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Progress in core activities

Black carbon

Report by the Co-Chairs of the Ad Hoc Expert Group on Black Carbon

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Executive summary and key recommendations

1. The Ad Hoc Expert Group on Black Carbon, co-chaired by the United States of America and Norway and with participation of Parties and observers to the Convention on Long-range Transboundary Air Pollution, has assessed available information on black carbon to, inter alia, articulate the rationale for addressing near-term and regional/Arctic climate change impacts of air pollution along with impacts on human health and ecosystems under the Convention. Nothing in this report should be interpreted as negating the need for ambitious and concurrent reductions in long-lived greenhouse gases.

2. There are clear environmental benefits to reducing emissions of black carbon (BC), based on available information. Given this fact and the success of the Convention in negotiating and achieving real emission reductions in air pollutants, the Executive Body should actively consider the options for action presented in this report. Combined, the regional climate impacts and the known health benefits that would accrue to the United Nations Economic Commission for Europe (UNECE) region by reducing particulate matter (PM) justify the Executive Body considering options to mitigate BC as a component of PM when making revisions to the Convention's 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol).

3. BC is a strongly light-absorbing carbonaceous aerosol produced by incomplete combustion of various fuels. There is general consensus that mitigation of BC will lead to positive regional impacts by reducing BC deposition in areas with snow and ice. There is also general consensus that reducing primary PM will benefit public health. Less certain are the direction and magnitude of the global radiative forcing associated with BC. This is due in large part to poorly understood mechanisms by which BC interacts with clouds.

4. The Arctic, as well as alpine regions, may benefit more than other regions from reducing emissions of BC, which both warms the atmosphere and when deposited increases the melting of snow and ice. BC contributes to the snow-albedo feedback, which may be altering the global radiative balance. Climate processes unique to the Arctic have significant effects that extend globally. The International Panel on Climate Change (IPCC) noted nearly 10 years ago that changes, which include melting of glaciers, sea ice, and permafrost, have already taken place. As a result, action must be taken in the very near term to reduce the rate of warming.

5. The Executive Body should consider the advantages of integrated air quality and climate policies. Climate and air quality are inextricably linked, and strategies devised for one will likely impact the other. For example, air quality management strategies that reduced emissions of secondary PM precursors (such as sulphur and nitrogen oxides) for public health and ecosystem protection resulted in a mainly cooling effect, which has had the effect of counteracting the levels of anthropogenic climate change that would have occurred in the absence of these emissions. It is imperative that the important work of improving public health by cleaning the air continue, but going forward in a way that is also beneficial for climate.

6. While it is clear that BC emission reductions would be expected to provide important health and climate benefits, there is substantial room for improving the knowledge base with respect to emissions and impacts. One of the greatest sources of scientific uncertainties arises from the lack of emission data. At this time, no country has a comprehensive programme to measure and report the emissions and ambient concentrations of black carbon (and other carbonaceous aerosols). To enable formulation of effective strategies and policies, technical work on BC under the Convention should be strengthened. The Executive Body should therefore consider tasking specific existing Convention bodies

to recommend the most constructive path forward for gathering and sharing data. This may include collaboration with groups working on BC outside the auspices of the Convention.

7. BC emissions in the UNECE region are expected to decline between 2000 and 2020 by about one third as a result of current emission control legislation, primarily in the transport sector. These reductions are dependent on full implementation of existing legislation, which is not necessarily guaranteed. Moreover, while overall BC emissions are expected to decrease, emissions from certain sectors may substantially increase. Currently available measures could reduce BC emissions by another 40 per cent by 2020.

8. Several possible options for including BC in a revised Gothenburg Protocol are included in the report, ranging from establishing relevant environmental objectives to taking action to reduce emissions. For emission reduction commitments, a range of options are identified, such as national emission ceilings and source-specific emission limit values. Important sectors with mitigation potential remaining after current legislation is implemented are residential combustion, non-road mobile machinery, road transport and open burning. Further elaboration of the type of emission reduction commitments may involve many existing Convention task forces, centres under the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), and expert groups.

