Synthesis
of the
Reports of the Scientific, Environmental Effects, and Technology and Economic Assessment Panels
of the Montreal Protocol

A Decade of Assessments for Decision Makers Regarding the Protection of the Ozone Layer: 1988-1999

UNEP

United Nations Environment Programme
Ozone Secretariat

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Preface

Goals. The goals of this Synthesis Report are twofold: (i) To synthesize the major 1998 findings and conclusions of the three Assessment Panels of the Montreal Protocol, and (ii) to place this information in the context of the past decade over which assessments have been provided to the Parties to the Protocol.

Origins. The genesis of the three Assessment Panels lies in the text of the Montreal Protocol under the Vienna Convention for the Protection of the Ozone Layer. Article 6, "Assessment and Review of Control Measures", defines the following assessment process:

> "Beginning in 1990, and at least every four years thereafter, the Parties shall assess the control measures provided for in Article 2 on the basis of available scientific, environmental, technical, and economic information. At least one year before each assessment, the Parties shall convene appropriate panels of experts qualified in the fields mentioned and determine the composition and terms of reference of any such panels. Within one year of being convened, the panels will report their conclusions, through the Secretariat, to the Parties."

Assessment Panels. This decision separated the assessment process from the political (i.e., decisionmaking) process and defined the process by which the communication of information from and to the Parties occurs. At its First Meeting, held in Helsinki in May 1989, the Parties decided to endorse the establishment of, in accordance with Articles 6, the following four Assessment Panels:

Panel for Scientific Assessment

Panel for Environmental Assessment

Panel for Technical Assessment, and

Panel for Economic Assessment.

After 1990, the last two united to form the Panel for Technology and Economic Assessment.

Methods. The current three Assessment Panels periodically carry out their state-of-understanding assessment charge in the following ways:

- *Scientific Panel.* The four Cochairs, with input from an ad hoc international steering group of researchers, plan the scope, content, and Authors of a forthcoming assessment report. The Cochairs and the current set of Lead Authors meet to further plan and coordinate the contents of the chapters and the preparation of first drafts. The Authors are aided by contributed information from a large body of researchers worldwide. The resulting drafts undergo a mail peer review (with several reviewers per chapter) and a subsequent week-long panel review, at which the chapter conclusions are agreed upon and the Executive Summary is finalized.

- *Environmental Effects Panel.* The Environmental Effects Panel has 25 Panel members. They are scientists working in photobiology and photochemistry, mainly in universities and research institutes. The Panel members write the different chapters, sometimes helped by co-authors for special topics. The chapter authors review each other's chapters, and the Panel takes responsibility for the entire assessment. A draft assessment is sent out to external scientific reviewers all over the world. Between major assessments, the Panel meets at least once a year and informs the Parties about new developments.

- *Technology and Economics Panel.* The Panel had, after 1990, five Technical Option Committees: Aerosols, Sterilants, and Miscellaneous Uses; Rigid and Flexible Foams; Halons; Refrigeration, Air Conditioning, and Heat Pumps; and Solvents, Coatings, and Adhesives. The Economics Committee was added in 1991, and the Methyl Bromide Technical Options Committee was added in 1993. The periodic assessment reports are prepared by the standing Committees of industry, government, and academic experts and are, for the large part, reviewed by the broader technical communities. Three Co-chairs co-ordinate all Panel and Options Committee activities. The Technology and Economics Panel publishes reports that include the executive summaries of the technical reports and that are reviewed internally. Furthermore, the Panel - with its 23 members from 17 countries - has become a "standing advisory group" on a large number of technical and economic issues as the Parties sought input to a growing variety of decisions. Consequently, the Panel has published annually general update reports, as well as numerous topical reports.

Appendix A lists the 60 assessment reports prepared for the Parties by the three Panels over the past decade: 1988 - 1999. The worldwide set of experts that helped prepare these state-of-understanding assessments are listed in Appendix B. Their expertise is the foundation upon which the information to the Parties rests.

The 1998 Reports. The information synthesized in the present report was drawn from the recently completed full reports of the three Assessment Panels:

> "Scientific Assessment of Ozone Depletion: 1998" (~750 pp)
>
> "Environmental Effects of Ozone Depletion: 1998 Assessment" (~200 pp)
>
> "1998 Report of the Technology and Economics Assessment Panel" (~300 pp)

Appendix C reproduces the Table of Contents and Executive Summary of each of the three 1998 reports.

How to Use This Synthesis Report: A short guide to the format of present Synthesis Report follows:

- *Section I* provides the "historical context", illustrating how the past assessments reports were utilized by and reflected in the sequence of decisions by the Parties.

- *Section II* gives capsule summaries of the major 1998 findings of the three Assessment Panels.

- *Section III* focuses on "the future(s)" by analyzing examples of possible options for policy consideration regarding potential further measures for the protection of the ozone layer. Specifically, this section describes the predicted atmospheric responses to those options and the technical and economic feasibilities of the options. The section also describes how atmospheric changes unrelated to chlorine- and bromine-containing compounds could influence the recovery of the ozone layer.

- *Appendices*: In addition to providing the supporting detail noted above, two sets of "Frequently Asked Questions" about the science of ozone change and its effects are included. Reprinted directly from the 1998 assessments of the Scientific Panel and the Environment Effects Panel, these questions are the ones that are most often asked by the public about the ozone layer issue. The answers given are based on the information in the assessments, but are written for non-technical readers.

The Past is Prologue to the Future. In the last section of this report, the Panels pause to describe "the world we avoided"; namely, to give a forecast of what could have occurred had there been no Montreal Protocol. The nature of "that world" underscores the high value of the efforts of so many people worldwide who wrestled with the challenging decisions and actions associated with the ozone depletion issue. The Assessment Panels are pleased to have provided, over the past decade, information to support the landmark Montreal Protocol process and remain committed to this ongoing process.

Section 1

The Past Decade: The Montreal Protocol and the Assessment Panels

A. Background: The Stage is Set

The Earth's stratospheric ozone layer is a natural feature of the planet's atmosphere. It was formed as the early atmosphere evolved. Beginning in the 1880s and extending into the early decades of the 20th century, scientists discovered that the ozone layer existed, began to explore its features, and sought to explain its existence. In the 1930s, researchers gradually clarified the chemical mechanisms whereby the ozone layer is maintained. Namely, these are a balance of (i) the production of ozone from oxygen by solar radiation and (ii) the destruction of ozone by chemical reactions with naturally occurring atmospheric chemical species (for example, hydrogen and nitrogen). The fact that this ozone loss occurred by "catalytic" reactions meant that relatively small amounts of the reacting chemicals could remove substantial ozone without themselves being consumed. It was also recognized very early that air motions distribute ozone globally to yield the observed patterns. (Indeed, global monitoring of the ozone layer was started in the 1950s to use ozone as a "tracer" partly to study large-scale atmospheric circulation.)

Parallel with this development of the understanding of the ozone layer itself grew the recognition of its importance to life on Earth. It was recognized very early (1880s) that the ozone layer absorbed most of the short-wavelength solar ultraviolet radiation, UV-B. Further, biological studies were characterizing the positive and negative impacts of UV-B radiation of various life forms. While it was noted that UV-B radiation would promote the formation of vitamin D in human skin (1937) and would kill bacteria (1929), it was also found that it had damaging effects on humans, such as sunburn (1922) and skin cancer (1928), and that it had important deleterious impacts on plants (1965).

In 1928, industrial chemistry developed a nonflammable, non-toxic compound - a chlorofluorocarbon (CFC) - to replace the hazardous compounds (such as methyl chloride and sulfur dioxide) then used in home refrigerators. During the 1950s, CFCs came into widespread use. Successful, low-cost, and sought-after CFC applications expanded in the 1970s: refrigerants, air conditioning, foam blowing agents, solvents, and medical applications, for which there were few alternatives that were recognized at the time. Similarly, halons (bromine-containing compounds) were developed and marketed aggressively as fire protection because of their effectiveness and low cost. In addition, over half of the CFC production was for "lower-value" applications, particularly aerosol-propelled personal care products, pesticides, noisemakers, dust blowers, and toys. While alternatives were available, they were not sought for several reasons, for example, for lack of substantial cost motivation and for safety considerations.

A newly developed sensitive analytical technique that could detect tiny traces of chlorine-containing chemicals was applied at various surface locations worldwide in the early 1970s. It was found that the CFCs, because of their industrial production, use, and emissions, were now a widespread part of the global atmosphere.

As a result of all of this, the "stage was set" for the ozone-layer "drama" whose scenes were to unfold over the last quarter of the 20th century. Namely, it was known by the early 1970s that natural chemical cycles - that of hydrogen and nitrogen - are a factor in maintaining the ambient ozone layer levels. It was known that the ambient ozone layer, as the shield from harmful solar UV-B, was important to the well being of humankind. It was known that we were producing and using growing amounts of new chemical compounds that were appearing in the lower atmosphere. What was *not yet* known were the facts that (i) we were overwhelming a third chemical cycle - that of chlorine, which was once a negligible factor for the ozone layer - and that (ii) our actions could lead to significant ozone reductions and UV-B increases. Namely, the picture that linked all of this information together was not there.

B. First Signs of the Gathering Issue

It was the feasibility of supersonic aviation in the stratosphere that changed atmospheric chemical catalytic reactions from being purely a scientific topic to one lying at the heart of environmental issues. Namely, in the early 1970s, atmospheric, environmental, and technical researchers began to examine the potential environmental impact of a possible worldwide fleet of supersonic aircraft. These studies highlighted the fact that the reactive nitrogen compounds in engine exhaust could enhance the stratospheric catalytic nitrogen chemistry. These emissions would increase this nitrogen-cycle component of ozone loss and thereby "unbalance" the processes that form and remove ozone, leading to a thinner ozone layer.

As noted above, the consequences of a thinner ozone layer had been recognized. The possibility that these would occur and would cause damaging effects to humans and other organisms focused public attention on the supersonic transport debate and established protection of the ozone layer as an issue.

In the mid-1970s, two discoveries opened wide the curtain on the ozone drama. First, it was hypothesized that *chlorine chemistry* could also participate in catalytic ozone destruction in the stratosphere. Second, it was proposed that break-up of CFCs in the stratosphere by solar radiation would greatly enhance the chlorine catalytic chemistry, that the growing use of CFCs would thereby lead to a thinning of the ozone layer, that harmful effects of UV-B radiation that would ensue. Further, since the CFCs were shown to have long (decades-to-centuries) residence times in the atmosphere, it implied that the ozone loss would continue long after any reductions in CFCs emissions.

Twenty years hence, the 1995 Nobel Prize in Chemistry would be awarded to three scientists for recognizing the significance of the atmospheric chemistry of ozone formation and loss, particularly the roles of nitrogen chemistry and the CFCs.

C. The Debate Years: Clarifying the Credibility of the Ozone Depletion Issue

The decade from the mid-1970s to the mid-1980s saw the initiation of comprehensive laboratory, field observations, and predictive modeling research activities in the atmospheric, biological, health sciences, as well as technological characterization, relevant to the ozone depletion issue. The accumulating results and the emerging mosaic of understanding from several assessments were producing a substantive characterization of the relation between the ozone layer and humankind. Major milestones along this road from hypothesis to predictive understanding stand out as examples.

CFCs were observed in the stratosphere in the predicted quantities. The key chlorine species in the ozone-loss chain reaction was also observed directly. Bromine was found to be many times more effective than chlorine in ozone loss. Global monitoring of CFCs and halons exhibited steady annual increases (several per cent per year) in their atmospheric abundance. An increase in ozone depletion was found to cause a larger percentage increase in the impacts (e.g., skin cancer) associated with the higher UV-B radiation. The suite of ozone-depleting compounds was identified and their production, and the quantification and inventorying of their release rates were begun, for example, the losses of CFCs from mobile air conditioning. The possibility of using hydrochlorofluorocarbons (HCFCs) as alternatives to CFCs was identified, and the refrigeration-relevant properties of some of the hydrofluorocarbons (HFCs) were characterized.

The public-policy debate was engaged. The results of a decade of focused research were being assessed and reported. In 1985, for example, while no current CFC-induced ozone depletion could yet be unequivocally distinguished from natural ozone-layer variation, it was predicted that, if CFC emissions were to continue to grow into the future, then (i) substantial ozone losses would likely occur in coming decades, (ii) ozone-layer recovery times would unavoidably be decades-to-centuries long, and (iii) the resulting elevated UV-B radiation over such extended time periods would cause significant impacts in humans, animals, and plants to be manifested in later decades. Furthermore, in 1985, a then-baffling discovery was reported; namely, the ozone layer over "the last place on Earth" - Antarctica - was behaving unexpectedly. On the other hand, it was pointed out that (i) CFCs and halons were substantial factors in current economic development, consumer welfare, and public health and that (ii) there was a current lack of available substitutes and that the expense associated with evaluating the toxicity and broad environmental acceptability of candidate substitute compounds could be considerable.

The debate was national and international. In addition to the mid-1980s status of the ozone layer, effects, and technical and economic information above, decision makers were also assimilating and weighing into the process the suite of governmental, legal, demographic, social, ethical, and political information. In 1985 and 1987, decisions were made formally.

D. 1985 Vienna Convention and 1987 Montreal Protocol

March 1985, Vienna Convention for the Protection of the Ozone Layer. Based on the current understanding of the multitude of factors noted above, this Convention signified (i) the belief that ozone depletion was a real issue, (ii) a global commitment to address it; and (iii) an agreed-upon process for doing so.

September 1987, Montreal Protocol on Substances That Deplete the Ozone Layer. The decisions became specific. A watershed had occurred: an international action on a global issue whose predicted impacts lay largely still in the future. Based on the information in hand by the mid-1980s, the nations crafted a Protocol that included the major long-lived CFCs and halons, a future-year freeze, and a subsequent 50% reduction in the production and consumption of CFCs and halons.

The Assessment Panels. In addition to its specific emission identification and amelioration steps, the Protocol recognized that research is an ongoing exercise, understanding is thereby continuously improving, and updated status reports are important input for any sequence of policy evaluation and/or re-evaluation. Specifically, Article 6 of the Montreal Protocol established the process for the Parties to gain such updated information from Assessment Panels. The Panel reports (Appendix A), which reflect the Montreal Protocol reporting requirement that began in 1988 and has extended to the present, describe the updating of ozone-layer-relevant knowledge by the world's ozone-layer, effects, and technological and economic experts. These experts, from many institutions in many countries (Appendix B), have provided the knowledge base that now has served the Parties for over a decade.

E. Post-1987: The Protocol's First Decade and the Assessment Panels

A succession of Assessment Panel reports have described the advancing status of scientific understanding and technical response. As requested by the Parties, these have preceded the periods in which the Parties have considered major decisions. In the following section, the major findings reported by the Assessment Panels are listed along side the major decisions by the Parties over the decade-plus from 1987 to the present. For reference, Appendix A lists the Panel reports by year.

How can the "progress" of the Montreal Protocol be tracked? It is a fair question, because accountability has been viewed by many as a necessary component of human endeavors. No doubt, there could be many indicators of such progress. One that lies in the early sequence of cause-to-effect in the ozone-depletion issue and one that can be evaluated very quantitatively is the abundance of ozone-depleting substances in the atmosphere. Figure 1 illustrates (i) the past observed abundances of atmospheric "equivalent" chlorine (which includes bromine, appropriately weighted) and (ii) the future abundances that would have been associated with each of the major "decision steps" of the Montreal Protocol. In any given year, the amount of human-caused ozone depletion is related to the effective chlorine abundance. Since many of the environmental effects of ozone depletion (for example, elevated incidences of skin cancer in humans) arise from long-term exposure, such impacts are related to the area under each of the curves - the larger the area, the larger the environmental effect and vice versa. Because of these associations, the summary below is linked to the figure and its messages.

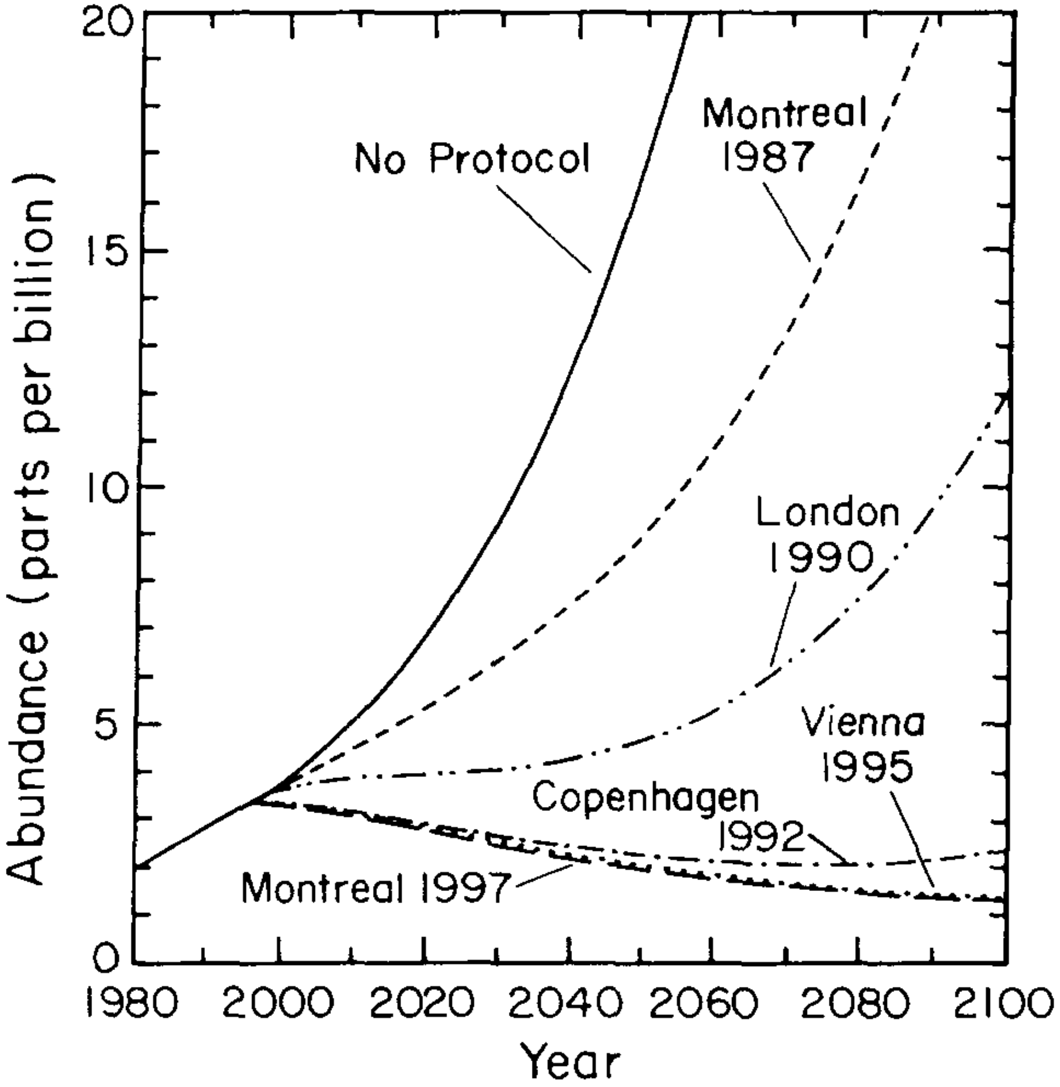

Figure 1. **Effect of the international agreements on ozone-depleting stratospheric chlorine/bromine.**

Figure 1 also illustrates the rationale for the time intervals used in the section below. The move beyond the 1987 Protocol "freeze" provision to introduce some "phase-outs" (London, 1990) dramatically lowered projected future effective chlorine growth rates over the period 2000 - 2040 (but still permitted a possible later return to significant growth rates). The advancement of phase-out dates and the addition of new controlled substances (Copenhagen, 1992) implied, for the first time, that a peak in effective chlorine burden would lie ahead (but still permitted a possible much later return to a positive growth. The setting of production and/or consumption caps on all controlled ozone depletors eventually for all countries (Vienna, 1995) implied (assuming full compliance) no return to positive growth rates. The advance of information as reflected in the Assessment Panel reports and the corresponding policy decisions are arranged by these "effective chlorine milestones".

1. From the Montreal Protocol (1987) to the London Amendment: (1990)

Ozone Science:

- The Antarctic ozone hole is attributed to human-produced chlorine/bromine compounds whose impact is enhanced by polar stratospheric clouds.

- A global downward trend in the ozone abundances is detected during winter months at the middle and high latitudes in the Northern Hemisphere.

- "Ozone-friendly" properties (for example, ozone depleting potentials of the first set of CFC substitutes - the hydrochlorofluorocarbons (HCFCs) are characterized.

- The Science Panel of the Montreal Protocol and the newly formed Intergovernmental Panel on Climate Change (IPCC) begin a continuing interaction on the assessment of the understanding of atmospheric phenomena in common to both issues; for example, the Global Warming Potentials of ozone-related gases are jointly evaluated.

Environmental Effects:

- Investigations show that UV-B radiation, especially at shorter wavelengths, has a multitude of effects and that most of them are damaging:
  - ◊ effects on eyes (cataracts and snow blindness) and suppression of the immune system;
  - ◊ plants (half of those studied grew less and had smaller leaves under increased UV-B);
  - ◊ effects on aquatic organisms (especially the smaller ones, like phytoplankton); and
  - ◊ damage to materials (UV-B exposure is the primary cause of outdoor plastic degradation).

Technology and Economics:

- Industry consortia start work on environmental acceptability and toxicity of CFC and halon substitutes and methods for accommodating phase-out of chemicals in industrial processes.

- Major efforts on recovery and recycling are initiated.

- Development begins on retrofit blends of chemicals without CFCs.

- Feasibility of non-halogen propellants is demonstrated.

- Not-in-kind substitutes for the cleaning of electronics are identified for CFC-113.

- Feasibility of dropping the use of halons in the training and testing of fire extinguishing equipment is demonstrated.

Policy - London Amendments:

- Other fully halogenated CFCs, carbon tetrachloride, and methyl chloroform are added.
- Phase-outs are established for these substances for future dates.
- HCFCs are included as transitional substances and their reporting is prescribed.
- An interim financial mechanism is established for meeting the agreed incremental costs of the phase out of production and consumption of ozone-depleting substances in developing countries.

2. From the London Amendment (1990) to the Copenhagen Amendment (1992)

Ozone Science:

- Outside of the tropics, global downward trends of lower-stratospheric ozone in the lower stratosphere are detected and quantified at middle and high latitudes in both hemispheres and in winter, spring, and summer.
- The Antarctic ozone hole becomes more intense.
- Significant, but variable, ozone losses are detected in the Arctic.
- Methyl bromide is identified as a significant ozone depletor.
- UV-B increases are observed to occur with large ozone losses over Antarctica.
- A preliminary evaluation is made of the effects of aviation, shuttles, and rockets on the ozone layer.
- The loss of ozone in the lower stratosphere is found to have a cooling effect on the tropospheric climate system.

Environmental Effects:

- A sustained 10% decrease in ozone is predicted to be associated with a 26% increase in non-melanoma skin cancer.
- The induction of immunosuppression by UV-B has now been demonstrated in humans, including deeply pigmented individuals.
- Research on plant responses to UV-B radiation underscores the concern for managed and natural ecosystems.

- It is shown that aquatic ecosystems is already under UV-B stress; hence, there is concern that additional stress will cause detrimental effects.

- Chemical reactivity in the troposphere is expected to increase in response to increases in UV-B.

Technology and Economics:

- For all sectors, a variety of substitutes are identified that enables a virtual phase-out of CFCs by the 1995-to-1997 time frame.

- Many multinational companies phase out the use of ozone-depleting chemicals much faster than the Protocol requirements.

- Analyses are promoted that combine considerations on both ozone depletion and global warming via the direct (chemical) and indirect (energy production) factors.

- The first refrigerators with HFC-134a are introduced on the market.

- The availability of HCFC substitutes for use in different types of foam cause rapid decrease in use of CFC-11 for that purpose.

- The first mobile air conditioning units with HFC-134a are introduced on the market.

Policy - Copenhagen Amendments:

- The phase-out dates are moved forward.

- Methyl bromide is included (with exceptions), specifying a developed-country freeze in a future year.

- HCFCs are now included as controlled substances, specifying a series of caps and reductions, leading to a distant-future phase-out (namely, confirmation of these compounds as "transitional substances"). Hydrobromofluorocarbons (HBFCs) are included for immediate phase-out by developed and developing countries.

- The Multilateral Fund becomes a permanent financial mechanism.

- Mechanisms (involving the Technology and Economics Assessment Panel) are established to identify "essential uses" of controlled substances.

3. From the Copenhagen Amendment (1992) to the Vienna/Montreal Amendment/Adjustments (1995/97)

Ozone Science:

- The slowing of the atmospheric growth rate of ozone-depleting gases in the lower atmosphere is detected.

- The increasing growth rates of the CFC substitutes are documented.

- Downward global ozone trends continue.

- The role of particles is explained in the halogen-caused, temporarily enhanced ozone losses that followed the 1991 eruption of Mt. Pinatubo volcano.

- Antarctic ozone losses continue unabated.

- Non-polar UV-B increases (clear sky) are recorded for low overhead ozone in non-polar regions.

- Negative impact on the ozone layer of illegal CFC production is quantified.

Environmental Effects:

- DNA-damaging UV-B radiation in Antarctica is characterized during the period of ozone depletion.

- Increased UV-B radiation is likely to cause substantial increases in the incidence of and morbidity from eye diseases, skin cancer, and infectious diseases, with risks now quantified for some effects (for example, skin cancer).

- Researchers have measured the increase in, and penetration of, UV-B radiation in Antarctic waters and have provided conclusive evidence of direct ozone-related effects on phytoplankton.

- In terrestrial ecosystems, increased UV-B could modify production/decomposition of plant matter, with concomitant changes in atmospheric trace gases.

Technology and Economics:

- Many HFC-blends are identified and tested as replacements for HCFC-22 in refrigeration.

- Hydrocarbon-based refrigerators enter the market.

- Commercial refrigeration units are designed so that substitutes like ammonia and hydrocarbons can be used.

- Cyclopentane-based and hydrocarbon-blend-based foams are developed and/or commercialized.

- Identification of halon essential-use exemptions opens consideration of earlier phase-outs.

- Considerable increases in halon production and consumption in the Article 5(1) countries are identified.

- Except for quarantine and preshipment uses, alternatives to the uses of methyl bromide are identified.

- Metered-dose inhalers based on HFC-134a are introduced on the market.

Policy - Vienna/Montreal Adjustments:

- The reduction/phase-out of methyl bromide in developed countries is accelerated, and a phase-out schedule in developing countries is established.

- For CFCs, halons, methyl chloroform, and carbon tetrachloride, the developing country phase-out dates are fixed to the developed country schedule that was adopted in 1990, plus ten years.

- Establishment of lower caps on and limited uses of HCFCs by developed countries and a freeze and distant-future phase-out by developing countries.

- A licensing system is established for the control of methyl bromide trade. (*Therefore, as of 1997, phase-outs and/or caps exist for all listed ozone depletors and for all Parties.*)

Section 2

Our Current Ozone Layer and Its Protection: The Status of Its Understanding

At the request of the Parties, the Assessment Panels have provided a new update on the understanding of the ozone science, effects, and technology and economics associated with the ozone issue. The Table of Contents and the full texts of the Executive Summaries of the 1998 assessment reports of the three Panels are given in Appendix C. The section that follows gives a shortened summary (grouped by Panel) of those status-of-understanding reports.

A. Major Current Findings: "Scientific Assessment of Ozone Depletion: 1998"

The updating of the scientific understanding of the ozone layer involved 304 researchers from 35 countries worldwide. The assessment report was planned and prepared over a two-year period, including a mail and panel peer reviews. The major findings are summarized as follows:

1. *Ozone-Depleting Gases*

- *The total combined abundance of ozone-depleting compounds in the lower atmosphere peaked in about 1994 and is now slowly declining.* Total chlorine is decreasing, but total bromine is still increasing. This turn-over was forecast in the 1994 assessment. The chlorine decline is largely due to decreases in methyl chloroform. Chlorine from CFCs is still increasing slightly. The abundances of most halons continue to increase (for example, 1211 at almost 6% per year). The observed abundances of CFCs and chlorocarbons in the lower atmosphere are consistent with reported emissions.

- *The observed abundances of the substitutes for the CFCs are increasing.* In 1996, the HCFCs contributed about 5% to the tropospheric chlorine from the long-lived gases. The HCFC growth, in terms of total combined effective abundance, does not offset the decline of the other chlorine-containing gases. The atmospheric abundances of HCFC-22 and HFC-134a agree with that expected from reported emissions, but the atmospheric observations of HCFC-141b and HCFC-142b are larger.

- *The combined abundance of chlorine and bromine is expected to peak in the stratosphere before the year 2000.* The delay reflects the average time for surface emissions to reach the lower stratosphere. While observations of key chlorine compounds in the stratosphere show a decline in growth rate, they also show that the peak abundance has not yet occurred at the time of this assessment.

- *The role of methyl bromide as an ozone-depleting compound is now considered to be less than was estimated in the 1994 assessment, although significant uncertainties remain.* The best current estimate of the Ozone Depleting Potential (ODP) of methyl bromide is 0.4, compared to 0.6 estimated in 1994. The change is due primarily to an increase in estimated oceanic and terrestrial removal rates. However, the current understanding of the sources and sinks of methyl bromide is incomplete.

2. Ozone Trends

- *The observed total column ozone losses from 1979 to the period 1994-1997 are about 5%, 3%, and 5%, respectively, for the northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and all seasons in the southern midlatitudes. But, the rate of decline in stratospheric ozone at midlatitudes has slowed; hence, the projections of ozone loss made in the 1994 assessment are larger than what has actually occurred.* Since 1991, the downward linear trend observed in earlier years has not continued, but rather has been almost constant since the recovery from the additional losses caused by the enhancement associated with the 1991 Mt. Pinatubo volcanic eruption.

- *The springtime Antarctic ozone hole continues unabated.* The overall extent of ozone depletion has remained essentially unchanged since the early 1990s. This behavior is expected because of the current near-complete destruction of ozone within the Antarctic lower stratosphere during springtime. The major factors contributing to the large continuing springtime depletion over Antarctica are well understood.

- *In the Arctic, the late-winter/spring ozone values were unusually low in 6 out of the last 9 years, the 6 being characterized by unusually cold and protracted stratospheric winters.* The possibility of such depletions was predicted in the 1989 assessment (Appendix A). Minimum Arctic temperatures are near the threshold for large chlorine chemical activation, and, as a result, the year-to-year variability, which is driven mainly by meteorology, leads to large ozone loss variability for the current chlorine amounts. While it is not possible to forecast the nature of an Arctic winter for a particular year, the elevated chlorine and bromine abundances over the next decade or so imply that the Arctic will continue to be vulnerable to large ozone losses.

3. Consequences

- *The understanding of the relation between increasing UV-B radiation and decreasing column ozone has been further strengthened by observations at several locations globally.* The influences of other variables besides ozone, such as clouds, particles, and surface reflectivity are better understood. Satellite data indicate that the largest UV-B increases occur during spring at high latitudes in both hemispheres.

- *Stratospheric ozone losses have caused a cooling of the global lower stratosphere and global-average negative radiative forcing of the climate system.* Model simulations indicate that much of the observed downward trends in temperatures in the lower stratosphere (about 0.6°C per decade from 1979 to 1994) is attributed to the loss of ozone in this region. Radiative calculations, using extrapolations based on the ozone trends reported in the 1994 assessment for reference, indicate that stratospheric ozone losses since 1980 may have offset about 30% of the positive forcing due to increases in the well-mixed greenhouse gases over the same time period. The climatic impact of the slowing of midlatitude ozone trends and the enhanced loss of ozone in the Arctic has not yet been assessed.

B. Major Current Findings: "Environmental Effects Panel Report: 1998"

The updating of the scientific understanding of the environmental effects of ozone layer depletion involved 102 researchers from 31 countries worldwide. The assessment report was prepared over a 1-year period, including a review process by 70 external reviewers, mostly by mail. The major findings are summarized as follows:

1. Changes in Ultraviolet Radiation

- *Long-term predictions of future UV-B levels are difficult and uncertain.* Nevertheless, current best estimates suggest that a slow recovery to pre-ozone-depletion levels may be expected during the next half-century. The recovery phase for surface UV-B radiation will probably not be detectable until many years after an ozone layer minimum because of the variation in other factors (such as clouds) that influence UV-B, but are not directly ozone-related.

