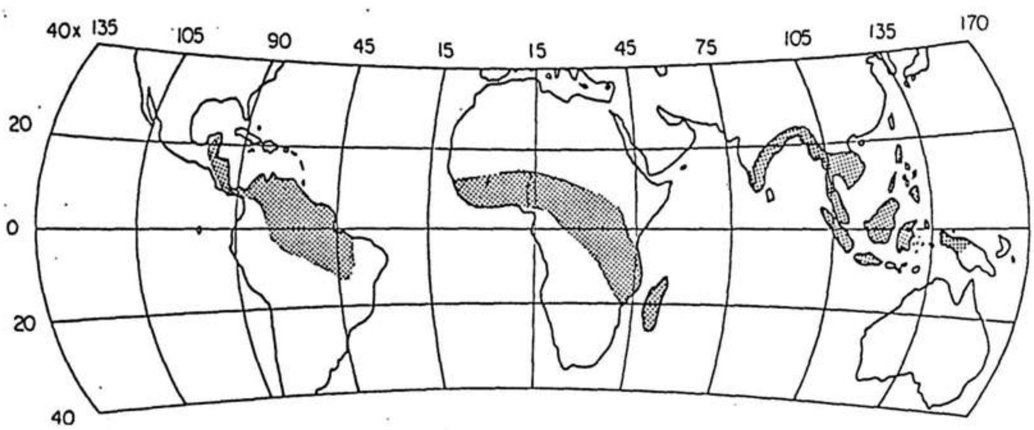

Figure 5. Areas of high thunderstorm frequency

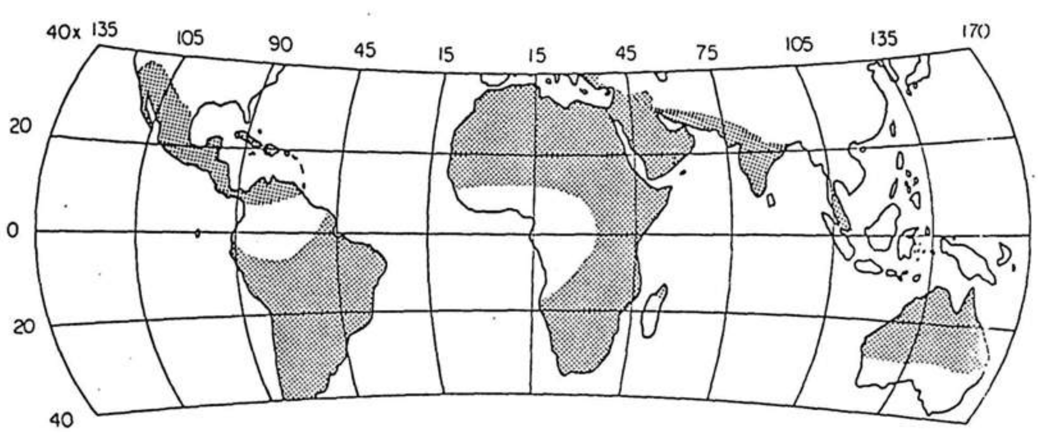

Figure 6. Areas with annual radiation received at the surface of > 200 W m^{-2}.

2. TROPICAL URBAN CLIMATES

What do we know specifically about the peculiarities of urban climates in the low latitudes? Admittedly there is very little in the literature. The available studies show clearly that tropical cities share one feature with all other urban areas; namely the heat island. Nakamura (1967) showed this first for Nairobi (Kenya) but the elevation and the local topography makes this less than typical for other tropical areas. The city population of about 1/4 million at the time also cannot compare with the megapolitan cities elsewhere. Preston-Whyte (1970) reported on a day-time urban heat island in Durban (S. Africa). More elaborate studies have been published for Johannesburg (S. Africa) by Tyson et al. (1972) and Goldreich et al. (1981). The heat island effect is clearly present but this city, while large, has a very complex topography which makes extrapolation to other urban areas inadvisable. More representative are the recent results for Delhi (India) by Padmanabhamurty and Bahl (1982). These too show heat islands in the urban fabric and the well-known mitigating effects of parkland.

Work by Padmanabhamurty and Mandal (1981) also established that Delhi has reduced total radiation flux in winter because of radiation interception by pollutants. This urban characteristic, too, is worldwide. Sharma (1983) writes:

> "All the large Indian cities suffer from air pollution. On the basis of regular fuel consumption alone, the quantity of air required in the city of Delhi is 65.5 cubic kilometres/ day; for Calcutta it is 86.0 cu km; and for Bombay 81.5 cu km."

Much of the fuel used is for motor vehicles and the exhaust products often undergo photochemical reactions. These create smog which lowers visibility and is composed of irritant reaction products of oxides of nitrogen and ozone. Aside from that the motor traffic, in many of the large tropical cities, has become unmanageable as have slum conditions. A typical example is Bangkok (Tuntawiroon and Samootsakorn, 1984). There, as in many other cities of the wet tropics, floods cause major damage and give rise to serious health hazards.

DESIGN FOR TROPICAL CITIES

The prevalent urban architecture and land-use has added micro-meteorological problems to the urban miseries of tropical cities. High-rise buildings for accommodation of the masses and the essential business have become formidable obstacles to air flow, a phenomenon which has now been well documented in similarly built-up areas of the higher latitude urban areas (Bornstein, 1983). Solid walls of tall buildings have risen in many places near the sea front of the harbour cities, thus blocking the welcome, cooling sea-breezes during the hot part of the day and adding to the physiological discomfort further inland.

The preceding brief survey of tropical urban climates, revealing heat islands, air pollution, ventilation problems, and floods in the rainy zones, indicates formidable problems for urban planning. In the dry tropics the flood problem is replaced by water supply problems and excessive sunshine, also often the plague of dust-bearing desert winds. Are there solutions to these problems? One cannot be very optimistic for the existing, already overgrown cities. Changes for the better there will be slow and costly. It seems even unrealistic to expect that the continuing growth can be halted. Yet the establishment of satellite towns with much smaller populations may in some areas be feasible. This is not an advocacy of "suburbia" but rather a plea for settlements at reasonable distance (tens of kilometres) from the major cities. You might call this a flight into fantasy but I have indulged once before in such thoughts for higher latitude settlements (Landsberg, 1973). The idea of a climate-adapted town is not advocacy of bedroom communities with work places elsewhere but rather of complete population centres.

3. "SWARAG" - A CLIMATICALLY SENSITIVE TROPICAL TOWN

When Sir Thomas More created the concept of Utopia he envisioned a city free of all societal miseries. Our concept is far more modest and tries only to achieve the best compromise with climate. The functions of a town need to be maintained. They include principally dwellings, employment opportunities, trade and communications, governmental and judicial functions, educational and cultural institutions, health and sanitary facilities. This implies a fairly sizeable community but less than the unmanageable million-inhabitant size. As we are dealing with the tropics we probably should call our visionary town by a Hindi name "Swarag".

Quite clearly, if we have a choice, many meteorological problems can be avoided if the new town site is carefully selected so that topographical conditions are favourable. Bitan (1975) has cogently pointed out the interactions of topoclimatology and cities. For example it is quite elementary, but while riparian sites have advantages, building on flood plains must be avoided. Similarly topographic troughs can only lead to aggravate any air pollution problems that may arise. Of course, the basic plan for "Swarag" will attempt to minimize air pollution. The town, therefore should have an electric transportation system. For mass transportation a subway system seems indicated, which at the outskirts can be fed by automated monorails of the proven variety now used between terminals at major airports (Dallas, Houston, Gatwick). Deliveries and private transportation will also use electric cars. Respectable and economical models are already on the market. Intercity motor traffic has to be on peripheral beltways with heavy loads transported on electric rail facilities. Although a carefully planned transportation system can drastically reduce air pollution and photochemical smog, other pollutant sources need close attention. Principally among them are power stations. Here again fossil fuel power production is to be eliminated. Alternative energy sources will have to provide the essential electricity. As has been pointed out by Smil (1984) power sources other than coal and oil not only are cleaner in thermal electricity production but more efficient in land use. Obviously renewable energy resources would be the primary choice for "Swarag": solar, wind, or hydroelectric. All of these are climate-related and one would hope that adequate prior climatic observations would provide the data to analyze their adequacy. Where hydro-electric power is feasible, dam sites and reservoirs offer flood control and recreational opportunities. At some locations geothermal energy sources may be available. Properly safe-guarded nuclear energy may be the solution for other sites.

Solar energy is usually a commodity in ample supply in the tropics. It is likely to become a more prevalent source as new technology gains. It is already widespread for passive purposes, such as hot water supplies. But the real promise is in the increased efficiency of photovoltaic electricity generation (DeMeo and Taylor, 1984). In some coastal areas or near a mountain range, wind power installations are gradually adding to the power supplies. Although the technology is presently more prevalent in higher latitude regions, Brazil and Australia have begun wind energy programmes (Anonymous, 1984). Certainly, an all-electric "Swarag" is entirely achievable.

Whilst utilization of solar energy is highly desirable avoidance of absorption of solar radiation by concrete, asphalt, and stony surfaces is also essential in our Utopian city. The large parking lots now found in many urban areas are prime offenders. In a new town parking should be planned under buildings but if surface lots are unavoidable the so-called "Green Parking Lot" should be adopted. This is built with openings in paving blocks which permit grass to grow through (e.g., Thurow, 1983). Such a remedy, of course, requires adequate rainfall for grass growth. This applies too for use of other plants in urban settings to offset the influence of solar radiation, such as shade trees and roof gardens. The beneficial influence of parkland on urban temperatures is a long established fact. It can alter the adverse energy balance that is a major cause of the urban heat island (Oke, 1982). Both, measurements and models prove the efficacy of plants to cool by evapotranspiration and by a higher albedo than building materials (O'Rourke and Terjung, 1981). The already cited Delhi observations (Padmanabhamurty and Bahl, 1982) show that the same principles hold in the tropics as in the higher latitudes. Plants also have the highly desirable effect of retarding runoff after heavy rainfall thus reducing the flood hazard in urban areas.

Solar energy problems are more difficult to solve in the dry tropics. A traditional protection is narrow streets, appropriately oriented, where buildings shade each other, the use of overhangs, arcade construction over sidewalks. The latter also have distinct advantages in wet regions for the protection of pedestrians. Highly reflecting surfaces also help. Use of light paint can reduce the absorption of solar radiation materially. The ideal desert city should emulate the desert lizards that escape the daytime heat by disappearing in burrows. Modern construction methods make underground construction quite feasible and the large diurnal variation of temperature is already damped out in about 0.5m depth and even the annual variation disappears at 10 metres. Even in dry Riyadh the annual mean air temperature (at that depth) would only be 16°C.

For our "Swarag" in the moist tropics, especially on the sea shore, the wind is perhaps the most important meteorological factor. In the areas of tropical storms building designs have to incorporate risks caused by high wind speeds. Damage to structures seems to increase exponentially with increasing peak gusts. But the wind is not only a hazard, it can also be a highly beneficial element. We have noted that already in relation to the air pollution factor. The urban design can greatly reduce the usual retardation of wind speed by the high roughness of urban fabric and by the outright deflection caused by massive structures. Wind tunnel experiments have demonstrated these effects dramatically. They show also the often highly undesirable eddy currents produced by tall buildings. Some of this can be avoided by selecting angles of exposure of such structures with respect to prevailing wind directions. One fact stands out from all observations: uniform height of houses and buildings creates essentially a new surface which becomes the lower boundary for ventilation. Similarly, tall structures which create a wall effect can block desirable breezes. This is particularly notable along sea or lake frontage where high-rise buildings can block or at least deflect the sea and lake breezes. Any meteorologically sensibly designed town will adopt open construction. Thus when laying out "Swarag" a wind tunnel study on a model can be of greatest value to the designer. In some higher latitude urban areas where topography plays a role and where slope breezes develop strict zoning rules to permit such circulations have been helpful. Stuttgart in the Federal Republic of Germany is a notable example. Experiences there are directly transferable to other regions including the tropics (Baumüller et al., 1981).

In many parts of the tropics, not only the arid or semi-arid areas but also the monsoonal regions, water supply problems loom large. Sharma (1983) has indicated that for the Indian cities with multi-million inhabitants recycling of water may become a necessity. There, and in the drier region water availability offers another argument for smaller settlements. The desalting of sea water, where available, remains an alternative and is another case for exploitation of solar energy. Conservation of water has also ties to the climate in hot regions. Open reservoirs are subjected to heavy losses by evaporation. The planner will have to think about restrictions to avoid these losses. Cisterns and covered reservoirs are practical only on a smaller scale but may well be incorporated for certain sections of a new town. On a larger scale, reduction of wind speed over the water surface by tall hedges or fences is advisable. Mono-molecular films or plastic covers might be suitable in some cases.

For any town, new or old, employment is an essential consideration. There will always be service jobs in a settlement and there will be shops selling the necessities of life. These offer no climatic problems. There also are a variety of industries which are essentially pollution-free. This applies to most of the electronic and optical industries which in fact seek an environment free of air pollution. Other non-polluting manufacturing such as clothing, jewellery, machine shops, etc., can offer many jobs. The principal planning factor is to make them accessible to the workers without requiring large parking lots. The major problems arise with the so-called smoke-stack industries, such as steel mills, smelters, and refineries. If they are unavoidable for our hypothetical town "Swarag", their location must be carefully controlled. They must be obviously down-wind from the town for low-wind speed stagnation cases with inversions. The most frequent wind directions for such cases are generally not identical with the frequency of all wind directions. Further, the factory sites must also avoid topographic trough locations. Dispersion of effluents from higher elevation by a smoke sewer has been a solution, if other pollution-eliminating practices cannot be avoided. Such planning principles have also been outlined by Padmanabhamurty (1981). They cannot be repeated often enough.

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CLIMATIC FACTORS IN THE SITING OF NEW TOWNS AND SPECIALIZED URBAN FACILITIES

T. J. Lyons
School of Environmental and Life Sciences
Murdoch University, Western Australia 6150, Australia

1. INTRODUCTION

The initial development of towns and cities has been determined essentially by the classical constraints of physical geography; a bridge town, a crossing of major traffic routes, a port or an available source of energy, such as coal (Hallsworth, 1978). As the city grows these initial constraints tend to become obscured. Ideally urban planning should tune the initial design, aiming at an optimal interplay of the land, water and air resources. Within this scenario, the role of climate is often overlooked, despite the fact that climatic factors affect the major functions of a town through their influence over the availability of energy, water and vegetation, as well as, impacting on the structure of the urban area and the design of the individual dwellings within that urban area (i.e. Landsberg, 1970; Peterson, 1971; Chandler, 1976; Moriarty, 1980).

Various authors (i.e. Page, 1970; Kalma and Byrne, 1975; Oke, 1975, 1984; Landsberg, 1981) have lamented the lack of meteorological input into the urban planning process and claimed that it is due in part to the lack of predictive power within urban climatology (Page, 1970) and/or the absence of clearly defined guidelines for the planner or engineer (Oke, 1984). Nevertheless, climate is a recognized planning constraint in harsh environments, such as deserts (i.e. Bitan, 1974, 1982, 1983) and the advent of environmental impact studies has further highlighted the meteorological input (i.e. Linacre, 1977; Mahoney and Spengler, 1975). These studies illustrate that although urban climatology may lack a full predictive power it has the ability to aid the planning process by providing planners with the capability to achieve a broader understanding of the relevant issues and hence lead to more informed judgements on the viability of various options. As with all planning exercises the dynamic aspect of the city must be recognized and the meteorological data continually used to update the various planning issues.