9. The recommendations here are a subset of the recommendations found in the report, with further detail available therein. In addition to including BC in the revisions of the Gothenburg Protocol, the Executive Body should consider the following recommendations for implementation in its 2011 draft workplan:

(a) Improving emission inventories will enable the Parties to select optimal control policies and identify sources that may be underreported or missing from known inventories. Careful evaluation of emission data is needed as differences for specific sectors can be very large because of different emission factors or varying methodological approaches. The Task Force on Emission Inventories and Projections should give priority to work on guidelines for BC inventories with a focus on BC reductions achievable from existing PM control measures or techniques;

(b) The Executive Body should support the initiative by EMEP to identify the relevant characteristics of BC to be monitored and reported and should support the swiftest possible implementation of EMEP's monitoring strategy for 2010-2019;

(c) If the Executive Body determines to include BC in the revisions to the Gothenburg Protocol, it may wish to consider charging the Ad Hoc Expert Group or some other Convention body to:

(i) Develop in greater detail the potential options for using both mandatory and/or voluntary provisions for BC in a revised Gothenburg Protocol;

(ii) Develop more information on existing and emerging control technologies for BC;

(iii) Develop additional options for mechanisms by which Parties that have not yet ratified a revised Protocol might make progress towards a stated environmental objective;

(d) BC emission from shipping in the Arctic may increase by a factor of two to three by 2050. This may have a significant impact on the Arctic environment. This issue is presently under consideration in the International Maritime Organization (IMO). Although emissions from international shipping are not included in the work under the Convention, the Executive Body could consider informing the IMO about its concern about the effects of BC on the Arctic.

10. The Executive Body should also consider the following recommendations for longer-term implementation:

(a) Institute mandatory monitoring and reporting requirements for BC and organic carbon (OC) emissions;

(b) Consider how to ensure implementation of any agreed upon requirements, including consideration of needed resources;

(c) Because the knowledge of BC is rapidly developing, the Executive Body should consider setting a time frame for incremental review of work and possible commitments on BC;

(d) Also suggested are possible outreach activities (e.g., capacity-building and cooperation on monitoring, developing emission inventories, and mitigation measures) to non-UNECE countries, countries with economies in transition, and countries preparing to ratify the Gothenburg Protocol.

I. Introduction

11. The Ad Hoc Expert Group on Black Carbon was established by the Executive Body of the Convention on Long Range Transboundary Air Pollution in December 2009. The mandate of the Ad Hoc Expert Group is to provide options for whether, and if so how, the Executive Body might consider addressing emissions of BC to benefit public health and reduce climate impacts, particularly impacts in areas of snow and ice. The Expert Group was specifically requested to identify options for potential revisions to the Gothenburg Protocol that would enable the Parties to mitigate BC as a component of PM.

12. This report was prepared by the Co-Chairs in collaboration with experts from across the Parties to the Convention and other invited experts. The Ad Hoc Expert Group had representation from Belgium, Canada, Denmark, Estonia, the European Union (EU), Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, the Russian Federation, Slovenia, Spain, Sweden, Switzerland, the United Kingdom of Great Britain and Northern Ireland, and the United States of America. Additional participants included representatives from the UNECE secretariat, the European Environmental Bureau, experts from the EMEP centres (Chemical Coordinating Centre, Meteorological Synthesizing Centre-West, Meteorological Synthesizing Centre-East and Centre for Integrated Assessment Modelling), the EMEP Task Force on Measurement and Modelling, the EMEP Task Force on Emission Inventories and Projections, the Task Force on Hemispheric Transport of Air Pollution and the Expert Group on Techno-economic Issues, as well as observers from several non-governmental organizations.

13. This report has five main objectives: (a) to articulate the rationale for addressing near-term and regional/Arctic climate change impacts of air pollution along with impacts on human health and ecosystems under the Convention; (b) to summarize the current work on black and organic carbon by Parties under the Convention; (c) to assess current black and organic carbon emissions information available for Parties to the Convention, particularly for key sectors; (d) to identify priority BC emission reduction opportunities in the UNECE region and the associated costs, implementation feasibility, and potential health, ecosystem, and near-term climate benefits of these measures; and (e) to identify the scientific and technical requirements, as well as non-technical measures, needed for implementing options to reduce BC and evaluate progress over time.

14. BC and OC are produced by incomplete combustion of various fuels. BC is a strongly light-absorbing carbonaceous aerosol and warms much more than OC cools, per ton. [1,2] Because of its light absorbing properties, BC contributes significantly to global warming by directly absorbing sunlight and to regional warming by darkening ice and snow. Direct BC warming is considerable at the global scale; however, the limited understanding of other climate impacts (e.g., BC-cloud interactions) make the net global climate impact uncertain.[3,4] Due to the fine size and chemical composition of BC, its negative health effects are also widely recognized.

15. Immediate climate benefits of BC mitigation are possible because it has a short atmospheric lifetime and it is strongly absorbing. There is general consensus that mitigation of BC will lead to beneficial regional impacts via reduction of BC deposition on snow and ice, though uncertainties remain in the understanding of global impacts. These limitations do not, however, minimize the need for mitigation activities in the near term.