2. Effects on Human and Animal Health

- *The increases in UV-B radiation associated with ozone depletion are likely to lead to increases in the incidence and/or severity of a variety of short-term and long-term health effects, if current exposure practices are not modified by changes in behavior.* Adverse effects on the eye will affect all populations irrespective of skin color. Effects on the immune system will also affect all populations, but may be both adverse and beneficial. The adverse effects include depressed resistance to certain tumors and infectious diseases. Effects on skin could include increases in photoaging and skin cancer, with the risk increasing with fairness of skin. Increases in UV-B are likely to accelerate the rate of photaging as well.

3. Effects on Terrestrial Ecosystems

- *Increased UV-B can be damaging for terrestrial organisms including plants and microbes, but these organisms also have protective and repair processes.* The balance between damage and protection varies among species and even varieties of crop species. Research the past few years indicates that increased UV-B exerts more often through altered patterns of gene activity, rather than damage.

4. Effects on Aquatic Ecosystems

- *Recent studies continue to demonstrate that solar UV-B and UV-A have adverse effects on the growth, photosynthesis, protein and pigment control, and reproduction of phytoplankton*, thus affecting the food web. Macroalgac and sea grasses show a pronounced sensitivity to solar UV-B.

- *UV-B radiation is absorbed by and breaks down dissolved organic carbon and particulate organic carbon*. This process makes the products available for bacterial degradation and remineralization.

- *Polar marine ecosystems are in the region where ozone-related UV-B increases are the greatest.* Therefore, these ecosystems are expected to be the oceanic ecosystems most influenced by ozone depletion.

- *The potential consequences of enhanced levels of exposure of aquatic ecosystems to UV-B radiation includes reduced uptake capacity for atmospheric carbon dioxide*. This could result in the potential augmentation of global warming.

5. Effects on Biogeochemical Cycles

- *The effects of increased UV-B radiation on emissions of carbon dioxide and carbon monoxide and on mineral cycling in the terrestrial biosphere have been confirmed by recent studies of a range of species and ecosystems*. The examination of long-term UV-B effects on carbon capture and storage are underway for natural ecosystems.

6. Effects on Air Quality

- *Increased UV-B will increase the chemical activity in the lower atmosphere*. Model studies suggest that additional UV-B radiation reduces tropospheric ozone in clean environments and increases tropospheric ozone in polluted areas. Assuming other factors remain constant, additional UV-B will increase the rate at which some primary pollutants are removed from the troposphere.

7. Effects on Materials

- *Physical and mechanical properties of polymers are negatively affected by increased UV-B in sunlight.* Conventional photostabilizers are likely to be able to mitigate the effects of increased UV-B levels in sunlight.

C. Major Current Findings: "Technology and Economics Panel Report: 1998"

The updating of the technical and economic options involved 230 technical experts from 46 countries worldwide and was organized into seven Technical Options Committees and the Technology and Economic Assessment Panel. The reports of the Technical Options Committees were prepared over a two-year period, including peer review. The Panel report was prepared during the year 1998. It contains the Executive Summaries of all Technical Options Committee reports.

1. Aerosol, Sterilants, Miscellaneous Uses, and Carbon Tetrachloride

Key points from the 1998 report of the Aerosols Technical Options Committee (ATOC) are the following:

- *Aerosol Products*. The ATOC estimates that the 1997 CFC consumption in the aerosol sector was less than 15,000 tonnes in Article 5(1) Parties and some Countries with Economies In Transition, excluding metered-dose inhaler use. For aerosol products, other than metered-dose inhalers, there are no technical barriers to global transition to alternatives.

- *Metered-Dose Inhalers*. Approximately 500 million metered-dose inhalers are used annually worldwide for the treatment of asthma and chronic obstructive pulmonary disease, using approximately 10,000 tonnes of CFCs annually. It is likely that a wide range of reformulated products will be available in many developed nations and transition will be making good progress by the year 2000. Minimal need for CFCs for metered-dose inhalers is envisaged by the year 2005 in non-Article 5(1) Parties.

- *Sterilants*. By the beginning of 1997, CFC-12 use in non-Article 5(1) Parties for sterilization (in a sterilant gas mixture with ethylene oxide) had virtually disappeared. Global consumption of CFC-12 in this sector is estimated to be less that 1,500 tonnes. Estimated use of substitute HCFC replacement is thought to be less than 3,000 tonnes (some 90 tonnes weighted by Ozone Depleting Potential).

- *Miscellaneous Uses and Laboratory and Analytical Uses*. CFCs have a number of miscellaneous uses, of which tobacco expansion is the most significant. After 1998, China may be the only remaining country to use significant quantities of CFCs for this purpose. Declining use in this country is expected. It has been estimated that global consumption of controlled substances for laboratory and analytical uses does not exceed 1,500 tonnes (currently subject to essential use exception).

- *Carbon Tetrachloride*. Atmospheric emissions of carbon tetrachloride in 1996 were estimated as 41,000 tonnes, of which some 26,000 tonnes originate from carbon tetrachloride production in Article 5(1) Parties and Countries with Economies In Transition. Emissions of carbon tetrachloride can be technically and economically reduced from both feed stock and process agent uses, although in some cases, alternatives to carbon tetrachloride use may not be available.

2. Rigid and Flexible Foams

Key points from the 1998 report of the Foams Technical Options Committee are the following:

- *Global use of ozone-depleting substances in rigid foams has decreased by almost 75% since reaching a peak in 1989*. Largely all CFC use in Non-Article 5(1) countries has been eliminated.

HCFC (ODP-weighted) use is less than 20% of the total rigid foam sector, with little use in non-rigid sectors.

- *Alternatives with zero Ozone Depleting Potentials (ODP) are the substitutes of choice in many applications including packaging, cushioning (flexible), and certain rigid thermal applications.* No single solution has emerged from transition, and thus, choices must be retained to allow optimal solutions for given applications, producer-specific and country-specific circumstances.

- *The development of HFC replacements for HCFC-141b continues for thermal insulating polyurethane, polyisocyanurate, and phenolic foams.* It is anticipated that products such as HFC-245fa and HFC-356mfc will be commercially available around the beginning of 2002. No toxicity issues have been identified. However, uncertainty over costs, availability, and long-term environmental management of greenhouse gases is slowing development.

- *Pentane-based technologies for rigid polyurethane foams continue to evolve.* Technical properties have been improved with the use of blends, with improved cost competitiveness for hydrocarbon-blown products.

- *Some barriers to transition away from ozone-depleting substances exist.* CFC and HCFC users are reluctant to finalize a transition strategy until there is greater certainty concerning the long-term availability and suitability of HFCs. Further, in Article 5(1) countries, CFC-11 continues to be widely available and is generally cheaper than current alternatives. Another factor constraining a rapid phase-out is that very few alternatives are manufactured in these countries.

3. Halons

Key points from the 1998 report of the Halons Technical Options Committee (HTOC) are the following:

- *Extensive research and development into new liquid and gaseous halocarbon replacements for halons and into the use of new and existing alternative approaches has resulted in the availability of a wide range of options.* There is an almost complete cessation of use of both halon 1211 and halon 1301 in Non-Article 5(1) and in many Article 5(1) Parties for new installations, as well as many retrofitting applications. Those systems that remain are substantially non-emissive in normal circumstances.

- *Despite this success, some concerns remain.* Vastly dominant amongst these is continuing significant use of halon 1211 by Article 5(1) Parties. Technology transfer is required for several applications. Countries with Economies In Transition require implementation of effective halon recovery and recycling, a halon 2402 management program, and information dissemination.

- *Military organizations in developed countries have eliminated virtually all halon uses, with some notable and important exceptions.* The important uses for which suitable alternatives are not yet available include those on board ships, submarines, aircraft, and tactical vehicles. While research on alternatives is ongoing, these applications will likely depend on the existing halon bank for some time.

- *Two other halons, 1011 and 1202, were much less widely used.* Recently reported increases in atmospheric abundance of halon 1202 cannot be explained by use as a fire extinguishant. The Parties may wish to examine the possibility of inadvertent production and release of halon 1202 during halon 1211 production in Article 5(1) countries.

- *The needs of "Critical Users" who still require halon 1301 - presently including aviation and some defense, oil and gas, shipping - are being met by management of the existing inventory.* These are in approximate balance, which is important to be maintained. Until there is a clear surplus of halon 1301, widespread destruction cannot be recommended.

- *Efforts to minimize emissions continue to be imperative, particularly during the now-beginning period of maximum ozone layer vulnerability.* Annual ODP weighted emissions of halon 1211 and halon 1301 from Article 5(1) countries now exceed annual ODP weighted halon emissions from non-Article 5(1) countries. Halon recovery and recycle programs have been effective in reducing total ODP weighted halon emissions from non-Article 5(1) countries by over 40% since 1992. Despite this success, concerns remain. Vastly dominant amongst these is continuing significant production and use of halon 1211 in Article 5(1) Parties.

4. Methyl Bromide

Key points from the 1998 report of the Methyl Bromide Technical Options Committee (MBTOC) are the following:

- *Of the 1996 global production of methyl bromide of 71,425 tonnes, quarantine and pre-shipment use was 15,000 tonnes and equivalent to 22% of global fumigant use.* Quarantine use is exempt control and is an emissive use unregulated under the Protocol. Moreover, this use appears to be increasing for both developing and developed countries. The MBTOC noted that there is some inconsistency in the interpretation of the terms "quarantine" and "pre-shipment" that may lead to some Parties incorrectly exempting this use. Multiple applications are being used when a single application of methyl bromide just prior to shipment would meet requirements.

- *In spite of the wide spread use of methyl bromide as a soil fumigant (accounting for about 75% of its global use), the MBTOC did not identify a single crop that cannot be produced successfully without methyl bromide.* Approximately 12% of the global consumption of methyl bromide is used for treating durable commodities and about 3% for structures. The principal alternatives are phosphine, heat, cold, and contact pesticides. In many cases, integrated pest management procedures can replace methyl bromide. The MBTOC did not identify any existing alternatives for some nonquarantine and pre-shipment uses, but these are likely to consume less than 50 tonnes per annum. About 9% of global methyl bromide consumption is used for disinfestation of perishable commodities, with about half used for disinfestation of fruit for quarantine purposes. Post-entry alternative treatments are particularly problematical as they neither have been developed and approved for treating products entering via multiple air and sea ports, nor would they be easy to implement.

- *Developing countries consume 23-26% of total methyl bromide production.* Some have greatly reduced their consumption or even officially phased out methyl bromide while others have substantially increased their usage and in some cases production.

- *There has been some limited further research into the development of recovery and recycling systems for methyl bromide*, mostly directed at recovery from commodity fumigation. Only a few special examples of recovery equipment are in current commercial use.

- *The MBTOC could find no existing alternatives to methyl bromide for about 2500 tonnes of methyl bromide per annum used for non-quarantine-and-preshipment treatments.* Existing alternatives as those nonchemical or chemical treatments and/or procedures that are technically feasible for controlling pests, thus avoiding and replacing the use of methyl bromide. Based on this relatively small consumption, the MBTOC considered there are existing alternatives for more than 95% of the current tonnage of methyl bromide excluding quarantine and preshipment. Significant effort must now be undertaken to transfer these alternatives to as many locations as possible and optimize the conditions under which they can be most effective.

5. Refrigeration, Air Conditioning, and Heat Pumps

Key points from the 1998 report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee are the following:

- *For the short term, the transitional HCFCs still form a valid, global option for CFCs in refrigeration and air conditioning equipment.* However, for the long term, there largely remain only five important different refrigerant options for the vapor compression cycle: HFCs and HFC blends, ammonia, hydrocarbons and blends, carbon dioxide, and water. None are perfect and all have advantages and disadvantages that need to be considered.

- *For new domestic refrigeration equipment, all manufacturers in Non-Article 5(1) countries have transitioned from CFC-12 to non-ozone-depleting substances.* Domestic refrigeration has been completely converted to the use of HFCs and hydrocarbons (i.e., HC-600a) for use in the refrigeration circuit. The conversion to these chemicals in the domestic sector is also now well underway in the Article 5(1) countries and Countries with Economies In Transition, where the transition in the former ones is faster than the Montreal Protocol requirements.

- *Commercial refrigeration includes a wide range of equipment and hence are in a variety of stages of transition away from ozone-depleting substances.* For most large stand-alone equipment, CFC-12 has been replaced by HFC-134a. Some smaller units use various hydrocarbons, mainly propane. HFC blends are often perceived as the economically preferred refrigerants, due to safety and initial costs considerations and therefore form the usual choice. Ammonia and HCFC-22 are currently common in cold storage and food processing applications. Hydrocarbons and carbon dioxide are applicable for specific applications.

- *Nearly all air-cooled air conditioners currently use HCFC-22.* However, there has been significant progress in developing HCFC-22 alternatives; e.g., HFC-blends such as R-

407C, which is widely available, and R-410A, as well as hydrocarbons. Water chillers use a variety of refrigerants, including fluorocarbons (dominant) and ammonia. Hydrocarbon chillers have been introduced on some regional markets.

- *Most mobile air conditioning units used in 1994 have either been retrofitted or scrapped.* Since 1994, all automobile manufacturers have converted to HFC-134a, and the designs are being improved to minimize charging and to maximize energy efficiency. New vehicles are expected to be equipped with HFC-134a until an alternative has been developed and commercialized that offers comparable performance, reliability, and safety characteristics, and an economically viable global-warming advantage.

- *Next to HFCs, non-fluorocarbons and not-in-kind alternatives are more and more perceived as important candidates for future use.* The servicing aspect in the developing countries remains a very important one to be addressed in order to substantially reduce CFC emissions here.

6. Solvents, Coatings, and Adhesives

Key points from the 1998 report of the Solvents Technical Options Committee (STOC) are the following:

- *Industry in developed countries has almost two years of experience without newly produced ozone depleting solvents.* The large majority of users have been successful at implementing alternatives in a very short period. The STOC is becoming more confident that alternatives exist or can expect to be created for nearly all solvent uses. However, the STOC is not completely without concerns for developed countries.

- *Continued dependency on stockpiled solvents is evidence that interest in more economical and effective alternatives are sought.* In the near future, users who still rely on 1,1,1-trichloroethane will feel increasing pressure to find alternatives.

- *With dwindling concerns over the production phase out of ozone depleting solvents in developed countries, the focus of the STOC has shifted to developing countries.* Although the phase-out effort is going well in developed countries, many unique challenges remain for developing countries. The STOC's primary concerns are related to the overall demand for ozone-depleting substances by small and medium enterprises and to eliminating carbon tetrachloride solvent use. One of the major problems yet to be resolved is the complete phase-out of controlled solvents in the small and medium enterprises who, when taken collectively, consume a significant volume of ozone depleting solvents.

- *For almost every solvents, coatings, and adhesives use, non-ozone-depleting alternatives are available.* However, in the near term, HCFCs and the non-ozone-depleting HFCs and PFCs may be necessary in some limited and unique applications.

- *Recently, two ozone-depleting brominated solvents have been commercially introduced, chlorobromomethane and n-propyl bromide* . Because of their capability for depleting the ozone layer and high probability of extensive use, STOC has recommended that the Parties of the Montreal Protocol consider the potential danger of these substances to the ozone layer.

7. Economics

Key points from the 1998 report of the Economics Options Committee (EOC) are the following:

- *Recent studies indicate that virtually all Article 5(1) Parties will meet the "1999 freeze" on production and consumption of Annex A - Group I controlled substances.* To meet subsequent control measures for 2002 and beyond, the Article 5(1) Parties will need to improve compliance by small and medium-sized enterprises. Several case studies have highlighted increasing use of market-based instruments, but some reliance on command-and-control measures remain active.

- *The trade provisions of the Montreal Protocol have reduced international trade in controlled substances as intended.* At the regional level, there is quantitative evidence that trade flows in the relevant product groups have been impacted by the Protocol. The reasons for these impacts are (i) reduced demand for products containing ozone-depleting substances, (ii) difficulty in switching production to non-ozone-depleting substances, and (iii) differential phase-out schedules for Article 5(1) and Non-Article 5(1) Parties. These factors are re-emerging with respect to trade in more recently listed controlled substances, such as HCFCs and methyl bromide.

- *Actions to constrain illegal trade are in hand*, especially with respect to (i) the decision to require import and export licensing systems to be implemented by all Parties, (ii) proposed additional controls on the use of controlled substances in some major countries, and (iii) reductions in the supply of illegal controlled substances due to the recent decision by ten donor countries to provide additional funding to phase out specific CFC production facilities.

8. Challenges for Article 5(1) and Countries with Economies In Transition

- *Regarding Article 5(1) challenges, the experience from developing countries indicates that strong leadership and commitment from government, industry, and individuals is important to establish and maintain momentum.* A major obstacle for several Article 5(1) Parties is the inadequacy of regulatory structure necessary to support the phase-out process. Uncertainties regarding availability and costs of technologies have been mostly resolved, and there are now alternatives to replace almost all ozone-depleting substances. The greatest challenges that remain are in the implementation of Multilateral Fund projects and in addressing the large informal servicing sector.

- *Many of the 16 Non-Article 5(1) Countries with Economies In Transition are lagging behind the phase-out schedule.* The special circumstances that are hampering progress include: the lack of trade and industry associations, no network of expects, no venue for reaching consensus, limited information exchange, and incomplete regulatory enforcement.

Section 3

Our Future Ozone Layer

The purpose of this section of the Synthesis Report is to look ahead. It will summarize the current knowledge about the factors that could influence the ozone layer in the 21st century. These factors include changes due to human actions and changes due to natural events and atmospheric variation. The human influenced factors will be presented and analyzed as possible options, vetted for magnitude and practicality by the 1998 Assessment Panel reports.

However, before laying out the descriptions of these quantified and assessed options, this section will pause to take a look at the future that was avoided by the Montreal Protocol and its subsequent amendments and adjustments. Such a pause seems particularly appropriate for this Synthesis Report, given the fact that the Protocol commemorated its 10th year in 1997 and that this Synthesis Report marks a decade of Assessment Panels input into that process.

A. The World We Avoided

1. The Depleted Ozone Layer

One measure of success of the 1987 Montreal Protocol, the processes that led to it, and its functioning over the subsequent years is the forecast of "the world that was avoided" by these actions and events. *In the year* 2050 (which is the approximate nominal time at which the ozone layer is now projected to recover nominally to pre-1980 levels), the abundance of ozone-depleting gases would have been about five times larger than today's value (Figure 1). Ozone depletion would have been much larger than today's. As a result, surface UV-B radiation would have doubled at midlatitudes in the Northern Hemisphere, for example. As Figure 2 shows, without any effort to protect the ozone layer, there would have been a runaway increase in the incidences of skin cancer throughout the next century.

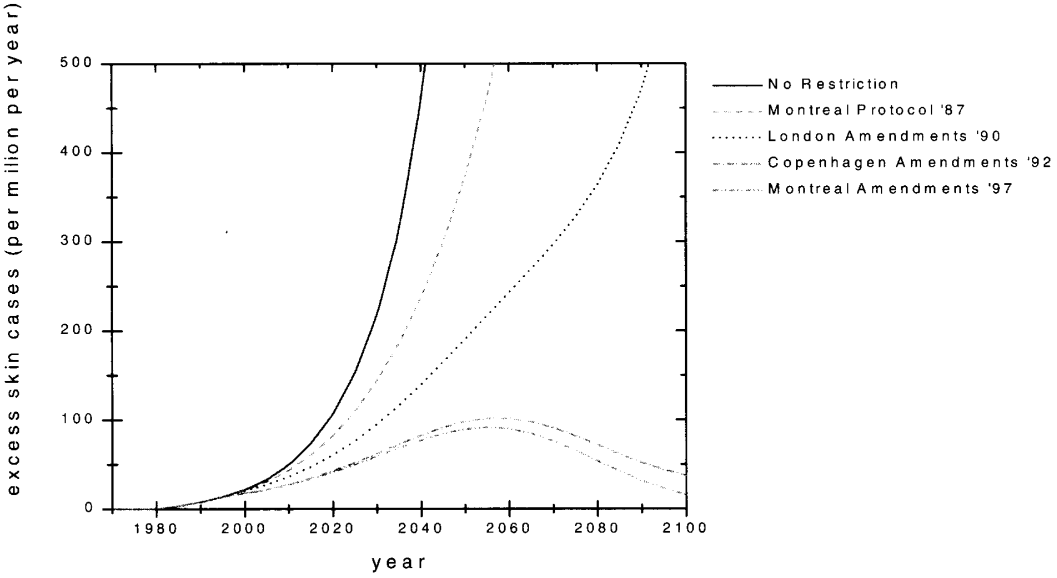

Figure 2: The excess annual incidence of future skin cancer, per million people, for five scenarios, for the current regulations (dashed, two dotted), the Copenhagen Amendment (dashed, one dotted), the London Amendment (dotted), the original 1987 Montreal Protocol (dashed), and no Protocol (solid).

Furthermore, the above impacts (and probably many others) would have continued to grow in the years beyond 2050 if there had been no Montreal Protocol. It is important to underscore that, while the provisions of the original Montreal Protocol in 1987 would have lowered the above growth rates, recovery (i.e., an improving situation) would have been impossible without the Amendments and Adjustments (London, 1990; Copenhagen, 1992, and Vienna, 1995).

2. The Technological Solutions

Even with intent by the nations to protect the ozone layer, the resulting agreements could not have been implemented without industrial commitment and innovation that led to the development and production of alternatives to the ozone-depleting substances. In this regard, it is important to note that when the Montreal Protocol was signed in 1987, there were few identified alternatives to CFC and halons. Most experts assumed that similar chemicals, primarily other fluorocarbons (HCFCs and HFCs), would be the primary substitutes for CFCs. The Montreal Protocol stimulated a global quest for substitutes and alternatives with the result that HCFCs and HFCs became a minority, albeit critical, portion of the current solution. Between 1987 and 1998, the total use of chemicals was reduced by approximately thirty percent through conservation strategies, such as containment and recycling. It was reduced by approximately 50% with non-fluorocarbon substitutes, including non-chemical options such as no-clean soldering and chemical options such as hydrocarbon propellants, cleaning agents, and blowing agents. Only 20% was reduced with HCFC and HFC alternatives. As is illustrated in Table 1, an indicator of this rapid technical progress is the evolution of the industry estimates of the expected mix of substitutes for the CFCs.

Table 1. **The change over time (1989-1992) of the mix of options that were expected to replace the CFCs during the 1990's and the current real (1998) status of CFC replacement.**

Substitute	Estimate (%) in year			Current Status
	1989	1991	1992	1998
Non-fluorocarbon	32	47	48	50
Conservation	29	12	26	30
HCFC	30	24	11	13
HFC	9	17	15	7

B. The World That Lies Ahead: The Current Status

1. The Scientific Forecast

- *Total stratospheric abundances of ozone depleting gases is expected to maximize before the year 2000.* All other things (for example, climatic fluctuations and volcanic eruptions) being unchanged, the current ozone losses (relative to values observed in the 1970s) would be close to the maximum. These are:

  - about 6% at Northern Hemisphere midlatitudes in winter/spring,
  - about 3% at Northern Hemisphere midlatitudes in summer/fall,
  - about 5% at Southern Hemisphere midlatitudes on a year-round basis,
  - about 50% in the Antarctic spring, and
  - about 15% in the Arctic spring.

  Such changes in ozone are predicted to be accompanied by increases in surface UV-B radiation of 7,4, 6, 130, and 22%, respectively, if other influences such as clouds remain constant.

- *The vulnerable period for ozone depletion will be extended into coming decades.* The falloff of total chlorine and bromine in the stratosphere will be much slower than the rate of increase observed in past decades. Extreme perturbations, such a natural events like volcanic eruptions during this period, could enhance the ozone loss from ozone-depleting chemicals.

- *The ozone layer will slowly recover over the next 50 years.* If there is full global compliance with the current provisions of Montreal Protocol and its Amendments and Adjustments up through Montreal, 1997, the stratospheric abundance of ozone-depleting substances is expected to return to its pre-1980 (i.e., "unperturbed") level by about 2050, assuming all other things (for example, global climate) remain equal.

- *Detection of the beginning of the recovery of the ozone layer is achievable only well after the maximum stratospheric abundance of ozone-depleting gases.* Potential future increases in other gases important to ozone chemistry (such as nitrous oxide, methane, and water vapor) and climate change will influence the recovery of the ozone layer.

- *Even then, excess incidences of skin cancer will continue to long after the time that the ozone layer has recovered.* The maxima of these excess incidences may be as late as the year 2035 for cataracts and 2060 for skin cancer. This lag arises from the lag between exposure and incidence.

- *It would be very desirable to have similar quantitative predictions for the other effects associated with ozone depletion, but current knowledge is unable to do so quantitatively.* Such areas include effects on forests and food supply in agriculture, and fisheries.

2. The Technological Opportunities

- *For all sectors that used ozone-depleting substances, a range of substitutes and alternative methods has been developed.* Many new products and manufacturing equipment currently use HFCs, HCs, and other non-ozone-depleting chemicals. Exceptions can still be found, e.g., HCFC-141b is used in insulating foam, and HCFC-22 and HCFC-123 are used in stationary air conditioning and water chillers. The uses of particularly HCFC-141b and HCFC-22 for new equipment are expected to halt after the year 2001, so that thereafter the main consumer of HCFCs will be the servicing sector. However, there is still substantial production and use of CFCs in the developing countries. Economic plans to come to a closure of facilities are likely to be finalized in 1999. This will be of direct influence on the availability and cost of CFCs, their resulting use, the use of alternatives, and the emissions of CFCs to the atmosphere.

- *Discussion is continuing on cost of HFC chemicals and the manufacturing of HFC products and equipment versus the cost of other chemicals and related manufacturing costs.* The issue is very related to global warming. The technical choices in the future will likely consider the provisions of both the Montreal Protocol and the Kyoto Protocol. The Technology and Economics Panel has begun to work with the Intergovernmental Panel on Climate Change (IPCC) to assess the possible consequences to the protection of the ozone layer of the control of HFCs and PFCs by the Kyoto Protocol. It could reasonably be expected that this interaction will ultimately lead to sound advice for choices or options with the best environmental properties, given the framework of both Protocols. However, the policy discussions can take considerable time, and any potential delay in the phase-out of CFCs (or any potential move back to CFCs) would slow down the recovery of the ozone layer. The future therefore will continue to ask for substantial involvement from the entire global community to address these complex issues.

C. The World That Lies Ahead: Options For Changes

- *Options to reduce the current and near-term vulnerability to ozone depletion are very limited.* The current vulnerability over the next few decades is primarily due to past use and emissions of the long-lived ozone-depleting substances, whose slow removal from the atmosphere is by natural processes beyond effective human control. Therefore, the main drivers of ozone depletion in the near term could be natural and anthropogenic processes not related to chlorine and bromine compounds (for example, greenhouse gases and climate fluctuations), but to which the ozone layer is sensitive because of the elevated abundances of ozone-depleting substances.

- *Over the longer term, few policy options are available to enhance the recovery of the ozone layer.* Relative to the current, but not yet ratified, control measures (Montreal, 1997), some options could be considered that could lower the cumulative amount of ozone depletion from now until the 1980 ozone level is re-attained. It is this cumulative ozone loss that relates to long-term UV-B exposure, and therefore serves as a relevant measure to consider for improvement. The Scientific Assessment Panel, in their 1998 Report (see Appendix C), has calculated the percentage improvements compared to Montreal (1997) for several scenarios. Furthermore, the Technology and Economic Assessment Panel has examined the feasibility, practicality, and potential costs associated with such types of scenarios. Therefore, such combined benefit/costs information can help characterize the extent to which these scientific scenarios are indeed practical options for consideration. The results are summarized as follows:

  ◊ *Scientific Scenario*: 9% future cumulative ozone loss would be avoided if global Halon-1211 emissions were to be eliminated in the year 2000.

  Technological and Economic Perspective: TEAP and its Halon Technical Options Committee (HTOC) find that the quantity of already-produced halon 1211 exceeds foreseeable needs for critical uses and that it is technically feasible to collect halon 1211 for secure storage or destruction. However, TEAP and the HTOC urge Parties to consider the likelihood that programs that mandate halon recovery at the expense of users could result in massive venting to the atmosphere at a time that the ozone layer is most vulnerable. It should be noted that total ODP-weighted emissions of halon 1211 and halon 1301 from Article 5(1) countries now exceeds those from non-Article 5(1) countries.

  ◊ *Scientific Scenario*: 7% future cumulative ozone loss would be avoided if global Halon-1301 emissions were to be eliminated in the year 2000.

  Technological and Economic Perspective: There is no excess halon 1301. Therefore, destruction cannot be recommended. Those systems that remain are substantially non-emissive in normal circumstances; emissions due to testing and training have been virtually eliminated; and recovery of agent during servicing and decommissioning is routine. Uses still requiring halon 1301 (including aviation and some defense, oil and gas, and shipping) are being met by management of the existing inventory. The halon 1301 made available as systems are decommissioned is supplying these critical uses. The market value of recycled halon 1301 created by its need for critical uses has encouraged good conservation practices. It is important to ensure that this balance is maintained and that the halon retains its asset value. Use bans and early decommissioning requirements will likely diminish the value of the halon 1301 and discourage good conservation practices.

◊ *Scientific Scenario*: 5% future cumulative ozone loss would be avoided if global emissions of HCFCs were to be eliminated in the year 2004.

Technological and Economic Perspective: In most applications, zero-ODP alternatives to ozone-depleting substances are available. However, in some cases (including specific uses as insulating foam and refrigerants) HCFCs are either technically necessary or deliver higher energy efficiency. If further HCFC controls caused a shift to new equipment with lower energy-efficiency, implementation of the Kyoto Protocol would face additional challenges. In many developing countries, uncertainties on availability, suitability, and economical viability of certain non-HCFC alternatives are already barriers to transition and more stringent HCFC controls may hinder progress in the CFC phase-out. HCFC alternatives to CFCs were available for many applications long before substitutes for the non-ozone-depleting-substances were commercialized, and, at that time, users were encouraged to take early action to protect the ozone layer. Parties may wish to consider the advantages of assuring that sufficient HCFC supplies are available to allow reasonable economic recovery from early HCFC investments.

◊ *Scientific Scenario*: 2.5% future cumulative ozone loss would be avoided if global production of all CFCs and carbon tetrachloride were to be eliminated in the year 2004.

Technological and Economic Perspective: It is technically feasible to virtually phase-out CFC production and use by 2004. CFC use by Countries with Economies In Transition and Article 5(1) countries is continued primarily due to limits in World Bank and Multilateral Fund financing and by the ability of implementing agencies, national authorities, and companies to manage the transition. In addition, Parties are already taking technically and economically feasible steps to limit carbon tetrachloride emissions from feed stock and process agent uses but could intensify efforts to eliminate carbon tetrachloride as a solvent and in laboratory and analytical uses (currently subject to an essential use exemption). TEAP and industry sources predict that CFC essential uses in metered-dose inhalers will be minimal in non-Article 5(1) countries by 2005. However, pharmaceutical grade CFCs will still be required for oral metered dose inhalers in Article 5(1) countries.

◊ *Scientific Scenario*: 1.6% future cumulative ozone loss would be avoided if the cap on HCFC production in developing countries were to be lowered from 2.8% to 2.0% in the year 2000, if the phase-out were to be advanced from the year 2030 to 2015, and if more rapid intermediate reductions were to be instituted.

Technological and Economic Perspective: TEAP and its Technical Options Committees did not undertake detailed analysis of this option. HCFCs are now clearly identified as "transitional substitutes" under the Montreal Protocol and are generally not used where substitutes have comparable costs. Further controls on HCFCs could increase the need for additional contributions to the Multilateral Fund and World Bank. Parties may wish to consider addition efforts to support informed choices of the most environmentally acceptable technology.

◊ *Scientific Scenario*: About 1% future cumulative ozone loss would be avoided if the global production of methyl bromide were to be eliminated in 2004.