Any planning model is based on the assumption that it is possible to predict future conditions by extrapolation of known trends or inspired guesswork. As such the model may never be validated in the full sense but it is important to recognize the constraints that apply. The climatic constraints are particularly relevant in designing cities for the Developing World where new forms of urbanization are developing out of necessity, due to the marked migration towards the cities (Dwyer, 1978).

Since climate is a complex aggregate of the interaction of many scales within the atmosphere and each city has a unique coupling with the surrounding landscape, the meteorological input to the planning process has to be made at a number of scales each demanding a different set of data (Chandler, 1976). These will be highlighted in terms of the initial location of a city, its overall structure, and the location of additional facilities within an existing city that may impact on air quality. Although the size of the city is not considered in discussing the general principles it will obviously impact on the climatic constraints. With a population of 10,000 inhabitants the city has a measurable impact on the atmosphere and this feedback between atmosphere and city becomes pronounced as the population increases beyond 1,000,000 (Landsberg, 1973).

2. URBAN LOCATION

Almost all sites are climatically possible for urbanization if the associated environmental risks are acceptable, but given a need to optimize the use of land, water and air resources, many sites are impractical. For instance, in discussing the location of a new city we first need to question whether the factors that controlled the areas of urbanization in the past will continue to do so in the future, or whether the need to use solar energy, the need to avoid pollution, and the need to conserve the land that is capable of sustaining rain-fed agriculture, can outweigh the classical constraints (Hallsworth, 1978). If we assume that the transfer of land from agricultural use to urban development cannot be accepted as a viable natural consequence of population growth then a climatic constraint on the location of a city is rainfall, or rather the lack of it. Those areas that receive insufficient rain for the growth of cultivated crops or improved pastures are thus candidates for urban development. Development of urban regions of an appreciable size outside this area will detract from the available rain-fed agricultural areas. Of course, some land that receives sufficient precipitation to support rain-fed agriculture may be ultimately unsuitable for agriculture due to other factors such as soil characteristics or slope.

The inhabitants of any new city will require a reliable source of water and if it is to be located in an area of low rainfall, this will require access to reliable surface water, underground supplies or the technology of water purification through desalination or recycling. The viability of such technology is clearly dependent on the scale of the proposed urban development (Swinton, 1978). Nevertheless a growing urban population demands more and more water and few modern cities are exempt from some threat of drought. Urban drought is not necessarily caused by insufficient precipitation but may be caused by inadequate storage to meet seasonal demands (Baumann and Kates, 1972). Clearly the seasonal variability of precipitation within the urban catchment area exercises a constraint on the availability of water. The availability of solar radiation data is a necessary basis to assess the feasibility of utilizing solar energy within a new urban area and for the design of appropriate solar energy conversion devices. Obviously the best data to use are radiant energy observations at the site of the proposed development. Where such observations are not available it may be possible to resort to predictive models based on routinely collected meteorological data or alternatively, interpolation between stations. However the use of such predictive models has been shown to give errors of the order of 15% for global irradiation (i.e. Lyons and Edwards, 1982) and interpolation beyond fifty kilometres can lead to similar errors (i.e. Hay and Suckling, 1979). Such accuracy may be insufficient to assess the viability of solar thermal power generation where the worth of the power station is highly dependent on the short term variation of station output and system load during the day.

The demand for energy is influenced directly by climatic considerations. Climate is a major determinant of domestic and commercial energy use for space heating, ventilation and cooling (Kalma and Byrne, 1975). Thus the location of a tropical town should maximize the use of local flow patterns to reduce heat stress by using, for example, the combined effects of increased height and cooling sea breezes to reduce temperatures, as in the case of the Israeli settlements in the Jordan valley (Bitan, 1983).

Although a coastal location may reduce heat stress and thus the demand for energy, in areas prone to tropical cyclones this introduces a further hazard. The major causes of damage from tropical cyclones are the strong winds, storm surges and heavy precipitation. Although damage caused by the wind depends on the quality of construction and the maximum wind speed, storm surges can lead to an increase in sea level of several metres (Anthes, 1982). Hence within tropical cyclone prone areas towns should be adequately sited to guard against possible storm-induced sea level rises.

The extreme precipitation from tropical cyclones and/or thunderstorms requires adequate methods of discharge. By its very nature urbanization increases surface runoff (Landsberg, 1970, Chandler, 1976) and this coupled with tropical storms means that the urban area must be sited to allow for increased peak discharge, without leading to flash floods and subsequent inundation of the urban area. To this end flood plains should not be used as sites for urbanization (Landsberg, 1981).

Clearly long range urban land-use planning requires careful consideration of the variability of weather events, as well as knowledge of the mean state of the atmosphere in that region.

3. URBAN STRUCTURE

The process of urbanization leads to a modification of the local climate and hence the climatic impact on the location of a city cannot be considered in isolation without also discussing the climatic feedback between city and atmosphere. For example, the old city of Jerusalem and other such settlements were built in dense clusters with narrow streets to minimize walking distances in the hot sun and maximize the shade (Bitan, 1983). Such a structure of high density is a direct response to large scale climatic forcing yet leads to a marked modification of the local climate and the introduction of the urban heat island through the creation of urban canyons (Oke, 1981).

On the other hand Berry (1974) suggests that increasing size, increasing urban sprawl, and increasing automobile usage are producing the very urban forms and land-use patterns that will increase rather than decrease environmental pollution. In particular, he noted that the core-oriented urban region with a radial transportation network and a steep density gradient displays greater intensity of land-use, a lower percentage of land developed and used for residential and commercial purposes, and more open space. As a consequence of this land-use mix and pattern, it has superior air quality to the dispersed urban region with a less focussed transportation network. Thus increased urban density promotes air quality but also enhances the urban heat island.

By varying building density and amount of open space ("green area") the urban heat island intensity can be controlled to some extent. Thus in warm climates, a heat island's intensity can be reduced by interspersing buildings with green areas and shade trees (Peterson, 1971) and yet maintaining the steep density gradient.

As the city develops, local topographical features may enhance or decrease the environmental quality and thus should be considered in the initial siting of the urban area. Typical effects of some topographical features are shown in Table 1.

In each case, the topographical feature will dominate the mesoclimate and have a profound effect on ventilation through the establishment of a secondary circulation. Residences on a valley slope may experience relatively clean and cool downslope winds during oppressive summer nights whereas those on the valley floor may be trapped in a pool of stagnant air with a high accumulation of air pollutants.

TABLE 1. *Effects of topographical features on air quality (after Mahoney and Spengler, 1975).*

Topographical Feature	Effect
Elevated region	Increased wind speed (and ventilation)
Deep valley	Channelling of wind flow along valley - higher pollution concentrations.
	Development of stable drainage winds. Stagnation - higher pollution concentrations.
Undulating regions	Increased turbulence in moderate/strong winds - lower pollution concentrations.
	Accumulation of pollutant in lower areas during calm, night-time conditions.
Bodies of water	Increased moisture content, i.e. fog formation.
	Land/sea breeze circulation - fumigation during sunny daytime conditions.

Residences by a sea or lake coast will experience the cooling effect of a sea breeze on hot afternoons. However, if industry is also located along the coast, residences inland may experience fumigation and the consequent decrease in air quality, during the sea breeze.

Such topographic effects are not confined to major relief features. Under calm stable conditions even minor topographic features can wield a marked influence and lead to pockets of cold stagnant air (i.e. Lyons and Steedman, 1981; Wyngaard, 1979) with the possible inherent decrease in air quality. Obviously in siting an urban area and planning for its future growth it is not possible to avoid topographical features, but their land-use can be arranged so as to enhance environmental quality through a proper consideration of the climatic constraint. It is not so much a question of reducing total emissions, although this is a major factor in air pollution control, but of reducing concentrations at points where human beings and sensitive objects are located by incorporating the meteorological factors of airborne pollutant dispersion in land-use planning.

4. URBAN FACILITY LOCATION

The development of urbanization has been intimately linked with industrialization and consequently the maintenance of urban air quality is a major challenge facing the planner. It has often been assumed that industrial complexes should be sited downwind of residential areas, as defined by the prevailing wind (Bach, 1972; Chandler, 1976). This is not necessarily true as the prevailing wind is often associated with strong, highly turbulent airflows which may lead to the lowest concentrations (Chandler, 1976).

The essential dilemma here is that most meteorological phenomena become more serious as the forcing functions become stronger whereas the concern about an air pollution situation increases rapidly as the transport and/or diffusion processes *decrease* in intensity, reaching an extreme where these values become near zero. This extreme situation is least tractable from a scientific viewpoint, in that the regional scale forcing functions become ill-defined or non-existent and small relatively disorganized local effects take over.

Under such conditions site selection for a new industrial complex, in the planning for a new city or within an existing city, must involve a full evaluation of the impact of air pollutants. Such an evaluation would consider the pathways of pollutants through the atmosphere from emission to the establishment of ambient concentration levels, as well as the impact of these pollutant levels in terms of exposure-damage models and the ultimate evaluation of the full environmental risk associated with the emission (i.e. Drake et al., 1979). Within this context the local meteorology is critical in determining the pollutant pathway through the atmosphere in terms of the transport, diffusion, transformation and ultimate removal of the pollutant (Johnson and Ruff, 1975).

Pollutants undergo transport through the action of the mean wind in carrying the pollutant away from its source whereas diffusion results from the turbulent characteristics of the atmosphere in diffusing the pollutant in all directions. Transformation accounts for the chemical processes that may take place in the atmosphere in changing a pollutant species. This may involve a chemical reaction between two atmospheric pollutants, the reaction of the pollutant with some other constituent of the atmosphere or reaction involving some other factor, such as sunlight in the case of the formation of photochemical smog. Pollutants are removed from the atmosphere through gravitational settling, interaction with surface features such as buildings, plants or topographical features, or washout through precipitation. Since a number of these processes have characteristic temporal and spatial scales, measurements required for a single point source differ considerably from those of, say, the general regional problem. The relevant meteorological variables are defined in Tables 2-4 according to the scale of interest and the elevation of emission sources.

TABLE 2. *Estimated importance of relevant variables according to scale of interest and elevation of emissions source (1 = most important, 5 = least important) (after Johnson and Ruff, 1975).*

Variable	Microscale (0 - 1 km)		Local Scale[d] (o - 10 km)		Mesoscale[d] (10 - 100 km)		Regional Scale (100 - 1000 km)	
	Surface	Elevated	Surface	Elevated	Surface	Elevated	Surface	Elevated
Near-surface wind direction	1	3	1	2	4	4	4	4
Vertical wind direction profile	3	1	2	1	1	1	1	1
Near-surface wind speed	1	3	1	2	4	4	4	4
Vertical wind speed profile	3	1	2	1	1	1	1	1
Horizontal wind variations	4	4	3	3	2	2	1	1
Atmospheric stability	4	2	2	2	3	3	4	4
Vertical diffusivity	2	2	2	2	4	4	4	4
Horizontal diffusivity	2	2	2	2	2	2	2	2
Mixing depth	5	4	3	3	2	2	2	2
Near-source aerodynamic effects	2	2	3	3	5	5	5	5
Surface conditions	3	4	4	4	5	5	5	5
Topographic effects	3	2	3	2	3	3	4	4
Solar radiation	4	2	2	2	3	3	4	4
Solar UV radiation[a]	5	5	4	4	2	2	3	3
Precipitation[b]	1	1	1	1	1	1	1	1
Temperature and humidity[c]	5	5	4	4	3	3	3	3

a,b,c) The indicated values assume that the pollutant of interest is (a) photochemically generated, or (b) particulate in nature, or (c) subject to chemical transformations.

d) The urban scale (5 - 50 km) overlaps the local and mesoscales.

TABLE 3. *Typical applications of direct sensors (after Johnson and Ruff, 1975).*

Meteorological Element	Symbol	Typical Direct Sensors
Near-surface mean wind speed	$\bar{V}_o$	Mechanical anemometer (cup, propeller)
Near-surface wind speed fluctuations	V'_o	Sensitive mechanical anemometer (cup, propeller); hot-wire anemometer; sonic anemometer
Near-surface mean wind direction	$\bar{\theta}_o$	Wind vane; multicomponent propeller anemometer
Turbulent fluctuations of near-surface horizontal and vertical wind directions	θ'_o, α'_o	Sensitive wind vane; bivane; sensitive multicomponent propeller anemometer
Wind velocity profile	V(z)	Tower-mounted anemometers and vanes; pilot balloons tracked by theodolite; balloons positioned by radar, navigational aids or Doppler radio techniques
Horizontal air trajectory	x,y(t)	Constant-level balloons (tetroons), positioned by transponder-aided radar or other radio techniques
Vertical temperature gradient	$\Delta T/\Delta z$	Differential thermometers (thermocouple, resistance-wire)
Temperature profile	T(z)	Tower-mounted thermometers; balloon-borne radiosondes (free-rising or tethered)
Dewpoint/relative humidity	DP	Wet-bulb thermometers; lithium chloride strips and other humidity-sensitive elements; dewpoint hygrometers
Solar radiation	SR	Pyranometers
Solar UV radiation	UV	Solar photometers
Net radiation	NR	Net radiometers
Turbidity/visual range	β	Transmissometer; nephelometer; visual observation
Precipitation	P	Rain/snow gauges (tipping bucket, weighing, etc.)
Cloud cover	C	Ceilometer; all-sky camera; visual observation

TABLE 4. *Determination of important variables in air pollution meteorology (after Johnson and Ruff, 1975).*

Process	Relevant Variable	Elements Required for Measurement	Elements Required for Estimation
Transport	Wind speed and direction (near-surface and profile)	$\bar{V}_o$, $\bar{\theta}_o$, V(z)	----
	Horizontal air trajectory (Lagrangian)	x(t), y(t) of moving balloon	V(x,y,t) at z of interest
Diffusion	Eddy diffusivity	----	V', θ', α'
	Gaussian diffusion coefficients	Tracer concentration distribution	Atmospheric stability; aerodynamic effects
	Atmospheric stability	----	Various combinations of $\Delta T/\Delta z$, $\Delta V/\Delta z$, θ'_o, $\bar{V}_o$, SR, NR, C
	Mixing depth	T(z), DP(z), V'(z), β(z), T'(z)	T_o at time of interest, plus T(z) at some earlier time
Transformation	Air physical state	T(z), DP(z), β(z)	----
	Precursor travel time	----	Horizontal air trajectory (see above)
	Solar UV radiation	UZ(z, t)	$(SR)_o$, β_o, mixing depth
Removal	Precipitation scavenging	Precipitation sampler	P(x,y,t); horizontal air trajectory
	Dry deposition	Dustfall plate	V'(x,y,t); horizontal air trajectory

These tables illustrate that the meteorological data requirements depend on the scale of impact of the proposed development. That is, in locating a new industrial complex it is important to consider its impact on the nearby urban area as well as the larger regional scale and the data requirements are scale dependent. The central requirements of an air quality assessment and the impact on a nearby urban area are the systematic evaluation of:

(i) the horizontal wind field measured at a number of stations depending on the complexity of the terrain and the horizontal variability of the wind field.