16. Particulate matter originates through two distinct processes. It can be directly emitted and referred to as primary PM; and it can be formed in the atmosphere from precursor emissions (e.g., such as sulphur oxides and nitrogen oxides) and referred to as secondary PM. BC is a constituent of primary PM emissions. Because BC is emitted in varying amounts with other pollutants that also impact climate and public health, (e.g., other aerosols such as OC, PM and ozone precursors, greenhouse gases and toxic air pollutants) BC mitigation measures must be evaluated in a way that recognizes the full range of impacts of these co-emitted pollutants. Mitigation measures focused on reducing secondary PM may or may not reduce BC.

17. Many terms are used, often interchangeably, to describe the strongly light absorbing subset of particulates. Soot, elemental carbon, refractive carbon and BC are all in use, but there remains no universal definition or means of identifying exactly which subset of aerosol particles are of concern when addressing climate change. For the purposes of this report, BC is synonymous with elemental carbon. Recent studies suggest that there is likely a larger group of aerosols — sometimes referred to as “brown carbon” or “light absorbing carbon” — that may influence climate and public health.[5] The work to define and establish measurement techniques for the entire suite of light-absorbing aerosols goes beyond the scope of this Expert Group, but should be encouraged or mandated by the Executive Body.

II. Rationale

18. Controlling emissions of BC will result in health benefits and climate benefits, especially in sensitive regions such as the Arctic. The magnitude of the net effects of direct and indirect radiative forcing of BC on the global climate is subject to some uncertainty; nevertheless, there is emerging consensus regarding the regional influence of BC on areas

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[1] Saathoff, H., K.–H. Naumann, M. Schnaiter, W. Schöck, O. Möhler, U. Schurath, E. Weingartner, M. Gysel, and U. Baltensperger. 2003. Coating of soot and $(NH_4)_2SO_4$ particles by ozonolysis products of α-pinene. Journal of Aerosol Science 34, (10): 1297-1321.

[2] Lesins, G., P. Chylek, and U. Lohmann. 2002. A study of internal and external mixing scenarios and its effect on aerosol optical properties and direct radiative forcing. Journal of Geophysical Research D: Atmospheres 107, (9-10): 5-1.

[3] V. Ramanathan and G. Carmichael, *Global and regional climate changes due to black carbon*, 1 Nature Geoscience 221-22 (23 March 2008).

[4] Jacobson, M. Z. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* 409, 695-697 (2001).

[5] M. O. Andreae and A. Gelencs´er: Black carbon or brown carbon? Atmos. Chem. Phys., 6, 3131–3148, 2006 www.atmos-chem-phys.net/.

of snow and ice.[6,7,8,9] Combined, the regional climate impacts and the known health benefits that would accrue to the UNECE region by reducing PM justify the Executive Body considering options to mitigate BC as a component of PM when making revisions to the Gothenburg Protocol. While it is clear that BC emission reductions would be expected to provide important health and climate benefits, there is substantial room for improving the knowledge base with respect to emissions and impacts.

19. *Impacts on global climate.* There is no scientific consensus on the overall global climate effect of BC. At the time this report was developed, concurrent efforts were under way to more systematically outline what is known and not known regarding the full range of effects. The Executive Body's decisions should be guided by these efforts: "Bounding the Role of Black Carbon in Climate" by the International Global Atmospheric Chemistry-Atmospheric Chemistry and Climate Initiative; and "Black Carbon and Tropospheric Ozone — Opportunities for limiting near-term climate change" by the United Nations Environment Programme (UNEP).

(a) *Direct radiative forcing of black carbon.* One of the ways BC impacts climate is by directly absorbing incoming solar radiation causing an imbalance in the Earth's radiation budget. Estimates of this effect, known as radiative forcing, vary, but are warming;

(b) *Indirect radiative forcing of black carbon.* Aerosols have other effects on radiative forcing, through their impact on clouds by deposition of BC on ice and snow fields which reduce the surface albedo. Estimates of these effects vary and remain highly uncertain.

20. *Arctic effects.* The IPCC noted nearly 10 years ago that changes in the Arctic have already taken place and continue to occur. They include melting of glaciers, sea ice and permafrost, and shifts in patterns of rain- and snowfall, freshwater run-off, and forest/tundra growth. The consequences include disrupted wildlife migration patterns, altered fish stocks, modified agricultural zones and increased forest fires.

21. BC, together with tropospheric ozone and methane, may contribute to Arctic warming to a degree comparable to the impacts of carbon dioxide (CO_2), though there remains considerable uncertainty regarding the magnitude of their effects.[10] Because of the dual role of BC in Arctic climate — atmospheric warming and its effect of darkening and melting snow and ice — reducing black carbon offers one pathway toward mitigating these effects. While this section highlights impacts on the Arctic, similar impacts are being experienced in alpine regions across the UNECE region and beyond.