Technological and Economic Perspective: TEAP and its Methyl Bromide Technical Options Committee have previously reported that a faster phase-out of methyl bromide is technically feasible. Users of methyl bromide would benefit from early notice of new controls to accelerate implementation. Current research, demonstration, and regulatory budgets are premised on the existing controls and may need to be increased if methyl bromide controls are made more stringent under the Protocol. Training is also an important element to the current phase-out schedule and would need to be intensified if controls are made more stringent.

- *Failure to comply with the international agreements of the Montreal Protocol will affect the recovery of the ozone layer*. For example, illegal production of 20-40 ktonnes per year of CFC-12 and CFC-113 for the next 10-20 years would increase the cumulative ozone losses noted above by about 1-4%.

- *The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal Protocol and the Kyoto Protocol.* Changes in ozone affect the Earth's climate, and changes in climate and meteorological conditions affect the ozone layer, because the ozone depletion and climate change phenomena share a number of common chemical and physical processes. Hence, decisions taken (or not taken) under one Protocol have the potential to influence the aims of the other Protocol. For example, if emission changes were to be made related to the greenhouse gases methane, nitrous oxide, and carbon dioxide, they would affect the rate of recovery of the ozone layer. Similarly, if decisions were to be made regarding HFCs, it could affect the ability to phase out ozone depleting substances.

D. Epilogue

There is an understandable tendency in society to ask scientists, technologists, and economists to devote themselves to solving the identified problems of humanity. Recently, this was done quite explicitly in the Seoul Declaration for Environmental Ethics (1997). It is clear that these expert communities have lived up to this expectation in their contributions to addressing the issue of depletion of the ozone layer. However, perhaps the most noteworthy feature of the contribution of scientists was the prediction of ozone depletion long before it was measurable. Subsequently, the phenomena associated with anthropogenic emissions of chlorine and bromine compounds, ozone-layer depletion, and accompanying environmental effects has been and continue to be identified and characterized. Technical alternatives have been rapidly proposed, vetted for suitability, produced, and marketed worldwide. Relevant information is assessed by the experts as input to the Parties, industry, and the public. The 1998 reports of the Assessment Panels of the Montreal Protocol, upon which this Synthesis Report draws, are but the latest step in that service. The continued utility of such service is a goal of the participants.

Appendices

Appendix A

List of Assessment Panel Publications: 1988 - 1999

Reports prepared and published by the Scientific, Environmental Effects and Technology and Economic Assessment Panels from 1988 until 1999.

Publications for 1988

WMO, UNEP, FAA, NASA, NOAA, ***Report of the International Ozone Trends Panel-1988,*** World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 18, United Nations Environment Programme (UNEP), Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Volume I, pp. 442, 1990.

WMO, UNEP, FAA, NASA, NOAA, ***Report of the International Ozone Trends Panel-1988,*** World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 18, United Nations Environment Programme (UNEP), Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Volume II, from pp. 443-830, 1990.

Publications for 1989

WMO, UNEP, NASA, NOAA, UKDoE, ***Scientific Assessment of Stratospheric Ozone: 1989****,* World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 20, United Nations Environment Programme (UNEP), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), United Kingdom Department of the Environment (UKDoE),Volume I, pp. 486, 1990. (ISBN 92-807-1255-1).

WMO, NASA, NOAA, UKDoE, UNEP, AFEAS, ***Scientific Assessment of Stratospheric Ozone: 1989****,* World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 20, National Aeronautics and Space Administration (NASA),United Kingdom Department of the Environment (UKDoE), National Oceanic and Atmospheric Administration (NOAA),United Nations Environment Programme (UNEP), Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), Volume II, Appendix: AFEAS Report, pp. 469, 1990.
(ISBN 92- 807-1255-1).

UNEP, ***Environmental Effects Panel Report***, United Nations Environment Programme, pp. 64, 1989. (ISBN 92-807-1245-4).

UNEP, ***Economic Panel Report,*** United Nations Environment Programme, 3 Volumes, Preliminary Draft, pp. 154, 1989.

UNEP, ***Report of the Technology Review Panel,*** United Nations Environment Programme, pp. 103, June 30, 1989.

UNEP, ***CFCs for Aerosols, Sterilants and Miscellaneous Uses Technical Options Report,*** United Nations Environment Programme, pp. 64, June 30, 1989.

UNEP, ***Report of the Flexible and Rigid Foams Technical Options Committee***, United Nations Environment Programme, pp. 85, June 30, 1989.

UNEP, ***Halon Fire Extinguishing Agents Technical Options Draft Report,*** United Nations Environment Programme, pp. 70, June 30, 1989.

UNEP, ***Refrigeration, Air Conditioning and Heat Pumps Technical Options Report,*** United Nations Environment Programme, pp. 148, June 30, 1989. (ISBN 92-807-1248-9).

UNEP, ***Electronics, Degreasing and Dry Cleaning Solvents Technical Options Report,*** United Nations Environment Programme, pp. 201, June 30, 1989.

Publications for 1991

WMO, UNEP, NASA, NOAA, UKDoE, ***Scientific Assessment of Ozone Depletion: 1991,*** World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 25, United Nations Environment Programme (UNEP), United Kingdom Department of the Environment (UKDoE), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), pp. 270, 1992.

UNEP, ***Environmental Effects of Ozone Depletion: 1991 Update***, United Nations Environment Programme, pp. 52, 1991. (ISBN 92-807-1309-4).

UNEP, ***Report of the Technology and Economic Assessment Panel, 1991 Assessment,*** United Nations Environment Programme, December 1991. (ISBN 92-807-1314-0).

UNEP, ***Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee, 1991 Assessment,*** United Nations Environment Programme, pp. 103, December 1991.

UNEP, ***Report of the Economic Options Committee, 1991 Assessment,*** United Nations Environment Programme, pp. 142, December 1991.

UNEP, ***Report of the Flexible and Rigid Foams Technical Options Committee, 1991 Assessment,*** United Nations Environment Programme, December 1991.

UNEP, ***Report of the Halons Technical Options Committee,*** United Nations Environment Programme, pp. 154, December 1991.

UNEP, ***Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 1991 Assessment,*** United Nations Environment Programme, pp. 294, December 1991.

Publications for 1992

UNEP, ***Report of the Ad-Hoc Technical Advisory Committee on ODS Destruction Technologies,*** United Nations Environment Programme, pp. 152, 1992.

UNEP, ***Methyl Bromide: Its Atmospheric Science, Technology, and Economics, Montreal Protocol Assessment Supplement,*** United Nations Environment Programme, pp. 41, 1992.

Publications for 1993

UNEP, ***1993 Report of the Technology and Economic Assessment Panel,*** United Nations Environment Programme, July 1993.

UNEP, ***Recommendations on Nominations for Essential Use Production/Consumption Exemptions and International Bank Management of Halons, Prepared by the Halons Technical Options Committee,*** United Nations Environment Programme, pp. 77, 1993.

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UNEP, ***1994 Report of the Technology and Economic Assessment Panel, March 1994,*** United Nations Environment Programme, March 1994.

UNEP, ***1994 Report of the Technology and Economic Assessment Panel, 1995 Assessment,*** United Nations Environment Programme, pp. 176, 1994. (ISBN 92-807-1450-3).

UNEP, ***1994 Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee,*** United Nations Environment Programme, October 1994. (ISBN 92-807-1451-1).

UNEP, ***1994 Report of the Economics Options Committee, 1995 Assessment***,United Nations Environment Programme, 1994. (ISBN 92-807-1452-X).

UNEP, ***1994 Report of the Flexible and Rigid Foams Technical Options Committee, 1995 Assessment,*** United Nations Environment Programme, 1994. (ISBN 92-807-1453-8).

UNEP, ***Report of the Halon Fire Extinguishing Agents Technical Options Committee,*** United Nations Environment Programme, pp. 174, December 1994.

UNEP, ***1994 Report of the Methyl Bromide Technical Options Committee, 1995 Assessment,*** United Nations Environment Programme, pp. 304, 1994. (ISBN 92-807-1448-1).

UNEP, ***1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 1995 Assessment,*** United Nations Environment Programme, pp. 301, 1994. (ISBN 92-807-1455-4).

UNEP, ***1994 Report of the Solvents, Coatings and Adhesives Technical Options Committee, 1995 Assessment,*** United Nations Environment Programme, 1994. (ISBN 92-807-1456-2).

UNEP, ***1993 ODS Destruction Technology Update,*** Technology and Economic Assessment Panel, Workshop Proceedings, October 20-21, 1993, Washington, D.C., USA, United Nations Environment Programme, pp. 332, 1994.

UNEP, ***Handbook on Essential Use Nominations, prepared by the Technology and Economic Assessment Panel***, United Nations Environment Programme, pp. 43, July 1994.

Publications for 1995

WMO, UNEP, NOAA, NASA, ***Scientific Assessment of Ozone Depletion: 1994, Executive Summary***, World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 37, pp. 36, 1995 (Translated: Six Languages). (ISBN 92-807-1569-0).

UNEP, ***Supplement to the 1994 Assessments, March 1995,*** Part I: Synthesis of the Reports of the Scientific Assessment Panel and Technology and Economic Assessment Panel; Part II: Report of the Technology and Economic Assessment Panel, pp. 149; Part III: Impact of HCFC and Methyl Bromide Emissions on Ozone Depletion: A Supplement Report of the Science Asessment Panel; United Nations Environment Programme, pp. 15, March 1995. (ISBN 92-807- 1476-7).

UNEP, ***Laboratory and Analytical Uses of Ozone-Depleting Substances, Workshop Proceedings, November 29-30, 1994, Burlington, Ontario, Canada, Report of the Laboratory and Analytical Uses Working Group of the TEAP,*** United Nations Environment Programme, pp. 229, February 1995.

UNEP, ***Evaluation of the Use of Ozone Depleting Substances as Chemical Process Agents and Alternatives, Report of the Chemical Process Agents Working Group of the TEAP,*** United Nations Environment Programme, pp. 48, 1995. (ISBN 92-807-1486-4)

UNEP, ***Assessment of Basic Problems Confronting Countries with Economies in Transition in Complying with the Montreal Protocol, Report of the TEAP Ad-Hoc Working Group on CEIT Aspects,*** United Nations Environment Programme, pp. 153, November 1995. (ISBN 92-807-1533-X).

UNEP, ***Technology and Economic Assessment Panel Report to the Parties***, *November 1995,* Part I: Economic and Financial Implications of Methyl Bromide Control Scenarios for Article 5(1) Countries; Part II: Economic and Financial Implications of Hydrochlorofluorocarbon Control Scenarios for Article 5(1) Countries; Part III: Economic and Financial Implications of CFC, Halon, Carbon Tetrachloride, and 1,1,1, trichloroethane Control Scenarios for Article 5(1) Countries; Part IV: Economic and Financial Implications of Trade in Annex A and Annex B Substances to Article 5(1) Countries After 1995, United Nations Environment Programme, November 1995.

Publications for 1996

UNEP, ***Technology and Economic Assessment Panel,*** *March 1996 Report,* Part I: Requests by Parties and TEAP Organization and Functioning; Part II: Essential Use Nominations; United Nations Environment Programme, pp. 25, March 1996. (ISBN 92-807-1582-8).

UNEP, ***Technology and Economic Assessment Panel,*** *June 1996 Report,* Part I: Assessment of the Funding Requirement for the Replenishment of the Multilateral Fund for the Period 1997-99; Part II: Phaseout Schedules for the Controlled Substances under the Montreal Protocol; Part III: Update on the 1994 TOC Aerosols Report and the MDI Transition Strategy; Part IV: Methyl Bromide Studies; Part V: Miscellaneous Issues; Part VI: Technology and Economic Assessment Panel Activities, Update and Terms of Reference for Operation; United Nations Environment Programme, pp. 162, June 1996. (ISBN 92-807- 1593-1).

WMO, UNEP, ***Report of the Third Meeting of the Ozone Research Managers of the Parties to the Vienna Convention for the Protection of the Ozone Layer***, World Meteorological Organization, United Nations Environment Programme, WMO Global Ozone Research and Monitoring Project-Report No. 41, 1996.

UNEP, ***Final Report of the TEAP Task Force on CEIT Aspects,*** United Nations Environment Programme, pp. 62, November 1996. (ISBN 92-807-1629-8).

Publications for 1997

UNEP, ***Technology and Economic Assessment Panel,*** *April 1997 Report,* Part I: Essential Use Nominations; Part II: The MBTOC April 1997 Progress Report to TEAP and

Miscellaneous Methyl Bromide Issues; Part III: TOC Progress Reports and Specific Progress Issues, Possible Applications of HCFCs, Executive Summaries of Volume II Reports; Part IV: Progress on the Restructuring of the Technology and Economic Assessment Panel, TEAP Membership Background Information, Contact Information for TEAP Members and TOCs; United Nations Environment Programme, Volume I, pp. 221, April 1997. (ISBN 92-807-1654-8).

UNEP, ***Technology and Economic Assessment Panel,*** Part I: Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride TOC, Update on Developments, Issues Surrounding a Transition to Non-CFC Treatments, Evaluation of Status of Use of ODS and Alternatives; Part II: Report of the Process Agents Task Force; Part III: Assessment of the Use of Flammable Refrigerants; Part IV: Assessment of the Economic Viability of Methyl Bromide Alternatives; United Nations Environment Programme, Volume II, pp. 311, April 1997. (ISBN 92-807-1655-6).

UNEP, ***Handbook on Essential Use Nominations prepared by the Technology and Economic Assessment Panel,*** United Nations Environment Programme, pp. 51, August 1997.

Publications for 1998

WMO, UNEP, NOAA, NASA, EC, ***Scientific Assessment of Ozone Depletion: 1998***, World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 44, United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), European Commission (EC), Vol. I, pp. 328, 1998 (with Translated Summary in the Synthesis of the reports). (ISBN 92-807-1722-7).

WMO, UNEP, NOAA, NASA, EC, ***Scientific Assessment of Ozone Depletion: 1998***, World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 44, United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), European Commission (EC), Vol. II, pp. 414, 1998. (ISBN 92-807-1722-7).

WMO, UNEP, NOAA, NASA, EC, ***Scientific Assessment of Ozone Depletion: 1998***, World Meteorological Organization, Global Ozone Research and Monitoring Project-Report No. 44, United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), European Commission (EC), pp. 732, 1999. (ISBN 92-807-1722-7).

UNEP, ***Environmental Effects of Ozone Depletion: 1998 Assessment***, United Nations Environment Programme, pp. 192, 1998 (with Translated Summary in the Synthesis of the reports). (ISBN 92-807-1724-3).

UNEP, ***April Report of the 1998 Technology and Economic Assessment Panel,*** United Nations Environment Programme, pp. 191, April 1998. (ISBN 92-807-1704-9).

UNEP, ***1998 Report of the Technology and Economic Assessment Panel, 1998 Assessment,*** United Nations Environment Programme, pp. 286, 1998 (with Translated Summary in the Synthesis of the reports). (ISBN 92-807-1725-1)

UNEP, ***1998 Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride Technical Options Committee, 1998 Assessment,*** United Nations Environment Programme, 1998. (ISBN 92-807-1726-X).

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UNEP, ***1998 Report of the Halon Fire Extinguishing Agents Technical Options Committee, 1998 Assessment,*** United Nations Environment Programme, 1998. (ISBN 92-807-1729-4).

UNEP, ***Report of the Methyl Bromide Technical Options Committee, 1998 Assessment of Alternatives to Methyl Bromide***, United Nations Environment Programme, 1998. (ISBN 92-807-1730-8).

UNEP, ***1998 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 1998 Assessment,*** United Nations Environment Programme, pp. 285, 1998. (ISBN 92-807-1731-6).

UNEP, ***1998 Report of the Solvents, Coatings and Adhesives Technical Options Committee, 1998 Assessment,*** United Nations Environment Programme, 1998. (ISBN 92-807-1732-4).

UNEP, ***Synthesis of the Reports of the Scientific, Environmental Effects, and Technology and Economic Assessment Panels of the Montreal Protocol.*** A Decade of Assessments for Decision Makers Regarding the Protection of the Ozone Layer: 1988 – 1999, pp. 161, 1999. (ISBN 92-807-1733-2).

Appendix B

List of Participants Contributing to the Assessment Panels' Reports: 1988 - 1999

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Part 2. Advances in Understanding the Processes Involved

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Part 3. Impacts of Ozone Changes

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Chapter 11. Halocarbon Scenarios for the Future Ozone Layer and Related Consequences
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Chapter 12. Predicting Future Ozone Changes and Detection of Recovery
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Executive Summary of the 1998 Report of the Scientific Assessment Panel

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer commemorated its 10th anniversary in September 1997. Among the provisions of the Protocol was the requirement that the Parties to the Protocol base their future decisions on the available scientific, environmental, technical, and economic information as assessed by the worldwide expert communities. The advances of the understanding in ozone science over this decade were assessed in 1988, 1989, 1991, and 1994. This information was input to the subsequent Amendments and Adjustments of the 1987 Protocol. The Assessment summarized here is the fifth in that series.

Recent Major Scientific Findings and Observations

Since the *Scientific Assessment of Ozone Depletion: 1994*, significant advances have continued to be made in the understanding of the impact of human activities on the ozone layer, the influence of changes in chemical composition on the radiative balance of the Earth's climate, and, indeed, the coupling of the ozone layer and the climate system. Numerous laboratory investigations, atmospheric observations, and theoretical and modeling studies have produced several key ozone- and climate-related findings:

- **The total combined abundance of ozone-depleting compounds in the lower atmosphere peaked in about 1994 and is now slowly declining. Total chlorine is declining, but total bromine is still increasing.** As forecast in the 1994 Assessment, the long period of increasing total chlorine abundances – primarily from the chlorofluorocarbons (CFCs), carbon tetrachloride, (CCl_4) and methyl chloroform (CH_3CCl_3) – has ended. The peak total tropospheric chlorine abundance was 3.7 ± 0.1 parts per billion (ppb) between mid-1992 and mid-1994. The declining abundance of total chlorine is due principally to reduced emissions of methyl chloroform. Chlorine from the major CFCs is still increasing slightly. The abundances of most of the halons continue to increase (for example, Halon-1211, almost 6% per year in 1996), but the rate has slowed in recent years. These halon increases are likely to be due to emissions in the 1990s from the halon "bank," largely in developed countries, and new production of halons in developing countries. The observed abundances of CFCs and chlorocarbons in the lower atmosphere are consistent with reported emissions.

- **The observed abundances of the substitutes for the CFCs are increasing.** The abundances of the hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are increasing as a result of a continuation of earlier uses and of their use as substitutes for the CFCs. In 1996, the HCFCs contributed about 5% to the tropospheric chlorine from the long-lived gases. This addition from the substitutes offsets some of the decline in tropospheric chlorine associated with methyl chloroform, but is nevertheless about 10 times less than that from the total tropospheric chlorine growth rate throughout the 1980s. The atmospheric abundances of HCFC-141b and HCFC-142b calculated from reported emissions data are factors of 1.3 and 2, respectively, smaller than observations. Observed and calculated abundances agree for HCFC-22 and HFC-134a.

- **The combined abundance of stratospheric chlorine and bromine is expected to peak before the year 2000.** The delay in this peak in the stratosphere compared with the lower atmosphere reflects the average time required for surface emissions to reach the lower stratosphere. The observations of key chlorine compounds in the stratosphere up through the present show the expected slower rate of increase and show that the peak had not occurred at the time of the most recent observations that were analyzed for this Assessment.

- **The role of methyl bromide as an ozone-depleting compound is now considered to be less than was estimated in the 1994 Assessment, although significant uncertainties remain.** The current best estimate of the Ozone Depletion Potential (ODP) for methyl bromide (CH_3Br) is 0.4, compared with an ODP of 0.6 estimated in the previous Assessment. The change is due primarily to both an increase in the estimate of ocean removal processes and the identification of an uptake by soils, with a smaller contribution from the change in our estimate of the atmospheric removal rate. Recent research has shown that the science of atmospheric methyl bromide is complex and still not well understood. The current understanding of the sources and sinks of atmospheric methyl bromide is incomplete.

- **The rate of decline in stratospheric ozone at midlatitudes has slowed; hence, the projections of ozone loss made in the 1994 Assessment are larger than what has actually occurred.** Total column ozone decreased significantly at midlatitudes (25–60^0) between 1979 and 1991, with estimated linear downward trends of 4.0, 1.8, and 3.8% per decade, respectively, for northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and southern midlatitudes year round. However, since 1991 the linear trend observed during the 1980s has not continued, but rather total column ozone has been almost constant at midlatitudes in both hemispheres since the recovery from the 1991 Mt. Pinatubo eruption. The observed total column ozone losses from 1979 to the period 1994–1997 are about 5.4, 2.8, and 5.0%, respectively, for northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and southern midlatitudes year round, rather than the values projected in the 1994 Assessment assuming a linear trend: 7.6, 3.4, and 7.2%, respectively. The understanding of how changes in stratospheric chlorine/bromine and aerosol loading affect ozone suggests some of the reasons for the unsuitability of using a linear extrapolation of the pre-1991 ozone trend to the present.

- **The link between the long-term build-up of chlorine and the decline of ozone in the upper stratosphere has been firmly established.** Model predictions based on the observed build-up of stratospheric chlorine in the upper stratosphere indicate a depletion of ozone that is in good quantitative agreement with the altitude and latitude dependence of the measured ozone decline during the past several decades, which peaks at about 7% per decade near 40 km at midlatitudes in both hemispheres.

- **The springtime Antarctic ozone hole continues unabated.** The extent of ozone depletion has remained essentially unchanged since the early 1990s. This behavior is expected given the near-complete destruction of ozone within the Antarctic lower stratosphere during springtime. The factors contributing to the continuing depletion are well understood.

- **The late-winter/spring ozone values in the Arctic were unusually low in 6 out of the last 9 years, the 6 being years that are characterized by unusually cold and protracted stratospheric winters.** The possibility of such depletions was predicted in the 1989 Assessment. Minimum Arctic vortex temperatures are near the threshold for large chlorine activation. Therefore, the year-to-year variability in temperature, which is driven by meteorology, leads to particularly large variability in ozone for current chlorine loading. As a result, it is not possible to forecast the behavior of Arctic ozone for a particular year. Elevated stratospheric halogen abundances over the next decade or so imply that the Arctic will continue to be vulnerable to large ozone losses.

- **The understanding of the relation between increasing surface UV-B radiation and decreasing column ozone has been further strengthened by ground-based observations, and newly developed satellite methods show promise for establishing global trends in UV radiation.** The inverse dependence of surface UV radiation and the overhead amount of ozone, which was demonstrated in earlier Assessments, has been further demonstrated and quantified by ground-based measurements under a wide range of atmospheric conditions. In addition, the influences of other variables, such as clouds, particles, and surface reflectivity, are better understood. These data have assisted the development of a satellite-based method to estimate global UV changes, taking into account the role of cloud cover. The satellite estimates for 1979–1992 indicate that the largest UV increases occur during spring at high latitudes in both hemispheres.

- **Stratospheric ozone losses have caused a cooling of the global lower stratosphere and global-average negative radiative forcing of the climate system.** The decadal temperature trends in the stratosphere have now been better quantified. Model simulations indicate that much of the observed downward trend in lower stratospheric temperatures (about 0.6°C per decade over 1979-1994) is attributed to the ozone loss in the lower stratosphere. A lower stratosphere that is cooler results in less infrared radiation reaching the surface/troposphere system. Radiative calculations, using extrapolations based on the ozone trends reported in the 1994 Assessment for reference, indicate that stratospheric ozone losses since 1980 may have offset about 30% of the positive forcing due to increases in the well-mixed greenhouse gases (i.e., carbon dioxide, methane, nitrous oxide, and the halocarbons) over the same time period. The climatic impact of the slowing of midlatitude ozone trends and the enhanced ozone loss in the Arctic has not yet been assessed.

- **Based on past emissions of ozone-depleting substances and a projection of the maximum allowances under the Montreal Protocol into the future, the maximum ozone depletion is estimated to lie within the current decade or the next two**

decades, but its identification and the evidence for the recovery of the ozone layer lie still further ahead. The falloff of total chlorine and bromine abundances in the stratosphere in the next century will be much slower than the rate of increase observed in past decades, because of the slow rate at which natural processes remove these compounds from the stratosphere. The most vulnerable period for ozone depletion will be extended into the coming decades. However, extreme perturbations, such as natural events like volcanic eruptions, could enhance the loss from ozone-depleting chemicals. Detection of the beginning of the recovery of the ozone layer could be achievable early in the next century if decreasing chlorine and bromine abundances were the only factor. However, potential future increases or decreases in other gases important in ozone chemistry (such as nitrous oxide, methane, and water vapor) and climate change will influence the recovery of the ozone layer. When combined with the natural variability of the ozone layer, these factors imply that unambiguous detection of the beginning of the recovery of the ozone layer is expected to be well after the maximum stratospheric loading of ozone-depleting gases.

Supporting Scientific Evidence and Related Issues

RECENT HALOGEN AND METHANE CHANGES

- Tropospheric abundances of total organic chlorine (Cl) contained in long- and short-lived halocarbons reached maximum values of 3.7 ± 0.1 parts per billion (ppb) between mid-1992 and mid-1994 and are beginning to decrease slowly in the global troposphere. The decline in the tropospheric abundance of methyl chloroform (CH_3CCl_3) (at a rate of about 40 to 42 parts per trillion (ppt) Cl yr^{-1} in 1996) is the principal cause of the decrease and reversal in the Cl growth rate. At the same time, chlorine from the sum of the major CFCs grew at 7 ppt Cl yr^{-1} (CFC-12, 9 ppt Cl yr^{-1}; CFC-11, -2 ppt Cl yr^{-1}; CFC-113, 0 ppt Cl yr^{-1}) and by 10 ppt Cl yr^{-1} from the three major hydrochlorofluorocarbons (HCFCs) (HCFC-22, 5 ppt Cl yr^{-1}; HCFC-141b, 4 ppt Cl yr^{-1}; HCFC-142b, 1 ppt Cl yr^{-1}). The rate of decay of CH_3CCl_3 is expected to slow down to less than 10 ppt Cl yr^{-1} by 2005. By that point its concentration should be so small that it will no longer be an important contributor to atmospheric organic chlorine.

- Space-based remote measurements of hydrogen chloride (HCl), hydrogen fluoride (HF), and total chlorine in the stratosphere, as well as column abundances of HCl, chlorine nitrate ($ClONO_2$), HF, and carbonyl difluoride (COF_2) from the ground, are consistent with the content and rate of change of the total organic chlorine and fluorine abundance of the troposphere. These observations provide evidence that the rate of increase of stratospheric chlorine loading has slowed in recent years.

- Growth in the tropospheric concentrations of HCFCs and hydrofluorocarbons (HFCs) has been observed as expected from continuation of previous uses and from their use as replacements for chlorofluorocarbons (CFCs). Emissions calculated by industry from sales and use data are in accordance with the current global abundances of HCFC-22 and HFC-134a. For HCFC-141b and -142b, the industry data underestimate the current global abundances by factors of approximately 1.3 and 2, respectively. No production and sales data are currently available for other HCFCs and HFCs being used as CFC alternatives.

- New studies suggest a major reduction in the magnitude of the estimated oceanic source of methyl chloride (CH_3Cl). As a result, the sum of known sources is inadequate to explain the observed atmospheric burden of CH_3Cl, thus requiring a larger contribution from other sources, either natural or anthropogenic.

- Tropospheric bromine loading continues to rise largely because of the ongoing growth of Halon-1211 (almost 6% yr^{-1}), Halon-2402 (2% yr^{-1}), and Halon-1301 (1% yr^{-1}). Possible causes are the large “banking” in developed countries of that compound during the 1980s and its subsequent use and release during the 1990s, and new production in developing countries. Continued increases of halons over the next few years could cause the abundance of equivalent chlorine to decline more slowly than predicted in the 1994 Assessment.

- Recent measurements and intercomparisons of calibration standards have confirmed that the average global mixing ratio of methyl bromide (CH_3Br) is between 9 and 10 ppt and that the interhemispheric ratio is 1.3 ± 0.1 (north/south). New estimates of methyl bromide losses yield magnitudes of 77 Gg yr^{-1} (ranging from 37 to 133 Gg yr^{-1}) for ocean uptake; 42 Gg yr^{-1} (ranging from 10 to 214 Gg yr^{-1}) for soil uptake; and 86 Gg yr^{-1} (ranging from 65 to 107 Gg yr^{-1}) for removal by hydroxyl radical (OH), for a total removal rate of 205 Gg yr^{-1} with a range of about 110 to 450 Gg yr^{-1}. The current best estimate of the lifetime of atmospheric CH_3Br, as calculated from losses within the atmosphere, to the ocean, and to soils, is 0.7 years, with a range of 0.4 to 0.9 years. The Ozone Depletion Potential (ODP) of methyl bromide is 0.4, with a range of 0.2 to 0.5.

- No new important sources of methyl bromide have been identified. The ocean now appears to be a net sink, with an estimated net flux from the atmosphere of -21 Gg yr^{-1} (ranging from -3 to -32 Gg yr^{-1}). Estimates of ocean emissions of order 60 Gg yr^{-1} can be directly deduced from the above estimates for uptake and net ocean flux. The total emission of CH_3Br from identified sources is 122 Gg yr^{-1}, with a range of 43 to 244 Gg yr^{-1}. The best-quantified source is fumigation, with a magnitude of 41 Gg yr^{-1} and a range of 28 to 64 Gg yr^{-1}. Other anthropogenic sources include biomass burning (20 Gg yr^{-1}, ranging from 10 to 40 Gg yr^{-1}) and leaded gasoline use (5 Gg yr^{-1}, ranging from negligible to 10 Gg yr^{-1}). Identified sources of CH_3Br thus constitute only about 60% of identified sinks on a globally averaged basis. This disagreement is difficult to reconcile with estimated uncertainties in the source and sink terms. The short lifetime of methyl bromide, coupled with the inhomogeneity of its sources and sinks, complicates the interpretation of its global budget.

- Based on the most recent analysis of the methyl chloroform (CH_3CCl_3) observational record (including a refinement in calibration), the estimated atmospheric lifetimes (with respect to reactive removal by OH) of CH_3CCl_3, HCFCs, HFCs, and CH_4 have been reduced by about 15% since the 1994 Assessment. The 1995 assessment of the Intergovernmental Panel on Climate Change (IPCC) mostly reflected these revisions, with a slightly smaller correction factor of about 10%. For species whose chemical lifetime is shorter than 1 to 2 years, the use of a global-mean lifetime may not be appropriate.

- The atmospheric abundance of CH_4 continues to increase, but with a declining growth rate. The average growth rate between 1980 and 1992 of about 10 ppb yr^{-1} can be compared with the 1996-1997 rate of approximately 3 to 4 ppb yr^{-1}. The current best estimate for the total atmospheric lifetime of methane has been lowered to 8.9 ± 0.6 years.

STRATOSPHERIC PARTICLES

- Observations and models have further confirmed that stratospheric sulfate aerosol (SSA) and polar stratospheric clouds (PSCs) play a key role in ozone loss chemistry through heterogeneous reactions that activate halogen species and deactivate nitrogen species.

- Observations have increased our knowledge of particle formation processes, the dispersal and decay of volcanic SSA, and particle climatology. They show that supercooled ternary solution (STS) droplets that form from SSA without a nucleation barrier are an important class of PSC particles. The formation processes of solid PSC particles that play a significant role in denitrification of the polar vortices remain uncertain. Recent studies suggest that mesoscale temperature fluctuations, especially over mountain ranges, may be important in PSC formation processes, particularly in the Arctic.

- The two most recent major volcanic eruptions, El Chichón (1982) and Mt. Pinatubo (1991), both temporarily increased SSA amounts by more than an order of magnitude.

- There is no clear trend in SSA abundances from 1979 to 1997, demonstrating that any anthropogenic contribution must be smaller than thought in the 1994 Assessment. SSA models including known tropospheric sulfur sources underpredict 1979 values, which were thought to represent the non-volcanic background, but it is not clear that this period was truly free of volcanic influence.