(ii) the atmospheric stability which partly controls the rate of dispersion and mixing of effluents discharged to the atmosphere.

(iii) the mixed layer height which may be maintained convectively by surface heating or mechanically by wind-generated turbulence, and

(iv) the turbulent diffusion coefficients through on-site measurements of turbulence intensity (Hanna _et al._, 1977; Hoffnagle _et al._, 1981).

Such measurements will enable an adequate data base to be established to model the pollutant pathways provided that these data are collected over at least a full year with the appropriate instrumentation (Hoffnagle _et al._, 1981) and a valid high rate of data capture is achieved for each instrument (Johnson and Ruff, 1975). These meteorological measurements should be supplemented by on-site tracer experiments (Johnson and Ruff, 1975 ; Johnson, 1983) to calibrate the air quality model.

In developing the air quality model it is important to ensure that model sophistication is commensurate with data availability, computational facilities and application purposes (Shir and Shieh, 1978). The details of various modelling approaches have been summarized by Hanna _et al._ (1982) and in assessing the viability of a particular location it is important to consider both the long-term climatological dispersion as well as short-term episode conditions. Such an approach may require the development of two distinct modelling strategies, because the data and computational requirements are less stringent for climatological models than they are for episode models. For example, a climatological model would consider the regional impact of a particular industrial site by computing the average ground-level concentration over a year whereas an episode model may attempt to model a fumigation episode wherein the plume has been brought rapidly to the surface. Such an episode is important for high surface concentrations lasting for the order of half an hour or so.

The development of such models can yield estimates of the pollutant concentration for various source configurations under all known meteorological conditions and thus provide the basis for realistic planning decisions depending on the pollutant criteria adopted. In particular, it can suggest the size of buffer zones that should be maintained between the industrial area and any subsequent residential development to maintain adequate air quality within the residential areas, as well as indicating the viability of particular options.

Ultimately the planning decision is a value judgement as to whether or not a particular environmental risk is appopriate. Nevertheless the lack of a careful evaluation of the meteorological factors can lead to hazardous pollution accumulation in both the short term (i.e. fumigation) or the long term with increased urbanization.

Air quality models and their inherent data bases need to be continually updated as the city develops in keeping with the on-going planning process. For example, as an urban area develops changes in surface roughness and heat input can significantly alter dispersion characteristics and thus modify the model predictions and more importantly the environmental risk. Consequently the technical input to the planning process needs to be an on-going exercise to ensure the viability of new planning options.

5. CONCLUSIONS

Ideally urban planning aims at the optimal utilization of the available air, water and land resources for constructive urban development through a consideration of technical information and value judgements. Without a full recognition of the technical constraints, the urban planner is unable to achieve the appropriate optimal interplay of these diminishing resources.

Assuming that future urban development will not be dominated by the classical constraints of the past, but rather new developments will seek to avoid the environmental unpleasantness and disasters of the developed world, implies that urban planners must be aware of the climatic constraint on the siting of new towns and urban facilities. This constraint ranges from the basic requirements of the urban dweller for energy, water and mitigation of environmental hazards to the maintenance of urban air quality. It is as much an on-going process as the development of the urban plan and needs to be continually updated if we are to seek to maintain and enhance future environmental quality.

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DESIGN FOR CLIMATE IN HOT, DRY CITIES

Baruch Givoni

Blaustein Institute for Desert Research
Ben-Gurion University of the Negev, Sede Boqer, Israel 84 990
and
School of Architecture and Urban Planning
University of California, Los Angeles, CA 90024

1. INTRODUCTION

Hot dry regions are characterized mainly by their aridity, high summer daytime temperatures, large diurnal temperature range and high solar radiation. These characteristics have direct impact on human comfort, building design and town planning principles.

From the comfort aspect the low humidity enables fast evaporation of sweat for physiological cooling. As a consequence, comfort can be maintained indoors, without daytime ventilation, at higher temperatures than is possible in the more humid regions.

The ability to eliminate ventilation during the hot hours of the day, combined with the large outdoor temperature range, enables a substantial reduction of the indoor daytime temperature below that outdoors.

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* This paper is based on chapters from a forthcoming book by the author: "Passive Cooling of Buildings", to be published by McGraw-Hill Book Company.

On the other hand, ventilation is essential in hot regions during the evening and night hours, both for direct comfort and for cooling the building's mass. This point should not be overlooked in designing cities and buildings for such regions.

Some regions which are hot in summer may experience comfortable, or even warm, winters, while others may have winter temperatures well below freezing. Because winter temperatures vary from place to place heating requirements may vary greatly in different hot dry regions of the World.

Considering town planning for hot dry regions it should be realized that the climatic conditions in a large, densely-built, urban area are distinctly different from those prevailing in the surrounding open areas. Differences can be found in the diurnal temperature pattern, wind speed near the ground, humidity, sky clearance, air purity, etc. Details of the physical design of the urban environment, from the scale of groups of buildings, through neighbourhoods and up to the scale of whole metropolitan areas, may greatly affect the local climatic conditions around the buildings and the provision of direct sunlight to open spaces where people congregate.

By designing some of the elements of the urban "structure" it is possible to modify in a predetermined way various elements of the urban climate so as to produce a more comfortable environment. In the case of a hot dry climate the objectives would mainly be to lower the daytime temperatures, to provide protection from the Sun, as well as from the hot winds, without impairing building ventilation, and to minimize dust levels. In winter the objective would be to enhance the potential for solar heating of buildings.

The modifications in the climatic conditions in the urban area, in turn, may affect human comfort, and the needs for thermal energy for heating and/or cooling. The urban design determines the *potential* for natural ventilation, solar energy utilization for heating and natural lighting in buildings.

The following elements of town and neighbourhood design affect the urban climate, comfort conditions and the energy demand of buildings and the potential for solar energy utilization:

- Size and density of the built-up area.
- Layout and width of streets, their orientation and relation to the prevailing winds.
- Patterns of the sub-division and the shape, size and orientation of the building lots.
- The height, shape and relative location of buildings.
- Shading conditions along streets and in parking areas.

In addition to the modification of the urban climate it is possible, even to a greater extent, to control by design, the climate inside buildings in hot dry regions. The effect on indoor climate of the following building design features will be discussed:

- The geometrical configuration of the building
- Orientation of the main facades
- Window size and location
- Properties of the building materials
- Colours of the external surfaces.

This paper deals with principles of town planning and building design aimed at maximizing human comfort and minimizing the energy demand for air conditioning in hot dry climates.

2. COMFORT REQUIREMENTS IN HOT CLIMATES

The state of thermal comfort can be defined as the absence of a feeling of discomfort. In the context of comfort in hot climates there are at least two separate and independent causes of discomfort: on one hand, the thermal sensation of excessive heat and, on the other hand, discomfort resulting from the sensation of wet skin.

Sometimes these two causes of discomfort are experienced simultaneously when one feels hot and at the same time the skin is too moist. However, in certain cases, typical of specific climates, one can be uncomfortable because of only one of these causes.

These two types of discomfort are caused by different environmental factors and the "remedies" may be different. Therefore some elaboration of this subject is useful.

2.1 The thermal sensation of heat discomfort

The thermal sensation of heat discomfort is experienced, under "steady state" conditions, when the average skin temperature is elevated above the level corresponding to the state of comfort. Under sedentary activity this is about 32-33^{o}C. The "comfort" skin temperature is *lower* with increasing metabolic rate (physical activity).

The main environmental conditions which effect the thermal sensation of heat are the air and radiant temperatures, and the air velocity *over the body*. The effect of air velocity on the thermal sensation depends on the environmental temperatures. At temperatures below about 33^{o}C (under sedentary activity) increasing air velocity reduces the heat sensation due to the higher convective heat loss from the body and lowering of the skin temperature. At temperatures between about 33 and 37^{o}C air velocity does not significantly affect the thermal sensation. At environmental temperatures above about 37^{o}C increased air velocity actually increases the thermal sensation of heat (although it still reduces the skin wetness and so might be desirable - see below).

The thermal sensation of heat is closely correlated with the sweat rate. Models are available to predict the sweat rate under any combination of metabolic rate, temperature, humidity, air velocity and clothing (Givoni, 1976). Therefore the thermal sensation, under heat conditions, can be predicted on the basis of objective criteria.

2.2 Sensible perspiration

Thermal comfort is also associated with a neutral state of the skin moisture. The skin moisture (wetness) itself depends on the balance between sweat secretion and evaporation. Under "neutral" skin wetness the sweat evaporates as it emerges from the pores of the skin.

When sweat secretion is increased, or when the evaporative capacity of the environment decreases, the sweat spreads out over a larger area of the skin. In this way the required evaporative cooling needed to maintain the thermal balance between the body and the environment is satisfied. The result is a feeling of discomfort due to "excessive" skin wetness.

Quantitatively the skin wetness sensation can be expressed as a function of the ratio: E/Emax, where E is the required evaporative cooling, namely the total heat load on the body, and Emax is the evaporative capacity of the environment. Both can be calculated (e.g. Givoni, 1976).

2.3 Relationship between heat sensation and sensible perspiration

In a desert the ambient humidity is very low, and the wind speed high. Discomfort is exclusively due to the feeling of excessive heat. The skin is actually too dry, although sweating is high (about 200 g h^{-1} for a resting person). The evaporative potential far exceeds the rate of sweat secretion, so that the sweat evaporation takes place within the skin pores. The skin's excessive dryness itself becomes a source of irritation.

This situation is a typical case of discomfort due only to one of the two potential causes. Alleviation of discomfort can be achieved by lowering the wind speed at the skin (e.g. by closing the openings) and especially by lowering the ambient temperature.

In contrast to the desert situation, discomfort in a warm-humid region, especially in still air conditions, may be mainly due to excessive skin wetness. The air temperature in such regions is often below 26°C and the rate of sweat secretion, in a sedentary state, is rather low (about 60 g h^{-1} per person).

The main cause of discomfort in such cases is the excessive wetness of the skin. In spite of the low rate of sweating the skin becomes wet because the evaporative potential of the still, humid air is very low. The physiological thermal balance is maintained, in spite of the lower evaporative potential, because the required evaporation rate is achieved over a larger wetted area of the skin.

In practice, when the air speed is suddenly increased a sensation of chilliness may even accompany the discomfort from the wet skin until the skin dries out sufficiently.

There are, of course, many climatic situations in which thermal discomfort results from the combined effects of heat sensation and sensible perspiration. Higher indoor air velocity can then be very effective in alleviating the discomfort, especially if the air temperature is below 33°C.

2.4 Comfort considerations for daytime and night-time

In many regions there is some conflict, from the building design aspect, between the provision of comfort during the daytime or during the night. For instance, by providing high mass inside an insulated "envelope" of the external surface the daytime temperature is lowered, but the same design solution elevates the night indoor temperature. When such conflicts exist it is worthwhile to know the physiological consequences of thermal discomfort during the two periods.

From the physiological viewpoint night comfort is more important than that during the day. If a person can have good, restful sleep they can tolerate high heat stress during the daytime because at night they can recuperate, so that fatigue is not accumulated.

On the other hand, if the nights are so uncomfortable as to prevent restful sleep then fatigue accumulates. Over the long period of the summer such accumulated fatigue can cause more severe consequences than daytime discomfort, from which one recovers every night.

2.5 Comfort ventilation requirements in hot, dry climates

One of the prevalent misconceptions about comfort requirements in hot dry climates is the notion that ventilation is not an important requirement in such regions. This notion is based mainly on the observation that many of the "traditional" buildings in desert regions have very small windows.

The rationale for this notion is that during the daytime the ambient air is hot and therefore ventilation should be minimized. Furthermore, it is argued that the low humidity enables adequate sweat evaporation even under still air conditions, so that there is no physiological need for a high indoor air speed.

In drawing conclusions from the traditional vernacular architecture the fact which is often overlooked is that other factors than climate, such as security, available technology and social-religious requirements, may have stronger influences on architecture than the comfort aspects. Repeating vernacular details under modern conditions, especially with respect to available materials and technology is not altogether justified.

In fact good ventilation is of primary importance in hot dry climates during summer evenings and at night, in order to enhance physiological comfort, as well as to increase the rate of cooling of the building's structural mass. Without effective night cross-ventilation the building's interior may be unbearably hot when comfort is essential for restful sleep.

The traditional way of life in vernacular houses in hot dry regions was to sleep on the roof or in a courtyard, testifying to the uncomfortable indoor conditions which prevailed during the nights. As will be discussed later, it is possible by proper design (with large windows!) to provide acceptable indoor comfort in hot dry regions both during the daytime and night hours.

3. PRINCIPLES OF TOWN PLANNING FOR HOT, DRY REGIONS

The main objectives in setting special principles for the planning of cities in hot dry regions are to minimize the environmental stresses on people when they stay outdoors (working, shopping, playing, strolling, etc.) and to improve the chances of individual buildings providing an indoor environment that is comfortable with a minimum usage of energy.

The outdoor environmental stress in hot dry regions is mainly of two types:

(a) High heat stress on summer days, resulting from the high ambient air temperature and the intense solar radiation.
(b) Prevalence of dust storms, mainly in the afternoons.

To ameliorate heat stress on summer days, neighbourhoods should be planned so that distances for people walking and children playing will be short. Sidewalks should be shaded as much as possible, either by trees or buildings along them. Shade is particularly desirable in places where people (and especially children) congregate outdoors during daytime hours. In this section the effect of various features of the urban physical design on the urban climate will be discussed. The discussion will be organized according to the main features of the urban climates important in hot dry regions: air temperature, urban ventilation, solar radiation, and dust level.

3.1 Urban Temperatures

3.1.1 The Urban "Heat Island"

The temperature modifications by a city are expressed mainly in the "heat island" phenomenon, especially during calm and clear nights. The urban air temperature is usually higher than that of the surrounding open country. This temperature elevation is caused by the lower cooling rate of the mass of buildings and the release, during the night, of heat which was absorbed in the building during the day. Another factor is the heat generated within the urban area by transportation, heating, air-conditioning, cooking and other household and industrial processes generating heat.

In big cities it is actually possible to observe air temperatures 3-5 Celsius degrees higher than the surrounding areas, and in the extreme cases, up to 8 degrees higher. During the daytime hours this difference in air temperature between the city and its surrounding area is smaller - only about 1-2 degrees. In hot regions the "heat island" phenomenon increases the discomfort, both outdoors and indoors.

3.1.2 Theoretical Possibilities to Reverse the "Heat Island" Phenomenon

It can be inferred from theoretical considerations that it might be possible to plan cities, especially in hot dry regions, so that the ambient air temperatures would be *lower* than those of the surrounding countryside. The main factor by which such a modification of the temperature seems possible is the albedo (solar reflectivity) of the whole area of the town. The average albedo of the roofs in an urban area with high density determines the radiation exchange which take place from the roof surfaces. By assuring that all the roofs in a densely-built area are coloured white - by yearly repainting, for example - it is possible to achieve a negative radiation balance: the longwave heat loss will exceed the solar heat gain even in mid-summer. Under these conditions, the average temperature of the roof surface will be lower than the average regional air temperature: and because cool air is heavier than warm air, it will sink into the city's streets. To the degree that the city is large enough, and built densely enough, it can be assumed that it would be possible to achieve a daytime air temperature lower than in the surrounding areas.