(a) *Changing albedo.* BC deposition decreases the reflectivity of Arctic snow and ice. Arctic albedo also changes when highly reflective sea ice melts and is replaced by dark ocean water, which in turn absorbs more incoming solar energy and exacerbates

[6] Qian, Y., et al. (2009), Effects of soot-induced snow albedo change on snowpack and hydrological cycle in western United States based on Weather Research and Forecasting chemistry and regional climate simulations, J. Geophys. Res., 114.

[7] Hadley et al. (2010), Measured black carbon deposition on the Sierra Nevada snow pack and implication for snow pack retreat Atmos. Chem. Phys., 10, 7505–7513.

[8] Xu, Baiqing et al. (2009), Black Soot and the Survival of Tibetan Glacier, Proc. Natl. Acad. Sci. Early Edition (2009).

[9] Flanner, M.G., et al., (2009), Springtime warming and reduced snow cover from carbonaceous particles, Atmos. Chem. Phys., 9, 2481.

[10] AMAP / Quinn et al., 2008. The Impact of Short-Lived Pollutants on Arctic Climate. AMAP Technical Report No. 1 (2008), Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

warming. BC contributes to this process, known as the snow-albedo feedback, and may be altering the global radiative balance. BC effects are particularly important during spring;

(b) *Rate of warming*. The Arctic continues to warm more rapidly than almost all other part of the globe. This rate of Arctic warming is significant, because it means that action must be taken in the very near term to reduce the rate of warming in comparison to other areas of the globe. As the Executive Body deliberates, it is critical to consider the timescale in which these impacts are occurring, the rate at which change is expected to occur in the future and the near immediate effect BC reductions will likely have. Mitigation of long-lived greenhouse gases (LLGHGs) is critical, but the benefits accrue over a much longer timescale. In the long term, reducing LLGHGs will be necessary because even if BC is eliminated, Arctic warming would still occur at a rate significantly greater than the global mean, due to ongoing emissions of these gases;[11]

(c) *Sea ice extent*. Sea ice extent and volume have been declining steadily over the past decades at a rate not seen in thousands of years.[12] If this decline continues, the Arctic may be free of summer sea ice as soon as 2040.[13] Such a change has consequences for the snow-albedo effect, but also implications for increased shipping and other activities, which in turn may increase emissions in the region;

(d) *Changes extend beyond the Arctic*. Climate processes unique to the Arctic have significant effects on global climate, with changes under way extending beyond the Arctic region. Examples of these global impacts include sea level rise from melting Arctic glaciers and increased global warming as a result of increased absorption of solar energy in the Arctic;

(e) *Indigenous groups*. As a result of these changes, indigenous groups who depend on subsistence hunting and gathering practices are at risk. Risks include food insecurity due to decline of marine and land wildlife species, reduced quality of other food sources such as wild berries and fish, disrupted land traffic due to infrastructure damage from melting permafrost and forced relocation due to increased coastal erosion;[14]

(f) *Arctic emissions*. International action to reduce LLGHGs cannot prevent these dramatic changes to the Arctic in the near term;[15] therefore additional complementary near-term strategies should be devised;

(i) Recent studies suggest that BC emitted in and near the Arctic has a stronger influence on Arctic warming and melting than emissions outside this region;[16,17]

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[11] Holland, M. M. and C. M. Bitz, 2003: Polar amplification of climate change in coupled models. Clim. Dynam., 21, 221-232.

[12] Polyak et al., History of Sea Ice in the Arctic, Quaterary Science Reviews, 2010.

[13] Holland, M. M., Bitz C. M. and Tremblay B., “Future abrupt reductions in the summer Arctic sea ice” *Geophys. Res. Lett.*, 33 . L23503 (2006).

[14] ACIA Impacts of a Warming Arctic: Arctic Climate Impact Assessment Cambridge University Press, 2004. Available at http://www.acia.uaf.edu.

[15] AMAP/Bluestein et al., 2008. Sources and Mitigation Opportunities to Reduce Emissions of Short-term Arctic Climate Forcers. AMAP Technical Report No. 2 (2008), Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

[16] Quinn, P. K., Bates, T. S., Baum, E., Doubleday, N., Fiore, A. M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl, A., and Warren, S. G.: Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, Atmos. Chem. Phys., 8, 1723-1735, 2008.