OZONE IN THE MIDLATITUDES AND TROPICS

- As noted in the 1994 Assessment, Northern Hemisphere midlatitude column ozone decreased markedly in 1992-1993, following the large enhancement of stratospheric aerosol caused by the eruption of Mt. Pinatubo in 1991. Column ozone has now reached amounts higher than a linear extrapolation of the pre-Pinatubo trend would predict. Between 25 and 60°N, ozone abundances for 1994–1997 averaged about 4% below 1979 values, although with large variability, while extrapolation of the pre-1991 trend would predict current (1997) abundances about 5.5% below 1979 values. The corresponding winter/spring and summer/fall losses average about 5.4 and 2.8%, respectively, while a linear extrapolation would predict 7.6 and 3.4%, respectively. The average ozone abundances between 25 and 60°S are currently about 4% (satellite) or 5% (ground) below 1979 values, while the linear extrapolation would predict 7.2% (both satellite and ground).

- Our understanding of how changes in halogen and aerosol loading affect ozone suggests some of the reasons for the unsuitability of using a linear extrapolation of the pre-1991 ozone trend to the present. For example, observations of stratospheric HCl and $ClONO_2$ show a build-up of stratospheric chlorine in recent years consistent with halocarbon emissions, but slower than would have been predicted by the chlorine trends observed before 1992. In addition, enhanced stratospheric aerosol was also present throughout much of the decade of the 1980s due to earlier volcanic eruptions (e.g., El Chichón and Ruiz), likely enhancing the downward trend of ozone observed even before Pinatubo.

- There are no statistically significant trends in total ozone in the equatorial regions (20°S to 20°N).

- The amplitude of the annual cycle of ozone at middle to high latitudes has decreased by approximately 15% in the last decades because larger declines have occurred during the season of maximum ozone values.

- For northern midlatitudes, combined vertical profile ozone trends through 1996 are negative at all altitudes between 12 and 45 km and are statistically significant at the 2σ level. The downward trend is largest near 40 and 15 km (approximately 7% per decade) and is smallest at 30 km (2% per decade). The bulk of column ozone decline is between the tropopause and 25 km.

- The reevaluation of the Stratospheric Aerosol and Gas Experiment (SAGE) I/II satellite data indicates that there are no significant interhemispheric differences in upper stratospheric trends through 1996. Agreement is good within estimated uncertainties, between SAGE I/II and ozonesonde trends in the lower to middle stratosphere in northern midlatitudes.

- The total ozone and the vertical profile trends derived for the northern midlatitudes are consistent with each other over the periods studied.

- Most of the midlatitude column ozone decline during the last two decades arose because of depletion in the lower stratosphere. That region is influenced by local chemical ozone loss that is enhanced by volcanic aerosol, and by transport from other regions. The vertical, latitudinal, and seasonal characteristics of the depletion of midlatitude ozone are broadly consistent with the understanding that halogens are the primary cause. The expected low ozone amounts in the midlatitude lower stratosphere following the Mt. Pinatubo eruption further strengthened the connection between ozone destruction and anthropogenic chlorine.

- Models that represent processes affecting ozone are able to calculate variations in ozone abundances that are broadly consistent with the observed midlatitude column ozone trend as well as the response to volcanic enhancement of stratospheric sulfate aerosol. In particular, models reproduce the lower ozone abundances observed immediately following Mt. Pinatubo and the subsequent increases as the aerosol disappeared.

- Current two-dimensional (2-D) assessment models that allow for the observed build-up of stratospheric chlorine calculate reductions in ozone that are in good quantitative agreement with the altitude and latitude dependence of the measured decline in upper stratospheric ozone during the past several decades. This clearly confirms the hypothesis put forth in 1974 that release of CFCs to the atmosphere would lead to a significant reduction of upper stratospheric ozone, with the peak percentage decline occurring around 40 km.

- Comparison of recent observations and model results shows that the overall partitioning of reactive nitrogen and chlorine species is well understood for the upper stratosphere. The previously noted discrepancy for the chlorine monoxide/hydrogen chloride (ClO/HCl) ratio has been resolved based on new kinetic information. Balloonborne observations of OH and hydroperoxyl radicals (HO_2) agree well with theory, but satellite and ground-based observations of these species exhibit systematic differences compared with model calculations.

- An improved understanding of the relevant kinetic processes has resulted in a close balance between the calculated production and loss of ozone at 40 km (i.e., the long-standing difference between calculated and observed ozone abundance has been mostly resolved).

- Constituent measurements show that the tropics are relatively isolated from midlatitudes in the lower stratosphere. The extent of isolation affects the budgets (and lifetimes) of chemical species that affect ozone abundance.

OZONE IN HIGH-LATITUDE POLAR REGIONS

- The large ozone losses in the Southern Hemisphere polar region during spring continued unabated with approximately the same magnitude and areal extent as in the early 1990s. In Antarctica, the monthly total ozone in September and October has continued to be 40 to 55% below the pre-ozone-hole values of approximately 320 m-atm cm ("Dobson units"), with up to a 70% decrease for periods of a week or so. This depletion occurs primarily over the 12- to 20-km altitude range, with most of the ozone in this layer disappearing during early October. These ozone changes are consistent overall with our understanding of chemistry and dynamics.

- In the Arctic vortex, low column ozone values were observed in the late-winter/spring for 6 out of the last 9 years. Monthly mean values were about 100 m-atm cm below 1960–1970 averages, with shorter-period differences exceeding 200 m-atm cm (equivalent to about 20 to 45% of values found in the 1960s and early 1970s). Within the column, the largest ozone differences were observed in the lower stratosphere.

- Years with large seasonal ozone depletion in the late-winter/spring Arctic are characterized by specific meteorological conditions. These conditions are lower-than-normal late-winter Arctic temperatures, which lead to enhanced activated chlorine, and a more isolated vortex and weaker planetary-wave driving, which lead to less transport of ozone-rich air into the Arctic. Low temperatures, an isolated vortex, and reduced wave driving are coupled processes that occur in concert in the stratosphere. Chemical ozone losses have been identified within the Arctic vortex and are associated with activated chlorine augmented by bromine. The total seasonal chemical ozone losses within the vortex have been estimated to be approximately 100 m-atm cm.

- With the present high abundances of chlorine loading, late-winter/spring Arctic chemical ozone loss is particularly sensitive to meteorological conditions (temperature and vortex isolation) because minimum vortex temperatures are at a critical value in terms of activating chlorine. Winter vortex temperatures in the 1990s have been particularly low. In the absence of low temperatures and an isolated vortex, reduced chemical ozone loss would be expected. However, such a reduced ozone loss would not indicate chemical recovery. The Arctic will remain vulnerable to extreme seasonal loss as long as chlorine loading remains high.

- Chlorine activation in liquid particles in the lower stratosphere (both SSA and liquid PSCs) increases strongly with decreases in temperature and is at least as effective as that on solid particles. Thus, chlorine activation is to a first approximation controlled by temperature and water vapor pressure and only secondarily by particle composition.

- Rapid polar ozone loss requires enhanced chlorine monoxide in the presence of sunlight. Maintenance of elevated ClO in late-winter/spring is dependent upon temperature and requires either repeated heterogeneous processing or denitrification. Since the 1994 Assessment, new understanding has shown that cold liquid aerosol can maintain elevated ClO in non-denitrified air.

STRATOSPHERIC TEMPERATURES

- Radiosonde and satellite observations indicate a decadal cooling trend of the global, annual-mean lower stratosphere (approximately 16 to 21 km) since about 1980. Over the period 1979 to 1994, its amplitude is approximately 0.6°C per decade. At midlatitudes the trend is larger (approximately 0.75°C per decade) and broadly coherent among the various datasets with regard to the magnitude and statistical significance.

- Substantial cooling (approximately 3°C per decade) is observed in the polar lower stratosphere during late-winter/spring in both hemispheres. A decadal-scale cooling is evident in the Antarctic since the early 1980s and in the Arctic since the early 1990s. However, the dynamical variability is large in these regions, particularly in the Arctic, and this introduces difficulties in establishing the statistical significance of trends.

- The vertical profile of the annual-mean stratospheric temperature change observed in the Northern Hemisphere midlatitudes is robust for the 1979–1994 period within the different datasets. The trend consists of an approximately 0.75°C per decade cooling of the 15- to 35-km region, a slight reduction in the cooling at about 35 km, and increased cooling with height above 35 km (approximately 2°C per decade at 50 km).

- Model simulations based on known changes in the stratospheric concentrations of various radiatively active species indicate that the depletion of lower stratospheric ozone is the dominant radiative factor in the explanation of the observed global-mean lower stratospheric cooling trends for the period 1979–1990 (approximately 0.5°C per decade). The contribution to these trends from increases in well-mixed greenhouse gases is estimated to be less than one-fourth that due to ozone loss.

- Model simulations indicate that ozone depletion is an important causal factor in the latitude-month pattern of the decadal (1979–1990) lower stratospheric cooling. The simulated lower stratosphere in Northern and Southern Hemisphere midlatitudes and in the Antarctic springtime generally exhibit a statistically significant cooling trend over this period consistent with observations.

- In the middle and upper stratosphere, both the well-mixed greenhouse gases and ozone change contribute in an important manner to the cooling. However, the computed cooling due to these gases underestimates the observed decadal trend.

TROPOSPHERIC OZONE

- Trends in tropospheric ozone since 1970 in the Northern Hemisphere show large regional differences, with increases in Europe and Japan, decreases in Canada, and only small changes in the United States. The trend in Europe since the mid-1980s has reduced to virtually zero (at two recording stations). In the Southern Hemisphere, small increases have now been observed in surface ozone.

- Recent field studies have shown that anthropogenic emissions of ozone precursors (nitrogen oxides, carbon monoxide, and hydrocarbons) lead to large-scale production of ozone, which, through long-range transport, influences the ozone concentration in large regions of the troposphere in both hemispheres. However, significant uncertainties remain in the budget of tropospheric ozone, its precursors, and the chemical and physical processes involved. Large spatial and temporal variability is observed in tropospheric ozone, resulting from important regional differences in the factors controlling its concentration.

- Important improvements in global chemical transport models (CTMs) have allowed better simulations of tropospheric ozone distributions and of ozone perturbations resulting from anthropogenic emissions.

- Considerable progress has been made in testing tropospheric photochemistry through field measurements. Our theoretical understanding of tropospheric OH is nevertheless incomplete, specifically in regard to sources of upper tropospheric OH and polluted conditions.

- Increases in air traffic and the resulting emissions could have impacts on atmospheric chemistry and cloud formation, with implications for the ozone layer and the climate system. The understanding of the effects of aircraft emissions are currently being assessed as part of the Intergovernmental Panel on Climate Change (IPCC) special report *Aviation and the Global Atmosphere: 1999*. Consequently, this topic is not included in the scope of the present Assessment.

CHANGES IN UV RADIATION

- The inverse correlation between ozone column amounts and ultraviolet-B (UV-B) irradiance has been reconfirmed and firmly established by numerous ground-based measurements. The ground-based measurements have increased our understanding of additional effects such as albedo, altitude, clouds and aerosols, and geographic differences on UV irradiance at the Earth's surface.

- A controversy concerning anomalous UV-trend estimates from the Robertson-Berger (RB) meter network located in the continental United States. (1974–1985) has been explained in terms of poor calibration stability. The reanalysis of this U.S. RB-meter dataset shows that the errors are too large for determining UV-irradiance trends over that period.

- Increases in UV-B irradiance (e.g., 1989–1997; 1.5% yr^{-1} at 300 nm, 0.8% yr^{-1} at 305 nm) have been detected with a few ground-based spectroradiometers at midlatitudes (near 40°) and are consistent with expected changes from the decreasing amounts of ozone. Although these UV changes are consistent with those estimated from satellite data, the ground-based data records from suitably stable and calibrated instruments are not yet long enough to determine decadal trends. Local irradiance changes, not seen in the coarse-spatial-resolution satellite data, caused by pollution and aerosols have been detected in both UV-B (280 to 315 nm) and UV-A (315 to 400 nm).

- New satellite estimates of global (±65°) UV irradiance that now include cloud, surface reflectivity, and aerosol effects have been estimated from measured backscattered radiances from the Total Ozone Mapping Spectrometer (TOMS) using radiative transfer models. Climatological maps of UV irradiance can be produced from the daily data. In addition, the satellite data have been used to estimate zonally averaged global and seasonal trends in UV irradiance from 1979 to 1992. For this period, annual erythemal UV-irradiance decadal increases were estimated to be 3.7 ± 3% at 60°N and 3 ± 2.8% at 40°N. Larger decadal increases were observed in the Southern Hemisphere: 3.6 ± 2% at 40°S and 9 ± 6% at 60°S. No statistically significant trends were observed between ±30° latitude. Zonally averaged UV-A irradiances have not changed.

- Current zonal-average UV-irradiance trend estimations from satellite data that include cloud effects are nearly identical to clear-sky estimates. The currently estimated trends are slightly lower than the clear-sky trend estimates in the 1994 Assessment because of the new TOMS retrieval algorithm.

- Instrument intercomparison and newly developed calibration and database centers have improved the quality and availability of ground-based data.

CHANGES IN CLIMATE PARAMETERS

- Increased penetration of UV radiation to the troposphere as a result of stratospheric ozone depletion influences key photochemical processes in the troposphere. Model results suggest that a 1% decrease in global total ozone leads to a global increase of 0.7 to 1% in globally averaged tropospheric OH, which would affect the lifetimes of several climate-related gases.

- The global average radiative forcing due to changes in stratospheric ozone since the late 1970s, using extrapolations based on the ozone trends reported in the 1994 Assessment for reference, is estimated to be -0.2 ± 0.15 W m^{-2}, which offsets about 30% of the forcing due to increases in other greenhouse gases over the same period. The climatic impact of the slowing of midlatitude trends and the enhanced ozone loss in the Arctic has not yet been assessed. Recovery of stratospheric ozone would reduce the offset to the radiative forcing of the other greenhouse gases. The ozone recovery will therefore lead to a more rapid increase in radiative forcing than would have occurred due to increases in other greenhouse gases alone.

- The global average radiative forcing due to increases in tropospheric ozone since preindustrial times is estimated to be $+0.35 \pm 0.15$ Wm^{-2}, which is about 10 to 20% of the forcing due to long-lived greenhouse gases over the same period.

- Coupled ocean-atmosphere general circulation models (GCMs) have been used to calculate the impact of stratospheric ozone loss on the thermal structure of the atmosphere. The calculated altitude of the transition from tropospheric warming to stratospheric cooling due to increases in well-mixed greenhouse gases is in better agreement with observations when ozone depletion is taken into account.

- Radiative forcings and Global Warming Potentials (GWPs) are now available for an expanded set of gases. New categories include fluorinated organic molecules. The CFC-11 radiative forcing has been revised by +12% from the value used since IPCC (1990), primarily because of the use of an improved vertical profile of CFC-11 mixing ratio. This and other updates lead to GWPs relative to CO_2 that are typically 20% higher than those in IPCC (1995).

FUTURE HALOGEN CHANGES

- Large reductions in the production and atmospheric release of ozone-depleting substances (ODSs) have been achieved by international regulations (Montreal Protocol and its Amendments and Adjustments). Without such controls, and assuming a (conservative) 3% annual growth rate in production, ODSs would have led to an equivalent effective chlorine loading of around 17 ppb in 2050. The control measures of the original Montreal Protocol (1987) reduce this to approximately 9 ppb; the Amendments of London (1990) to about 4.6 ppb; and the Amendments of Copenhagen (1992) to approximately 2.2 ppb (but with stratospheric halogen loading increasing again in the second half of the 21st century). The Adjustments of Vienna (1995) and the

Amendments of Montreal (1997) further reduce this to about 2.0 ppb (approximately the 1980 abundance) around the year 2050.

- Stratospheric halogen loading lags tropospheric loading by up to 6 years. Given that tropospheric halogen loading peaked around 1994 and assuming a scenario with a 3-yr lag time, the equivalent effective stratospheric chlorine loading is estimated to have peaked in 1997, at an abundance 1.7 times higher than in 1980. If annual ozone trends observed in the 1980s are attributed solely to these halogen increases, the peak ozone reductions in 1997, relative to 1980, are estimated to be about 5% at 45°N and 6% at 45°S. The corresponding increases in erythemally weighted UV radiation in 1997 are estimated to be 5% at 45°N and 8% at 45°S relative to the 1980 values.

RECOVERY OF THE OZONE LAYER

- In the absence of other changes, stratospheric ozone abundances should rise in the future as the halogen loading falls in response to regulation. However, the future behavior of ozone will also be affected by the changing atmospheric abundances of methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), sulfate aerosol, and changing climate. Thus, for a given halogen loading in the future, the atmospheric ozone abundance may not be the same as found in the past for that same halogen loading.

- Several two-dimensional models were used to look at the response of ozone to past and future changes in atmospheric composition. Future global ozone abundances are predicted to recover only slowly toward their 1980 values. The return toward 1980 ozone values in the models depends sensitively on the emission scenarios used. The CH_4 scenario used here has a lower growth rate than in previous assessments, which slows the modeled ozone recovery significantly. Understanding the methane trend is an important priority for understanding the future ozone recovery.

- Temperatures in the Arctic winter lower stratosphere are generally close to the threshold for substantial chlorine activation, making Arctic ozone particularly sensitive to small changes in temperature (e.g., cooling of the lower stratosphere by changes in greenhouse gases). Preliminary calculations with coupled chemistry/climate models suggest that recovery in the Arctic could be delayed by this cooling and, because of the large natural variability, recovery will be difficult to detect unambiguously until well into the next century.

- The detection of the onset of ozone recovery from halogen-induced depletion should be possible earlier in the Antarctic than in the Arctic or globally because there is less variability in the ozone loss in the Antarctic. Estimates of the timing of the detection of the onset of ozone recovery are uncertain. However, it is clear that unambiguous detection of the beginning of recovery will be delayed beyond the maximum loading of stratospheric halogens.

Implications for Policy Formulation

The results from more than two decades of research have provided a progressively better understanding of the interaction of human activities and the chemistry and physics of the global atmosphere. New policy-relevant insights to the roles of trace atmospheric constituents have been conveyed to decision-makers through the international state-of-the-understanding assessment process. This information has served as a key input to policy decisions by governments, industry, and other organizations worldwide to limit the anthropogenic emissions of gases that cause environmental degradation: (1) the 1987 Montreal Protocol on ozone-depleting substances, and its subsequent Amendments and Adjustments, and (2) the 1997 Kyoto Protocol on substances that alter the radiative forcing of the climate system.

The research findings that are summarized above are of direct interest and significance as scientific input to governmental, industrial, and other policy decisions associated with the Montreal Protocol (ozone layer) and the Kyoto Protocol (climate change):

- **The Montreal Protocol is working.** Global observations have shown that the combined abundance of anthropogenic chlorine-containing and bromine-containing ozone-depleting substances in the lower atmosphere peaked in 1994 and has now started to decline. One measure of success of the Montreal Protocol and its subsequent Amendments and Adjustments is the forecast of “the world that was avoided” by the Protocol:

  - The abundance of ozone-depleting gases in 2050, the approximate time at which the ozone layer is now projected to recover to pre-1980 levels, would be at least 17 ppb of equivalent effective chlorine (this is based on the conservative assumption of a 3% per annum growth in ozone-depleting gases), which is about 5 times larger than today’s value.

  - Ozone depletion would be at least 50% at midlatitudes in the Northern Hemisphere and 70% at midlatitudes in the Southern Hemisphere, about 10 times larger than today.

  - Surface UV-B radiation would at least double at midlatitudes in the Northern Hemisphere and quadruple at midlatitudes in the Southern Hemisphere compared with an unperturbed atmosphere. This compares to the current increases of 5% and 8% in the Northern and Southern Hemispheres, respectively, since 1980.

  Furthermore, all of the above impacts would have continued to grow in the years beyond 2050. It is important to note that, while the provisions of the original Montreal Protocol in 1987 would have lowered the above growth rates, recovery (i.e., an improving situation) would have been impossible without the Amendments and Adjustments (London, 1990; Copenhagen, 1992; and Vienna, 1995).

- **The ozone layer is currently in its most vulnerable state.** Total stratospheric loading of ozone-depleting substances is expected to maximize before the year 2000. All other things being equal, the current ozone losses (relative to the values observed in the 1970s) would be close to the maximum. These are:

- about 6% at Northern Hemisphere midlatitudes in winter/spring;
- about 3% at Northern Hemisphere midlatitudes in summer/fall;
- about 5% at Southern Hemisphere midlatitudes on a year-round basis;
- about 50% in the Antarctic spring; and
- about 15% in the Arctic spring.

Such changes in ozone are predicted to be accompanied by increases in surface erythemal radiation of 7, 4, 6, 130, and 22%, respectively, if other influences such as clouds remain constant. It should be noted that these values for ozone depletion at midlatitudes are nearly a factor of 2 lower than projected in 1994, primarily because the linear trend in ozone observed in the 1980s did not continue in the 1990s. However, springtime depletion of ozone in Antarctica continues unabated at the same levels as observed in the early 1990s, and large depletions of ozone have been observed in the Arctic in most years since 1990, which are characterized by unusually cold and protracted winters.

Some natural and anthropogenic processes that do not in themselves cause ozone depletion can modulate the ozone loss from chlorine and bromine compounds, in some cases very strongly. For example, in coming decades midlatitude ozone depletion could be enhanced by major volcanic eruptions, and Arctic ozone depletion could be increased by cold polar temperatures, which in turn could be linked to greenhouse gases or to natural temperature fluctuations. On the other hand, increases in methane would tend to decrease chlorine-catalyzed ozone loss.

The current vulnerability to ozone depletion over the next few decades is primarily due to past use and emissions of the long-lived ozone-depleting substances. The options to reduce this vulnerability over the next two decades are thus rather limited. The main drivers of ozone change could be natural and anthropogenic processes not related to chlorine and bromine compounds, but to which the ozone layer is sensitive because of the elevated abundances of ozone-depleting substances.

- **The ozone layer will slowly recover over the next 50 years.** The stratospheric abundance of halogenated ozone-depleting substances is expected to return to its pre-1980 (i.e., “unperturbed”) level of 2 ppb chlorine equivalent by about 2050, assuming full compliance with the Montreal Protocol and its Amendments and Adjustments. The atmospheric abundances of global and Antarctic ozone will start to slowly recover within coming decades toward their pre-1980 levels once the stratospheric abundances of ozone-depleting (halogen) gases start to decrease. However, the future abundance of ozone will be controlled not only by the abundance of halogens, but also by the atmospheric abundances of methane, nitrous oxide, water vapor, and sulfate aerosols and by the Earth's climate. Therefore, for a given halogen loading in the future, atmospheric ozone abundance is unlikely to be the same as found in the past for the same halogen loading.

- **Few policy options are available to enhance the recovery of the ozone layer.** Relative to the current, but not yet ratified, control measures (Montreal, 1997), the equivalent effective chlorine loading above the 1980 level, integrated from now until the 1980 level is re-attained, could be decreased by:

  - 9% by eliminating global Halon-1211 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1211 in existing equipment;

  - 7% by eliminating global Halon-1301 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1301 in existing equipment;

  - 5% by eliminating the global production of all HCFCs in the year 2004;

  - 2.5% by eliminating the global production of all CFCs and carbon tetrachloride in the year 2004;

  - 1.6% by reducing the cap on HCFC production in developed countries from 2.8% to 2.0% in the year 2000, by advancing the phase-out from the year 2030 to 2015, and by instituting more rapid intermediate reductions; and

  - about 1% by eliminating the global production of methyl bromide beginning in 2004.

  These policy actions would advance the date at which the abundance of effective chlorine returns to the 1980 value by 1-3 years. A complete and immediate global elimination of all emissions of ozone-depleting substances would result in the stratospheric halogen loading returning to the pre-1980 values by the year 2033. It should also be noted that if the currently allowed essential uses for metered dose inhalers are extended from the year 2000 to 2004, then the equivalent effective chlorine loading above the 1980 level would increase by 0.3%.

- **Failure to comply with the international agreements of the Montreal Protocol will affect the recovery of the ozone layer.** For example, illegal production of 20-40 ktonnes per year of CFC-12 and CFC-113 for the next 10-20 years would increase the equivalent effective chlorine loading above the 1980 abundance, integrated from now until the 1980 abundance is re-attained, by about 1-4% and delay the return to pre-1980 abundances by about a year.

- **The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal and Kyoto Protocols.** Changes in ozone affect the Earth’s climate, and changes in climate and meteorological conditions affect the ozone layer, because the ozone depletion and climate change phenomena share a number of common physical and chemical processes. Hence, decisions taken (or not taken) under one Protocol have an impact on the aims of the other Protocol. For example, decisions made under the Kyoto Protocol with respect to methane, nitrous oxide, and carbon dioxide will affect the rate of recovery of ozone, while decisions regarding controlling HFCs may affect decisions regarding the ability to phase out ozone-depleting substances.

Executive Summary of the 1998 Report of the Environmental Effects Assessment Panel

Decreased quantities of total-column ozone are now observed over large parts of the globe, permitting increased penetration of solar UV-B radiation (280-315 nm) to the Earth´s surface. The present assessment deals with the possible consequences. The Atmospheric Science Panel predicts that the ozone layer will be in its most vulnerable state during the coming two decades. Some of the effects are expected to occur during most of the next century. Recent studies show that the effects of ozone depletion would have been dramatically worse without the protective measures taken under the Montreal Protocol.

The assessment is given in seven chapters, summarised as follows:

Changes in Ultraviolet Radiation

- **Stratospheric ozone levels are near their lowest point since measurements began, so current UV-B radiation levels are thought to be close to their maximum.** Total stratospheric content of ozone-depleting substances is expected to reach a maximum before the year 2000. All other things being equal, the current ozone losses and related UV-B increases should be close to their maximum. Increases in surface erythemal (sunburning) UV radiation relative to the values in the 1970s are estimated to be:
    - about 7% at Northern Hemisphere mid-latitudes in winter/spring;
    - about 4% at Northern Hemisphere mid-latitudes in summer/fall;
    - about 6% at Southern Hemisphere mid-latitudes on a year-round basis;
    - about 130% in the Antarctic in the spring; and
    - about 22% in the Arctic in the spring.

- **The correlation between increases in surface UV-B radiation and decreases in overhead ozone has been further demonstrated and quantified by ground-based instruments under a wide range of conditions.** Improved measurements of UV-B radiation are now providing better geographical and temporal coverage. Surface UV-B radiation levels are highly variable because of sun angle, cloud cover, and also because of local effects including pollutants and surface reflections. With a few exceptions, the direct detection of UV-B trends at low and mid-latitudes remains problematic due to this high natural variability, the relatively small ozone changes, and the practical difficulties of maintaining long-term stability in networks of UV-measuring instruments. Few reliable UV-B radiation measurements are available from pre-ozone depletion days.

- **Satellite-based observations of atmospheric ozone and clouds are being used, together with models of atmospheric transmission, to provide global coverage and long-term estimates of surface UV-B radiation.** Estimates of long term (1979-1992) trends in zonally-averaged UV-irradiances that include cloud effects are nearly identical to those for clear-sky estimates, providing evidence that clouds have not influenced the UV-B trends. However, the limitations of satellite-derived UV estimates should be recognized. To assess uncertainties inherent in this approach, additional validations involving comparisons with ground-based observations are required.

- **Direct comparisons of ground-based UV-B radiation measurements between a few mid-latitude sites in the Northern and Southern Hemispheres have shown larger differences than those estimated using satellite data.** Ground-based measurements show that summertime erythemal UV irradiances in the Southern Hemisphere exceed those at comparable latitudes of the Northern Hemisphere by up to 40%, whereas corresponding satellite-based estimates yield only 10 to 15% differences. Atmospheric pollution may be a factor in this discrepancy between ground-based measurements and satellite-derived estimates. UV-B measurements at more sites are required to determine whether the larger observed differences are globally representative.

- **High levels of UV-B radiation continue to be observed in Antarctica during the recurrent spring-time ozone hole.** For example, during ozone hole episodes, measured biologically-damaging radiation at Palmer Station, Antarctica (64°S) has been found to approach and occasionally even exceed maximum summer values at San Diego, USA (32°N).

- **Long term predictions of future UV-B levels are difficult and uncertain. Nevertheless, current best estimates suggest that a slow recovery to pre-ozone depletion levels may be expected during the next half-century.** Although the maximum ozone depletion, and hence maximum UV-B increase, is likely to occur in the current decade, the ozone layer will continue to be in its most vulnerable state into the next century. The peak depletion and the recovery phase could be delayed by decades because of interactions with other long-term atmospheric changes, e.g. increasing concentrations of greenhouse gases. Other factors that could influence the recovery include non-ratification and/or non-compliance with the Montreal Protocol and its Amendments and Adjustments, and future volcanic eruptions. The recovery phase for surface UV-B irradiances will probably not be detectable until many years after the ozone minimum.

Effects on Human and Animal Health

- **Recent estimates suggest that the increase in the risk of cataract and skin cancer due to ozone depletion would not have been adequately controlled by implementation of the Montreal Protocol (1987) alone but can be achieved through implementation of its later provisions.** Risk assessments for the US and the Northwestern Europe indicate large increases in cataracts and skin cancers under either the ‘no Protocol’ or the early Montreal Protocol scenarios. Under scenarios based on the later amendments, Copenhagen (1992) and Montreal (1997), increases in cataracts and skin cancer attributable to ozone depletion return almost to zero by the end of the next century.

- **The increases in UV-B radiation associated with ozone depletion are likely to lead to increases in the incidence and/or severity of a variety of short-term and long-**

term health effects, if current exposure practices are not modified by changes in behavior.

- **Adverse effects on the eye will affect all populations irrespective of skin color.** Adverse impacts could include: more cases of acute reactions such as 'snowblindness'; increases in cataract incidence and/or severity (and thus the incidence of cataract-associated blindness); and increases in the incidence (and mortality) from ocular melanoma and squamous cell carcinoma of the eye.

- **Effects on the immune system will also affect all populations but may be both adverse and beneficial.** Adverse effects include depressed resistance to certain tumors and infectious diseases, potential impairment of vaccination responses, and possibly increased severity of some autoimmune and allergic responses. Beneficial effects could include decreases in the severity of certain immunologic diseases/conditions such as psoriasis and nickel allergy.

- **Effects on the skin could include increases in photoaging, and skin cancer with risk increasing with fairness of skin.** Increases in UV-B are likely to accelerate the rate of photoaging, as well as increase the incidence (and associated mortality) of melanoma and the non-melanoma skin cancer, basal cell and squamous cell carcinoma.

- **Research is generating much new information that is being used to help reduce the uncertainties associated with the current risk estimates.** Evaluation of the impact of susceptibility genes is helping to identify highly susceptible populations so that their special risk can be assessed. Examination of the impacts of behavior changes such as consuming diets that are high in antioxidants, avoiding sun exposure during the four hours around solar noon, wearing covering apparel, e.g., hats, sunglasses, is beginning to identify important exposure patterns as well as possible mitigation strategies.

- **Quantitative risk assessments for a variety of other effects, such as UV-B induced immunosuppression of infectious diseases, are not yet possible.** New information continues to confirm the reasonableness of these concerns, but data adequate for quantitative risk assessment are not yet available.

Effects on Terrestrial Ecosystems

- **Increased UV-B can be damaging for terrestrial organisms including plants and microbes, but these organisms also have protective and repair processes.** The balance between damage and protection varies among species and even varieties of crop species; many species and varieties can accommodate increased UV-B. Tolerance of elevated UV-B by some species and crop varieties provides opportunities for genetic engineering and breeding to deal with potential crop yield reductions due to elevated UV-B in agricultural systems.

- **Research in the past few years indicates that increased UV-B exerts effects more often through altered patterns of gene activity rather than damage.** These UV-B effects on regulation manifest themselves in many ways including changes in life cycle timing, changes in plant form and production of plant chemicals not directly involved in primary metabolism. These plant chemicals play a role in protecting plants from pathogens and insect attack, and affect food quality for humans and grazing animals.

- **Terrestrial ecosystem responses to increased UV-B are evident primarily in interactions among species, rather than in the performance of individual species.** Much of the recent experimentation indicates that increased UV-B affects the balance of competition among higher plants, the degree to which higher plants are consumed by insects and susceptibility of plants to pathogens. These effects can be mediated in large part by changes in plant form and chemistry, but effects of UV-B on insects and microbes are also possible. The direction of these UV-B-mediated interactions among species is often difficult to predict based only on single-organism responses to increased UV-B.