At night the drainage of the cooled air from the roofs to the ground level will cool the air surrounding the building. The temperature difference between the warmer indoor and the cooler outdoor air in arid regions can be utilized for ventilation.

Since large size and higher density render the urban area more independent of the regional climate, any such lowering of the urban temperature would be more noticeable the larger and denser the urban area is.

No experimental evidence is available yet to examine this hypothesis and such a study would be of great practical importance for town planning in hot dry regions.

3.2 Urban Ventilation

It is usually assumed that an increase in building density lessens the air flow in the urban area, as a result of increased friction near the ground. However, this influence depends on the various details of urban planning, including the mutual relationship between the buildings and their orientation with regard to wind direction. It is possible therefore to have a wide range of urban air flow conditions for a specific level of density.

3.2.1 Building Height and Ventilation

One of the main factors determining urban air flow conditions in the city is the average height, as well as the difference in heights, of buildings: single buildings rising high above those around them create strong air currents in the area. A pocket of high air pressure is formed over the facade of the high-rise building which faces the wind, thereby causing a strong downward current. During the summer, in many warm, and especially in warm-humid regions, the stronger air currents are most welcome for the comfort they afford to the local residents. However, in hot dry regions the strong, turbulent daytime winds may not be desirable. A design which would enable ventilation of the buildings during the evenings, without too much "agitation" of the urban wind field, would be more desirable, as is discussed in the section on building design.

When the streets are perpendicular to the wind direction, and the buildings lining the streets are long row buildings, the principal air current flows above the buildings and the air flow in the streets is the result of a secondary air current, caused by the friction of the main air current against the buildings lining the streets. Under these conditions, the ventilation of urban space is hardly affected by the width of the streets.

When the streets are angled in an oblique direction to the wind, the flow is distributed between two components. The first flows in the direction of the street, but is concentrated mainly on the down-wind side of the street. The second causes pressure on the buildings that are on the upwind side of the street. On the upwind side of the street the air movement is gentler and a low pressure zone surrounds the building. In this case, widening the streets improves the ventilation conditions both within the buildings and in the streets.

The desirability of higher or lower wind speeds depends, of course, on the climatic conditions. In general, in hot dry regions, higher (but not excessive) urban wind speed is desirable, unless the urban daytime air temperature could be lowered below the regional level.

3.3 Urban Solar Control

In hot dry regions protection of the buildings and the pedestrian sidewalks from the Sun in summer should be considered as one of the major urban design objectives. On the other hand, creating the potential for solar heating in winter is also an important urban objective. These two seemingly conflicting objectives should be taken into account in the detailing of such urban design features as density, building heights and details, street orientation, etc.

Generally speaking, medium-density low-rise urban planning in residential districts can provide the optimum solution for solar protection in summer and for solar utilization in winter. In predominantly commercial "downtown" districts, typically of high-density high-rise characteristics, special design features should be applied, like ample overhangs or colonnades along the sidewalks, transverse "passages" etc. Such design details can provide effective protection from the Sun, rain and wind to pedestrians walking throughout the shopping districts.

Low-rise residential buildings enable effective utilization of solar radiation for heating in winter and the application of various passive cooling systems in summer, such as nocturnal radiant cooling, shaded roof ponds, soil cooling, etc. A short description of these passive cooling systems is presented below, in Section 5.

3.4 Reducing Dust by Town Planning

Dust storms in desert regions are of two types:

(a) Regional storms, in which dust extends to great heights (hundreds of metres) and covers very large areas (hundreds or thousands of kilometres). Such dust storms occur from time to time but are not a daily phenomenon.

(b) Local dust "waves", originating in the local area and extending in height to several metres and in distance covered to several hundred metres. Such "storms" are in many places a daily phenomenon.

Nothing can be done on the neighbourhood scale to stop or even minimize the impact of regional dust storms outdoors, although it is possible to minimize the penetration of dust indoors. On the other hand, much can be done in neighbourhood planning to reduce the occurrence and minimize the impact of local, more frequent, dust "waves".

The main factors affecting the frequency, intensity and range of local dust storms are ground cover and the wind speed near ground level. Both factors can be affected by neighbourhood design features.

Treatment and upkeep of ground cover should be analyzed separately for privately-owned and public areas. But any bare ground not planted, irrigated, or paved, may constitute a source of local dust storms. The extent of such bare land should not, therefore, be overlooked in planning outdoor space on either a neighbourhood or private scale.

Except for the atypical wealthy desert dweller, particularly in developed countries, plot sizes for single family low cost housing should be minimal. Small lots can be accommodated best to water scarcity and concomitant water costs. Planting and cultivation of gardens can then be done efficiently by the individual family.

Public areas within the neighbourhood borders should also be limited in size to areas which can be well kept. Large public bare land is frequently the source of dust nuisance for the built-up area around it.

Low hedges are effective in reducing wind speed near the ground, while not blocking the wind at higher elevations. Their use, together with other types of vegetation, should be considered as a means for controlling dust in the neighbourhood.

In the development of new neighbourhoods in desert regions, special attention should be paid to the treatment of the windward borders. The land should be kept in its natural condition as far as possible, so that the natural ground cover of desert plants will limit the source of dust.

3.5 Vegetation as Micro-climate Control in Hot Dry Regions

"Green" areas, covered by plants, have some properties by which they differ from built-up and hard-surfaced unplanted areas.

The main differences are:

- Plants have lower heat capacity and thermal conductivity than building materials and hard surfaces.
- Solar radiation is absorbed mostly on first impingement, so that the reflected radiation is very small (low albedo).
- Rain water is absorbed in the soil. Water is evaporated from the soil and mainly from the leaves. The evaporation rate is much higher in green areas than in unplanted areas.
- Plant leaves can filter dust out of the air.
- Plants reduce the wind speed and its fluctuations near the ground.

As a result of these properties the micro-climate in the immediate vicinity of green areas differs from that prevalent in unplanted, built-up areas. The main differences are in the temperature, wind velocity and turbulence, humidity and air cleanliness.

Evaporation of water from leaves prevents their heating by the absorption of solar radiation, and also significantly lowers the temperature of the air in contact with them.

The evaporation from the leaves elevates the air humidity. In arid climates the evaporation rate is higher and its effects on comfort are welcome.

As a result of the lower temperature of the leaves and the air passing by them, the temperatures in green areas are significantly lower than above hard surfaces such as along roads or in a hard-surfaced open area.

3.5.1 Design of parks and playgrounds

From the human comfort point of view, parks and playgrounds should include ample shade and protection from dust in summer, as well as protection from cold winds in winter. Large lawns and flower beds without shade contribute little to the recreation possibilities of the inhabitants - ordinary citizens, elderly, and children alike. They need possibilities to rest, relax, or play on a hot sunny day. Thus, plenty of places to sit in the shade should be provided along roads and trails in public parks, and in children's playgrounds. Shaded spaces for play and rest minimize the danger of overstress and heat strokes.

Provision for wind protection is of particular importance in arid regions with cold winters. The availability of sunshine and the absence of much rain in winter can enhance greatly the attraction of settlements in these regions as winter resorts. Protection from cold winds will help greatly in enjoying these qualities.

4. BUILDING DESIGN GUIDELINES FOR HOT, DRY REGIONS

The following objectives can be stated for building design in hot, dry regions:

(a) Minimize solar heating of the building during the hot season.
(b) Minimize the rate of indoor temperature elevation in summer during the daytime hours.
(c) Maximize the rate of cooling of the indoor temperature in summer during the evening hours, and ensure indoor comfort during the night.
(d) Utilize natural energies for passive cooling in summer.
(e) Minimize the heat loss of the building in winter.
(f) Utilize solar energy, by passive systems, for heating in winter.

The performance of a building, in terms of the above objectives, depends on various architectural features such as:

- building layout
- orientation of the main facades and windows

- window size, location and details
- shading of windows, roofs and walls
- the colours of the buildings
- thermal properties of the building materials

4.1 Building Layout

The more compact the house plan, the smaller the surface area of the walls for a given floor area. As a result, the net exchange by conduction between the house and the ambient air is decreased. On the other hand, a spacious plan may offer better opportunities for natural ventilation, and more freedom and flexibility in the design of the building's layout.

Furthermore, buildings heated by passive solar energy systems or cooled by several passive cooling systems are using various elements of the envelope as their energy source.

Thus, for example, a passive solar building may use its southern wall and windows as the solar collection elements. A building elongated along the east-west axis will be more energy efficient than a square building, in spite of its larger wall surface area.

Similarly, the roof of a building may be its main source of cooling, either by radiant cooling systems, or by roof ponds, etc. In this case a single storey building may be more efficient in a hot climate than a multi-storey apartment building.

Therefore, any analysis of the effect of the building's layout upon its energy performance in hot dry regions should be related to its modes of heating and cooling

4.2 Building Orientation and Shading

The main objective in deciding upon a given orientation in hot regions is to minimize the impact of the Sun in summer. In regions with cold winters a second objective is to maximize the solar impact in winter.

The highest intensities of the impinging solar radiation in summer occur on the eastern and western walls. The highest intensity of impinging radiation in winter is on the southern wall.

This pattern of solar impingement on the different walls results in a clear preference for north-south orientation for the main facades, and especially for the windows. Such orientation enables easy and inexpensive shading in summer of the southern windows, and the walls in general, by horizontal overhangs. In winter, the rays of the lower Sun (altitude at solar noon of 20-30 degrees) can penetrate below the overhang and be used for heating.

However, it should be remembered that fixed overhangs do not block the radiation reflected from the ground or that diffused from the sky. In the late summer months the overhangs also do not block completely the direct radiation. Therefore orientation and fixed shading devices may not be sufficient to minimize unwanted solar heating.

In many cases operable shading devices such as rotable louvres, shutters, retractable awnings, etc., would be needed for effective solar control, especially in hot dry regions.

4.3 Window Size, Location and Details

Windows can perform four functions, whose relative importance varies under different conditions:

- provision of daylight
- provision of view and visual contact with the outdoors
- provision of natural ventilation for direct physiological comfort
- provision of natural ventilation for structural cooling.

The size and details of the windows could be optimized in each climatic region to accommodate specific human requirements.

In hot regions ordinary windows tend to raise the indoor daytime temperature, and the larger the window area the greater is their heating effect, especially when penetration of sunlight is not effectively prevented by shading or orientation. Their small thermal resistance and air infiltration through the surrounding cracks makes them the weakest point from the aspect of heat gain in summer and heat loss in winter.

It is generally considered that small windows are more suitable in hot dry regions for preventing indoor temperature elevation than larger ones. Often small windows are recommended for hot dry regions. However, with special design details, such as insulated shutters, large windows can be an advantage from the thermal point of view.

When highly insulated shutters are added to large windows their thermal effect can be adjusted to the varying needs, both diurnally and annually. In summer, the shutters can be closed during the hot hours, admitting light into the house only through small, shaded glazing sections. In the evening and night hours the shutters and the windows can be left open, increasing the rate of cooling of the interior.

In winter, large southern windows can provide significant direct passive solar heating of the interior. Closing the insulated shutters during the night traps the heat indoors and reduces the rate of cooling and thus helps in maintaining comfortable indoor night temperatures.

4.4 The Colours Of Buildings

The colour of the walls and the roof has a tremendous effect on the solar impact of the building and its indoor climate, particularly in hot dry regions where solar intensity is higher than in other regions.

For the roof, the influence of colour is at a maximum. The difference in the maximum surface temperature in summer between a white and a black roof in a desert can be about 40°C. The resulting heat gain to the building interior depends on the insulation properties of the roof, but in general it is quite significant.

Eastern and western walls are also very sensitive to their external colour, while the northern wall is the least sensitive. The southern wall presents a special case because it receives most radiation in winter, when heating may be desired.

4.5 The Thermal Properties of the Building Materials

High thermal insulation of the building envelope in hot dry regions, coupled with effective shading of the windows, minimizes the heat gain of the building in summer and enables a lowering of the daytime indoor temperature. High mass (heat capacity) of the building envelope, as well as of the internal building elements (partitions, floors, etc.) minimizes the daily indoor temperature swing.

Both of these properties reduce the indoor maximum temperature, but elevate the indoor evening and night temperatures.

The comfort at night is more important in residential buildings than that in the daytime therefore a high mass, well-insulated building may be quite uncomfortable during the more "critical" hours, unless fast cooling of the interior is secured. A combination of slow heating during the daytime and fast cooling in the evenings can be achieved by providing large windows, equipped with insulating shutters. The windows should be located on both the windward and the leeward sides of the building, to enable effective cross-ventilation.

During the hot daytime hours the windows and the insulated shutters should be kept closed. Thus the whole envelope provides high resistance to heat gain. The high mass further reduces the rate of temperature elevation.

During the evening hours the windows and the shutters should be operated. The resulting cross-ventilation enables fast convective cooling, bypassing the thermal resistance of the envelope.

4.6 Internal Patio in Hot Dry Regions

It is commonly assumed that courtyards and internal patios, which are typical of building design in many hot dry regions (e.g. the Middle East and North Africa) help in maintaining indoor cooler temperatures.

DESIGN FOR HOT, DRY CITIES

An internal patio provides many functional and social amenities. It enables being outdoors in a completely private and secure area. This factor is of special importance in societies which require a high degree of privacy, especially for women.

However, analysis of the effect of the internal patios on the heat flow and on ventilation conditions suggests that, without specific details, they may actually cause higher indoor daytime temperature, and poor ventilation in the rooms on the leeward side of the patio.

An internal patio "introduces" the outdoor climate into the "core" of the building, thus in effect increasing the surface area of the envelope. Compared with a building with the same floor area but without an internal patio the former would have a higher rate of daytime temperature elevation.

During the daytime hours the patio is exposed to solar radiation because of the high elevation of the Sun in summer. Thus an "ordinary" internal patio does not provide a shaded outdoor space, unless it itself is shaded.

In dealing with the effect of an internal patio on the ventilation conditions it should be realized that the patio is a "low pressure" area. For rooms which are on its windward side the patio provides a good location for outlet openings. Such rooms can have good cross-ventilation. However, the rooms located on the leeward side of the patio usually have poorer ventilation conditions.

With suitable design details, however, it is possible to achieve daytime shading and night-time "cold accumulation" in an internal patio, thus transforming it into a cooling element for the building.

Such details should include effective shading of the patio during the summer (e.g. by a pergola) and drainage of cool air, from the roof, into the patio space. In practice it means that the roofs of the rooms around the patio should slope down towards it, while the outer periphery of the roofs should be surrounded by a solid parapet. A gutter around the patio should be able to collect and dispose of rain, with any expected intensity.

5. PASSIVE COOLING IN HOT DRY REGIONS

Cooling of buildings by passive systems can be provided through the utilization of several natural heat sinks, or sources of "natural cooling energies" such as:

- The ambient air (convective cooling)
- The upper atmosphere (radiant cooling)
- The ambient water vapour gradient (evaporative cooling)
- The sub-surface earth ("natural" or cooled)

Combinations of these cooling sources are also possible, such as combining convective and evaporative nocturnal cooling, combining initial nocturnal radiant cooling of air with subsequent additional cooling by water evaporation, etc.