[17] Hirdman, D., Sodemann, H., Eckhardt, S., Burkhart, J. F., Jefferson, A., Mefford, T., Sharma, S., Strom, J., and Stohl, A. (2010a) Source identification of short-lived air pollutants in the Arctic using statistical analysis of measurement data and particle dispersion model output. *Atmos. Chem. Phys., 10. 669-693.*

(ii) Over highly reflective surfaces such as ice and snow, even a small amount of BC mixed in with OC and sulphate-containing aerosols can be "warming" because the resulting mix is less reflective than the surface below. As a result, some sources and aerosol mixtures that might be cooling in other regions result in warming over the Arctic;[18]

(iii) A recent report to the IMO Marine Environment Protection Committee suggests that BC emissions from shipping in the Arctic may increase by a factor of two to three by 2050. With BC constituting between 5–15 per cent of shipping particulate emissions,[19] this is a source category that merits more attention.

22. *Other climate impacts.* The climate impacts of aerosols (including but not limited to BC) are not limited to temperature impacts but also include: contributing to changes in rainfall patterns and rainfall suppression; reducing surface water evaporation; changing clouds properties; and creating a positive feedback loop that worsens air pollution episodes. This latter effect occurs when BC heats the lower atmosphere, limiting the amount of solar radiation that reaches the Earth's surface (sometimes called surface dimming). The effect of this lower atmosphere heating and surface dimming is to stabilize the boundary layer, making air pollution episodes worse, and perhaps affecting rainfall. Surface dimming may also negatively impact agriculture.[20]

23. *Human health impacts.* In the same way that co-emitted pollutants must be considered to understand the full suite of climate impacts, so must these emissions be accounted for when considering public health. There is broad scientific consensus that fine particles are associated with significant adverse health effects. Many scientific studies have linked levels of $PM_{2.5}$ and PM_{10} to a wide range of serious health effects, including increased morbidity and mortality from cardiovascular and respiratory conditions and lung cancer. Current knowledge does not allow precise quantification or definitive ranking of the health effects of PM emissions from different sources or of individual PM components. Available studies do not attribute the observed health effects to a particular characteristic of PM (other than mass). While it is difficult to link a single constituent of particulate matter to a specific health outcome, a World Health Organization (WHO) workshop acknowledged that the available evidence on the hazardous nature of combustion-related PM (from both mobile and stationary sources) is more consistent than from PM from other sources.[21] It is known, for example, that polycyclic aromatic hydrocarbons, a variety of persistent organic pollutants, and other toxics are inevitable products of incomplete carbonaceous fuel combustion. BC, a primary pollutant and a good indicator of combustion related PM, has been associated with respiratory[22] and cardiovascular[23] health effects.

24. Available human evidence shows that diesel soot — composed in large part of BC — represents a lung cancer hazard at occupational exposures. It is reasonable to presume the hazard extends to environmental exposure levels. The United States Environmental Protection Agency (USEPA) concludes the overall evidence for a potential cancer hazard to humans resulting from chronic inhalation exposure to diesel soot is

[18] Flanner et al., "Springtime warming and reduced snow cover from carbonaceous particles", Atmos. Chem. Phys., 9, 2481–2497, 2009, www.atmos-chem-phys.net/9/2481/2009/.

[19] Lack, D., et al. (2009) "Particulate emissions from commercial shipping; chemical, physical and optical properties." J. Geophysical Research, 114, D00F04.

[20] V. Ramanathan and G. Carmichael, Nature Geoscience 1, 221 - 227 (2008).

[21] Health relevance of particulate matter from various sources. Report on a WHO workshop Bonn, Germany, 26–27 march 2007. WHO Regional Office for Europe 2007.

[22] N. Kulkarni et al., N Engl J Med 355, 21–30 (2006).

[23] A. Peters et al., Epidemiology, 1, 11–17 (2000).

persuasive, even though assumptions and uncertainties are involved[24] and that diesel soot is "likely to be carcinogenic to humans by inhalation".

25. *Effect of current air quality and climate strategies.* Climate and air quality are inextricably linked, and strategies devised for one will very likely impact the other. For example, air quality strategies that have focused on reducing emissions of sulphate precursors, because of the importance of this pollutant for public health and ecosystem protection, have produced a mostly cooling effect. This cooling has had the effect of counteracting the levels of anthropogenic climate change that would have occurred in the absence of these emissions. Similarly, the use of biomass is growing in some countries due in part to a desire to decrease CO_2 emissions from fossil fuel use. This may result in the increase of local and regional levels of BC. It is imperative for the global community to continue the important work of improving public health by cleaning the air, but also that it do so now in a way that is also beneficial for climate in the near term. The Executive Body should consider the advantages of integrated air quality and climate policies. Specifically, the Executive Body should continue to seek health driven reductions in "climate cooling" pollutants (e.g., sulphates) while also pursuing reductions in "climate warming" pollutants (e.g., black carbon).[25,26,27]