- **Effects of increased UV-B radiation may accumulate from year to year in long-lived perennial plants and from generation to generation in annual plants.** This effect has been shown in a few recent studies, but the generality of this accumulation among species is not presently known. If this phenomenon is widespread, this would amplify otherwise subtle responses to UV-B seen in a single growing season, for example in forest trees.

- **Effects of increased UV-B must be taken into account together with other environmental factors including those associated with global change.** Responses of plants and other organisms to increased UV-B are modified by other environmental factors such as CO_2, water stress, mineral nutrient availability, heavy metals and temperature. Many of these factors also are changing as the global climate is altered.

Effects on Aquatic Ecosystems

- **Recent studies continue to demonstrate that solar UV-B and UV-A have adverse effects on the growth, photosynthesis, protein and pigment content, and reproduction of phytoplankton, thus affecting the food web.** These studies have determined biological weighting functions and exposure-response curves for phytoplankton, and have developed new models for the estimation of UV-related photoinhibition. In spite of this increased understanding and enhanced ability to model aquatic impacts, considerable uncertainty remains with respect to quantifying effects of ozone-related UV-B increases at the ecosystem level.

- **Macroalgae and seagrasses show a pronounced sensitivity to solar UV-B.** They are important biomass producers in aquatic ecosystems. Most of these organisms are attached and so cannot avoid being exposed to solar radiation at their growth site. Effects have been found throughout the top 10-15 m of the water column.

- **Zooplankton communities as well as other aquatic organisms including sea urchins, corals and amphibians are sensitive to UV-B.** There is evidence that for some of these populations even current levels of solar UV-B radiation, acting in conjunction with other environmental stresses, may be a limiting factor but quantitative evaluation of possible effects remains uncertain.

- **UV-B radiation is absorbed by and breaks down dissolved organic carbon (DOC) and particulate organic carbon (POC) and makes the products available for bacterial degradation and remineralization.** The degradation products are of importance in the cycling of carbon in aquatic ecosystems. Because UV-B breaks down DOC as it is absorbed, increases in UV-B can increase the penetration of both UV-B and UV-A radiation into the water column. As a consequence, the quantity of UV-B penetrating to a given depth both influences and is influenced by DOC. Warming and acidification result in faster degradation of these substances and thus enhance the penetration of UV radiation into the water column.

- **Polar marine ecosystems, where ozone-related UV-B increases are the greatest, are expected to be the oceanic ecosystems most influenced by ozone depletion.** Oceanic ecosystems are characterized by large spatial and temporal variabilities that make it difficult to select out UV-B specific effects on single species or whole phytoplankton communities. While estimates of reduction in both Arctic and Antarctic productivity are based upon measurable short-term effects, there remain considerable uncertainties in estimating long-term consequences, including possible shifts in community structure. Reduced productivity of fish and other marine crops could have an economic impact as well as affect natural predators; however quantitative estimation of the possible effects of reduced production remain controversial.

- **Potential consequences of enhanced levels of exposure of aquatic ecosystems to UV-B radiation include reduced uptake capacity for atmospheric carbon dioxide, resulting in the potential augmentation of global warming.** The oceans play a key role with respect to the budget of greenhouse gases. Marine phytoplankton are a major sink for atmospheric carbon dioxide and they have a decisive role in the development of future trends of carbon dioxide concentrations in the atmosphere. The relative importance of the net uptake of carbon dioxide by the biological pump and the possible role of increased UV-B in the ocean are still controversial.

Effects on Biogeochemical Cycles

- **Effects of increased UV-B on emissions of carbon dioxide and carbon monoxide (CO) and on mineral nutrient cycling in the terrestrial biosphere have been confirmed by recent studies of a range of species and ecosystems.** The effects, both in magnitude and direction, of UV-B on trace gas emissions and mineral nutrient cycling are species-specific and operate on a number of processes. These processes include changes in the chemical composition in living plant tissue, photodegradation (breakdown by light) of dead plant matter, including litter, release of carbon monoxide from vegetation previously charred by fire, changes in the communities of microbial decomposers and effects on nitrogen-fixing micro-organisms and plants. Long-term experiments are in place to examine UV-B effects on carbon capture and storage in biomass within natural terrestrial ecosystems.

- **Studies in natural aquatic ecosystems have indicated that organic matter is the primary regulator of UV-B penetration.** Enhanced UV-B can affect the balance between the biological processes that produce the organic matter and the chemical and microbial processes that degrade it**.** Changes in the balance have broad impacts on the effects of enhanced UV-B on biogeochemical cycles. These changes, which are reinforced by changes in climate and acidification, result from clarification of the water and changes in light quality.

- **Increased UV-B has positive and negative impacts on microbial activity in aquatic ecosystems that can affect carbon and mineral nutrient cycling as well as the uptake and release of greenhouse and chemically-reactive gases.** Photoinhibition of surface aquatic micro-organisms by UV-B can be partially offset by photodegradation of dissolved organic matter to produce substrates, such as organic acids and ammonium, that stimulate microbial activity.

- **Modeling and experimental approaches are being developed to predict and measure the interactions and feedbacks between climate change and UV-B induced changes in marine and terrestrial biogeochemical cycles.** These interactions include alterations in the oxidative environment in the upper ocean and in the marine boundary layer and oceanic production and release of CO, volatile organic compounds (VOC), and reactive oxygen species (such as hydrogen peroxide and hydroxyl radicals). Climate related changes in temperature and water supply in terrestrial ecosystems interact with UV-B radiation through biogeochemical processes operating on a wide range of time scales.

Effects on Air Quality

- **Increased UV-B will increase the chemical activity in the lower atmosphere (the troposphere).** Tropospheric ozone levels are sensitive to local concentrations of nitrogen oxides (NO_x) and hydrocarbons. Model studies suggest that additional UV-B radiation reduces tropospheric ozone in clean environments (low NO_x), and increases tropospheric ozone in polluted areas (high NO_x).

- **Assuming other factors remain constant, additional UV-B will increase the rate at which primary pollutants are removed from the troposphere**. Increased UV-B is expected to increase the concentration of hydroxyl radicals (OH) and result in faster removal of pollutants. Increased concentrations of oxidants such as hydrogen peroxide and organic peroxides are also expected. The effects of UV-B increases on tropospheric ozone, OH, methane, carbon monoxide, and possibly other tropospheric constituents, while not negligible, will be difficult to detect because the concentrations of these species are also influenced by many other variable factors (e.g., emissions).

- **No significant effects on humans or the environment have been identified from TFA produced by atmospheric degradation of HCFCs and HFCs.** Numerous studies have shown that TFA has, at most, moderate short-term toxicity. Insufficient information is available to assess potential chronic, developmental, or reproductive effects. The atmospheric degradation mechanisms of most substitutes for ozone depleting substances are well established. HCFCs and HFCs are two important classes of substitutes. Atmospheric degradation of HCFC-123 (CF_3CHCl_2), HCFC-124 (CF_3CHFCl), and HFC-134a (CF_3CH_2F) produces trifluoroacetic acid (TFA). Reported measurements of TFA in rain, rivers, lakes, and oceans show it to be a ubiquitous component of the hydrosphere, present at levels much higher than can be explained by currently reported sources. The levels of TFA currently produced by the atmospheric degradation of HFCs and HCFCs are estimated to be orders of magnitude below those of concern and make only a minor contribution to the current environmental burden of TFA.

Effects on Materials

- **Physical and mechanical properties of polymers are negatively affected by increased UV-B in sunlight.** Increased UV-B reduces the useful lifetimes of synthetic polymer products used outdoors and of biopolymer materials such as wood, paper, wool and cotton. The reduction in service life of materials depends on the synergistic effect of increased UV-B and other factors, especially the temperature of the material during exposure to sunlight. Even under harsh UV exposure conditions the higher temperatures largely determine the extent of increased UV-induced damage to photostabilized polyethylenes. However, accurate assessment of such damage to various materials is presently difficult to make due to limited availability of technical data, especially on the relationship between the dose of UV-B radiation and the resulting damage of the polymer or other material.

- **Conventional photostabilizers are likely to be able to mitigate the effects of increased UV levels in sunlight.** More effective photostabilizers for plastics have been commercialized in recent years. The use of these compounds allows plastic polymer products to be used in a wide range of different UV environments found worldwide. It is reasonable to expect existing photostabilizer technologies to be able to mitigate these effects of an increased UV-B on polymer materials. This, however, would increase the cost of the relevant polymer products, surface coatings, and treated biopolymer materials. However, the efficiencies of even the conventional photostabilizers under the unique exposure environments resulting from an increase in solar UV-B have not been well studied.

Executive Summary of the 1998 Report of the Technology and Economic Assessment Panel

ES.1 Aerosol, Sterilants, Miscellaneous Uses and Carbon Tetrachloride

ES.1.1 Aerosol products (other than MDIs)

For aerosol products, other than metered dose inhalers (MDIs), there are no technical barriers to global transition to alternatives. The major issue remaining is the use of CFCs in Article 5(1) Parties and CEIT. The ATOC estimates that 1997 CFC consumption in the aerosol sector was less than 15,000 tonnes in Article 5(1) Parties and some CEIT, excluding MDI use.

The remaining use of CFCs in most countries – especially Latin America and South East Asia Pacific (SEAP) – is concentrated in the industrial/technical aerosols (principally electronics contact cleaners) and in non-MDI pharmaceutical products. In China, remaining consumption is mostly in non-MDI pharmaceuticals.

There is a declining trend in the use of CFCs in aerosols, and the pace of reduction is currently slow. However, it could accelerate if the specific problems of (1) availability of hydrocarbon aerosol propellants, (2) industrial/technical aerosols and non-MDI pharmaceutical products, and (3) conversion of small and very small CFC users, were resolved.

ES.1.2 Metered dose inhalers

Currently, approximately 500 million metered dose inhalers (MDIs) are used annually worldwide, using approximately 10,000 tonnes of CFCs. Non-Article 5(1) Parties that requested essential use nominations for MDIs are reported to have used 7,893 tonnes of CFCs in 1996.

There is international consensus that primary treatment of asthma and chronic obstructive pulmonary disease (COPD) should be by the inhaled route. Overall, use of inhaled medication is increasing because of increased disease prevalence. MDIs remain the dominant inhaled delivery system in most countries and for all categories of drugs.

Currently available alternatives to CFC-based MDIs are CFC-free MDIs, dry powder inhalers (DPIs), nebulisers, orally administered drugs and injectable drugs.

DPIs have been formulated successfully for most anti-asthma drugs. These inhalers are an immediately available alternative for a large proportion of patients, but they may not represent a satisfactory alternative to the pressurised MDIs for all patients or for all drugs.

DPI usage globally as a percentage of all inhaled medication is estimated to be around 17 percent. This figure varies considerably from country to country, e.g. currently from 85 percent in Sweden to less than 2 percent in the USA and there are no DPIs yet available in Japan. It seems unlikely that the uptake of DPIs in most countries will be at the levels seen in Scandinavian countries.

A number of pharmaceutical companies have introduced or plan to introduce a number of CFC-free MDIs. In the ATOC 1997 Update Report, projected timetables for the launches of HFC MDI products in both the European Union and the USA were included. More recent company specific data are available that indicate that a number of companies are well advanced with their reformulation programs. However, it would appear that the projected "best case" scenario is now not possible due to technical and regulatory delays.

It is likely that a wide range of reformulated products will be available in many developed nations and transition will be making good progress by the year 2000. Minimal need for CFCs for MDIs is envisaged by the year 2005 in non-Article 5(1) Parties. Remaining technical, patent, safety and regulatory issues for some commonly used drugs still make it difficult to predict the schedule for full phase-out with precision.

The ATOC does not believe that a rigid global transition strategy is appropriate in view of the widely differing circumstances of individual Parties. However, the Parties could consider the benefits of a "Global Transition Framework" which would underpin national strategies and ensure that they are complementary. Because the phase-out of CFC-containing MDIs in non-Article 5(1) Parties is anticipated in the next few years, the Parties may wish to recommend that Article 5(1) Parties and CEIT start work on preparing their national transition strategies.

In Article 5(1) Parties, the first control measure on the total consumption of CFCs commences in the year beginning 1 July 1999. Controls on CFCs make no allowance to permit exemptions for essential uses prior to the phase-out date of 2010. This will mean that MDI manufacturers in Article 5(1) Parties will be competing for CFC supply in their local markets with other users of CFCs. Parties may wish to consider a procedure by which non-Article 5(1) Parties that no longer need CFCs for their own use can continue to produce CFC MDIs for export for a limited period, as necessary.

Continued provision of MDIs in Article 5(1) Parties and CEIT will depend either upon import of products, or local production. The local production of CFC MDIs is likely to continue for some time after cessation of their use in non-Article 5(1) Parties and will overlap with the importation and local production of CFC-free MDIs by multinational and national companies. Local production of CFC-free MDIs will require the transfer of new technologies and may require new licensing arrangements and transfer of intellectual property. This is true whether production is by a local producer, a multinational company or by a local producer in collaboration with a multinational company. The costs of local CFC-free inhaler production will involve capital costs and licensing arrangements.

In relation to Article 5(1) Parties, the ATOC suggests that Parties may wish to consider:

- the importance of maintaining adequate supplies of the necessary range of inhaled medications during transition in non-Article 5(1) Parties

- encouraging the introduction of CFC-free technologies into these countries
- encouraging these Parties to start work on preparing their national transition strategies.

ES.1.3 Sterilants

By the beginning of 1997, CFC-12 use in non-Article 5(1) Parties for 12/88 (a sterilant gas based on ethylene oxide (EO)), had virtually disappeared. There remain no technical barriers to the phase-out of CFCs in sterilisation, but in some Article 5(1) Parties there are indications of increased use of CFC-12 as a sterilant gas diluent.

In non-Article 5(1) countries, low temperature medical device sterilisation is being met by HCFC-diluent replacement sterilant gas, 8.5/91.5 EO/CO_2, and pure EO. In some European countries formaldehyde is also used. There are a variety of not-in-kind substitutes, but some of these substitutes may have materials compatibility problems or may be less robust processes. Not-in-kind substitutes include radiation (gamma and electron beam), plasma systems and liquid chemical systems. In other instances medical devices compatible with the steam process have been developed.

Global consumption of CFC-12 in this sector is very difficult to estimate since it is basically located in Article 5(1) Parties; it is estimated to be less than 1,500 tonnes. Estimated use of substitute HCFC replacement is thought to be less than 3,000 tonnes (some 90 ODP tonnes). CEIT and Article 5(1) Parties could convert to EO/HCFC-124 sterilant gas rapidly with reasonable cost and no changes in operating procedures.

ES.1.4 Miscellaneous Uses

CFCs have a number of miscellaneous uses, of which tobacco expansion is the most significant. It is difficult to estimate the 1998 worldwide use of CFC-11 to expand tobacco. Most countries have stopped or will shortly stop the use of CFCs to expand tobacco. After 1998, China may be the only remaining country to use significant quantities of CFCs for this purpose. In 1996, 4050 tonnes were used in China compared with 900 tonnes in 1992. Based on the recent and planned installation of alternative carbon dioxide technology in China, declining use in this country is expected.

ES.1.5 Laboratory and Analytical Uses

Typical uses include: equipment calibration; extraction solvents, diluents, or carriers for specific chemical analyses; inducing chemical specific health effects for biochemical research; as a carrier for laboratory chemicals; and for other critical purposes in research and development where substitutes are not readily available or where standards set by agencies require specific use of the controlled substances.

Essential uses of ODS for laboratory and analytical uses were authorised by the Parties to the Montreal Protocol, Decision VI/9(3). Manufacture as highly pure chemicals for final marketing in small, labelled containers was to discourage non-essential use.

A number of Parties have now reported on the use of controlled substances for analytical and laboratory uses. The European Union, Australia, the Czech Republic and the United States have adopted licensing systems in order to manage supplies into these applications. Registration of many thousands of small users in this sector is generally impracticable. Therefore, supplies are usually licensed to the distributors of controlled substances for analytical and laboratory uses.

It has been estimated that the total global use of controlled substances for these applications in non-Article 5(1) Parties will not exceed a maximum of 500 metric tonnes. Use in CEIT is unlikely to be more than a few hundred metric tonnes. Additionally, up to 500 metric tonnes could be used in Article 5(1) Parties for an estimated global consumption of 1,500 tonnes of controlled substances for laboratory and analytical uses.

TEAP has learned that the following specific uses have identified alternatives and substitutes and therefore do not require the use of ODS:

- testing of oil, grease, and total petroleum hydrocarbons in surface and saline waters and industrial and domestic aqueous wastes including the testing of water which is separated from oil and discharged from offshore drilling and production platforms
- testing of tar in road paving materials by dissolving tar and separating it from aggregate
- forensic fingerprinting.

ES.1.6 Carbon tetrachloride

CTC can be used:

- As a feedstock for the production of other chemicals. The 1997 Report of the Process Agents Task Force (PATF), offered the following definition of feedstock:

  > *A controlled substance that undergoes transformation in a process in which it is converted from its original composition except for insignificant trace emissions as allowed by Decision IV/12.*

- As a process agent. The 1997 Report of the PATF offered the following definition of process agent:

  > *A controlled substance that because of its unique chemical and/or physical properties, facilitates an intended chemical reaction and/or inhibits an unintended chemical reaction.*

  Note 1: Refrigeration, solvent cleaning, sterilisation, aerosol propellants and fire-fighting are not process agents according to this definition.

  Note 2: Parties need not consider use of ODS for foam blowing, tobacco puffing, caffeine extraction, or fumigation because these uses are already covered in other Decisions and/or by Technical Options Committee Reports.

- As a solvent. This includes simple solvent extraction such as caffeine extraction and palm oil extraction, and cleaning applications such as metal degreasing and textile spotting. Substitutes are commercially available and economic and, thus, these uses should be discontinued to protect the ozone layer as well as to safeguard the health and safety of people now using CTC.

- In miscellaneous applications such as fire extinguishers, as grain insecticide fumigant, and in an anti-helminthic agent (especially for the treatment of liver fluke in sheep). These uses also should be discontinued for the same reasons stated above.
- As a laboratory chemical.

In the past, data on both CTC production and consumption have been difficult to obtain. The new UNEP data reporting formats will enable the collection of much clearer data and a more detailed analysis of CTC applications. Indeed, total CTC production data including production for feedstock use is well known for 1996 and was reported to UNEP as 203,820 ODP tonnes.

ATOC has estimated atmospheric emissions of CTC to be 41,000 tonnes (-25 percent, +50 percent) for 1996. The primary source of atmospheric CTC emissions is from the use as a feedstock to produce CFCs. This has been estimated to be between 27,500 and 29,100 tonnes for 1996 (67-71 percent of total emissions). The majority of the emissions from feedstock use originate from CFC production in Article 5(1) Parties and CEIT (25,700 to 27,300 tonnes, 64-67 percent of total emissions).

Atmospheric CTC levels have declined as a result of the CFC phase-out by non-Article 5(1) Parties. However, they will only fall significantly in the near future if CFC and CTC the use Article 5(1) Parties is phased out at a faster pace than required by the Montreal Protocol. Otherwise use of CFC and CTC will remain frozen until 1 January 2005 and CTC emissions will remain unchanged until that time.

There are a number of measures, which could lead to reductions in CTC emissions to the environment:

- Closure of CFC manufacturing facilities in Article 5(1) Parties and CEIT with accelerated introduction of alternatives.
- Conversion of facilities using CTC as process agents in Article 5(1) Parties to alternatives.
- Use of improved emission control technology in CTC and CFC manufacturing facilities in Article 5(1) Parties and CEIT.
- Use of improved containment and emission control technology in Article 5(1) Parties and CEIT manufacturing facilities using CTC as process agents.

The ATOC wishes to point out that projects to phase out solvent uses of CTC are eligible for financing under the Multilateral Fund. The ATOC further believes that in some cases eligible solvent uses have been presented to the Multilateral Fund incorrectly as process agent uses and, therefore, have not been funded.

ES.2 Economics Options Committee

ES.2.1 Introduction

The theme of the 1998 Assessment Report of the Economic Options Committee (EOC) is progress made towards full implementation of the Montreal Protocol control schedules. The analyses address economic aspects of the implementation process, including assessments of the essential elements of national policy regimes. Updates on economic aspects of selected controlled substances, trade issues, and "lessons learned" from the Montreal Protocol experience are presented.

The policy challenge is to design and implement policy regimes that are appropriate to national institutional capacities, industrial structure and trade patterns with respect to ODS production and consumption. Evidence suggests that there is ample scope for more extensive use of market-based instruments to improve the cost-efficiency of implementation

ES.2.2 Implementation: Article 5(1) Parties

The issues facing Article 5(1) Parties include compliance, inter alia, with their first control target for Annex A, Group I chlorofluorocarbons (CFCs). Studies addressing this issue conclude that virtually all Article 5(1) Parties will comply with 1995-1997 "freeze level". To meet subsequent control measures for 2002 and beyond, the Article 5(1) Parties will need to improve compliance by the small and medium-sized enterprises (SMEs), including the informal sectors. The use of market-based instruments is likely to be more effective than command-and-control policies in raising compliance levels by the SMEs and the informal sector. The quality of data reporting and management has important implications for assessing compliance. Recent studies highlight the need to improve data quality and management. Case studies for China and India highlights China's increasing use of market-based instruments in contrast to India's more extensive reliance on command-and-control measures.

ES.2.3 Implementation: CEITs

CEITs have had trouble in complying with the control schedules and paying their assessed contributions to the Multilateral Fund. Overall, significant progress in reducing the ODS consumption has been achieved by the CEITs. However some Non-Article 5(1) CEITs, most significantly the Russian Federation, failed to comply with the January 1, 1996 phase-out target for Annex A and Annex B substances. A formal extension for Russian compliance, although requested, was not granted leaving Russia in breach of the Protocol. This matter has not been resolved. However, by encouraging the funding of Russian phase-out projects through the GEF and ad hoc donors, the Parties have kept open a channel for influencing and participating in the design, implementation and monitoring of Russian responses to its Protocol obligations. The problems that Russia faces in switching out of ODS consumption also apply to other CEITs. These are principally difficulties in obtaining funds for switching production to non-ODS substances at a time when industrial prospects are poor and capital is extremely scarce. At the same time, the option of closure is very unattractive when unemployment is already very high.

ES.2.4 The Use & Cost Effectiveness Criteria of the MLF and GEF

The role and application of cost-effectiveness thresholds continue to evolve as the Executive Committee takes decisions on new concepts of investment projects such as "umbrella projects", "terminal umbrella projects" and "sector approach projects" (e.g., the Halon Sector Plan in China). Further developments are likely as the Executive Committee progresses in its work on the application of cost-effectiveness criteria to projects designed to phase out ODS production capacity in the Article 5(1) Parties.

ES.2.5 Methyl Bromide

The Non-Article 5(1) Parties, in aggregate, are well within reach of the required 25 percent reduction in consumption by January 1, 1999 for methyl bromide. However, most of the overall decline in methyl bromide consumption has occurred in the United States while several other non-Article 5(1) Parties have not yet achieved significant reductions. Therefore, it appears that some Parties may have not achieved significant reductions, and will face difficult challenges in meeting the 25 percent reduction target. The 20 percent reduction target for Article 5(1) Parties by January 1, 2005 is unlikely to cause concern, if technical innovation and investment projects progress as expected.

ES.2.6 HFCs and HCFCs

There are trade-offs between the benefits of using HFCs and HCFCs for ozone protection and the environmental costs associated with their emissions. Economic analyses can go some way in providing appropriate frameworks for assessing these costs and benefits. However, not all costs and benefits can be quantified and economic analysis alone may not be sufficient to guide decisions on alternatives that might have widely different distributions of costs and benefits.

ES.2.7 Halons

China is using market-based instruments to improve economic efficiency in the implementation of the Halon Sector Plan. The main economic instruments are a tradable production quota system and a bidding system for MLF grants. The results of this initiative were (1) economic efficiency improved; (2) significant environmental benefits were achieved; and (3) the cost of the phase-out to the Multilateral Fund was reduced by about 27 percent compared with normal project-by-project approach. Based on this experience, China is moving quickly to apply this approach to other ODS sectors, e.g., for the CFC production sector plan, the solvent sector plan and the tobacco sector plan.

ES.2.8 International Trade Issues

The trade provisions of the Montreal Protocol have undoubtedly reduced international trade in controlled substances as intended. At the regional level, there is quantitative evidence that trade flows in relevant product groups have been impacted by the Protocol.

Unrestricted trade in second-hand ODS-using equipment can create problems. The attraction for Article 5(1) Parties is low initial cost, however the derived demand for ODS for recharge and the costs of disposal drive up long term costs, and can create additional ODS emissions.

ES.2.9 Transferability of Lessons Learned from the Montreal Protocol

"Lessons learned" and their possible transferability to the design and implementation of other international environmental agreements are updated from the 1994 EOC Assessment Report. Important lessons include the: (1) *role of science;* (2) *role of independent, objective technical experts;* (3) *role of co-operation;* (4) *role of equity;* (5) *economic costs;* (6) *similarities and differences;* and (7) a*pplication of "lessons learned*".

ES.3 Foams Technical Options Committee

ES.3.1 Technology Status

Zero-ODP alternatives are the substitutes of choice in many applications including packaging, cushioning (flexible) and certain rigid thermal applications. No single solution has emerged from transition, and thus, choices must be retained to allow optimal solutions for given applications, producer-specific and country-specific circumstances.

The development of liquid HFC replacements for HCFC-141b continues for thermal insulating polyurethane, polyisocyanurate and phenolic foams. HFC-245fa and HFC-365mfc, liquid HFCs, are being actively developed as zero-ODP, near drop-in replacements for HCFC-141b. It is anticipated that both of these products will be commercially available around the beginning of 2002. No toxicity issues have been identified. Uncertainty, however, over cost, availability and the long term environmental management of greenhouse gases is slowing development. For polystyrene and polyolefin insulating foam, the most likely long-term candidates are CO_2 (liquid carbon dioxide), HFC-152a, HFC-134a, or blends thereof.

Pentane-based technologies for rigid polyurethane foams continue to evolve. Technical properties including thermal insulation and lower density have been improved with the use of blends of cyclopentane with iso-pentane or with iso-butane. These gains, have also led to improved cost competitiveness for hydrocarbon blown products.

Whichever types of blowing agent are chosen, an increasing trend in the development of newer technologies is the use of optimised blends. These often combine new and existing materials and are typically low or, most commonly, zero ODP. Blends are preferred because they more closely match the performance of the original CFC technologies. This trend is seen in most sectors. It appears that use of single blowing agent systems has ended in several foam applications.

ES.3.2 Transition Status

Global use of ozone depleting substances in rigid foams has decreased by almost 75 percent since reaching a peak in 1989. All CFC use in Non-Article 5(1) countries (except for some CEIT) has been eliminated. As of 1997, HCFC use represents less than 20 percent of the total rigid foam sector use of ozone depleting substances, as measured in ODP tonnes. There is very little, if any, use of HCFCs in non-rigid foam sectors.

For Article 5(1) Parties, CFC phase-out is technically feasible around the year 2001 provided Multilateral Fund projects are implemented without delay. However, the foam sector is growing very rapidly in a number of Article 5(1) countries. In addition to expanded CFC use among manufacturers who have not yet completed transition, some new operations are starting up with CFC technology. In some Article 5(1) countries this market growth and related CFC use outpaces the phase-out progress. It may be difficult in these countries to meet applicable phase-out deadlines.

ES.3.3 Transition Barriers

Some CFC and HCFC users are reluctant to finalise a transition strategy until there is greater certainty concerning the availability and suitability of HFCs long-term CFC replacements. Depending on the situation of the individual foam manufacturer, some technically viable alternatives may not be economically viable owing to high cost of capital investment, and the sensitivity of unit foam costs to blowing agent costs.

In Article 5(1) countries, CFC-11 continues to be widely available and is generally much cheaper to use than the currently available alternatives. Another factor constraining a more rapid phase-out is that very few alternatives are manufactured in Article 5(1) countries. The technical options for low volume CFC consumers in Article 5(1) countries are also limited because funding cannot cover the capital costs of, for example, hydrocarbon or CO_2 (liquid carbon dioxide). Given the advantage of using existing equipment with liquid HFCs, once the uncertainties in price and availability are clarified these substitutes may serve as a cost-effective replacement in Article 5(1) countries in some applications. Consistent use of safe practices by manufacturers during storage, production and transportation of products - especially extruded polystyrene sheet - manufactured with flammable blowing agents continue to be of concern.

ES.4 Halons Technical Options Committee

Extensive R&D into new liquid and gaseous halocarbon replacements for halons and into the use of new and existing alternative approaches has resulted in the availability of a wide range of options. This has led to the almost complete cessation of use of both halon 1211 and halon 1301 in non-Article 5(1) and in many Article 5(1) Parties for new installations across most applications, as well as to significant retrofitting. Those systems that remain are substantially non-emissive in normal circumstances; emissions due to testing and training have been virtually eliminated; and recovery of agent during servicing and decommissioning is routine. Based on these achievements, the cessation date for halon production in non-Article 5(1) Parties was successfully brought forward to January 1994. Only a single Essential Use production exemption has been approved, in the special case of halon 2402.

Despite this success, concerns remain. Vastly dominant amongst these is continuing significant halon 1211 in Article 5(1) Parties. Technology transfer is required, especially for high quality ABC powder manufacture as an alternative to halon 1211 and for hydraulic and installation design for fixed systems alternatives to halon 1301. New National Standards for alternatives will help in reducing costs. Countries with Economies in Transition require implementation of effective halon recovery and recycling, establishment of a halon 2402 management program and a continuing process of information dissemination and awareness improvement.

Two other halons, 1011 and 1202, were much less widely used. Increases in atmospheric concentrations of halon 1202, recently reported in scientific journals, cannot be explained by use as a fire extinguishant. Halon 1202 was only used as a fire extinguishant on a few aircraft types that are no longer produced. Parties may wish to examine the possibility that inadvertent production and release of halon 1202 during halon 1211 production in Article 5(1) countries is the source of these atmospheric concentrations.

The needs of "Critical Users" who still require halon 1301 - including, at present, aviation and some defence, oil and gas, and shipping - are being met by management of the existing inventory. They are in approximate balance (within the estimating error) with the rate at which agent is coming onto the market as systems reach the end of their useful life and are decommissioned. It is important to ensure that this balance is maintained, that the halon retains its asset value, and that it finds its way to the Critical Uses. Until there is a clear surplus of halon 1301, widespread destruction cannot be recommended.

Efforts to minimise emissions continue to be imperative, especially bearing in mind that near term emissions are more damaging to the ozone layer than later ones. It should be noted that total ODP weighted emissions of halon 1211 and halon 1301 from Article 5(1) countries now exceeds those from non-Article 5(1) countries. It is expected that Article 5(1) country halon emissions will increase significantly until production ceases.

ES.5 Methyl Bromide

MBTOC addresses the technical feasibility of chemical and non-chemical alternatives for the current uses of MB. Of the 1996 global MB production of 71,425 tonnes, quarantine and pre-shipment (QPS) use was 15,000 tonnes and equivalent to 22 percent of global fumigant use. QPS use is exempt from control and is an emissive use unregulated under the Protocol and moreover, this use appears to be increasing for both developing and developed countries.

ES.5.1 Soil Fumigation

MB as a soil fumigant is the single largest use category accounting for about 75 percent of global use. In spite of the widespread use of MB as a soil fumigant MBTOC did not identify a single crop that cannot be produced successfully without MB.

ES.5.2 Durable Commodities

Durable commodities include grains, dried fruits and beverage crops, and non-foods such as wood products and tobacco. Approximately 13 percent of the global consumption of MB is used for treating durable commodities and about 3 percent for structures. The principal alternatives are phosphine, heat, cold and contact pesticides. In many cases, integrated pest management procedures can replace MB. MBTOC did not identify any existing alternatives for some non-QPS uses but these are likely to consume less than 50 tonnes per annum.

ES.5.3 Perishable Commodities

Perishable commodities include fresh fruit and vegetables, cut flowers, ornamental plants, fresh root crops and bulbs. About 9 percent of global MB consumption is used for disinfestation of perishable commodities, with about half used for disinfestation of fruit for quarantine purposes. Post-entry alternative treatments are particularly problematical as they have neither been developed and approved for treating products entering via multiple air and sea ports, and nor would they be easy to implement.