5.1 Comfort Ventilation and Convective Cooling

Ventilation can serve two distinct functions in hot regions or seasons:

(a) Ventilation for enhancing comfort of the occupants
(b) Ventilation for cooling the structural mass of the building (convective cooling).

Introducing outdoor air with a given speed into a building may provide a direct physiological cooling effect and enhances the feeling of comfort when the indoor air temperature is rather warm. Hence the term "comfort ventilation".

Comfort ventilation can be provided at any time when it is physiologically beneficial, during daytime and/or during the evening and night hours. With a high ventilation rate the indoor air temperature tends to approach the outdoor level, although the *radiant* temperature of the indoor surfaces may be at a significantly different, and usually higher, value.

On the other hand, cooling of the structural mass of the building by ventilation (convective cooling) can be achieved only if the outdoor air is cooler than the indoor air. In hot regions the summer indoor temperatures, in a well-built building, are usually below the level of the outdoor air during the daytime hours. This is especially the case in hot dry regions with a large diurnal temperature swing. Therefore convective cooling can, in most cases, be provided *only* during the night hours.

As buildings are usually occupied during the daytime hours, convective cooling can be effective only to the extent that it can lower the indoor temperatures also during the following daytime, and especially lower the indoor maximum temperature.

Such lower indoor temperatures can occur only if the building is closed and unventilated during the daytime hours. In this respect daytime comfort ventilation and convective cooling are mutually exclusive. At any given place, or day, one or the other should be considered as the best approach to provide daytime comfort.

When a building is ventilated at night, its structural mass is being cooled by convection from the inside, by-passing the thermal resistance of the envelope. During the daytime, the cooled mass, if adequately insulated from the outdoors, can serve as a heat sink to absorb the heat penetrating into, and generated inside, the building. To this effect the building should be *closed* (unventilated) during the daytime, to prevent heating the interior by the hotter outdoor air.

Convective cooling is applicable mainly in arid and desert regions, which have a large diurnal temperature range and where the night temperature in summer is below the comfort range, e.g. below about 20°C (68°F). In such regions it is possible to store the coolness of the night air, either in the structural mass of the building and/or in specialized storage such as a gravel bed. The air flow at night through the building, or through the storage mass, can be induced naturally by the wind (where the nocturnal wind speed at the building site is sufficient) or by a fan.

During the following day it is possible to utilize the cooled mass as a heat sink, to keep the indoor temperature within the comfort range. The building should be well-insulated and closed during the hot hours.

There are some problems which may result from nocturnal natural ventilation. Leaving large openings open during the night might be problematic from the privacy and security viewpoints. Also, the indoor air temperature during the late hours of the night may be too low for comfort with a high wind speed.

To circumvent these problems, another approach to nocturnal convective cooling can be applied, namely by directing the outdoor air *through* the structural mass instead of through the indoor space. In practice, this means using a fan and directing the air through channels imbedded inside the floors, ceiling, walls, etc.

Floors of reinforced concrete with embedded channels can be precast or cast *in situ*, utilizing hollow concrete blocks. There are also industrially prefabricated floor panels with embedded channels available in many countries.

5.2 Radiant Cooling

Any element of the external envelope of the building which "sees" the sky loses heat by the emission of long-wave radiation (with peak radiation at a wave-length of about 10 microns). As the roof of the building is the element most exposed to the sky it can be the most effective location for a specialized long-wave radiator. It can also itself serve as the radiator, provided it is insulated during the daytime. The cooling effect resulting from the radiant heat loss can be utilized as a cooling source for the buildings. In hot regions the rate of radiant heat loss is higher than in other regions (about 70 W m^{-2}).

5.2.1 Design Approaches to Radiant Cooling Utilization

The cooling effect resulting from the net radiant heat loss by an ordinary roof cannot be utilized directly for cooling the building below it. This is because an ordinary roof must have a reasonable thermal resistance, in order to minimize heat loss in winter and daytime heat gain in summer. Almost all the "cold" resulting from the radiant heat loss at the roof's external surface is dispersed by the ambient air above the roof. Therefore, specialized design details, or systems, have to be applied in order to utilize the potential available in radiant heat loss.

5.2.2 The Roof Itself as a Nocturnal Radiator

The simplest concept of radiant cooling, although complex and expensive in practice, comprises a heavy and highly conductive roof (e.g., made of dense concrete) which is exposed to the sky during the night but highly-insulated externally (by means of operable insulation) during the daytime. Such roofs are most efficient in losing heat at night, both by long-wave radiation and by convection. During the daytime the external insulation minimizes the heat gain from solar radiation and the hotter ambient air. The cooled mass of the roof can then serve as a heat sink and absorb, through the ceiling, the heat penetrating into, and generated inside, the building interior.

From the viewpoint of performance such a system is the most efficient because the mass of the roof is heated during the day by heat absorbed from the interior. As the outgoing radiation takes place from a surface with a higher temperature than that of a specialized lightweight radiator the rate of heat loss is much higher.

However, at present no simple and inexpensive system is available for operable insulation. Consequently such systems, although highly effective, would be quite expensive.

5.2.3 "Ordinary" Specialized Radiators

In order to utilize the cooling effect of the nocturnal radiation for buildings with ordinary roofs, ways have to be found by which the cold produced at the external surface is transferred into the building's interior. Usually this "cold transfer" is provided by air flow under the radiating element. The cold generated by the nocturnal radiation is thus transferred to a "cold storage" mass, either the structural mass of the building or a rock bed.

In practice a building cooled by such a system would have a horizontal, or slightly-inclined, roof, for instance a concrete roof or a built-up light roof. No expensive water proofing is needed as the nocturnal radiator can serve also as the rain-proofing element, although the roof should be well insulated thermally.

The radiator can be any metallic layer placed over the roof proper, with an air space of about 50-100 mm under it. The metal should be painted, with almost any (except "metallic") paint, to provide an "emissive" surface (metals have low emissivity).

During the night, the radiating surface is cooled, in arid regions, to a temperature some 5-7 Celsius degrees below ambient dry-bulb temperatures. The actual temperature depression depends on cloudiness and wind speed.

The high conductivity of the metal sheet ensures that its underside approaches the temperature of the emitting surface. Ambient air drawn under this surface is cooled by approximately one half to two thirds of the temperature depression achieved by the radiator, depending on the flow rate. The cool air is drawn through the building interior, to cool its structural mass. The cooled mass serves during the following daytime as a sink for heat penetrating into and generated inside the building.

5.3 Evaporative Cooling

Cooling of buildings by utilizing the energy consumed in the process of water evaporation can be accomplished by two different approaches. The first is to cool directly by evaporation of outdoor air which is introduced into the building. The air is thus humidified, while its temperature is lowered, and the indoor water concentration is elevated above that outdoors. This is *direct* evaporative cooling.

The other approach is to cool, by evaporation, a given element of the building, which then serves as a heat sink and absorbs heat penetrating into the building through its envelope or that generated indoors. This is *indirect* evaporative cooling. With such systems the indoor temperature is lowered *without* elevation of the indoor vapour content of the air.

5.3.1 Direct Evaporative Cooling

In direct evaporative cooling the dry-bulb temperature (DBT) of the air is lowered and its water content (and vapour pressure) is raised, along a constant wet-bulb temperature (WBT).

Direct (mechanical) evaporative cooling reduces the DBT by about 70-80% of the difference between the DBT and the WBT. It involves very high rates of (outdoor) air flow (about 15-30 air changes per hour) resulting in high and concentrated indoor air flow, with high variability of the indoor air speed distribution.

Direct evaporative cooling is used extensively in arid regions. Mechanical equipment is available commercially in many countries.

5.3.2 Indirect Evaporative Cooling by Roof-Ponds

Evaporative cooling can also be passive and indirect, by providing a shaded water pond over an un-insulated roof. The roof's surface temperature follows closely the ambient wet-bulb temperature, while the ceiling acts as a radiant convective cooling panel for the space under it. Thus, the indoor air and radiant temperatures can be lowered without elevating the indoor humidity level.

When the water is in thermal contact with the roof, and the roof itself is made of materials with high thermal conductivity, the combined water and roof structure serves as an integrated "cold" storage. The ceiling temperature follows closely the water temperature. Consequently the soffit of the system, the ceiling, serves as a passive cooling panel for the space below, cooling it both by radiation and by natural convection. Thus the heat exchange between the ceiling and the indoor space is maximized, enabling satisfactory cooling even with a small temperature difference of about 2-3^{o}C.

Several techniques are possible for shading a roof pond. They differ in cost as well as in the efficiency of the evaporative cooling in summer and in the thermal performance of the roof in winter.

Currently there are three different types of shading and insulation for roof ponds:

(a) a permanent, insulated shading structure over the pond, continuously opened and ventilated in summer but closed in winter.

(b) shading by pebbles, with insulation embedded within the water pond under a layer of pebbles.

(c) insulation floating over the water, with water circulated above the insulation by pumping during the night.

In all of these systems the roof should be able to structurally support the water pond (about 200-400 kg m^{-2}, depending on the system) and provided with "perfect" waterproofing. It should be noted, however, that once the "perfect" waterproofing is installed it is protected from the Sun and the effects of sharply changing weather conditions (especially humidity) by the pond and its insulation. Therefore the factors which usually destroy the waterproofing are almost eliminated so that a long lifetime for the membrane is likely.

5.4 The Earth as a Cooling Source

The earth mass under, around, and sometimes also above the building can serve in most climatic regions as a natural cooling source for the building, either in a passive or an active way.

In summer the soil temperature, at a depth of a few metres, is always below the average ambient temperature, and especially below the daytime air temperature, forming the potential for serving as a heat sink. Theoretical models of the annual patterns of the soil temperature at different depths are based on the soil's diffusivity. However, the soil's diffusivity itself is not a constant property even at a given place but changes with the time and with depth.

In regions where the annual average temperature is below about 10°C (50°F) cooling of buildings in summer can be provided by thermally coupling the building with the under-surface soil in its "natural" temperature. The soil then can serve as a sink for heat generated inside or penetrating into the building.

If the annual average temperature is above about 10°C (50°F), cooling of the soil in summer below its "natural" temperature might be required in order to enable its utilization as a heat sink.

5.4.1 Method of Soil Cooling

It is possible by simple means to lower the earth temperature well below the "natural" temperature characterizing a given location. This effect can be achieved by lowering the temperature of the ground surface and/or by directly cooling the soil mass at a given depth in winter.

To date two methods have been tried successfully to lower the soil temperature:

(a) Raising the building off the ground and enabling evaporation from the surface either by irrigation or by summer rains.
(b) Covering the soil with a layer of gravel, at least 0.1 m thick and, in regions with dry summers, irrigating it.

Experiments in Israel and North Florida have demonstrated that it is possible to lower the average surface temperature by about 8-10^{o}C, below the summer temperature of exposed soil. The difference between the outdoor maximum temperature and the cooled soil temperature can be up to about 15^{o}C (in mid summer), providing a potential for a heat sink for the building.

5.4.2 Options for Utilizing the Cooling Potential of the Earth

When the underground soil temperature is cool enough, it is possible to utilize it for cooling buildings by several methods. In the case of earth-integrated buildings, in which the walls are bermed and the roof covered by earth, cooling of the soil mass adjacent to the building provides a direct passive cooling effect on the building. Another approach, an active one, is to install air pipes in the soil, and to circulate through them the air from the building or the ventilation air. The cooler earth mass serves as a heat sink to cool the air which is then introduced into the building.

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DESIGN FOR CLIMATE IN HOT, HUMID CITIES

S. Nieuwolt
6004 KC Weert, The Netherlands

1. INTRODUCTION

In equatorial lowlands the combination of high temperatures and high humidity of the air may prevail during most of the year. But similar conditions also occur seasonally in many other parts of the tropics, for example in areas under the influence of the Indian and south-east Asian summer monsoons.

In these climates, urban heat islands exist as in other climates, though the relative importance of the various causes may be different from that in the mid-latitudes: there are fewer anthropogenic heat sources, as there is no heating, but the effect of increased absorption of solar radiation and of decreased evapotranspiration in cities are probably stronger (Daniel and Krishnamurty, 1973; Hannell, 1976; Pradhan, 1976; Oke, 1982; Sastry, 1982).

It is clear that climatic discomfort is strongly increased by these urban heat islands. The temperature differences between urban centres and rural areas are generally only a few degrees, but they are very important when the air humidity is also high. It has been determined that the slightly lower humidity in city centres does not compensate for the effects of the higher temperatures, and that a further deterioration of conditions is caused by the lower wind velocities in cities (Nieuwolt, 1968; Giacottino, 1979; Lasserre, 1982; Pagney and Besancenot, 1982).

DESIGN FOR HOT, HUMID CITIES

The purpose of this paper is to indicate some ways and methods for urban planners and architects to contribute to a reduction of climatic discomfort in these cities. This will not only help to reduce energy demands for air-conditioning and ventilators, but also improve the urban environment for the many human activities performed outdoors in these climates. A local amelioration of climatic conditions is particularly necessary in the centres of some cities dating from the colonial era, which occupy rather insalubrious sites near coastal swamps (Giacottino, 1979; Lasserre, 1982).

Another problem in many of these cities is the frequent occurrence of flash floods and inundations, because the effects of a high rainfall intensity are strongly magnified by urban development. Proper planning and engineering can help to reduce this risk.

It seems logical to start at the source: the climatic information supplied, in the first instance, by the meteorological services.

2. CLIMATIC INFORMATION

2.1 General climate

Fundamental data about a city's microclimate will normally be available from the local meteorological station. In the hot and humid climates, where diurnal variations are at least as important as seasonal differences, this information should include hourly, or 3-hourly values. Monthly means and extremes may conceal large diurnal differences and they are therefore of little use in urban planning and design.

The climatic data should preferably be produced in the form of diagrams, which are easier to interpret than tables and more appealing to architects and engineers.

The first need is, of course, for temperature data (Figure 1). In the low latitudes inter-annual temperature variations are generally quite small, therefore hourly values can be based on relatively short periods of observation and still be reasonably representative (Nieuwolt, 1968). Both diagrams of Figure 1 are constructed from data with more than 10 years of record.

Similar graphs for atmospheric humidity are also needed (Figure 2). The two sets of data allow the computation of the Temperature-Humidity-Index or similar indicators to quantify climatic stress for human beings (Smith, 1955; Thom, 1959; Webb, 1959, 1960; Givoni, 1969, p. 68-95; Fanger, 1972; Penicaud, 1978; Pagney and Besancenot, 1982).