26. After it is emitted, BC mixes with other pollutants and ages in the air. Understanding this complex chemistry and how it impacts global and regional climate is one of the largest areas of uncertainty associated with BC mitigation and climate change. The limitations in the current understanding about the mixtures and their influence point to the need for better measurement data and investments in emission characterization activities. There is general consensus that mitigating BC will lead to positive regional impacts by reducing BC deposition on snow and ice, though uncertainties remain in the understanding of global impacts. These limitations do not, however, minimize the need for action in the near term.

27. *Short atmospheric residence time.* The fact that BC stays in the atmosphere for a few days to a few weeks means atmospheric concentration of BC can be reduced quickly, unlike long-lived gases. BC reductions do not supplant the need for ambitious reductions in CO_2 and other greenhouse gases. Rather, BC, methane and ozone reductions offer the best opportunity to reduce the near-term climate effects that are critical for sensitive regions of the globe. Known control measures for these substances offer an opportunity to reduce near-term climate damage and reap significant health benefits in the regions investing in mitigation measures.

28. *A note about metrics.* There is a strong desire to put the effects of black carbon into a framework to compare and contrast with the effects and influence of LLGHGs. To do so detracts from the science and policy case that can be made for taking action to reduce BC in its own right. At this time, there are several efforts to develop new metrics that will capture the unique aspects and regional dimension of short-lived climate forcers. However, none of these metrics has evolved to the point of widespread acceptance.

[24] USEPA Health Assessment Document for Diesel Engine Exhaust. United States Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Washington Office, Washington, D.C., EPA/600/8-90/057F, 2002.

[25] M. V. Ramana et al., Warming influenced by the ratio of black carbon to sulphate and the black carbon source, *Nature* Geoscience, Published online 25 July 2010.

[26] Kloster et al., A GCM study of future climate response to aerosol pollution reductions, Climate Dynamics, 34, 2010.

[27] Raes and Seinfeld, New Directions: Climate change and air pollution abatement: A bumpy road. Atmospheric Environment, 43 (32). pp. 5132-5133. ISSN 1352-2310.

29. *Role of the Gothenburg Protocol.* There are clear environmental benefits to reducing emissions of BC. Reductions will benefit the Arctic and alpine regions, benefit public health, and are likely to be a no-regrets strategy for reducing global radiative forcing. Given the Convention's stature and success in negotiating and achieving real emission reductions in air pollutants, the Executive Body should actively consider the options for action presented in this report.

30. *Summary of current activity.* Parties to the Convention and other external bodies are actively involved in assessing BC and its climate and public health impacts. There will be some overlap between all these efforts, but each may contribute more refined information on various aspects of the role of BC in climate change. At this time, however, it is not anticipated that the outcome of any of these assessments would fundamentally change the recommendations of this Expert Group.

III. Emission inventories

31. Understanding the emissions of BC is needed for well-designed mitigation strategies capable of achieving both climate and public health benefits. Several global emission inventories are widely used and referenced, in addition to a number of national level data sets. These different inventories vary in both total amount of black and organic carbon emissions and the relative contributions of the emitting sectors. BC and OC inventories have an estimated uncertainty up to a factor of two (higher for open burning).[28] The disparity between existing inventories derives from large uncertainties in the magnitude of emissions, lack of information regarding the physical distribution of sources and gaps in knowledge regarding the emissions from specific source categories. Information is lacking for several potentially important sectors such as flaring, shipping and agriculture and forest burning. Not only is information lacking or deficient for BC, but also for the emissions of the co-emitted pollutants. Improving emission inventories will enable the Parties to both identify optimal control measures and identify sources that may be underreported or missing from known inventories.

32. For BC, as with other air pollutants, there is a challenge of identifying sources located far from where impacts are felt. At present, observation-based approaches alone cannot provide the information on source attribution and source-receptor relationships. While there is some confidence in source-receptor relationships within Europe, less is known about intercontinental transport and deposition patterns. Sampling of Arctic snow and ice combined with modelling studies indicate significant amounts of BC are anthropogenic; however, at this time, particles in receptor regions cannot be unequivocally attributed to specific sources or source regions.[29] The Executive Body should support the efforts under way to improve the quality of emission inventories, the performance of transport models and the coverage and resolution of observations.