ES.5.4 Article 5(1) Parties Perspective

Based on official data, Article 5(1) Parties consumed 15,350 - 17,500 tonnes of MB per annum, equivalent to 23-26 percent of global consumption. Some have greatly reduced their consumption or even officially phased out MB, while others have substantially increased their usage and in some cases production. Demonstration projects currently being implemented in a number of countries will curb this increase and ultimately encourage phase out.

ES.5.5 Quarantine and Pre-shipment (QPS)

MBTOC noted there is some inconsistency in the interpretation of the terms ‘quarantine’ and ‘pre-shipment’ that may lead to some Parties incorrectly exempting this use. In addition, multiple MB applications are being used when a single application just prior to shipment would meet QPS requirements.

ES.5.6 Emission Reduction

There has been some limited further research into the development of recovery and recycling systems for MB, mostly directed at recovery from commodity fumigation. Only a few special examples of recovery equipment are in current commercial use.

ES.5.7 Alternatives to Methyl Bromide

MBTOC could find no existing alternatives to MB for about 2500 tonnes of MB per annum used for non-QPS treatments. Existing alternatives as those non-chemical or chemical treatments and/or procedures that are technically feasible for controlling pests, thus avoiding or replacing the use of MB. Based on this relatively small consumption, MBTOC considered there are existing alternatives for more than 95 percent of the current tonnage of MB, excluding QPS. Significant effort must now be undertaken to transfer these alternatives to as many locations as possible and optimise the conditions under which they can be most effective.

ES.6 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

ES.6.1 Introduction

This Refrigeration, AC and Heat Pumps Technical Options Committee (TOC) Report forms part of the regular assessments carried out pursuant to Article 6 of the Montreal Protocol. It is also part of the 1998 assessment of the Technology and Economic Assessment Panel. The 1998 Technical Options Committee included 48 representatives from African, Asian, European, Latin and North American countries. Several drafts of the report were made, reviewed by the separate chapters and discussed in six TOC meetings, held in Denmark, France and in the United States in 1996 and 1997, and in India, Norway and Germany in 1998. The report was peer reviewed and completed in a TOC meeting following the peer review.

CFC production has been phased out in the non-Article 5(1) countries, and phase-out is underway in the Article 5(1) countries. In both the non-Article 5(1) and the Article 5(1) countries, HCFCs and HFCs have been the primary substitutes for CFCs. In many applications, alternatives to HCFCs have become commercially available, mainly as blends of HFCs. As a result, HFCs have currently gained a large share of the replacement market. A rational approach to phase out HCFC consumption should allow a minimum time period to permit the industry to develop and commercialise alternatives; and a rational phasing in of new equipment in order to avoid high obsolescence costs. For the short term, the transitional HCFCs still form a valid, global option for refrigeration and AC equipment. However, for the long term, there remain (in addition to various non vapour compression methods) only five important different refrigerant options for the vapour compression cycle:

- hydrofluorocarbons (HFCs, HFC-blends with 400 and 500 number designation);
- ammonia (R-717);
- hydrocarbons and blends (HCs, e.g. HC-290, HC-600, HC-600a etc.);
- carbon dioxide (CO_2, R-744);
- water (R-718).

None of the above refrigerants is perfect, and all have both advantages and disadvantages that should be considered by governments, equipment manufacturers and equipment users. For example, HFCs have relatively high global warming potentials, ammonia is more toxic than the other options, and ammonia and hydrocarbons are flammable to certain extents. Appropriate equipment design, maintenance and use can mitigate these concerns, though sometimes at the cost of greater capital investment or lower energy efficiency. Energy efficiency relates directly to global warming and greenhouse gas emissions. Therefore, it remains an important issue for all refrigeration technologies, and should be considered along with the other factors described above.

Next to ozone depletion, global warming is the main environmental issue governing the selection of refrigerant technologies for the near-, mid- and long-term. Although this issue is not covered by the Montreal Protocol, it nevertheless forms an important criterion in the ongoing “environmental acceptability” discussion. Interest in ammonia and the hydrocarbons is stimulated, at least in part, by the fact that the HFCs are greenhouse gases for which emissions may be controlled in future. However, safety aspects also imply stringent emission controls for ammonia and hydrocarbons. Similarly, energy efficiency research is partly spurred by the role of energy production in carbon dioxide emissions. The five refrigerant options described above are in different stages of development or commercialisation; HFCs are widely applied in many sectors, ammonia and hydrocarbons enjoy growth in sectors where they can be easily accommodated, and for certain applications, CO_2 equipment is under development and the first demonstration components have reached the market. Equipment using water has been developed and may see some increase in limited applications. Work is being done by several committees in developing standards to permit the application of new refrigerants, and it is the intent of companies to reach worldwide accepted limits in those different standards.

ES.6.2 Global CFC and HCFC Production and Consumption

CFC production in the non-Article 5(1) countries shows a decrease from 866 to 53 ODP-ktonnes in the years 1986 and 1996, respectively. The total aggregated production volume in Article 5(1) countries seems to have stabilised over the period 1994-1996. CFC production in all Article 5(1) countries amounted to 109 ODP-ktonnes in 1996. The total global CFC production available for consumption in the Article 5(1) countries in the year 1996 was on the order of 145-150 ODP-ktonnes. If Article 5(1) countries were to continue producing on the order of 110 ODP-ktonnes annually, exports by non-Article 5(1) Parties could be rapidly reduced. This is because Article 5(1) consumption is expected to decrease due to project implementation and national measures being implemented by many Article 5(1) Parties.

HCFC production increased from about 12.7 ODP ktonnes in 1989 to about 30.8 ODP ktonnes in 1996 in countries, which have facilities belonging to the AFEAS manufacturer group. According to the 1996 manufacturers’ data, the largest ODP consumption of HCFCs was not in refrigeration and air conditioning, but in the foams sector (HCFC-141b). HCFC global consumption is expected to decrease from 412 to 163 ktonnes between the years 1998 and 2015, respectively. HFC-134a production has shown a continuous growth over the period 1990 -1996, with a consumption of about 74 and 84 ktonnes in the years 1995 and 1996, respectively, which represents growth percentages of 45 and 13 percent. Annual HFC-134a consumption for all applications in 2015 is forecast to be 207 ktonnes. This represents an increase of about 250 percent between 1997 and 2015; this figure includes 174 ktonnes for the use of HFC-134a in refrigeration and A/C. The same growth percentage also applies for the consumption of other HFCs in the 1997-2015 period (forecast consumption of 133 ktonnes in 2015). These growth estimates should be considered against a substantial decrease in HCFC consumption over the period 1997-2015.

ES.6.3 Domestic Refrigeration

All manufacturers in non-Article 5(1) countries have transitioned from CFC-12 to non-ODS refrigerants in new domestic refrigeration equipment. Transitions in the Article 5(1) countries are occurring faster than the Montreal Protocol requirements. Preferred alternatives were assessed considering safety, environmental, functional and performance requirements. Broad based OEM refrigerant alternatives have narrowed to HFC-134a and

HC-600a. Both can provide safe, reliable and efficient domestic refrigerators and freezers. Analysis of regional requirements and consumer - selected product differences provides insight into refrigerant selections. Field repair complexity is expanding with the introduction of new refrigerants which involves several potential issues and OEMs should be consulted regarding proper repair procedures for their equipment. Equipment design for use with CFC-12 should be carefully assessed for safety prior to undertaking drop-in repair, particularly when using flammables. There is a significant difference in field repair rates between developed and developing countries, at approximately 2 percent and 10 percent, respectively. Differences result from use environment, extended life and uncertain power service, aggressive transport conditions and deficient service training. The premium value of capital goods relative to labour expense in many countries promotes component rebuilding by small, decentralised service shops. This has the strategic consequence of extending the use of obsolete materials and components. CFC-12 continues to globally dominate the aftermarket service demand. Energy efficiency of domestic refrigeration is a subject of accelerating interest. Retirement and replacement of less efficient older units and extended application of conventional state of the art technology could result in large reductions in global energy consumption.

ES.6.4 Commercial Refrigeration

Commercial refrigeration includes a wide range of equipment. While the refrigeration capacity of centralised systems in supermarkets varies typically from 20 kW to 1000 kW, stand-alone equipment capacities are comparable to domestic equipment. Stand-alone equipment traditionally used CFC-12; most new equipment uses HFC-134a. Several manufacturers in Denmark, India, Sweden and the UK have introduced small commercial equipment using various hydrocarbons. The expected more rapid HCFC phase-out in Europe has led to the choice of R-404A and R-507A in new, centralised systems. In some European countries certain industries are supplying units that either use ammonia or hydrocarbons. However, HFC blends as economically preferred refrigerants form the usual choice, due to safety considerations and initial costs. A number of units have been installed to evaluate the advantages and the drawbacks of indirect systems (using a secondary circuit with heat transfer fluids), and new concepts for direct expansion using water cooling, now in operation, are also being evaluated. Other developmental efforts are focused on improving energy efficiency, minimising charge size, and minimising refrigerant emissions. The early CFC phase-out in some Article 5(1) countries and their level of refrigerant consumption (which can be up to 50 percent of the overall country CFC consumption), provide incentives for both system owners and repair shops to replace CFC-12 with low- or non-ODP refrigerants.

ES.6.5 Industrial Refrigeration and Cold Storage

Most industrial systems are custom made and erected on site. Therefore, the refrigerant choice has to be evaluated on a case-by-case basis, whether it concerns a new installation or the retrofit of an existing one. Ammonia and HCFC-22 are currently the most commonly used refrigerants for industrial refrigeration including cold storage and food processing; it is expected that ammonia will increase its importance in the future. In these sectors CFCs have been replaced by new systems using ammonia, HCFC-22 and HFCs, where the currently used HFCs are HFC-134a, R-404A and R-507A. The blend R-410A is expected to become the leading HFC in future.

Hydrocarbons and CO_2 are applicable for specific applications. Retrofit activities in the industrial sectors have been lower than expected several years ago, although the various retrofit options, i.e., HCFC-22, HCFC blends and HFCs have proven to be viable solutions. In a certain number of cases retrofit cannot be performed due to economic or technical reasons, and the systems have to be replaced. Compared to industrial refrigeration, cold storage and food processing is a more important sector in the Article 5(1) countries; the refrigerants used are, to a certain degree, CFCs as well as the substitutes HCFC-22 and ammonia.

ES.6.6 Air Conditioning and Heat Pumps (Air Cooled Systems)

Air cooled air conditioners and heat pumps ranging in size from 2 kW to 420 kW comprise the vast majority of the air conditioning market. Nearly all of these units use HCFC-22 as working fluid; this represents an inventory of approximately 423 ktonnes of HCFC-22. There has been significant progress made in developing HCFC-22 alternatives for this category of products. Hydrocarbon refrigerants might also be suitable replacements for HCFC-22 in some categories of products: air-to-water heat pumps and possibly very low charge level air-to-air systems. Article 5(1) Parties will have a significant need for the transfer of reclamation and retrofit technologies in the air conditioning sector. At least one retrofit candidate for HCFC-22 is commercially available: the HFC-blend R-407C.

ES.6.7 Air Conditioning (Water Chillers)

The continuously growing number of water chillers for air conditioning, in service around the world, uses refrigerants including fluorocarbons (CFCs, HCFCs, HFCs), ammonia and hydrocarbons. The chillers employing the fluorocarbons dominate in terms of the installed base and new production, due to relatively low initial costs. Because HCFCs and HFCs are relatively similar to the CFCs physically and chemically, they can often replace the CFCs in new and existing chillers with less extensive modification of chillers and equipment rooms than are required for other replacement refrigerants. However, the ammonia and hydrocarbon chillers are enjoying some growth, particularly in Northern Europe. The largest chillers, those with the highest cooling capacity, employ centrifugal compressors, where the smaller chillers have traditionally employed reciprocating piston compressors. Today, these are being complemented, and in come cases replaced, by screw and scroll compressors. The principal changes that have occurred since the 1993-1995 period are (i) the phase-out of the use of CFC-11 in existing chillers has been significantly slower than forecast in 1994, (ii) the use of ammonia in new systems has grown more rapidly than anticipated in 1994, (iii) very low emission chillers are now being installed by all manufacturers, and (iv) hydrocarbon chillers have been introduced on several regional markets.

ES.6.8 Transport Refrigeration

Transport refrigeration includes refrigeration in ships, railcars, containers and road transport equipment; it also includes refrigeration and air conditioning on merchant ships, buses and railcars. Most systems that used CFCs in 1994 have been retrofitted or scrapped, except for refrigerated containers and trucks, due to the large existing CFC fleets. Particularly in all segments of transport refrigeration, the emission rate can be significant, due to the rough operating conditions; therefore containment and maintenance are very important together with system design improvement. Nearly all shipboard systems use HCFC-22 but HFCs offer the preferred future option. Apart from HFCs, there is limited work on alternatives including hydrocarbons, ammonia, air-cycle and CO_2 for new systems in transport refrigeration. About half of the refrigerated containers and road vehicles still use CFC-12 today, but retrofit options, mainly HCFCs and HFCs, are fully available (only in some cases hydrocarbon options exist).

ES.6.9 Automotive Air Conditioning

By the end of 1994, all automobile manufacturers had converted mobile air conditioning systems to HFC-134a. Existing vehicles with CFC-12 air conditioning are expected to be phased out due to "old age" by the year 2008. The major issues remaining are to encourage the Article 5(1) Parties to phase out CFC-12 in motor vehicles as soon as possible and prevent unnecessary emissions during servicing. Accordingly, automobile manufacturers and their international associations have provided information on available retrofit technology, recovery and recycling of refrigerant, service technician training, and current service and retrofit trends; this has already been used in several Article 5(1) country Refrigerant Management Plans. Manufacturers of HFC-134a systems are working to improve their designs to minimise refrigerant charge and refrigerant emissions, and to maximise total system energy efficiency. Hydrocarbons and CO_2 have been proposed as possible long-term replacements for HFC-134a and are being evaluated. New vehicles are expected to be equipped with HFC-134a until an alternative is developed and commercialised that offers comparable performance, reliability and safety characteristics, and an economically viable global warming advantage.

ES.6.10 Heating Only Heat Pumps

It is estimated that the total existing heating-only heat pump stock in the residential, commercial/industrial and district heating sectors is roughly 1.7 million units, with a total heating capacity of about 13,300 MW. The corresponding figures for industrial heat pumps are 8,500 units with a total heating capacity of 3,000 MW. Virtually all heat pumps are in use in the developed countries. HFCs are the most important alternative refrigerant for heat pumps, both for retrofit and in new installations: HFC-134a is applied in medium/large capacity units as a replacement for CFC-12, where R-404A, R-407C and R-410A are the most promising HFC blend alternatives to replace HCFC-22. So far, the number of heat pump retrofits has been lower than expected. Ammonia has in the recent years attained a small, but growing market share in medium and large capacity heat pumps in Northern Europe; propane, propylene and certain hydrocarbon blends are being used in a limited number of residential heat pumps, mainly in Europe. In addition, the use of CO_2 is being evaluated and components for CO_2 have been developed.

ES.6.11 Refrigerant Conservation

Refrigerant conservation is critical both to maintaining the stock of existing CFC equipment and to minimising any environmental (e.g., global warming) or safety (e.g., flammability) impacts that may be associated with the transition away from ozone-depleting substances. Parties may wish to consider taking measures to encourage conservation. Measures successfully applied in the past have included financial incentives and regulations making containment compulsory. In Article 5(1) countries, important first steps include tightening up systems by finding and repairing leaks, and recovering refrigerant when opening the system for service. To be effective, conservation technologies must be matched by technician training and, in some cases, adaptation of technology. Replacing CFCs in new and existing equipment; ending the purchase of CFC equipment; and conservation through recovery, recycling and leak reduction are all steps that could be taken in the short term by Article 5(1) Parties in order to meet the initial 1999 control measures.

ES.7 Solvents, Coatings and Adhesives Technical Options Committee

ES.7.1 Non-Article 5(1) Party Progress

Industries in non-Article 5(1) countries have successfully complied with the production phase out of ozone-depleting solvents, which occurred nearly two years ago. A small quantity of ozone-depleting solvents is still produced for post-phase-out Essential Uses Exemptions.

Over the past four years the number of Essential Use Exemption Nominations for OD-solvents has decreased significantly, and only a few of these requests have been granted by the Parties. The users of ozone-depleting solvents have been quite successful in the phase-out, however several industries still rely on them. Aqueous cleaning methods have been successful for many applications and indications are that a large percentage of users [about 50 - 60 percent] have made the transition to this alternative.

However, in several applications such as precision cleaning where factors such as high reliability, compatibility and short cycle time (e.g., fast, spot-free drying) are required, users are converting to alternative solvent processes. Many of these alternative solvents are more expensive on a per kilogram basis and do not possess many of the desirable properties of the original ozone-depleting cleaning solvents.

The number of new ozone friendly solvents is quite small and the projection for continued research into new solvents is not high. Cost of research, time for governmental approval and user acceptance continue to be major concerns for developers. Continued dependency on stockpiled OD solvents and ongoing enthusiastic attendance at conferences and workshops provide evidence that interest in more economical and effective alternatives still remains.

An additional issue worth mentioning is the cost of solvent alternatives. Unlike the ozone-depleting solvents, the alternatives market is made up of many suppliers with numerous alternatives, many of which are variations or blends marketed under trade names of the same alternative. This dispersed nature of this market has made the economics of scale that were realised in the past, impossible today. Therefore, alternatives in general remain expensive relative to the OD solvents they replace, particularly those for speciality uses.

The STOC continues to be aware of new solvents offered in the market that have ODPs and lack complete toxicological assessment. The rush to promote these alternatives has been such that this information is being overlooked and minimised.

ES.7.2 Article 5(1) Parties Progress

Although the phase-out effort is going well in developed countries, many unique challenges remain for Article 5(1) Parties. These Parties have an allowance under the Protocol to produce per capita quantities of ODS for their domestic use, some have very large populations, and industrial development is a high domestic priority. As a result, ODS production in these countries could easily cancel out much of the progress made during the first ten years of the phase-out. Thus, the STOC's primary concerns should be the rapid reduction in overall ODS demand by targeting SMEs and eliminating carbon tetrachloride solvent use.

Another challenge is providing awareness and training on both the ozone-depletion problem and solvent sector alternatives.

The freeze in OD solvent production at mid-1999 levels, and production phase-down over the next ten years, pose extremely difficult challenges to many users in Article 5(1) countries. The apparent ease by which the non-Article 5(1) Parties phased out may not be replicated in Article 5(1) countries. The challenges include: the inability to accurately identify products containing ODSs, the inability to identify end users, a complex distribution chain, and lack of communications and infrastructure needed to translate technical information into local languages, and distribute the information to large numbers of small and medium size enterprises. Additional challenges include the higher cost of some alternatives, capital costs of new cleaning and waste treatment equipment, and operating costs of alternative processes. Fortunately, most of these costs are eligible for funding through the MLF. A brief description of progress and challenges in some sub-sectors is given below:

- *Metal cleaning* - A speedy phase-out in the metal cleaning sub-sector is hampered by the large number of small users, most of whom are under-capitalised. Trichloroethylene, perchloroethylene, dichloromethane and hydrocarbons (e.g. mineral spirits) do not deplete the ozone layer and offer low operative costs. The under-capitalised metal cleaning enterprises can use them as alternatives for rapid phase-out, provided they take proper workplace exposure, safety and waste solvent disposal measures. Part of this sub-sector is involved with maintenance cleaning, which is not generally addressed by seminars or other outreach programmes. Much large scale metal cleaning has traditionally been done by aqueous or semi-aqueous processes, where the equipment and waste treatment requirements are easily justified by the volumes processed.
- *Precision cleaning* - In precision cleaning applications, users have been aggressively implementing alternatives due to critical end-use requirements. Isopropyl alcohol has turned out to be the preferred choice for many precision cleaning applications because of its good cleaning property (although it does not have a high soil loading capability) and its low cost. However, in some cases users are still searching for solutions to precision cleaning of parts that are especially vulnerable to residues or reactions, or that have unusually stringent cleanliness, cycle time or compatibility

criteria. In many of these cases an alternative solvent is the preferred choice.

ES.7.3 Small- and Medium-Size Enterprises (SMEs)

One of the major problems yet to be resolved is the phase-out of controlled solvents in SMEs, which collectively consume the greatest volume of OD solvents. The SME problem, though common everywhere, assumes serious proportions in Article 5(1) countries. However, some situations are easier to manage, such as Malaysia, Thailand, Indonesia and Mexico, where almost all the SMEs are clustered in one region. Here, SMEs have successfully implemented a phase-out program, mainly through the concept of umbrella projects. In countries like China and India, the SMEs are distributed over a wider range of regions and the immensity of the task of user identification becomes almost impossible.

The SMEs problem is compounded by the fact that some of the alternatives to OD solvents are not produced in Article 5(1) countries, and must be imported. As a result, price and availability become barriers to widespread implementation.

Projected authorisations from the MLF for SME solvents projects can also be difficult to establish. The high cost per kilogram of OD solvents phased out in SME projects as typically above threshold values, due to the capital and operating costs of most replacement processes.

Despite these difficulties, the rate of phase-out rate of OD solvent phase-out by the SMEs has been encouraging, especially in Article 5(1) countries. However, the magnitude of the global ODS phase-out task that remains is significant.

ES.7.4 Carbon Tetrachloride Use in Article 5(1) Parties

Since the last report, the STOC has become aware of very significant use of carbon tetrachloride (CTC) in various cleaning processes in Article 5(1) countries. It is being used in simple open containers which presents not only a serious threat to the health of a large number of workers due to its proven toxic effects, but also to the ozone layer, because of its very high ODP. Such cleaning operations are also coupled with significant spillage of CTC on the floor where it enters the soil, even through cement or concrete, and often contaminates ground water, often a major source of public drinking water. There are a large number of small users in Article 5(1) countries using CTC under very emissive conditions and they have limited resources for change. Developed countries are presently spending large sums to clean soil and groundwater that was contaminated by such practices in the past, and these practices are now illegal in the developed countries.

Some medium and large enterprises use CTC in inadequately sealed vapour degreasing machines, with equal risk to the environment and worker health and safety. It is the preferred solvent for metal cleaning as it is the cheapest, easily obtainable in many countries and is a very efficient as a degreaser.

CTC is widely used in some countries for the dry cleaning of textiles. One STOC member recently witnessed the use of CTC in an old, leaky, rotary drum machine. The clothes removed from the machine were still quite damp with the solvent, but they were immediately passed to workers for pressing with both hand irons and rotary calender machines. The long-term health effects on these operators resulting from dermal absorption and inhalation of CTC are significant.

The committee consensus is that such cleaning processes using CTC must be avoided for many reasons. This is especially true because non-OD alternatives (notably, trichloroethylene and perchloroethylene) that would improve the effects of worker exposure are readily available and could be easily implemented, provided suitable equipment is available. These solvents are not ideal, but they do offer a simple and immediate alternative to ODS, and offer an improvement to workers.

ES.7.5 HCFCs

HCFCs are transition substances that meet the needs of some limited and unique applications where non-OD alternatives have not been identified. These include:

- cleaning delicate materials such as cultural heritage and archival property
- cleaning assemblies or components with sensitive materials or particular soils
- cleaning certain oxygen systems
- cleaning where explosive or flammable conditions are possible
- as a carrier of oil in precision applications.

In countries where HCFCs are prohibited, enterprises may, in certain specific cases, select perfluorinated carbons (PFCs) as an adjunct to specialised cleaning systems. PFCs have extremely long atmospheric lifetimes and have potent global warming potentials (GWPs) and should therefore be avoided where possible.

The Committee does not recommend the use of HCFC-141b to replace 1,1,1-trichloroethane as a solvent. HCFC-141b has an ozone-depletion potential (ODP) comparable to 1,1,1-trichloroethane and is not technically suitable for many cleaning applications.

It is estimated that HCFC-141b and HCFC-225 together will not replace more than 1 percent of global CFC-113 uses unless HCFC-225 becomes a substitute for CFC-113 in dry cleaning, which could increase use to approximately 5 percent. In some countries, HCFC producers are engaged in aggressive marketing efforts. However, only about 5 percent of CFC-113 solvent use (excluding dry-cleaning, which may increase use) may be replaced with HCFC-141b. It is estimated that HCFCs overall may replace only about 1-5 percent of 1986 CFC-113 and 1,1,1-trichloroethane as a short term transitional substances in situations where no other alternatives are currently available.

ES.7.6 Brominated Solvents

Recently, two brominated OD solvents have been commercially introduced: chlorobromomethane (CBM) and n-propyl bromide (nPB). These two substances are also blended into solvent mixtures that are sold under many trade names. They are being marketed as substitutes for non-ozone depleting solvents (trichloroethylene and perchloroethylene) and ozone-depleting solvents (HCFCs, CFC-113 and 1,1,1-trichloroethane).

The UNEP Scientific Assessment Panel recently assigned chlorobromomethane (CBM) an ozone-depleting potential of 0.15, which is comparable to that of 1,1,1-trichloroethane. Additionally, CBM has significant toxicological concerns. The STOC does not recommend the use of CBM as a solvent alternative.

Likewise nPB is ozone depleting. The Committee does not recommend this solvent as a substitute for other OD solvents. This view is further substantiated by the fact that non-OD solutions exist for all cleaning applications for which nPB is being promoted.

ES.7.7 Military Progress

Military organisations in most developed countries have eliminated virtually all uses of OD solvents. The majority of military solvent uses are identical to those found in the commercial sector, and implementation of ODS alternatives in both sectors is virtually complete.

Very few Parties operating under Article 5(1) have provided information to TEAP regarding military ODS solvent uses and on their efforts to find alternatives. With the first control measure coming into force in 1999 for Article 5(1) Parties it is important that military organisations in these countries identify their uses, and begin planning their transition to alternatives. There is a wealth of experience in non-Article 5(1) Parties on specific military uses. Developed country militaries have approved a wide range of alternatives for specific military applications, and are willing to share this information with militaries from Article 5(1) countries in order to simplify the transition. UNEP IE is producing a set of guidelines that capture the experiences from developed country military organisations and offer a framework for Article 5(1) militaries to begin implementing programs to manage their ODS uses.

ES.7.8 Oxygen Systems

Most oxygen systems have components and assemblies with similar functions such as tubing, gauges, regulators, valves, thermal compensators and cylinders. A large variety of metallic and non-metallic parts are used to fabricate the system devices.

The use of oxygen involves a degree of risk because oxygen vigorously supports combustion when in contact with many substances. Thus a high level of cleanliness is prerequisite for oxygen system components.

CFC-113 was the solvent of choice for many years in cleaning oxygen systems. This solvent displayed performance and safety characteristics that were uniquely suited for the cleaning of oxygen systems.

Progress has been made to introduce alternative cleaning methods without the use of CFC-113. For example, the US Navy and Lufthansa German Airlines have been using aqueous cleaning methods with no processing or operational problems. Some other organisations have started using HFE-7100, HCFC-225, HFC-43-10 and HFC-141b with certain limitations for components used in their oxygen systems. The acceptance of alternatives to CFC-113 by the industry has been slow because of stringent specifications requirements on the degree of cleanliness and its verification. These requirements in many cases have been arbitrarily fixed.

ES.7.9 Sub-Sector Progress

In the following sub-sectors progress has been made to perform almost all tasks without the use of controlled ozone-depleting solvents:

- Electronics cleaning
- Precision cleaning
- Metal cleaning
- Dry cleaning
- Adhesives
- Aerosols solvent products and
- Fingerprinting.

In many applications HCFCs, HFCs and HFEs have replaced the use of CFC-113 and methyl chloroform.

For further details, see the 1998 STOC-Report.

ES.8 Challenges for Article 5(1) and CEIT

Some unresolved issues raised in the past are still pending for both Article 5(1) Parties and CEIT. Several concerns are still to be fully addressed in order to assure the continued success of the Protocol. Some issues are common to both Article 5(1) Parties and CEIT but others are specific either to non-Article 5(1) CEIT or to Article 5(1) Parties, and they are discussed separately in the report.

ES.8.1 Article 5(1) Parties

Capacity to access the enormous amount of information now available varies in Article 5(1) countries. Internet access has made increased the rate at which information is transferred internationally. However, access and language remain barriers, especially for SMEs. It is also important to keep national and international experts informed of technical developments, as well as successes and failures of the technologies offered or transferred to Article 5(1) Parties to avoid unwise choices and implementation delays.

With the freeze of 1999 and the reductions mandated for 2005, Governments are faced with great challenges. Experience from developed countries indicates that strong leadership and commitment from government, industry and individuals is important to establish and maintain momentum. Support from the MLF to strengthen institutions is an important mechanism to educate decision makers and stakeholders in government, industry and the public. During project formulation and implementation, prompt reaction to requests to and from the Implementing Agencies and good Cooperation between the Ozone Unit and the Implementing Agencies is also important to accelerating implementation. Data reporting is also important. Accurate consumption data by sector/sub-sector is not available from several Article 5(1) Parties. Many kinds of support, including institutional strengthening, capacity building, information exchange and training are important, but ultimate responsibility lies with Governments to make effective use of this support.

A major obstacle for several Article 5(1) Parties is the inadequacy of the regulatory structure to support the phase-out process. In several Article 5(1) countries the price of ODS is very low and imported alternatives are taxed. Therefore, enterprises which have MLF funded projects finalised may find themselves in a situation where high costs of non-ODS alternatives prohibit them to be competitive with enterprises which still have not converted to non-ODS. In addition, fiscal cultures that rely on collecting taxes for imported machinery can pose potential problems for MLF projects. Resolving these tax issue adds to project implementation delays because of the need to waive taxes for equipment procured through the MLF.

Uncertainties regarding availability and cost of technology have been mostly resolved. The Montreal Protocol brought high levels of technical innovation and business opportunities. Market strategies were designed to respond to increased consumer awareness in developed countries as well as in several Article 5(1) countries. Environmentally friendly products and better public image by industry brought gains in competitive global and regional markets. Industry creativity, research efforts and Cooperation among industry sectors, and widespread adoption of new technologies were successful in lowering costs.

There are now alternatives to replace almost all ODS uses. Therefore, the greatest challenge that remains is the implementation of projects in Article 5(1) countries and ways to address and reach out the large informal servicing sector. In general technology transfer has been very successful with mature, proven technology being transferred to Article 5(1) Parties. Still, even with these technologies, training remains an important part of the projects to assure that technologies are correctly adopted and adapted to local capacity.

It is possible to conclude that the Montreal Protocol has forced the replacement of several mature technologies by many new alternatives. In some cases, these new technologies were easy to identify and offered clear paybacks, as was generally the case in the aerosols sector. However, in other cases, replacements were not as evident, and a number of possible solutions are available and must be carefully evaluated in the context of each specific application.

ES.8.2 CEIT

Many of the 16 non-Article 5(1) CEIT are lagging behind phase-out schedule set by the Montreal Protocol. Their non-compliance cases was and is going to be discussed by the Implementation Committee and reported to the Parties. The ODS consumption of these countries is decreasing year by year; its quantity in 1998 might be in the range of 10,000-12,000 tonnes.

Some especial circumstance hampering timely phase-out are still existing in these countries:

- Most CEIT lack the trade and industry associations that typically exist in other countries. The absence of trade and industry associations hampers the phase-out because there is no network of experts and because there is no venue for reaching consensus.
- Information exchange, training and raising of public awareness is necessary to be continued and/or improved. GEF supported projects might serve as proper channel for such activities
- Governments continue in most CEIT to be challenged to improve inter-agency co-ordination, to introduce or strengthen substantially license and custom control system for ODS and generally to improve enforcement of existing new regulatory measures.

GEF-supported ODS phase-out projects are being implemented or implementation will begin soon in non-complying countries. It can be expected that around 2001 compliance will be accomplished.

Several factors might however challenge the goal of full non-Article 5(1) CEIT compliance by that point of time. The most important ones are:

- To get those states which are not yet Parties to the Protocol involved in the process of the Protocol, including ratification of the Amendments (or of the London Amendment as a minimum);
- To agree on a Special Initiative for funding the phase-out of ODS production in the Russian Federation, and an early start of its implementation;
- That the latest extensive economic difficulties in the Russian Federation and in other CIS countries do not ruin the financial viability of recipient enterprises in these countries.