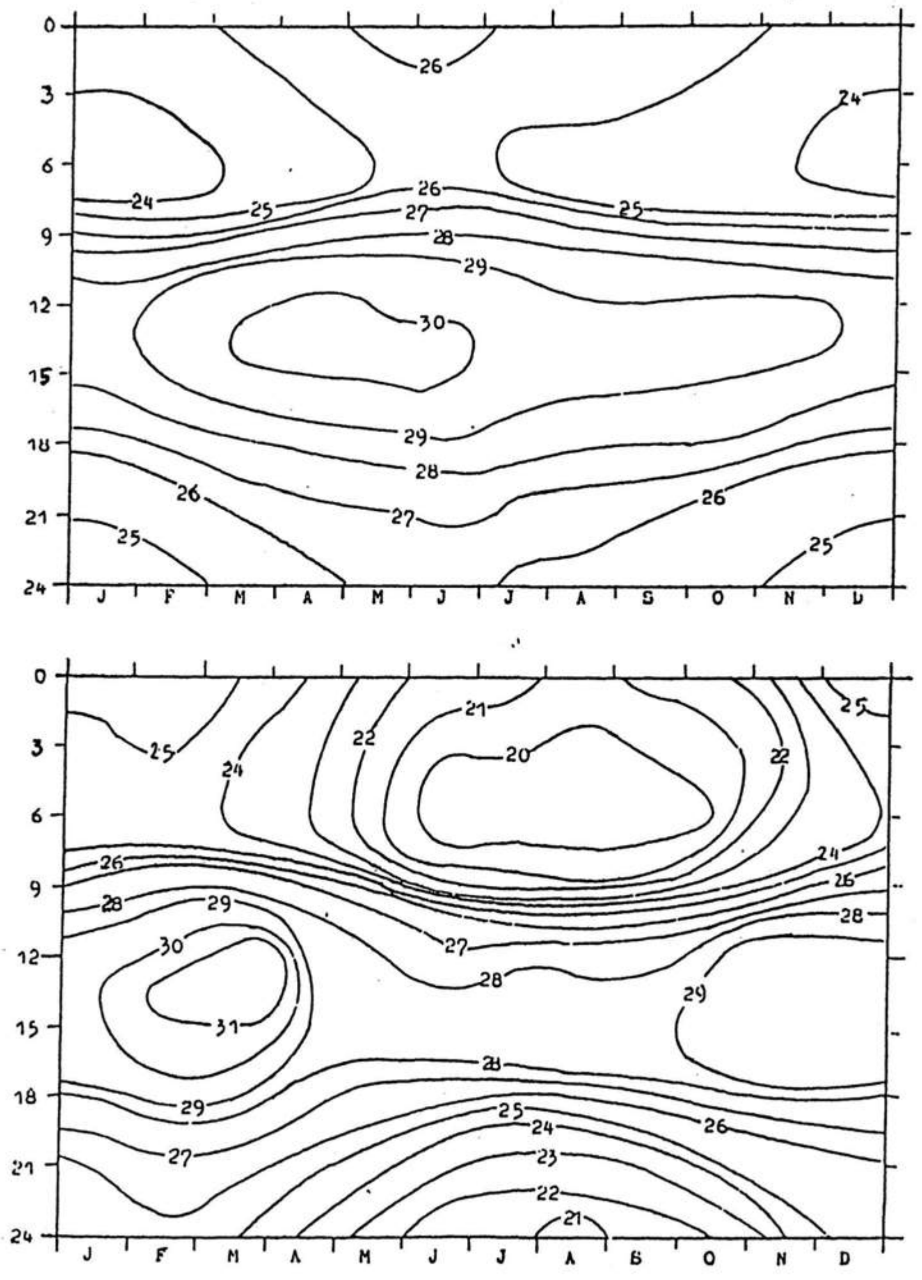


Figure 1. Hourly means of air temperature at Singapore (above) and Dar es Salaam (below).

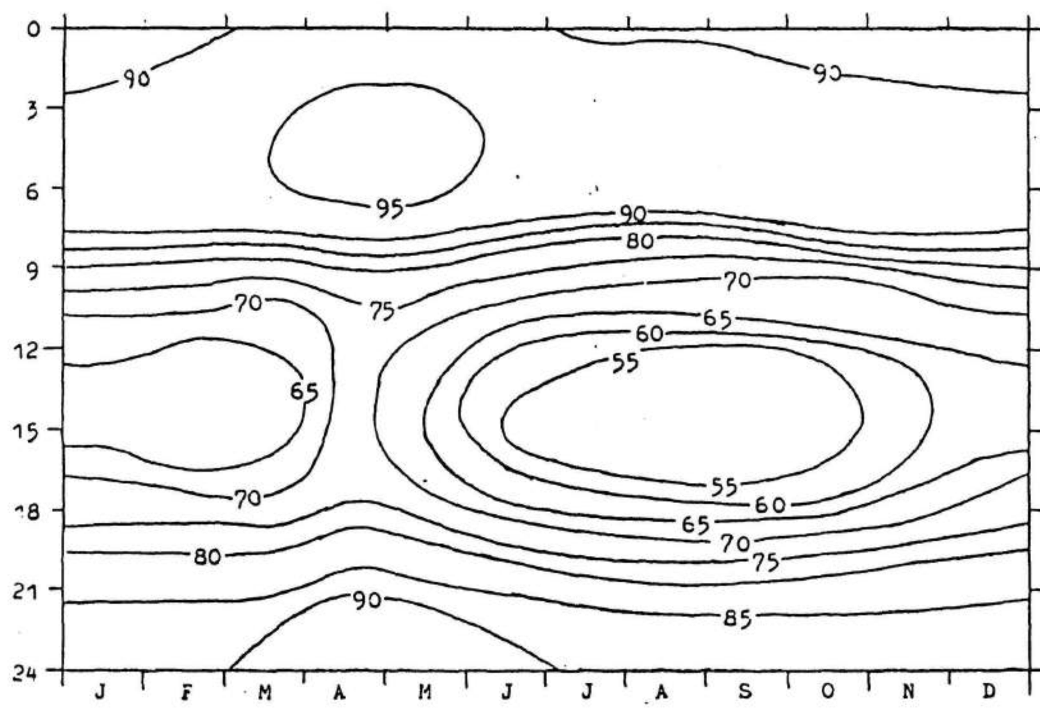


Figure 2. Hourly means of relative humidity at Dar es Salaam (%).

These calculations will provide a first indication of the periods when the combined effects of temperature and humidity are most likely to create uncomfortable conditions. For instance, when the Temperature-Humidity-Index reaches values over 26, thermal stress will occur when no ventilation is provided. In Singapore these critical periods last from about 10 to 17 hours throughout the year, but in Dar es Salaam they are limited to the afternoons from January to March (Figure 3). It is important that planners and architects are aware of these periods, as their efforts to reduce climatic discomfort should be concentrated on conditions at that time.

The effects of natural ventilation by the wind can be quantified when hourly mean wind speeds are known (Figure 4). Formulae for this purpose indicate that the cooling effect of the wind is approximately proportional to $V^{0.3}$ or $V^{0.5}$, V being the wind speed, and to the difference between the temperature of the air and that of the skin (35°C) (Siple and Passel, 1945; Court, 1948; Thomas and Boyd, 1957). Therefore, natural ventilation becomes much less effective in reducing thermal stress when the air temperature reaches values around 35°C. Temperatures of that order occur in the centres of hot, humid cities during the hottest hours of the day (Nieuwolt, 1966).

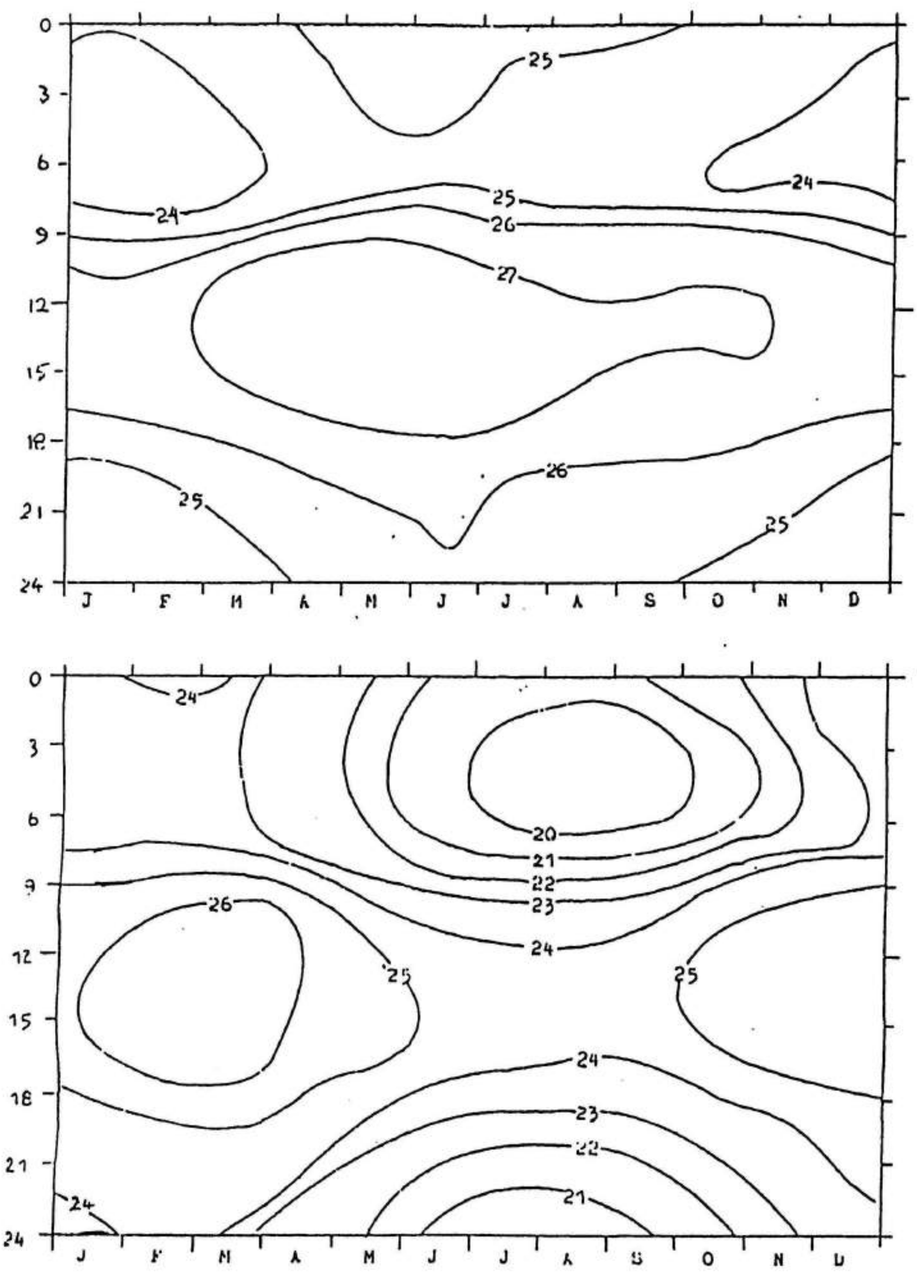


Figure 3. Hourly means of the Temperature-Humidity-Index at Singapore (above) and Dar es Salaam (below).

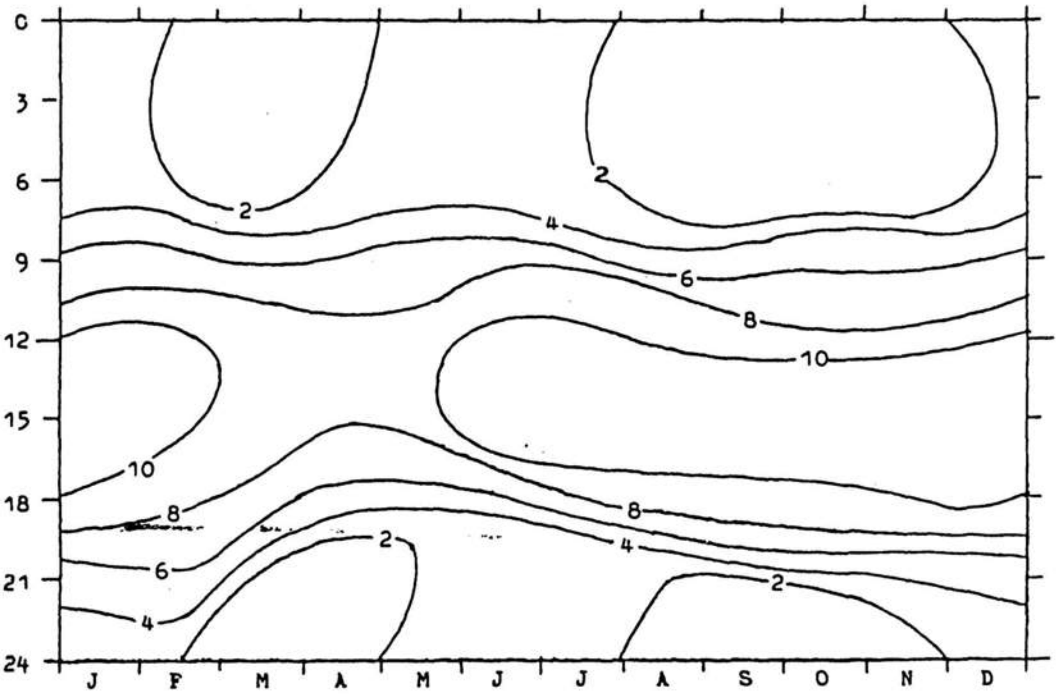


Figure 4. Mean wind speed (knots) at Dar es Salaam Airport.

The efficiency of natural ventilation in reducing thermal stress is illustrated by the corrected values of the Temperature-Humidity-Index for Dar es Salaam airport (Figure 5). These show that there are no periods of thermal discomfort, the highest value of the corrected index being only 22. Both diurnal and seasonal differences of climatic comfort are strongly reduced, because hot afternoons are usually accompanied by strong sea breezes, while at night wind velocities are generally low. It should be emphasized that wind conditions are particularly favourable at most airports and that the illustrated pattern is not representative for conditions in Dar es Salaam city centre.

Wind speeds within cities are generally only about one half of those recorded at the local rural airport. There are, however, exceptional situations where much higher wind velocities can be expected due to local factors such as shape and height of buildings. For instance, when a street runs in the direction of a strong wind, or when funnel-shaped openings exist between high buildings, wind speeds may be higher than at the meteorological station. But normally a strong reduction of wind speed can be expected within a city.

Indoor wind speeds are again reduced by about half compared to those outside, even with good ventilation. But here the effects of elevation are important: at higher floor levels outside winds may have speeds comparable to those recorded at the airport.

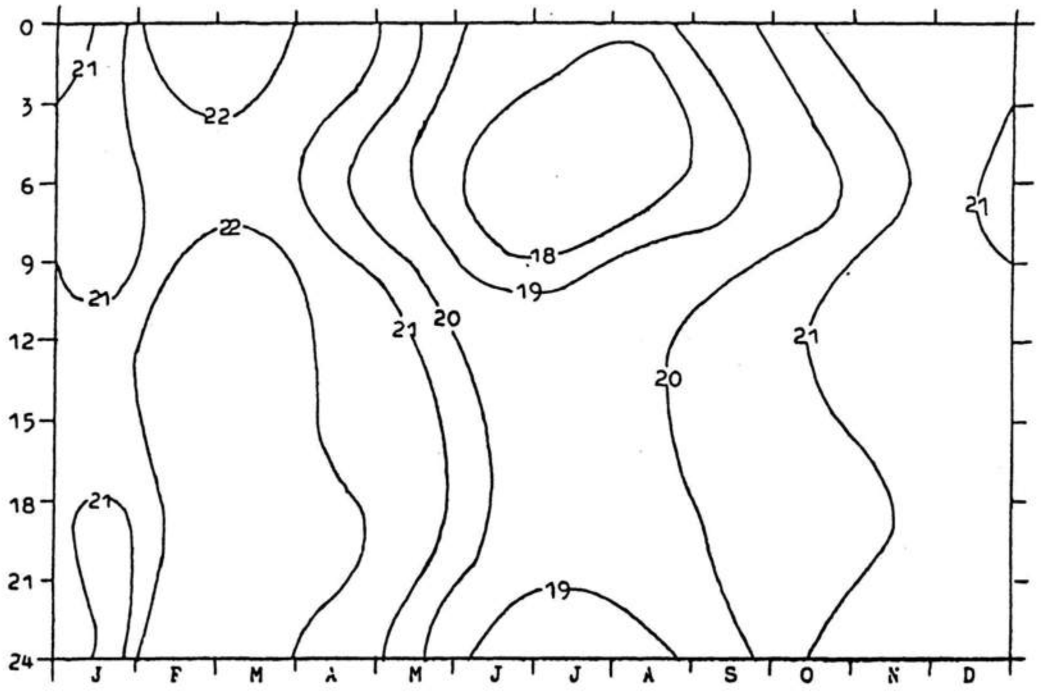


Figure 5. The Temperature-Humidity-Index corrected for the mean wind speed at Dar es Salaam Airport.