IV. Black carbon reductions achieved under current legislation

33. Because BC is a constituent of primary PM, BC reductions in most of the UNECE region to date have occurred as a result of PM controls. Data collected across Europe

[28] Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H. and Klimont, Z., 2004, A technology-based global inventory of black and organic carbon emissions from combustion J. Geophys. Res. 109 D14203.

[29] Draft 2010 Assessment report on the Hemispheric Transport of Air Pollution, Part A 06/07/2010 2-31.

suggest a large portion of anthropogenic PM — up to 50 per cent — is formed from emissions of the secondary particulate precursors (sulphur dioxide (SO_2), nitrogen oxide (NOx), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs)).[30] While the reductions of the secondary particulate precursors have resulted in significant positive impacts on public health and ecosystem protection, the net climate benefits of these reductions are less certain, and may in fact be warming due to reduced cooling resulting from lower concentrations of the secondary precursors.[31]

34. The reductions in total emissions of PM between 1990 and 2007 have been mainly due to the control technologies applied to energy, road transport and industry sectors, as well as non-technical measures, such as fuel switching in industrial and domestic sectors. Emissions are expected to decrease in the future as vehicle emission control technologies are further improved and stationary combustion emissions are controlled through abatement or use of low sulphur fuels such as natural gas. Despite this, it is expected that within many urban areas across the EU, concentrations will still be well above the EU limit values for PM_{10}. Substantial further reductions in emissions will therefore be needed if the air quality limit value set in EU Directive 2008/50/EC on ambient air quality and cleaner air for Europe is to be reached.[32]

35. Total BC and OC emissions of 2005 in the UNECE region are estimated at 1.0 and 1.4 Tg, respectively. The majority of BC emissions in 2005 originated from the residential (30 per cent) and transport sectors (50 per cent). There are, however, important regional and sectoral variations. As reductions occur as a result of current legislation, the relative importance of other source categories may become important. For example, significant reductions are expected in the on-road transport sector, which may increase the relative contribution of the residential, industrial and non-road sectors in the longer term.

36. Although there is no specific legislation targeting carbonaceous aerosols, existing and proposed PM and SO_2 regulations are expected to bring significant reductions of BC and primary OC.

(a) While residential combustion is and remains in the future a key BC emitting sector, emissions from the transport sector (especially on-road) are expected to decline by about 70 per cent by 2020 provided current policies (Diesel Particulate Filter (DPF) technology) bring expected reductions;

(b) Current legislation is expected to have less of an impact on emissions from stationary diesel engines and non-road mobile machinery (including the marine sector), which will increase these sectors' relative importance for future mitigation efforts;

(c) On-road measurement studies of vehicle emissions conducted in some countries show that a small fraction of the vehicle fleet is responsible for a large share of emissions. These vehicles are referred to as high emitters or super emitters.[33] A preliminary estimate with the greenhouse gas and air pollution interactions and synergies (GAINS) model indicates that high emitting vehicles could increase the transport of BC emissions in

[30] Putaud et al. A European aerosol phenomenology — 3: Physical and chemical characteristics of particulate matter from 60 rural, urban, and kerbside sites across Europe, Atmospheric Environment, Vol. 44, Issue 10, March 2010, pages 1308-1320.

[31] Raes and Seinfeld, New Directions: Climate change and air pollution abatement: A bumpy road. Atmospheric Environment, 43 (32). pp. 5132-5133.

[32] Emissions of primary particles and secondary particulate matter precursors (version 2) — Assessment published Jan 2010 — http://www.eea.europa.eu/data-and-maps/indicators/emissions-of-primary-particles-and-1/emissions-of-primary-particles-and-1.

[33] Ban-Weiss et al. 2009. Measurement of Black Carbon and Particle Number Emission Factors from Individual Heavy-Duty Trucks. Environ. Sci. Technol. 43, 1419-1424.

the UNECE region by about 10 and 15 percent in 2005 and 2030, respectively, even with current legislation;

(d) Non-road mobile machinery may offer some potential for future mitigation. The United States has adopted a comprehensive national programme to reduce emissions from future non-road diesel engines by integrating engine and fuel controls as a system to gain the greatest emission reductions. Because these reductions apply to newly built engines and controls are not required for the existing fleet, these engines are expected to be a continuing source of BC emissions.

37. Because estimates of future emission reductions rely on the assumption of successful full implementation of current legislation, and the economic downturn and other factors may influence the applicability of this assumption, there remains a need to test the validity of the assumptions used.

V. Potential additional reductions

38. Specific PM control measures already under discussion for potential inclusion in a revised Annex VII (Particulate Matter) to the Gothenburg Protocol may or may not result in significant BC reductions. More testing needs to be conducted to determine the exact efficiency of control measures and technology for BC removal. For example, in general fabric filters and electrostatic precipitators will reduce BC, while cyclones and scrubbers will not reduce BC to any significant degree, but can reduce the larger particle species.