Appendix D

Frequently Asked Questions About the Ozone Layer and Related Environmental Effects

Frequently Asked Questions About Ozone to the Scientific Assessment Panel

Ozone is very rare in our atmosphere, averaging about 3 molecules of ozone for every 10 million air molecules. In spite of this small amount, ozone plays vital roles in the atmosphere. This appendix to the Executive Summary of the *Scientific Assessment of Ozone Depletion: 1998* provides answers to some of the questions that are most frequently asked about ozone and the changes that have been occurring in recent years. These questions and answers are based on the information presented in this 1998 report, which was prepared by 304 scientists from 35 countries worldwide. Therefore, the information presented here represents the knowledge of a large group of experts from the international scientific community.

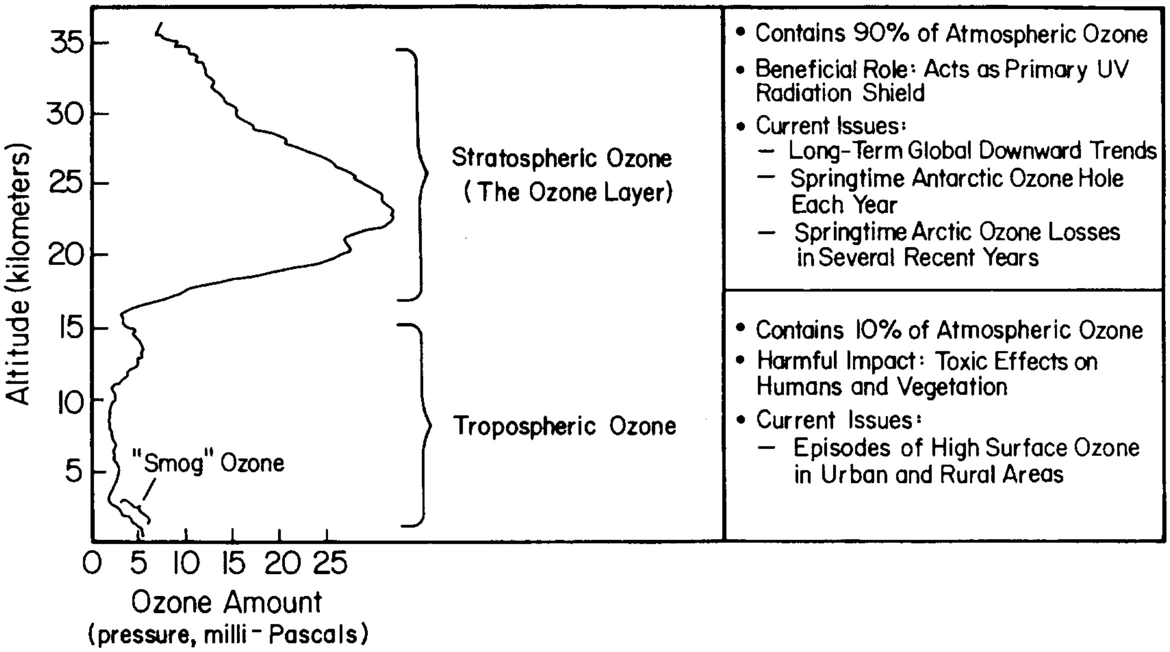
Ozone is mainly found in two regions of the Earth's atmosphere. Most ozone (about 90%) resides in a layer that begins between 8 and 18 kilometers (5 and 11 miles) above the Earth's surface and extends up to about 50 kilometers (30 miles). This region of the atmosphere is called the stratosphere. The ozone in this region is commonly known as the ozone layer. The remaining ozone is in the lower region of the atmosphere, which is commonly called the troposphere. The figure below shows an example of how ozone is distributed in the atmosphere.

The ozone molecules in these two regions are chemically identical, because they all consist of three oxygen atoms and have the chemical formula 0_3. However, they have very different effects on humans and other living beings. Stratospheric ozone plays a beneficial role by absorbing most of the biologically damaging ultraviolet sunlight (called UV-B), allowing only a small amount to reach the Earth's surface. The absorption of ultraviolet radiation by ozone creates a source of heat, which actually forms the stratosphere itself (a region in which the temperature rises as one goes to higher altitudes). Ozone thus plays a key role in the temperature structure of the Earth's atmosphere. Without the filtering action of the ozone layer, more of the Sun's UV-B radiation would penetrate the atmosphere and would reach the Earth's surface. Many experimental studies of plants and animals and clinical studies of humans have shown the harmful effects of excessive exposure to UV-B radiation.

At the Earth's surface, ozone comes into direct contact with life-forms and displays its destructive side. Because ozone reacts strongly with other molecules, high levels of ozone are toxic to living systems. Several studies have documented the harmful effects of ozone on crop production, forest growth, and human health. The substantial negative effects of surface-level tropospheric ozone from this direct toxicity contrast with the benefits of the additional filtering of UV-B radiation that it provides.

The dual role of ozone leads to two separate environmental issues. There is concern about *increases in* ozone in the troposphere. Low-lying ozone is a key component of photochemical smog, a familiar problem in the atmosphere of many cities around the world. Higher amounts of surface-level ozone are increasingly being observed in rural

Atmospheric Ozone



areas as well.

There is also widespread scientific and public interest and concern about *losses* of ozone in the stratosphere. Ground-based and satellite instruments have measured decreases in the amount of stratospheric ozone in our atmosphere. Over some parts of Antarctica, up to 60% of the total overhead amount of ozone (known as the column ozone) is depleted during Antarctic spring (September-November). This phenomenon is known as the Antarctic ozone hole. In the Arctic polar regions, similar processes occur that have also led to significant chemical depletion of the column ozone during late winter and spring in 6 out of the last 9 years. The ozone loss from January through late March has been typically 20-25%, and shorter-period losses have been higher, depending on the meteorological conditions encountered in the Arctic stratosphere. Smaller, but still significant, stratospheric decreases have been seen at other, more populated regions of the Earth. Increases in surface UV-B radiation have been observed in association with local decreases in stratospheric ozone, from both ground-based and satellite-borne instruments.

The scientific evidence, accumulated over more than two decades of study by the international research community, has shown that human-produced chemicals are responsible for the observed depletions of the ozone layer. The ozone-depleting compounds contain various combinations of the chemical elements chlorine, fluorine, bromine, carbon, and hydrogen and are often described by the general term halocarbons. The compounds that contain only chlorine, fluorine, and carbon are called chlorofluorocarbons, usually abbreviated as CFCs. CFCs, carbon tetrachloride, and methyl chloroform are important human-produced ozone-depleting gases that have been used in many applications including refrigeration, air conditioning, foam blowing, cleaning of electronic components, and as solvents. Another important group of human-produced halocarbons is the halons, which contain carbon, bromine, fluorine, and (in some cases) chlorine and have been mainly used as fire extinguishants. Governments have decided to eventually discontinue production of CFCs, halons, carbon tetrachloride, and methyl chloroform (except for a few special uses), and industry has developed more "ozone-friendly" substitutes.

Two responses are natural when a new problem has been identified: cure and prevention. When the problem is the destruction of the stratospheric ozone layer, the corresponding questions have been the following ones: Can we repair the damage already done? How can we prevent further destruction? Remedies have been investigated that could (1) remove CFCs selectively from the atmosphere, (2) intercept ozone-depleting chlorine before much depletion has taken place, or (3) replace the ozone lost in the stratosphere (perhaps by shipping the ozone from cities that have too much smog or by making new ozone). However, because ozone reacts strongly with other molecules, it is too unstable to be made elsewhere (e.g., in the smog of cities) and transported to the stratosphere. Considering the huge volume of the Earth's atmosphere and the magnitude of global stratospheric ozone depletion, the suggested remedies quickly become much too expensive, too energy consuming, impractical, and potentially damaging to the global environment.

Repair involves the internationally agreed-upon Montreal Protocol and its Amendments and Adjustments. This agreement regulates the production of CFCs and other ozone-depleting substances. Production of the most damaging ozone-depleting substances was eliminated, except for a few critical uses, by 1996 in developed countries and will be eliminated by 2010 in developing countries. As a result, the total concentration of chlorine in the lower atmosphere that can be carried to the stratosphere has peaked already. The concentrations in the stratosphere will likely peak by the end of this decade and then will start to decrease slowly as natural processes remove the ozone-depleting substances. All other things being equal, and with adherence to the international agreements, the ozone layer is expected to recover over the next 50 years or so.

How Can Chlorofluorocarbons (CFCs) Get to the Stratosphere If They're Heavier than Air?

CFCs reach the stratosphere because the Earth's atmosphere is always in motion and mixes the chemicals added into it.

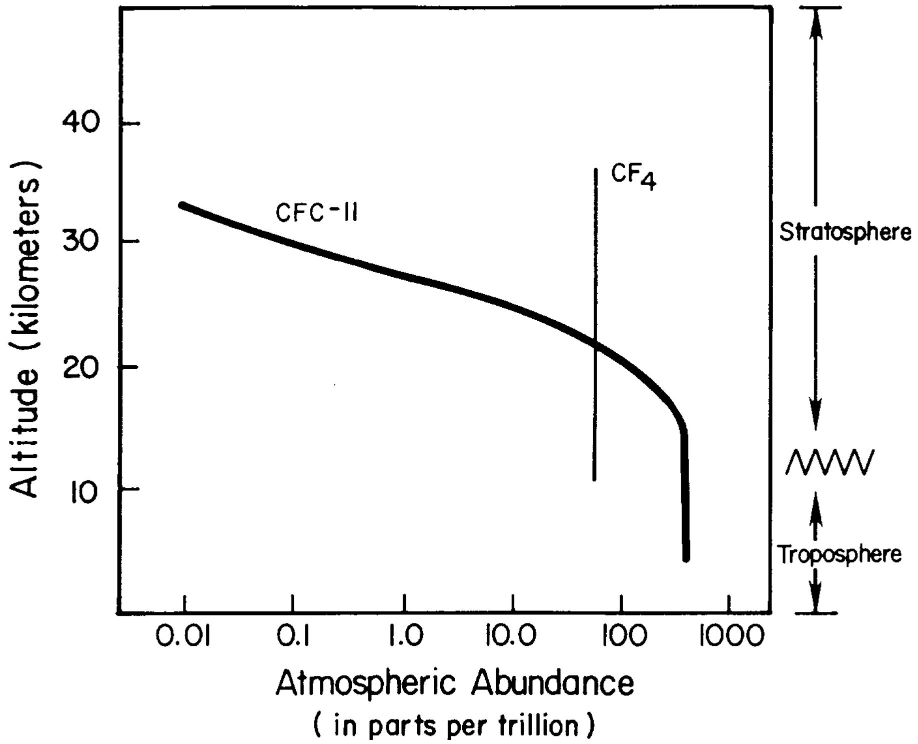
CFC molecules are indeed several times heavier than air. Nevertheless, thousands of measurements from balloons, aircraft, and satellites demonstrate that the CFCs are actually present in the stratosphere. This is because winds and other air motions mix the atmosphere to altitudes far above the top of the stratosphere much faster than molecules can settle according to their weight. Gases such as CFCs that do not dissolve in water and that are relatively unreactive in the lower atmosphere are mixed relatively quickly and therefore reach the stratosphere regardless of their weight.

Measured changes in concentration of constituents versus altitude teaches us more about the fate of compounds in the atmosphere. For example, the two gases carbon tetrafluoride (CF_4, produced mainly as a by-product of the manufacture of aluminum) and CFC-11 (CCl_3F, used in a variety of human activities) are both heavier than air.

Carbon tetrafluoride is completely unreactive at altitudes up to at least 50 kilometers in the atmosphere. Measurements show it to be nearly uniformly distributed throughout the atmosphere, as illustrated in the figure below. There have been measurements over the past two decades of several other completely unreactive gases, both lighter than air (neon) and heavier than air (argon and krypton), that show that they also mix upward through the stratosphere regardless of their weight.

CFC-11 is unreactive in the lower atmosphere and is similarly uniformly mixed there, as shown in the figure. However, the abundance of CFC-11 decreases as the gas reaches higher altitudes, because it is broken down by high-energy solar ultraviolet radiation. Chlorine released from this breakdown of CFC-11 and other CFCs remains in the stratosphere for several years, where every chlorine atom destroys many thousands of molecules of ozone.

Atmospheric Measurements of CFC-11 and CF_4



What is the Evidence that Stratospheric Ozone is Destroyed by Chlorine and Bromine?

Numerous laboratory investigations and analyses of worldwide measurements made in the stratosphere have demonstrated that chlorine- and bromine-containing chemicals destroy ozone molecules.

Research studies in the laboratory show that chlorine (Cl) reacts very rapidly with ozone. They also show that the reactive chemical chlorine monoxide (ClO) formed in that reaction can undergo further processes that regenerate the original chlorine, allowing the sequence to be repeated very many times (a chain reaction). Similar reactions also take place between bromine and ozone.

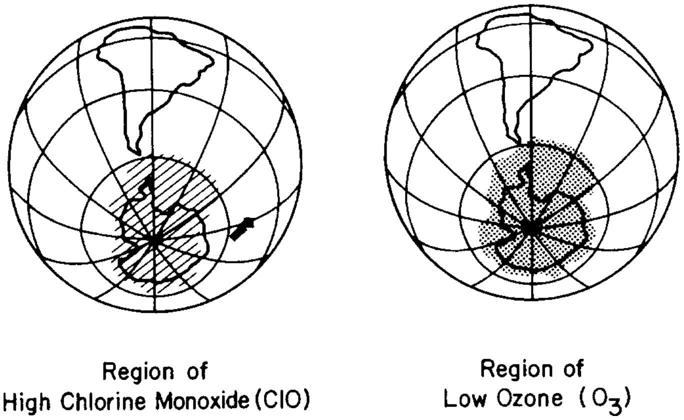
But do these ozone-destroying reactions occur in the "real world"? All the accumulated scientific experience demonstrates that the same chemical reactions do take place in nature. Many other reactions (including those of other chemical species) are often also taking place simultaneously in the stratosphere. This makes the connections among the changes difficult to untangle. Nevertheless, whenever chlorine (or bromine) and ozone are found together in the stratosphere, the ozone-destroying reactions are taking place.

Sometimes a small number of chemical reactions are so dominant in the natural circumstance that the connections are almost as clear as in laboratory experiments. Such a situation occurs in the Antarctic stratosphere during the springtime formation of the ozone hole. Independent measurements made by instruments from the ground and from balloons, aircraft, and satellites have provided a detailed understanding of the chemical reactions in the Antarctic stratosphere. Large areas reach temperatures so low (less than -80°C, or -112°F) that stratospheric clouds form, which is a rare occurrence, except during the polar winters. These polar stratospheric clouds allow chemical reactions that transform chlorine species from those that do *not* cause ozone depletion into those that do. Among the latter is chlorine monoxide, which initiates ozone destruction in the presence of sunlight. The amount of reactive chlorine in such regions is therefore much higher than that observed in the middle latitudes, which leads to much faster chemical ozone destruction. The chemical reactions occurring in the presence of these clouds are now well understood from studies under laboratory conditions that mimic those found naturally in the atmosphere.

Scientists have repeatedly observed a large number of chemical species over Antarctica since 1986. Among the chemicals measured were ozone and chlorine monoxide, which is the reactive chemical identified in the laboratory as one of the participants in the ozone-destroying chain reactions. The satellite maps shown in the figure below relate the accumulation of chlorine monoxide observed over Antarctica and the subsequent ozone depletion that occurs rapidly in a few days over very similar areas.

Similar reactions involving chlorine and bromine have also been shown to occur during winter and spring in the Arctic polar regions, which leads to some chemical depletion of ozone in that region. Because the Arctic is not usually as persistently cold as the Antarctic, fewer stratospheric clouds form, and therefore there is less ozone depletion in the Arctic, which is the subject of a later question.

Chlorine Monoxide and the Antarctic Ozone Hole: Late August 1996



Region of
High Chlorine Monoxide (ClO)

Region of
Low Ozone (O_3)

Does Most of the Chlorine in the Stratosphere Come from Human or Natural Sources?

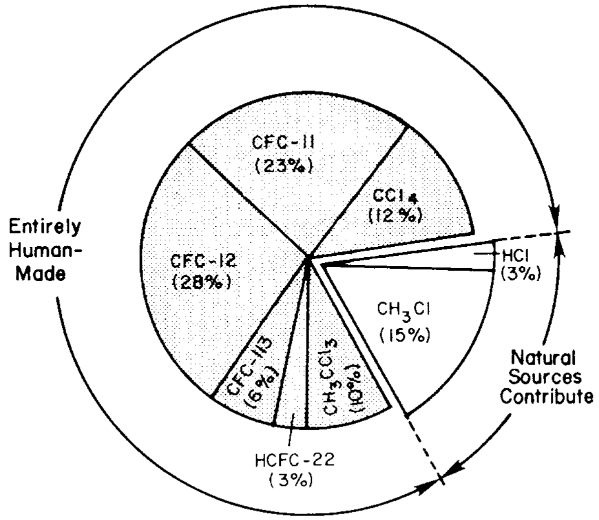
Most of the chlorine in the stratosphere is there as a result of human activities, as the figure below illustrates.

Many compounds containing chlorine are released at the ground. Those that dissolve in water cannot reach stratospheric altitudes in significant amounts because they are "washed out" of the atmosphere in rain or snow. For example, large quantities of chlorine are released from evaporated ocean spray as sea salt (sodium chloride) particles. However, because sea salt dissolves in water, this chlorine is taken up quickly in clouds or in ice, snow, or rain droplets and does not reach the stratosphere. Another ground-level source of chlorine is from its use in swimming pools and as household bleach. When released, this chlorine is rapidly converted to forms that dissolve in water and therefore are removed from the lower atmosphere. Such chlorine never reaches the stratosphere in significant amounts. Volcanoes can emit large quantities of hydrogen chloride, but this gas is rapidly converted to hydrochloric acid, which dissolves in rain water, ice, and snow and does not reach the stratosphere. Even in explosive volcanic plumes that rise high in the atmosphere, nearly all of the hydrogen chloride is removed by precipitation before reaching stratospheric altitudes. Finally, although the exhaust from the Space Shuttle and from some rockets does inject some chlorine directly into the stratosphere, the quantities are very small (less than 1% of the annual input from halocarbons in the present stratosphere).

In contrast, the major ozone-depleting human-produced halocarbons - such as chlorofluorocarbons (CFCs) and carbon tetrachloride (CCl_4) - are not soluble in water, do not react with snow or other natural surfaces, and are not broken down chemically in the lower atmosphere. Therefore, these and other human-produced substances containing chlorine do reach the stratosphere.

Several pieces of evidence combine to establish human-produced halocarbons as the primary source of stratospheric chlorine. First, measurements have shown that the chlorinated species that rise to the stratosphere are primarily manufactured compounds [mainly CFCs, carbon tetrachloride, methyl chloroform, and the hydrochlorofluorocarbon (HCFC) substitutes for CFCs], together with small amounts of hydrochloric acid (HCl) and methyl chloride (CH_3Cl), which are partly natural in origin. Second, researchers have measured nearly all known gases containing chlorine in the stratosphere. They have found that the emissions of the human-produced halocarbons, plus the much smaller contribution from natural sources, could account for all of the stratospheric chlorine. Third, the *increase in* total stratospheric chlorine measured between 1980 and 1998 corresponds to the known increases in concentrations of human-produced halocarbons during that time.

Primary Sources of Chlorine Entering the Stratosphere in the Early 1990s



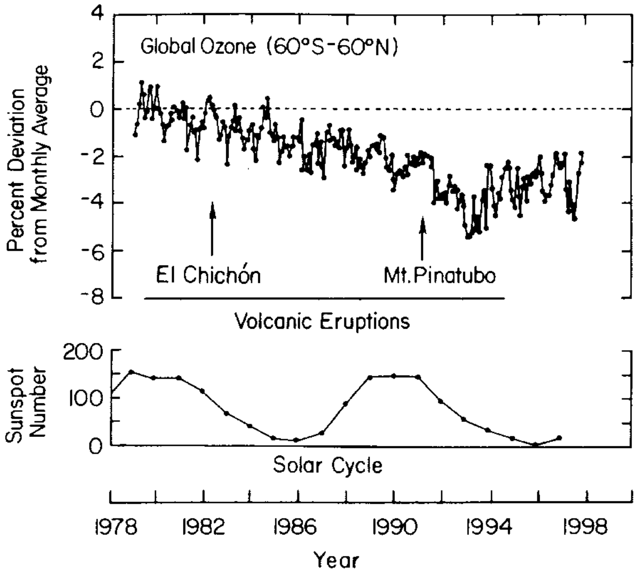
Can Natural Changes Such As the Sun's Output and Volcanic Eruptions Be Responsible for the Observed Changes in Ozone?

Although there are natural forces that cause fluctuations in ozone amounts, there is no evidence that natural changes are contributing significantly to the observed long-term trend of decreasing ozone.

The formation of stratospheric ozone is initiated by ultraviolet (UV) light coming from the Sun. As a result, the Sun's output affects the rate at which ozone is produced. The Sun's energy release (both as UV light and as charged particles such as electrons and protons) does vary, especially over the well-known 11-year sunspot cycle. Observations over several solar cycles (since the 1960s) show that total global ozone levels vary by 1-2% from the maximum to the minimum of a typical cycle. However, changes in the Sun's output cannot be responsible for the observed long-term changes in ozone, because the ozone downward trends are much larger than 1-2%. As the figure below shows, since 1978 the Sun's energy output has gone through maximum values in about 1980 and 1991 and minimum values in about 1985 and 1996. It is now increasing again toward its next maximum around the year 2002. However, the trend in ozone was downward throughout that time. The ozone trends presented in this and previous international scientific assessments have been obtained by evaluating the long-term changes in ozone after accounting for the solar influence (as has been done in the figure below).

Major, explosive volcanic eruptions can inject material directly into the ozone layer. Observations and model calculations show that volcanic particles cannot on their own deplete ozone. It is only the interaction of human-produced chlorine with particle surfaces that enhances ozone depletion in today's atmosphere. Specifically, laboratory measurements and observations in the atmosphere have shown that chemical reactions on and within the surface of volcanic particles injected into the lower stratosphere lead to enhanced ozone destruction by increasing the concentration of chemically active forms of chlorine that arise from the human-produced compounds like the chlorofluorocarbons (CFCs). The eruptions of Mt. Agung (1963), Mt. Fuego (1974), El Chichón (1982) and particularly Mt. Pinatubo (1991) are examples. The eruption of Mt. Pinatubo resulted in a 30- to 40-fold increase in the total surface area of particles available for enhancing chemical reactions. The effect of such natural events on the ozone layer is then dependent on the concentration of chlorine-containing molecules and particles available in the stratosphere, in a manner similar to polar stratospheric clouds. Because the particles are removed from the stratosphere in 2 to 5 years, the effect on ozone is only temporary, and such episodes cannot account for observed long-term changes. Observations and calculations indicate that the record-low ozone levels observed in 1992-1993 reflect the importance of the relatively large number of particles produced by the Mt. Pinatubo eruption, coupled with the relatively higher amount of human-produced stratospheric chlorine in the 1990s compared to that at times of earlier volcanic eruptions.

Global Ozone Trend, Major Volcanic Eruptions, and Solar Cycles



When Did the Antarctic Ozone Hole First Appear?

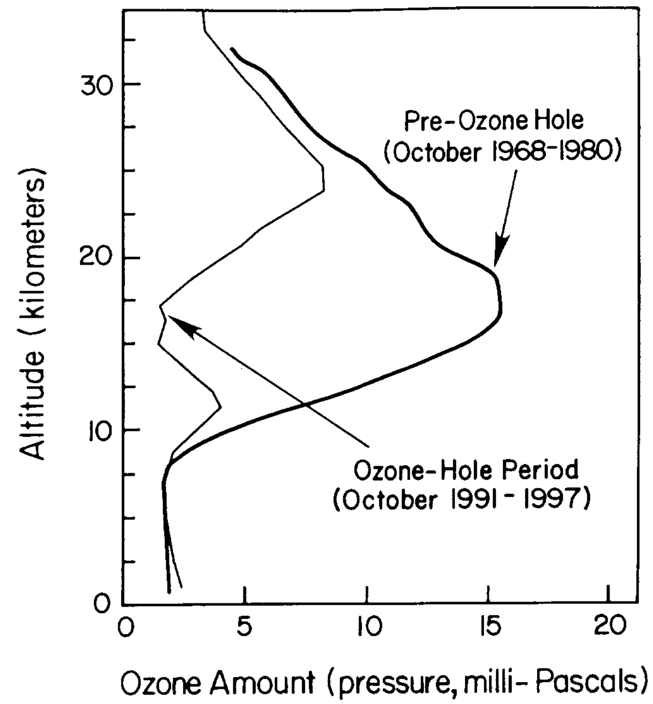
The Springtime Antarctic ozone hole is a new phenomenon that appeared in the early 1980s.

The observed average amount of ozone during September, October, and November over the British Antarctic Survey station at Halley, Antarctica, first revealed notable decreases in the early 1980s, compared with the preceding data obtained starting in 1957. The ozone hole is formed each year when there is a sharp decline (currently up to 60%) in the total ozone over most of Antarctica for a period of about three months (September-November) during spring in the Southern Hemisphere. Late-summer (January-March) ozone amounts show no such sharp decline in the 1980s and 1990s. Observations from three other stations in Antarctica and from satellite-based instruments reveal similar decreases in springtime amount of ozone overhead. Balloon-borne ozone instruments show dramatic changes in the way ozone is distributed with altitude. As the figure below from the Syowa site shows, almost all of the ozone is now depleted at some altitudes as the ozone hole forms each springtime, compared to the normal ozone profile that existed before 1980. As explained in an earlier question (page 144), the ozone hole has been shown to result from destruction of stratospheric ozone by gases containing chlorine and bromine, whose sources are mainly human-produced halocarbon gases.

Before the stratosphere was affected by human-produced chlorine and bromine, the naturally occurring springtime ozone levels over Antarctica were about 30-40% lower than springtime ozone levels over the Arctic. This natural difference between Antarctic and Arctic conditions was first observed in the late 1950s by Dobson. It stems from the exceptionally cold temperatures and different winter wind patterns within the Antarctic stratosphere as compared with the Arctic. This is not at all the same phenomenon as the marked downward trend in total ozone in recent years.

Changes in stratospheric meteorology cannot explain the ozone hole. Measurements show that wintertime Antarctic stratospheric temperatures of past decades had not changed prior to the development of the ozone hole each September. Ground, aircraft, and satellite measurements have provided, in contrast, clear evidence of the importance of the chemistry of chlorine and bromine originating from human-made, compounds in depleting Antarctic ozone in recent years.

Springtime Depletion of the Ozone Layer over Syowa, Antarctica



Why Has an Ozone Hole Appeared over Antarctica When CFCs and Halons Are Released Mainly in the Northern Hemisphere?

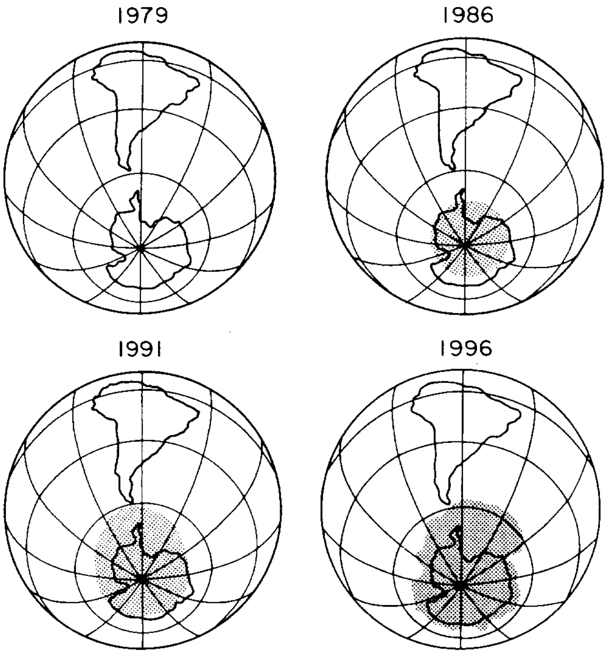
The Earth's atmosphere is continuously stirred over the globe by winds. As a result, ozone-depleting gases get mixed throughout the atmosphere, including Antarctica, regardless of where they are emitted. The special meteorological conditions in Antarctica cause these gases to be more effective there in depleting ozone compared to anywhere else.

Human emissions of chlorofluorocarbons (CFCs) and halons (bromine-containing gases) have occurred mainly in the Northern Hemisphere. About 90% have been released in the latitudes corresponding to Europe, Russia, Japan, and North America. Gases such as CFCs and halons, which are insoluble in water and relatively unreactive, are mixed within a year or two throughout the lower atmosphere. The CFCs and halons in this well-mixed air rise from the lower atmosphere into the stratosphere mainly in tropical latitudes. Winds then move this air poleward - both north and south - from the tropics, so that air throughout the global stratosphere contains nearly equal amounts of chlorine and bromine.

In the Southern Hemisphere, the South Pole is part of a very large land mass (Antarctica) that is completely surrounded by ocean. This symmetry is reflected in the meteorological conditions that allow the formation in winter of a very cold region in the stratosphere over the Antarctic continent, isolated by a band of strong winds circulating around the edge of that region. The very low stratospheric temperatures lead to the formation of clouds (polar stratospheric clouds) that are responsible for chemical changes that promote production of chemically active chlorine and bromine. This chlorine and bromine activation then leads to rapid ozone loss when sunlight returns to Antarctica in September and October of each year, which then results in the Antarctic ozone hole. As the figure below depicts, the magnitude of the ozone loss has generally grown through the 1980s as the amount of human-produced ozone-depleting compounds has grown in the atmosphere.

Similar conditions do not exist over the Arctic. The wintertime temperatures in the Arctic stratosphere are not persistently low for as many weeks as over Antarctica, which results in correspondingly less ozone depletion in the Arctic (see the next question).

Schematic of the Growth of the Antarctic Ozone Hole



Is There an Ozone Hole over the Arctic?

Significant reductions in ozone content in the stratosphere above the Arctic have been observed during the late winter and early spring (January-March) in 6 of the last 9 years. However, these reductions, typically 20-25%, are much smaller than those observed currently each spring over the Antarctic (the ozone hole).

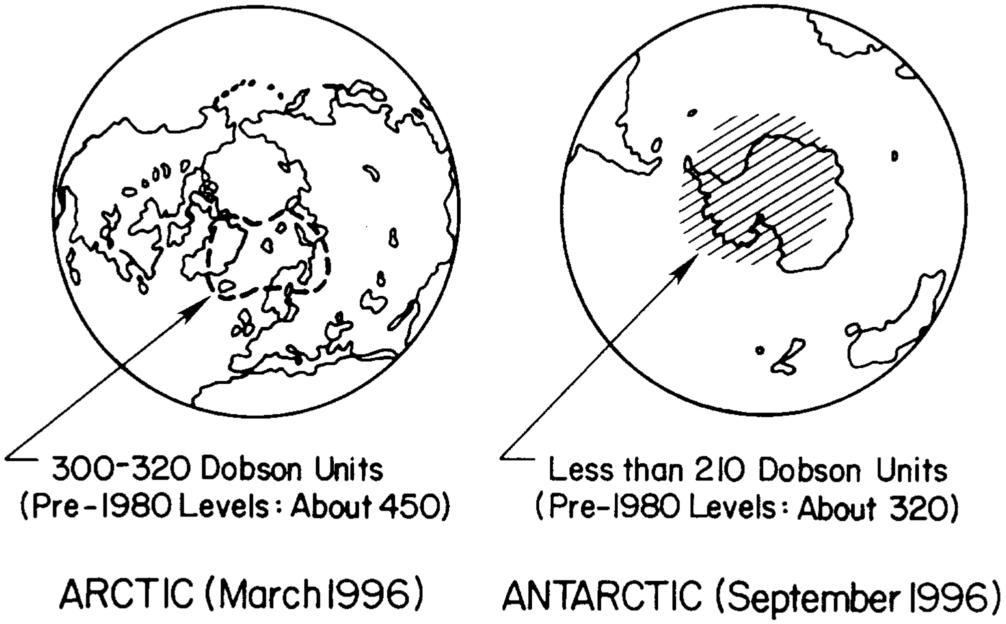
The difference between ozone content in the two polar regions (see figure below) is caused by the dissimilar weather patterns. The Antarctic continent is a very large land mass surrounded by oceans. This symmetrical condition produces very low stratospheric temperatures within a meteorologically isolated region, the so-called polar vortex, which extends from about 65°S to the pole. The cold temperatures lead in turn to the formation of clouds, known as polar stratospheric clouds. These clouds provide chemical changes that promote production of chemically active chlorine and bromine that rapidly destroy ozone. The conditions that maintain elevated levels of chemically active chlorine and bromine persist into September and October in Antarctica, when sunlight returns over the region to initiate ozone depletion.