The combination of wind-directions and -speeds, even at 3-hourly intervals and for a few typical months, can be of great assistance to designers (Figure 6). They allow the detection of local variations in the wind pattern and thereby a good valuation of the potential natural ventilation at the construction site.

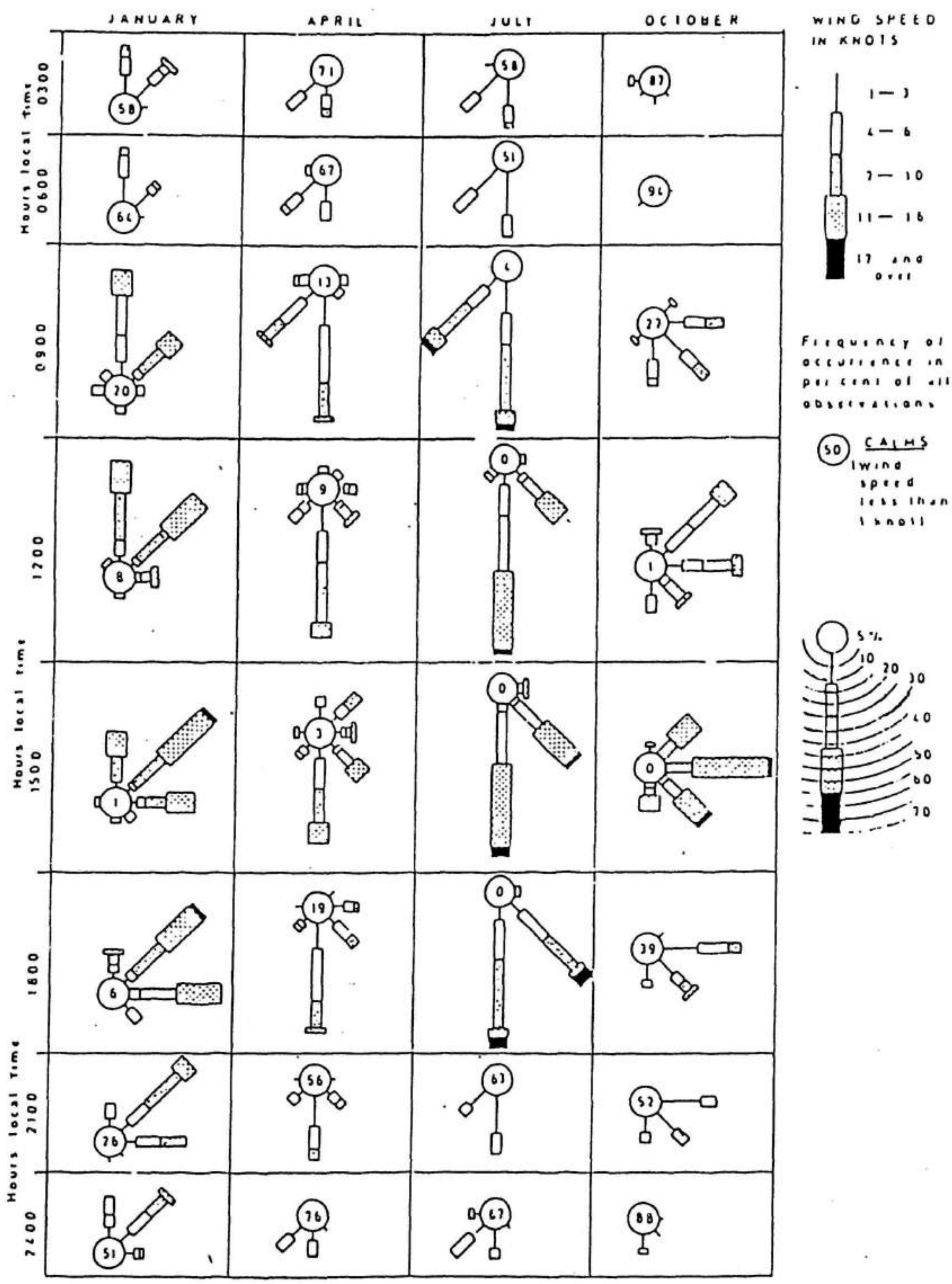


Figure 6. Mean wind-directions and -speeds at Dar es Salaam (based on observations during the period 1955-1958).

A new method to quantify the combined effects of all three factors on human comfort in hot and humid climates has been presented recently by Meffert (1980). Thermal stress in these climates is largely controlled by evaporation from the skin, which is proportional to the vapour pressure difference between the skin and the surrounding air. Therefore there is, at any level of relative humidity, a marginal temperature (T_m) at which comfort is optimal (Figure 7a). The difference between the actual air temperature T and T_m is called the hygrothermal factor HGT (HGT = T_m - T), which indicates the degree of hygrothermal stress when related to air movement or wind speed V (Figure 7b). On this diagram a position to the left of the comfort zone (shaded) indicates sultriness, to the right conditions are too hot. Diurnal and seasonal variations of the HGT factor, both indoors and outside, have been used to indicate thermal stress in a small city on the Kenyan east coast (Meffert, 1980).

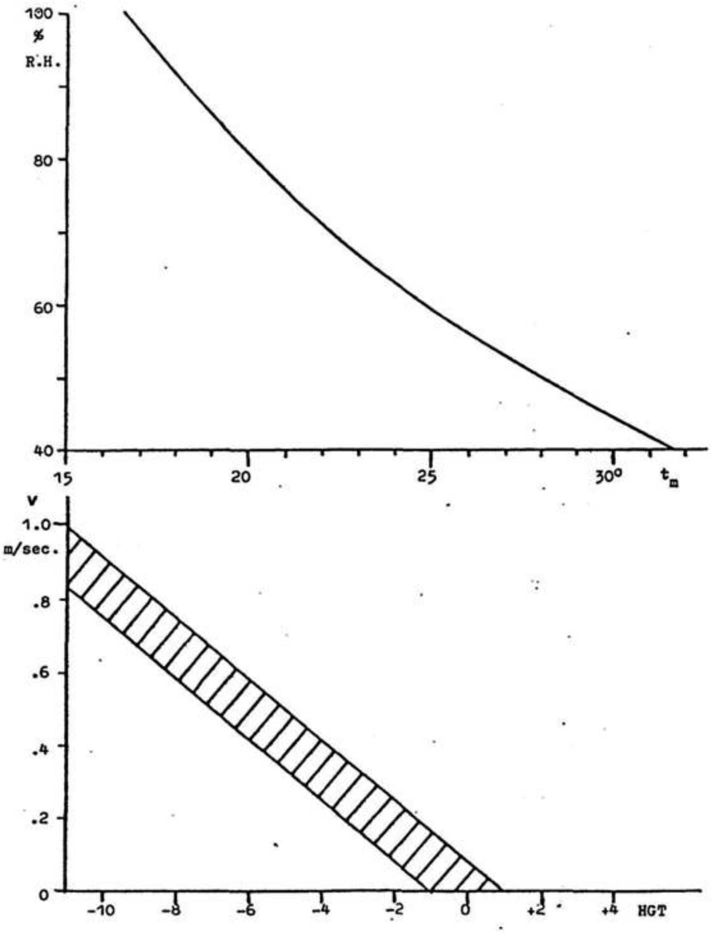


Figure 7. Hygrothermal comfort related to temperature, humidity and ventilation (after Meffert, 1980.

In some hot, humid cities tropical cyclones or the "burst" of the beginning summer monsoon may bring very high intensity rainfall. But even where these phenomena are absent, a large proportion of total rainfall comes in the form of rainstorms, short periods of very intensive rain (Nieuwolt, 1974; Riehl, 1979). This high intensity rainfall can cause serious problems of "flash floods" or inundations in lower parts of cities, and urban planners and engineers should therefore obtain full information about the maximum that can be expected over various periods and their recurrence intervals, to design adequate drainage canals and eventually storage space for rainfall that cannot be disposed of immediately (Figure 8).

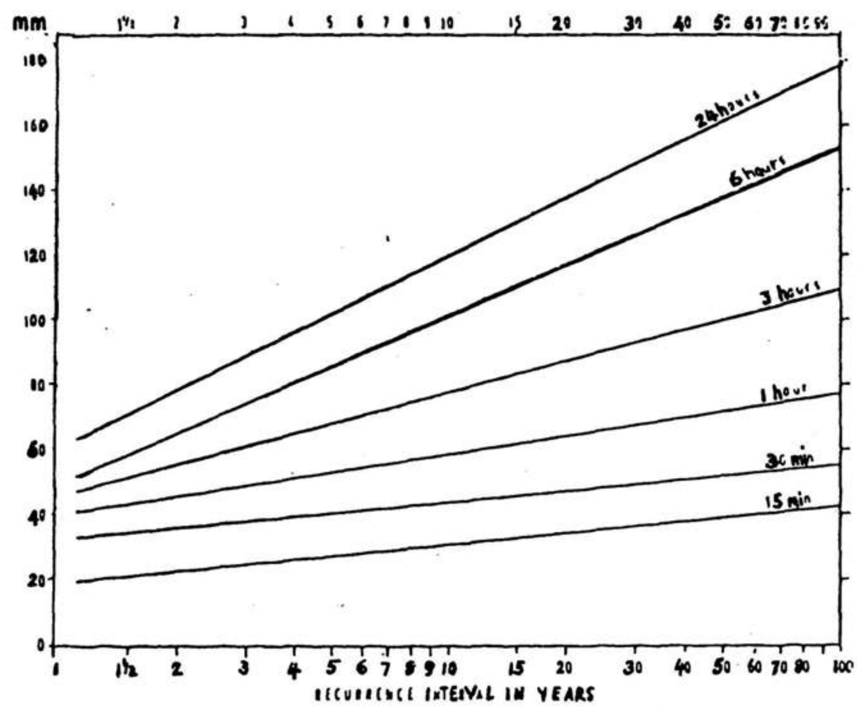
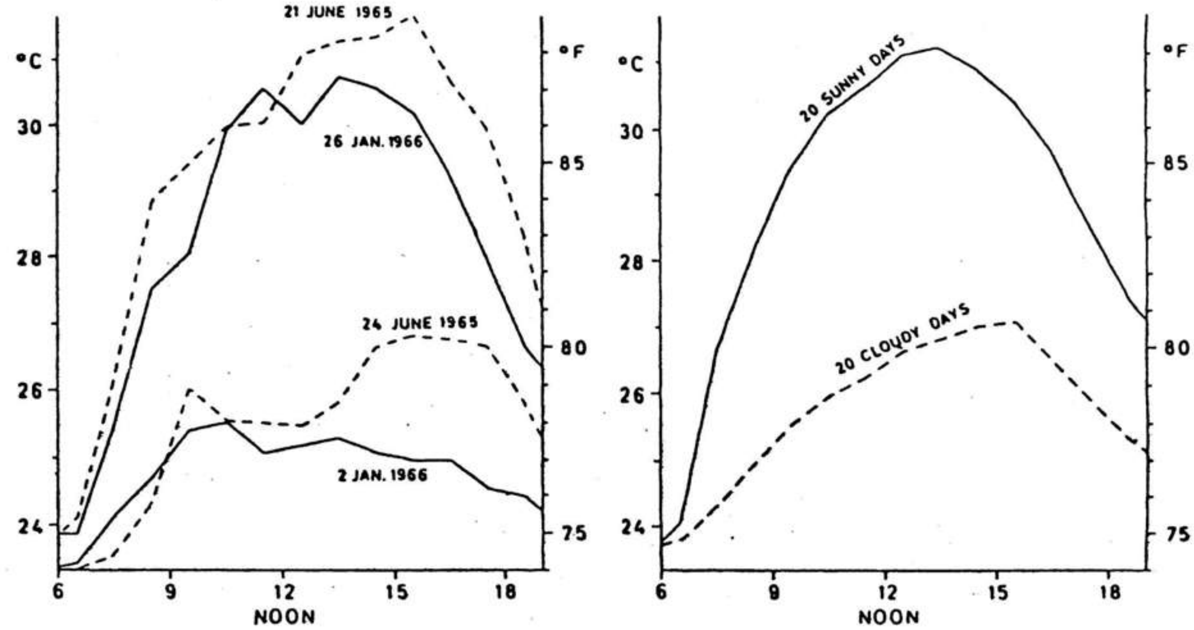


Figure 8. Maximum rainfall intensities for various recurrence intervals at Dar es Salaam (21 years).

Other useful climatic data that can be supplied by meteorological services concern sunshine hours and cloudiness. Again, hourly values should be supplied rather than monthly means, so that they may be related to the critical periods of potential climatic stress.

Users of the climatic data should be reminded that these consist mainly of averages over a number of years and that actual values may depart from these means to some extent. For instance, daytime temperatures vary according to sunshine conditions (Figure 9). While the differences of a few degrees may seem small to the outsider, they are quite important when conditions are close to thermal stress. Also, these small differences are strongly felt by inhabitants of climates where seasonal variations are small, as is the case near the equator. Wind speeds and -directions are particularly variable and their means should never be considered as fixed values.



Left: 21 June, 1965: 10.45 hours of sunshine.
24 „ „ : 0 „ „ „
2 Jan., 1966: 0 „ „ „
26 „ „ : 11.00 „ „ „

Right: 20 sunny days: more than 9 hours of sunshine each day (1965)
20 cloudy days: less than 1 hour of sunshine each day (1965)
The two groups were equally distributed over the different months of the year.

Figure 9. Temperatures during sunny and cloudy days in Singapore.

2.2 Determining the Microclimate

Data supplied by meteorological services are usually based on observations at the local airport. Not only are airports often at considerable distances from the city, but they also represent a somewhat artificial environment, since the vegetation cover is reduced to grass and a few bushes, and paved surfaces of runways and aprons dominate in the vicinity of the meteorological site. The official climatic data are therefore not representative for conditions at the planning or building site and should be corrected to indicate the microclimate there, at least for the periods of potential climatic discomfort.

This correction can be made with a simple set of instruments, consisting of a psychrometer, a hand-held anemometer and a wind vane. Observations should be taken as often as possible, but at least once an hour during critical periods. Usually one position at the building site will be sufficient for temperature and humidity observations, but wind data should be obtained at various locations and different levels above the ground, because both the wind speed and its direction may vary considerably over very short distances, due to factors such as slope, exposure, vegetation cover and existing buildings. Wind observations should also be taken at other times, for instance at night, because the wind is an important factor in providing protection against cool nights.

The next step is to determine differences using synchronous climatic data from the meteorological stations. While there is no guarantee that these differences will always be the same, there is usually a clear tendency, and it is possible to extrapolate the variations with some caution and leave a margin of error. Once the microclimate has been established, it is possible to determine periods of climatic discomfort: thermal stress in the afternoons, cool nights, possibly even periods of thunderstorm activity.

All efforts to design for climate should concentrate on conditions during these critical periods. It is therefore imperative that wind conditions at those times are well known when planning starts.

In the rest of this paper a distinction is made between urban planning and architectural design. The main difference is one of scale, but ways to reduce climatic discomfort are also different. However, there are many instances where this distinction is purely academic and where methods mentioned under both headings may be used.

3. URBAN PLANNING

A major problem in hot and humid climates is the *prevention of floods and inundations* in cities, caused by the high intensity of rainfall. This problem is particularly serious in urban areas, because surface runoff is much faster than in rural areas, where the vegetation and soil cover constitutes a large reservoir for rainwater. Drainage systems which were quite sufficient to deal with the removal of rainwater in rural areas therefore become too small when urban development takes place, as is illustrated by the frequent floods occurring in rapidly developing cities like Kuala Lumpur.

The danger is particularly acute in cities located on coastal plains, where even under relatively dry conditions regular drainage is necessary to prevent flooding (Giacottino, 1979). Unfortunately, uncontrolled illegal settlements often occupy sites where stagnant water constitutes a danger to human health.

Urban planners should therefore start their design for new areas of urban development with the planning of adequate drainage systems and they should prohibit all construction on sites threatened by flooding. Rainfall statistics will enable the engineers to calculate the necessary size of drainage pipes and storage areas for excess rainfall (see Dunne, this volume).

We shall now concentrate on the planning and design of residential buildings. Most cities in the hot and humid climates have experienced a very rapid growth in population during the last twenty years or so. Consequently there is an enormous demand for residential accommodation at a reasonable cost, but in most of these cities this demand is still largely unsatisfied, with some very unhealthy and even dangerous consequences(Lainé, 1971). The design of low-cost housing estates to replace shanty towns and squatter settlements excludes the use of air-conditioning. Comfort and health of the inhabitants are therefore strongly affected by the planning and design of the buildings.

New industrial, administrative and public buildings are usually designed with air-conditioning, the only way to prevent climatic stress and improve work-efficiency, as ventilation disturbs paper work in schools, banks and other offices. Nevertheless, climatic factors should be considered in their design, but there are many instances of quite unsuitable architecture in this respect in hot, humid cities. Glass walls, or large and unshaded windows on sides exposed to the afternoon sun, and the use of dark building materials which absorb too much solar radiation come to mind. Such construction increases the cost and energy consumption of the air-conditioning systems.

When new residential areas are planned in peripheral parts of a city, *natural ventilation* is probably the most efficient way to reduce thermal stress. Local wind data are needed to decide where the best wind conditions prevail during periods of potential climatic discomfort caused by a hot, humid environment. Usually, these will be the higher land and coastal areas and these should be given preference for the location of residential blocks or houses. If there is a dominant wind direction during the critical periods, streets should be laid out in that direction to reinforce the circulation of the air. Buildings should be oriented with their long sides perpendicular to the wind direction, but some departure from this angle is possible, as wind directions are often variable and oblique winds are almost as effective regarding indoors ventilation as winds arriving at a right angle (Givoni, 1969, p. 260-262).

If residential buildings are planned in older parts of a city, in the process of rehabilitation of decrepit or impoverished quarters, ventilation might not be very effective. It will be impossible to lay out new streets in a different direction from the existing pattern, wind velocities are generally lower near the city centre and temperatures may reach the critical value of 35°C. Here, architectural design may help, particularly by constructing high buildings, taking advantage of the high wind speeds above the roofs of existing structures.

In any case, plenty of space should be left open between residential buildings in the form of lawns or parks, not only to allow a free flow of air, but also to reduce noise pollution. Trees should preferably have high and broad canopies, providing shade without impeding ventilation near ground level. Wherever possible grass should be given preference over paved surfaces, because it has a smaller heat storage capacity and keeps ground temperatures lower because it uses much of the solar heat for transpiration.

A second method to reduce thermal stress in hot, humid cities is to provide *protection from solar radiation*. The layout of new streets can reduce the potential absorption of solar heat by avoiding narrow streets and those in an east-west direction (Terjung and Louie, 1973).

Little roofs can be constructed over foot- and bicycle paths at low cost. It is easy to determine the position of the Sun in the sky during periods of thermal discomfort by using simple solar charts (Figure 10). Usually the Sun will be quite high at that time, so the roofs need not be much broader than the paths. They may also provide some protection against rain.

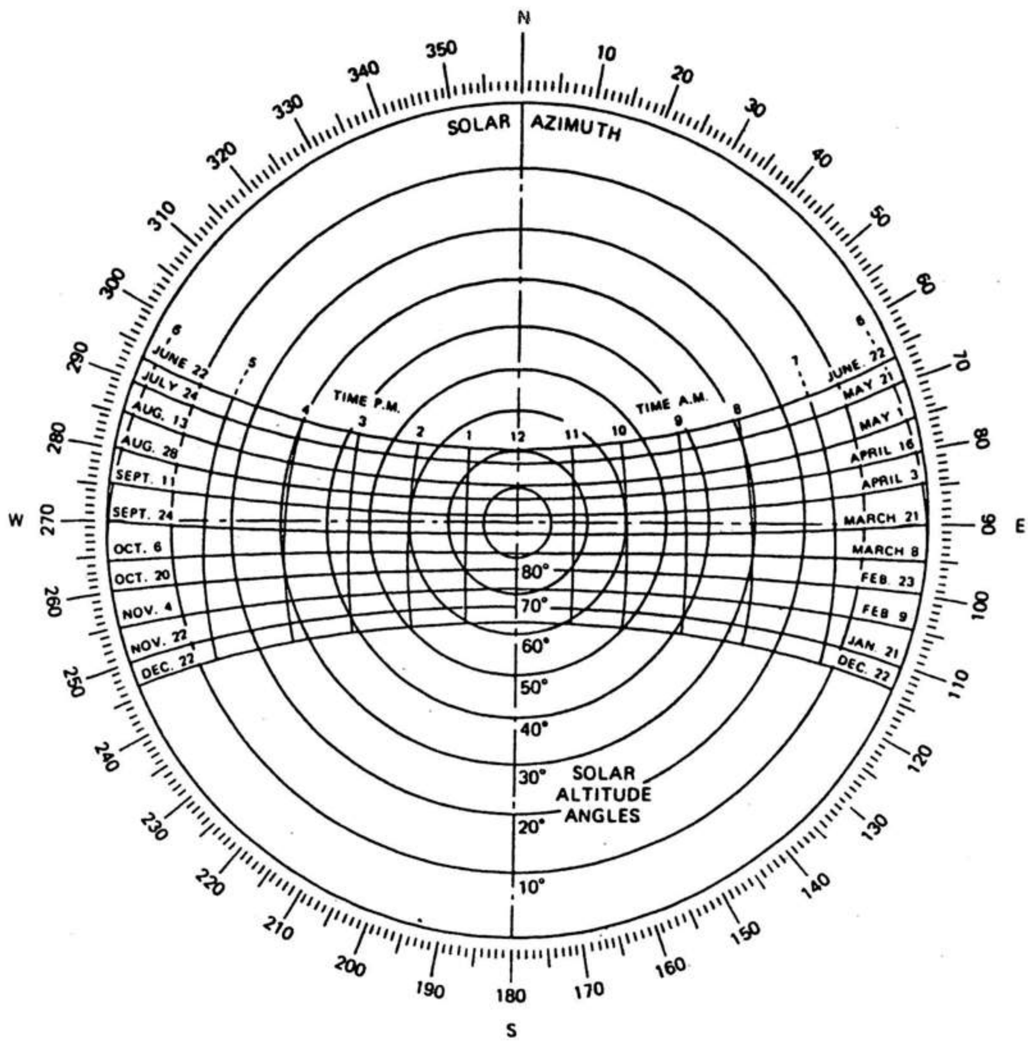


Figure 10. Example of a solar chart - for 4°North. (Source: Building Research Station, Watford, England).

Awnings and roofs should also be planned for areas of outdoor activities. In these climates many of those spring up rapidly near housing estates: food stalls and restaurants, workshops for repairs and services, markets and shops tend to be outside and they should have adequate protection, both against the Sun and the rain.

Private developers will not always readily accept the above restrictions and recommendations. These should therefore be incorporated into the local building laws.

4. ARCHITECTURAL DESIGN

Continuous ventilation is the most efficient way to reduce climatic stress in residential houses and apartment blocks in hot, humid cities, where air-conditioning cannot be installed for economic reasons. Ventilation is necessary in these climates to reduce indoor humidity and it helps the body to evaporate perspiration, thereby preventing the unpleasant feeling of skin wetness. Ventilation equalizes outdoor and indoor temperatures.

However, artificial ventilation is cheaply provided by electric ventilators or ceiling fans. These are now produced at low cost in many tropical countries and form an efficient way to relieve thermal stress indoors in hot and humid conditions as they promote evaporation from the skin (Figure 7b). Electric ventilators are found in large numbers in hot, humid cities, even in low cost housing estates.

With the right orientation to the main wind directions during the critical periods, cross ventilation is possible by a design of large openings on both wind- and leeward sides of a building. Verandahs or balconies, vertical projections and the location of the larger rooms on the windward side will intensify ventilation. Free circulation of the air between rooms should be made possible by sliding or folding walls. Unshaded glass windows with fixed panes should be avoided; they can often be replaced by louvres.

It may be necessary to reduce ventilation during rainy days or cool nights, which may occur occasionally even in equatorial cities. In these climates, where seasonal temperature differences are very small, people are sensitive to cooling, even by a few degrees. Protection by blankets or warm clothing is also often not available. Therefore, screens, shutters and louvres should be adjustable, and it should be possible to close them completely.

A disadvantage of the open construction in apartment blocks is the noise pollution and a certain lack of privacy.

Fly screens are necessary in many hot, humid cities. They may reduce ventilation by as much as 50%, particularly with low wind speeds. A solution is to screen only bedrooms, or to apply fly screens to whole balconies rather than to windows. In many tropical countries fly screens are not used, people employ only mosquito nets over the bed at night. A reduction in ventilation is unavoidable in any case.

Ventilation is particularly important around the roof. High-pitched roofs create their own ventilation systems, and a well ventilated attic also helps to reduce the effects of solar radiation on top of the building. Flat roofs should be avoided in hot, humid cities.

Indoor comfort can also be improved by designing *high buildings*. Urban heat islands normally reach levels of at least a few hundred metres above the ground, so it is obviously impossible to escape their effects entirely by constructing high buildings (Oke, 1982). But within the heat islands, wind speeds usually increase rapidly with elevation, while both temperatures and humidity of the air tend to decrease. Higher levels therefore provide lower physiological temperatures as well as better ventilation (Greenwood and Hill, 1968). High buildings reduce the cost of construction and services in comparison with low residential blocks. When sufficient space is left between high apartment blocks, they provide an attractive form of residential development at relatively low cost, as illustrated by many new constructions in hot, humid cities, for example in Singapore.

In this respect, it may be a good idea to return to the traditional style of construction in many hot and humid climates, by building *houses on stilts*. This style was originally designed to protect the inhabitants against floods, termites, wild animals and intruders, with the use of removable steps. In a city it provides the advantage of better ventilation, as even the lowest storey is some distance from the ground, where wind speeds are usually higher. Moreover, cooling is provided by ventilation under the floor, particularly at night, and the humidity from the ground is kept away from the residents. If the ground floors of urban residential buildings are reserved for use as garages these advantages are preserved.

The advantages of high buildings have been recognized in many hot, humid cities, where the rents of apartments go up with elevation. Higher wind speeds, particularly above the roofs of surrounding buildings, distance from the dust and noise at street level, and the free view all contribute to this preference for high residences.

Residents should also be *protected against solar radiation*. In hot, humid cities both direct and indirect insolation are important sources of thermal discomfort. In the first instance this protection is provided by an overhanging roof. Awnings can also be installed, but they may reflect heat into the windows of the next higher storey. In any case, roofs and awnings are only effective as long as the Sun is in a high position in the sky. Where the critical periods of potential thermal discomfort last well into the afternoon, as for instance in Singapore (Figure 3), vertical adjustable shades are preferable on the Sun-facing sides of buildings. These can be installed so that they actually improve ventilation and they also allow better indoor light than horizontal devices.

In some equatorial climates, where temperatures reach their maximum in the late afternoon, west-facing walls may be left without openings. However, this may impede ventilation and the effects may also be reduced by heavy cloudiness on many afternoons. Local climatic data and experience should guide the designer in this matter.

At latitudes of about 10^{o} or more, a similar consideration can be made regarding south- or north-facing walls to reduce exposure to the midday Sun. But in most cases the advantages of good ventilation are more important than the effect of direct insolation, especially in coastal areas where a sea breeze will often bring cooler air from the sea during the midday period (Nieuwolt, 1973).

To increase reflection, all surfaces exposed to the Sun should be whitewashed. However, in hot and humid climates colours tend to deteriorate rapidly because moulds and fungi grow on walls and roofs. Modern paints have a good resistance against them, nevertheless frequent repainting will be necessary.

Solar water heaters and electric cells are efficient but expensive instruments to use solar energy and protect buildings from solar heat at the same time. One-sided roofs, oriented towards the midday Sun, are particularly suitable for this purpose.

In many hot, humid cities nights are too warm for comfort. It is therefore important that *heat storage* in buildings is kept as low as possible. This can be done by using the correct materials for construction. Generally, wood stores much less heat than bricks, concrete or stone, and it is therefore the best material for roofs (Greenwood and Hill, 1968). Lightweight double roofs with well ventilated attics are preferable, but even here insulation may be advisable to prevent the penetration of heat into residential premises. Insulation layers are absolutely necessary where heavy or flat roofs are used (Givoni, 1969, p. 121-125). Galvanized metal sheets are widely used because they are cheap. Though they reflect solar radiation reasonably well when new, they tend to loose their shine rapidly in hot and humid environments and then absorb heat easily. Protection by white paint and insulation with board or wood shavings may help.

All internal sources of heat, particularly kitchens, should be located on the leeward side of buildings, so that the heat is rapidly removed by draughts. Outside kitchens on verandahs are used in many hot climates. Bathrooms and water heaters should also be on the leeward side.

Protection against rain is important. Roofs, awnings and screens should be designed with this function in mind. Architects should use climatic data concerning the maximum rainfall intensities and design gutters, rainpipes and drains large enough to cope with sudden intensive rainstorms. Driving rain is a problem in hot, humid cities. Some prediction regarding the direction from which rain comes is possible where wind directions are constant, as in coastal locations, where the sea breeze prevails during most afternoons, or in monsoon climates. But in most cities, driving rain may come from almost any direction as local factors control the sudden wind gusts during thunderstorms. A prediction of the main direction of these gusts is often impossible until a building is completed and creates its own wind pattern.

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