The winter meteorological conditions in the Northern Hemisphere, just like in the Southern Hemisphere, lead to the formation of an isolated region bounded by strong winds, in which the temperature is also cold enough for polar stratospheric clouds to form. However, the geographic symmetry about the North Pole is less than about the South Pole. As a result, large-scale weather systems disturb the wind flow, making it less stable over the Arctic region than over the Antarctic continent. These disturbances prevent the temperature in the Arctic stratosphere from being as cold as in the Antarctic stratosphere, and fewer polar stratospheric clouds are therefore formed. Nevertheless, chemically active chlorine and bromine compounds are also formed over the Arctic, as they are over Antarctica, from reactions at the surface of the clouds. But the cold conditions rarely persist into March, when sufficient sunlight is available to initiate large ozone depletion.

In recent years, there has been a string of unusually cold winters in the Arctic, compared with those in the preceding 30 years. The cold and persistent conditions have led to enhanced ozone depletion, since the atmospheric concentrations of ozone-depleting gases have also been relatively large during these years. However, the cause of the observed change in meteorological conditions is not yet understood. Such conditions might persist over the coming years, further enhancing ozone depletion. But it is also possible that, in the next few years, they could revert to conditions characteristic of a decade ago. In the latter case, chemical ozone depletion in the Arctic would be expected to diminish.

Therefore, although there has been significant ozone depletion in the Arctic in recent years, it is difficult to predict what may lie ahead, because the future climate of the Arctic stratosphere cannot be predicted with confidence.

A Schematic of the Ozone over the Arctic and Antarctica in 1996



Is the Depletion of the Ozone Layer Leading to an Increase in Ground-Level Ultraviolet Radiation?

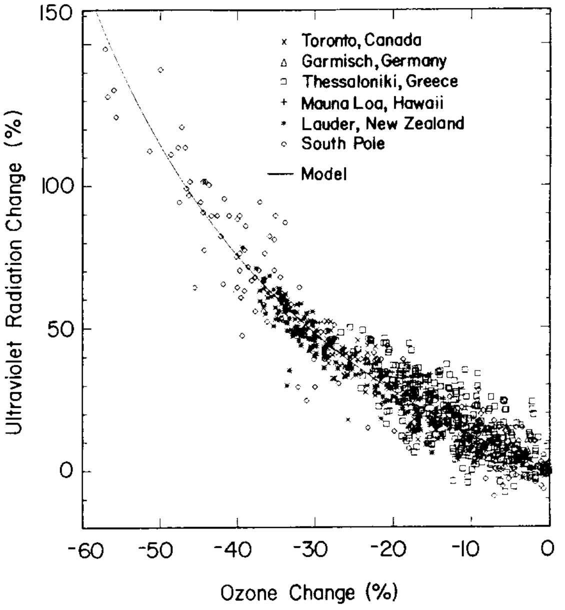
The depletion of the ozone layer leads, on the average, to an increase in ground-level ultraviolet radiation, because ozone is an effective absorber of ultra-violet radiation.

The Sun emits radiation over a wide range of energies, with about 2% in the form of high-energy, ultraviolet (UV) radiation. Some of this UV radiation (UV-B) is especially effective in causing damage to living beings, for example, sunburn, skin cancer, and eye damage to humans. The amount of solar UV radiation received at any particular location on the Earth's surface depends upon the position of the Sun above the horizon, the amount of ozone in the atmosphere, and local cloudiness and pollution. Scientists agree that, in the absence of changes in clouds or pollution, decreases in atmospheric ozone lead to increases in ground-level UV radiation.

The largest decreases in ozone during the past 15 years have been observed over Antarctica, especially during each September and October when the ozone hole forms. During the last several years, simultaneous measurements of UV radiation and total ozone have been made at several Antarctic stations. In the late spring, the biologically damaging ultraviolet radiation in parts of the Antarctic continent can exceed that in San Diego, California, where the Sun is much higher above the horizon.

In areas where smaller ozone depletion has been observed, UV-B increases are more difficult to detect. In particular, detection of trends in UV-B radiation associated with ozone decreases can be further complicated by changes in cloudiness, by local pollution, and by difficulties in keeping the detection instrument in precisely the same condition over many years. Prior to the late 1980s, instruments with the necessary accuracy and stability for measurement of small long-term trends in ground-level UV-B were not available. Therefore, the data from urban locations with older, less-specialized instruments provide much less reliable information, especially since simultaneous measurements of changes in cloudiness or local pollution are not available. When high-quality measurements have been made in other areas far from major cities and their associated air pollution, decreases in ozone have regularly been accompanied by increases in UV-B. This is shown in the figure below, where clear-sky measurements performed at six different stations demonstrate that ozone decreases lead to increased UV-B radiation at the surface in amounts that are in good agreement with that expected from calculations (the "model" curve).

Increases in Erythemal (Sunburning) Ultraviolet Radiation Due to Ozone Decreases



Does Ozone Depletion Cause Climate Change?

Ozone depletion and climate change are linked in a number of ways, but ozone depletion is not a major cause of climate change.

Atmospheric ozone has two effects on the temperature balance of the Earth. It absorbs solar ultraviolet radiation, which heats the stratosphere. It also absorbs infrared radiation emitted by the Earth's surface, effectively trapping heat in the troposphere. Therefore, the climate impact of changes in ozone concentrations varies with the altitude at which these ozone changes occur. The major ozone losses that have been observed in the lower stratosphere due to the human-produced chlorine- and bromine-containing gases have a cooling effect on the Earth's surface. On the other hand, the ozone increases that are estimated to have occurred in the troposphere because of surface-pollution gases have a warming effect on the Earth's surface, thereby contributing to the “greenhouse” effect.

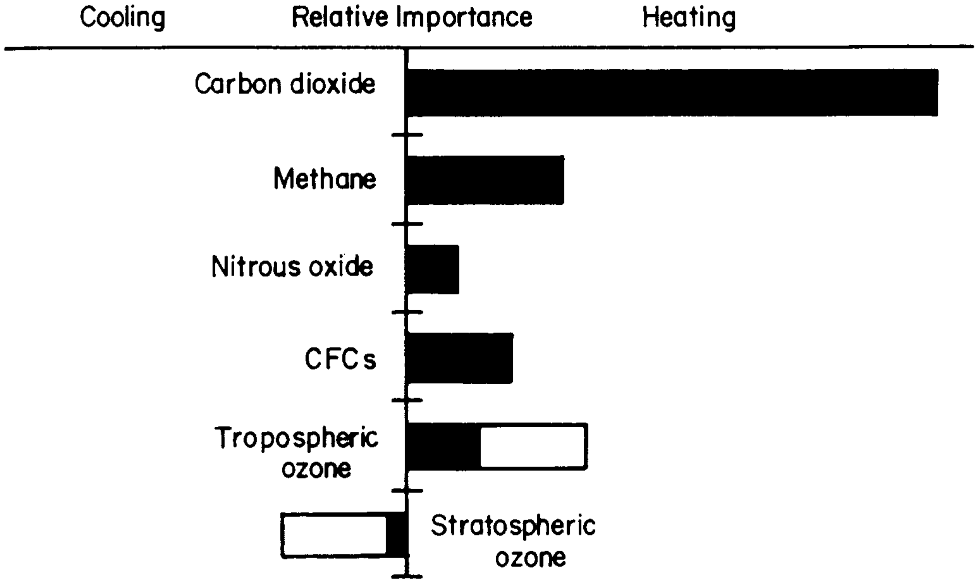
In comparison to the effects of changes in other atmospheric gases, the effects of both of these ozone changes are difficult to calculate accurately. In the figure below, the upper ranges of possible effects for the ozone changes are indicated by the open bars, and the lower ranges are indicated by the solid bars.

As shown in the figure, increases in carbon dioxide is the major contributor to climate change. Carbon dioxide concentrations are increasing in the atmosphere primarily as the result of the burning of coal, oil, and natural gas for energy and transportation. The atmospheric abundance of carbon dioxide is currently about 30% above what it was 150 years ago. The relative impacts on climate of various other “greenhouse” gases are also shown on the figure.

There is an additional factor that indirectly links ozone depletion to climate change; namely, many of the same gases that are causing ozone depletion are also contributing to climate change. These gases, such as the chlorofluorocarbons (CFCs), are green-house gases, absorbing some of the infrared radiation emitted by the Earth's surface, thereby effectively heating the Earth's surface.

Conversely, changes in the climate of the Earth could affect the behavior of the ozone layer, because ozone is influenced by changes in the meteorological conditions and by changes in the atmospheric composition that could result from climate change. The major issue is that the stratosphere will most probably cool in response to climate change, therefore preserving over a longer time period the conditions that promote chlorine-caused ozone depletion in the lower stratosphere, particularly in polar regions. At present, the amplitude and extent of such a cooling, and therefore the delay in the recovery of the ozone layer, still have to be assessed.

Relative Importance of the Changes in the Abundance of Various Gases in the Atmosphere



How Severe Is the Ozone Depletion Now?

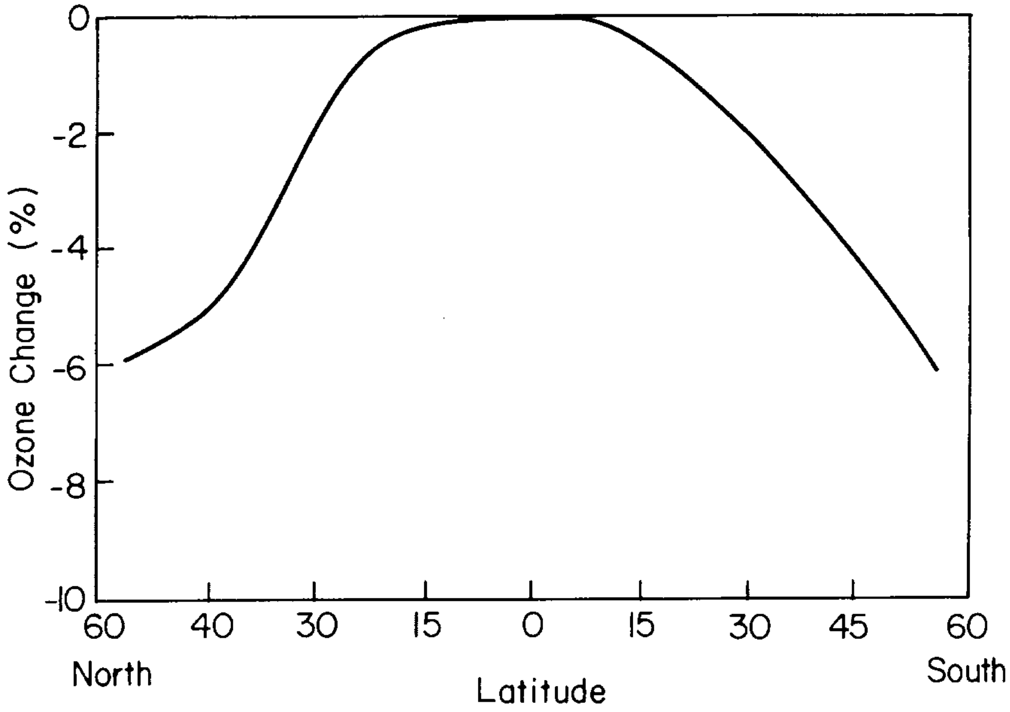
Stratospheric ozone depletion, caused by increasing concentrations of human-produced chemicals, has increased since the 1980s. The springtime loss in Antarctica is the largest depletion. Currently, in non-polar regions, the ozone layer has been depleted up to several percent compared with that of two decades ago.

As the figure below indicates, the magnitude of ozone depletion varies between the regions of the Earth. For example, there has been little or no ozone depletion in the tropics (about 20 degrees north and south of the equator). The magnitude of the depletion also depends on the season. From 1979 to 1997, the observed losses in the amount of ozone overhead have totaled about 5-6% for northern midlatitudes in winter and spring, about 3% for northern midlatitudes in summer and fall, and about 5% year round for southern midlatitudes. Since the early 1980s, the ozone hole has formed over Antarctica during every Southern Hemisphere spring (September to November), in which up to 60% of the total ozone is depleted. Since the early 1990s, ozone depletion has also been observed over the Arctic, with the ozone loss from January through late March typically being typically 20-25% in most of the recent years. All of these decreases are larger than known long-term natural variations.

The large increase in atmospheric concentrations of human-made chlorine and bromine compounds is responsible for the formation of the Antarctic ozone hole. Furthermore, the overwhelming weight of evidence indicates that it also plays a major role in the ozone depletion in the Arctic and at midlatitudes.

In addition to these long-term changes, transient effects have also been observed in the stratospheric ozone layer following major volcanic eruptions such as Mt. Pinatubo in 1991. During 1992 and 1993, ozone in many locations dropped to record low values. For example, springtime depletions exceeded 20% in some populated northern midlatitude regions, and the levels in the Antarctic ozone hole fell to the lowest values ever recorded. These unusually large, but short-term, ozone decreases of 1992 and 1993 are believed to be related in part to the large amounts of volcanic particles injected into stratosphere, which temporarily increased the ozone depletion caused by human-produced chlorine and bromine compounds, much as polar stratospheric clouds increase these chemicals' effect on ozone depletion in polar regions. Because these particles settle out of the stratosphere within a few years, the ozone concentrations have largely returned to the depleted levels consistent with the downward trend observed before the Mt. Pinatubo eruption. Should a similar eruption occur in the coming decade, ozone losses of the same magnitude might be expected, because the chlorine levels in the stratosphere will still be high.

Schematic of the North-to-South Ozone Depletion: 1979-1997



Is the Ozone Layer Expected to Recover? If So, When?

The ozone depletion caused by human-produced chlorine and bromine compounds is expected to gradually disappear by about the middle of the 21st century as these compounds are slowly removed from the stratosphere by natural processes. This environmental achievement is due to the landmark international agreement to control the production and use of ozone-depleting substances. Full compliance would be required to achieve this expected recovery.

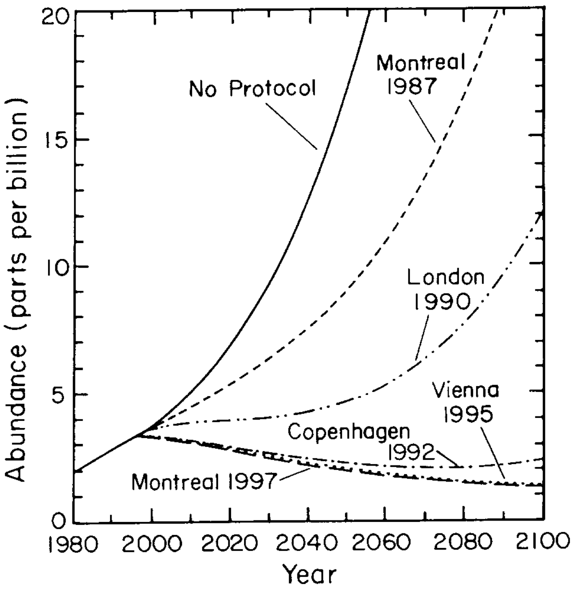
In 1987, the recognition of the potential for chlorine and bromine to destroy stratospheric ozone led to the Montreal Protocol on Substances that Deplete the Ozone Layer, as part of the 1985 Vienna Convention for the Protection of the Ozone Layer, to reduce the global production of ozone-depleting substances. Subsequently, global observations of significant ozone depletion have prompted amendments to strengthen the treaty. The 1990 London Amendment calls for a ban on the production of the most damaging ozone-depleting substances by 2000 in developed countries and 2010 in developing countries. The 1992 Copenhagen Amendment changed the date of the ban to 1996 in developed countries. Further restrictions on ozone-depleting substances have been agreed upon in Vienna (1995) and Montreal (1997).

The figure below shows past and projected stratospheric abundances of chlorine and bromine without the Protocol, under the Protocol's original provisions, and under its subsequent agreements. Without the Montreal Protocol and its Amendments, continuing use of chlorofluorocarbons (CFCs) and other ozone-depleting substances would have increased the stratospheric abundances of chlorine and bromine tenfold by the mid-2050s compared with the 1980 amounts. Such high chlorine and bromine abundances would have caused very large ozone losses, which would have been far larger than the depletion observed at present.

In contrast, under the current international agreements that are now reducing the human-caused emissions of ozone-depleting gases, the net tropospheric concentrations of chlorine- and bromine-containing compounds started to decrease in 1995. Because 3 to 6 years are required for the mixing from the troposphere to the stratosphere, the stratospheric abundances of chlorine are starting to reach a constant level and will slowly decline thereafter. With full compliance, the international agreements will eventually eliminate most of the emissions of the major ozone-depleting gases. All other things being constant, the ozone layer would be expected to return to a normal state during the middle of the next century. This slow recovery, as compared with the relatively rapid onset of the ozone depletion due to CFC and bromine-containing halon emissions, is related primarily to the time required for natural processes to eliminate the CFCs and halons from the atmosphere. Most of the CFCs and halons have atmospheric residence times of about 50 to several hundred years.

However, the future state of the ozone layer depends on more factors than just the stratospheric concentrations of human-produced chlorine and bromine. It will also be affected to some extent by the changing atmospheric abundances of several other human-influenced constituents, such as methane, nitrous oxide, and sulfate particles, as well as by the changing climate of the Earth. As a result, the ozone layer is unlikely to be identical to the ozone layer that existed prior to the 1980s. Nevertheless, the discovery and characterization of the issue of ozone depletion from chlorine and bromine compound and a full global compliance with the international regulations on their emissions will have eliminated what would have been, as the figure illustrates, a major deterioration of the Earth's protective ultraviolet shield.

Effect of the International Agreements on Ozone-Depleting Stratospheric Chlorine/Bromine



Frequently Asked Questions About Ozone to the Environmental Effects Assessment Panel

co-ordinated by

Janet F. Bornman and Jan C. van der Leun

Health Effects

1) How do we balance the good and bad effects of sunlight on human health?

In general, moderate exposure to sunlight in the course of everyday life is not detrimental. This basic exposure evidently allows us to function normally, and it proves to be sufficient to maintain an adequate level of vitamin D (in combination with our dietary intake). While sunlight is important for physical health it also causes various adverse health effects such as skin cancer, ageing of the skin, eye disorders and suppression of the immune system. It is clear that excessive UV exposure should be avoided to minimise the risk of development of such disorders.

2) How strong is the evidence that UV-B radiation causes skin cancer in humans?

The evidence is strong. The earliest experimental evidence that UV-B radiation causes skin cancer was acquired with animals; in humans there was a clear association between sun exposure and skin cancer, but that did not point specifically to UV-B. In recent years the advancement of molecular biology has provided us with analyses that produce direct evidence that genetic alterations found in human skin carcinomas are indeed caused by UV-B radiation.

3) Should one have all moles removed to decrease the risk of skin cancer?

No, there is no evidence to suggest that removing all of the moles would reduce the risk of skin cancer. However, it is important to be alert to atypical moles, especially those exhibiting changes in appearance (in colour or at the edges), and to screen those individuals that are known to run a high risk, either from a family history of melanoma mortality or of atypical moles.

4) Do sunglasses protect against cataracts?

Sunglasses that markedly reduce the UV-exposure of the eyes will reduce UV damage, such as cataracts. The best protection is achieved by a combination of UV-absorbing glasses and a shielding against light coming into the eyes from the sides. However, some sunglasses may not effectively block UV radiation and eye damage may occur.

Duration of Exposure to UV-B Radiation

5) Is the UV amount one receives as a child important even in later years?

Yes. Children should not be overexposed to UV radiation: sunbathing should be strongly discouraged. UV exposure, and especially sunburns, in early life can substantially increase the skin cancer risk later in life (especially the risk of basal cell carcinoma and melanoma).

Even if the risk is related to total accumulated exposure, as appears to be the case for a part of the non-melanocytic skin cancers (SCC), exposures early in life still may carry a greater risk. There is a long lag time, typically of several decades, between exposure and the development of a tumour. Therefore, early exposures have a greater probability in resulting in a tumour.

Are Animals at Risk?

6) Are hair-covered animals at any risk?

Yes. Skin cancer is found in almost all animals that have been studied in the long-term, for example, cattle, goats, sheep, cats, dogs, guinea pigs, rats, and mice. Direct effects of UV-B radiation on body parts which are covered by thick hair are negligible. However, even furred animals usually have exposed skin around mouth and nostrils, and sometimes on some other parts of the body. These parts, unless they are heavily pigmented, can be damaged by radiation.

7) Will penguins be affected by the ozone hole?

To our knowledge there are no studies concerning UV-B effects on penguins. As their eyes are exposed to a lot of UV due to the high reflectivity of snow and a marked enhancement during the ozone hole, investigation into the impact on penguins is desirable. The fact that penguins are visual predators, eating krill or fish in the water column, would make any eye damage an important issue for survival.

8) Is UV-B radiation a factor in the decline of frogs and other amphibians?

Possibly. Amphibian populations are in serious decline in many areas of the world, and scientists are seeking explanations for this. Most amphibian population declines are probably due to habitat destruction or habitat alteration. Some declines are probably the result of natural population fluctuations. Other explanations for the population declines, as well as the reductions in range of habitation, include disease, pollution, atmospheric changes and introduced competitors and predators. UV-B radiation is one agent that may act in conjunction with other stresses to adversely affect amphibian populations. Field studies in which embryos of frogs, toads, and salamanders were exposed to natural sunlight or to sunlight with UV-B radiation removed have shown conflicting results. Some studies resulted in increased embryonic mortality after UV-B exposure, whereas others show that current levels of UV-B radiation are not detrimental. Factors such as water depth, water colour, and the dissolved organic content of the water at the sites of egg deposition effectively reduce UV-B penetration through the water and reduce exposure to UV-B radiation at all life history stages. Biotic factors, such as jelly capsules around eggs, melanin pigmentation of eggs, and colour of larvae and metamorphosed forms, further reduce the effects of UV-B exposure.

Aquatic Life

9) Does water effectively shield aquatic organisms from UV exposure?

No. Pure water is quite transparent to UV radiation; a beam of UV-B radiation must travel over one-half kilometre through pure water in order to be completely absorbed. Natural waters do contain UV-absorbing substances, such as dissolved organic matter, that partly shields aquatic organisms from UV-B, but the degree of shielding varies widely from one water body to another. In clear ocean and lake waters ecologically-significant levels of UV-B can penetrate to several tens of meters; in contrast, in turbid rivers and wetlands UV-B may be completely absorbed within the top few decimetres. Most organisms in aquatic ecosystems, such as phytoplankton, live in the illuminated euphotic zone close to the water surface where exposure to UV-B can occur. In particular, UV-B radiation may damage those organisms that live at the surface of the water during their early life stages.

Terrestrial Plant Life

10) What will be the effects of an increased UV-B radiation on crop and forest yields?

There are some UV-B-sensitive varieties of crops that experience reductions in yield. However, there are also UV-B-tolerant varieties, providing the opportunity to breed and genetically engineer UV-B tolerant varieties. For commercial forests, tree breeding and genetic engineering may be used to improve UV-B tolerance. For unmanaged or natural forests, these methods are not an option. While many forest tree species appear to be UV-B tolerant, there is some evidence that UV-B effects, sometimes detrimental, can slowly accumulate from year to year. If this finding is a general phenomenon, this would be cause for concern since it would greatly complicate breeding efforts in commercial forests and negatively affect natural forests.

11) Can plants protect themselves against increased UV-B?

Yes, partly. Plants already have reasonable UV shielding; for most plants only a small proportion of the UV-B radiation striking a leaf actually penetrates very far into the inner tissues. Also, when exposed to an enhanced UV-B level, many species of plants can increase the UV-absorbing pigments in their tissues. Other adaptations include increased thickness of leaves which reduces the proportion of inner tissues exposed to UV-B radiation. Several repair mechanisms also exist in plants, as is the case for other organisms. This includes repair systems for DNA damage or oxidant injury. The net damage a plant experiences is the result of the balance among damage, protection and repair processes. For many plants, the net damage is negligible.

Location-specific Issues

12) Is the increase in UV-B radiation caused by ozone depletion equivalent to that incurred by moving several hundred kilometres towards the equator?

Yes, but this comparison does not nullify the serious impact of an ozone depletion, as is sometimes suggested by questions like this. The suggestion is based on a fallacy, namely, comparing a personal risk perception with the effect on a population. An elevation of say 10% in risk would not be noticeable for the person involved. For a population it is quite different. With regard to skin cancer such an increase could mean 100-200 extra cases a year per million people. This would be an important public health effect. However, movements of entire populations, or even ecosystems, do not usually occur in a human lifetime, and the comparison is therefore inappropriate.

13) Can organisms adjust to a changed UV environment?

Yes, many organisms can respond physiologically with changes such as development of UV screening compounds and additional layers of protective tissues. However, there are genetic limitations to the degree to which these physiological adjustments can take place for each organism. Some can adjust more effectively than others. Over long periods of time and several generations of populations, there is the possibility that genetic adaptation can develop as well. However, in organisms with moderately long life spans and small population sizes, the genetic adaptation is likely to be very slow.

14) Does ozone depletion pose any danger in the tropics?

Probably not. Increases in UV-B radiation are unlikely, since no significant trend in stratospheric ozone has been observed in the tropics. However, viewing the biosphere as a unit, there may be indirect effects of ozone depletion at other latitudes on tropical ecosystems. If ozone were to be depleted in the tropics, this would constitute a serious danger because of the naturally occurring high levels of UV-B radiation due to the high solar angles and already relatively low normal stratospheric ozone levels.

15) Do we need to worry about relatively small increases in UV-B due to ozone depletion, when natural variability is so much larger?

Yes. The change in UV-B from ozone depletion is systematically upward. The natural variability (e.g., from time of day, or clouds) can be larger, but goes in both directions, up and down. While the evidence for ozone depletion is very strong, there is little evidence for long-term changes in cloud cover.

Many detrimental effects of UV-B are proportional to the cumulative UV-B exposure. For example, skin cancer results from the total exposure accumulated over many years under both sunny and cloudy conditions. Any systematic increase in UV-B radiation will increase incidence among a population (as well as individual risk) regardless of the natural variability of the UV-B radiation.

16) Does one get higher UV exposures at higher elevations?

Yes. Higher elevations have less atmosphere overhead, as evidenced by the thinner air and lower atmospheric pressure. The increase in sun-burning UV radiation is typically about 5-10% for each kilometre of elevation, the exact number depending on the specific wavelength, solar angle, reflections, and other local conditions. Frequently, other factors besides thickness of the atmosphere cause even larger differences in UV radiation between elevations. Snow is more common at higher elevations, and reflections from it can lead to very large increases in exposure.

Lower locations tend to have more haze and more polluted atmosphere which can block some UV radiation.

17) Does air pollution protect one from UV-B radiation?

Yes, but at a high price. Air pollution is generally undesirable due to the numerous other serious problems associated with it, including respiratory illness, eye irritation, and damage to vegetation. While most of the atmospheric ozone resides in the stratosphere, some ozone is also made in the troposphere by the chemical interactions of pollutants such as nitrogen oxides and hydrocarbons. This tropospheric ozone is a component of the photochemical smog found in many polluted areas. Airborne particles (smoke, dust, sulphate aerosols) can also block UV radiation, but they can also increase the amount of scattered light (haze) and therefore increase the UV exposure of side-facing surfaces (e.g., face, eyes).

No single value can be given for the amount of UV-B reduction by pollution, because pollution events tend to be highly variable and local. Comparisons of measurements made in industrialised regions of the Northern Hemisphere (e.g., central Europe) and in very clean locations at similar latitudes in the Southern Hemisphere (e.g., New Zealand) suggest pollution-related UV-B reductions can be important.

Clear Skies vs. Cloud Cover

18) Can changes in cloudiness cause larger UV changes than ozone depletion?

Long-term trends in cloud type and amount are largely unknown due to the relatively short data record of comprehensive cloud observations, and the high variability of clouds on inter-annual and longer time scales. Some evidence exists showing that, at least over the time span of satellite-based ozone measurements, changes in cloud cover have been much less important than stratospheric ozone reductions in causing surface UV changes.

19) Are the risks of ultraviolet (UV) exposure at the beach less on a cloudy day?

Not necessarily. The effect of clouds on UV radiation is as varied as the clouds themselves. Fully overcast skies lead to reductions in surface UV irradiance. On average, scattered or broken clouds also cause reductions, but short-term or localised UV levels can be larger than for cloud-free skies if direct sunlight is also present. Clouds tend to randomise the directions of the incoming radiation (because of scattering) so that a hat may provide less protection on a cloudy day relative to a clear day.

Furthermore, people often change their behaviour on cloudy days. If they spend more time out in the open, or forego the use of sunscreen, they may end up with a very bad sunburn. In general, less UV radiation is received per hour under an overcast sky than under a clear sky, but extending one's stay at the beach may easily compensate for this effect. A completely cloud-covered sky may still transmit substantial amounts of UV-B radiation. In principle, any amount of UV-B radiation exposure contributes to the skin cancer risk.

Sunbathing

20) Will sunscreens protect one from harmful effects of increased UV-B radiation?

Not always. Sunscreens applied to human skin limit the penetration of UV radiation into the skin, and thus sunburn can be prevented. Sunscreens were primarily developed for this purpose. The effectiveness of sunscreens in protecting against skin cancer and immune suppressions is under debate. Any effectiveness in these respects may well be lost if the sunscreen is used to stay out in the sunlight longer than would be done without the sunscreen. It should also be kept in mind that there are other ways to protect the skin. These include staying out of the sunlight during the hours when the UV-B is maximal around solar noon, seeking the shade, wearing clothes, and especially hats.

21) Will getting a suntan help prevent skin cancer?

No. There is no evidence that getting a suntan will help prevent skin cancer. The UV exposure needed to acquire the tan adds to the skin cancer risk. The fact that one is able to tan well does, however, signify that the personal risk is lower (by a factor of 2 to 3) than for people who do not tan. Naturally dark-skinned people have a built-in protection of their skin against sunlight.

22) Is tanning with UV lamps safer than with sunlight?

No. The risks are approximately equal. For some time it was hoped that UV lamps could be made safer by making more use of long-wavelength (UV-A) radiation. That type of radiation is much less carcinogenic than the shorter-wavelength UV-B radiation, but one needs more UV-A than UV-B for acquiring a tan.

Economic Consequences

23) Has the benefit of the Montreal Protocol been worth the cost?

Yes. Several attempts have been made to investigate the economic impacts of the problem of a depleted ozone layer. Such attempts meet with many problems. There are good reasons for concern for effects on humans, animals, plants and materials, but most of these cannot be estimated in quantitative terms. Calculating the economic impact of such effects is uncertain. Moreover, economic terms are applicable only to some of the effects, such as the cost of medical treatments, and the loss of production in fisheries and agriculture, and damage to materials; but what is the cost equivalent of suffering, of a person becoming blind or dying, or the loss of a rare plant or animal species?

In spite of all these difficulties, attempts have been made. The most comprehensive example is a study initiated by Environment Canada for the 10th anniversary of the Montreal Protocol on Substances that Deplete the Ozone Layer. In this study, 'Global Costs and Benefits of the Montreal Protocol' (1997), the costs were calculated for all measures taken internationally to protect the ozone layer, such as replacement of technologies using ozone-depleting substances. The benefits are the total value of the damaging effects avoided in this way. The total costs of the measures taken to protect the ozone layer were calculated to be 235 billion US (1997) dollars. The effects avoided world-wide, though far less quantifiable, were estimated to be almost twice that amount. This latter estimate included only reduced damage to fisheries, agriculture and materials. The cataracts and skin cancers, as well as the potential associated fatalities avoided, were listed as additional benefits, and not expressed in economic terms.