39. Because of the public health benefits of reducing BC, as well as the location of the countries across the Convention regions in relation to the Arctic, the Executive Body should consider taking additional (BC-specific) measures to reduce BC. Impacts on the Arctic and alpine areas will vary by country, but all countries will benefit from local emission reductions of BC and other co-emitted pollutants. All countries will benefit from improving public health and preventing the melting of the Arctic ice cap.

40. Similarly, the Executive Body should consider not only specific new measures, but assess whether the existing measures are being implemented with an adequate fidelity and speed needed to avoid the most catastrophic results, for example sea ice and ice sheet melt. It is important for the Executive Body to consider whether the reductions projected under this analysis will happen at an appropriately rapid rate to mitigate the impacts of BC on sensitive regions such as the Arctic. More analysis is needed to determine the rate and rigour of implementation of current legislation, particularly for heavy duty transport and non-road vehicles, and the impact of these reductions on sensitive regions. The Executive Body should consider careful monitoring of existing legislation and strengthening policies in this area.

41. If the decision is taken to consider additional measures to ensure needed reductions in BC as part of a broader PM strategy under the Gothenburg protocol, current analysis shows there are potential emission reductions available across a range of source categories. The cost and feasibility of these measures will vary across regions and countries. There is limited analysis currently available that can provide definitive estimates of the precise climate benefits, though they are thought to be positive. Health impacts are better understood and estimates do exist for the health benefits of PM reductions, especially those in urban areas where exposures (and therefore benefits of reductions) are concentrated. As stated earlier in this report, any control measure considered should be assessed in an integrated way for its overall climate and public health impact, including the full range of co-emitted pollutants.

42. *Potential mitigation measures*. Overall, BC emissions in the UNECE region are expected to decline between 2000 and 2020 by about one third, primarily as a result of ongoing implementation of current emission control legislation in the transport sector. The International Institute for Applied Systems Analysis (IIASA) estimates suggest that additional measures are available to reduce BC emission by another 40 per cent by 2020. These measures are discussed in the paragraphs below.

43. *Residential combustion.* By 2020, small-scale residential heating will become the dominating source of BC emissions in most countries and cause about half of total emissions. This trend could be even stronger if additional biomass combustion is promoted as a climate policy measure. Thus, effective reduction strategies must address residential combustion as a priority, with an estimated nearly 50 per cent of the remaining mitigation potential in the UNECE region resting in this sector. Implementation will require a combination of technical and non-technical measures. Appropriate technology exists and is available on most markets. However, it is essential to explore implementation barriers and the practical feasibility of implementing specific measures within a given time horizon.

44. Emissions from new residential combustion stoves and boilers could be reduced through product standards and emission limit values that reflect state-of-the-art combustion technology. For example, modern pellet stoves and boilers could significantly reduce BC emissions from biomass combustion. Emissions from existing residential combustion installations can be reduced through retrofit programmes and improved operation practices, for which public information and awareness programmes will be necessary. Dedicated programmes could provide incentives to replace the oldest boilers and stoves by modern installations and stimulate the exchange or retrofit of old appliances.

45. For effective implementation of all these measures, international harmonization of measurement methods and certification tests that account for fuel savings will be necessary.

46. *Non-road machinery.* As off-road machinery has a long lifetime and often poor maintenance, this sector offers the second largest reduction potential for BC emissions in the UNECE region. While current legislation should lead to lower emissions in this sector, compliance will be critical. Emissions could be further reduced through accelerated introduction of particle traps (DPF) for new machinery and retrofitting of existing machinery with DPFs. This could be implemented by mandating that all non-road diesel engines comply with emission standards similar to heavy duty vehicles, i.e., the upcoming Euro VI standard. Eliminating high emitting vehicles and enforcing Euro-VI standards (where applicable) accounts for nearly 20 per cent of the total reduction potential in the region.

47. *Road transport.* Current legislation is expected to achieve significant reductions of BC emissions in the next decade in the road transport sector, though it is essential to assure the effectiveness of this policy, e.g., through regular (annual) emission testing programmes in all UNECE countries. Additional reductions include elimination of high emitting vehicles (super emitters) and accelerated introduction of particle traps (DPF) for light duty and heavy duty vehicles, as well as retrofitting of existing vehicles. Overall, in 2020 these measures account for less than 10 per cent of the total mitigation potential in the UNECE region.

48. *Open burning*. Although open burning of agricultural residues is already banned in several UNECE countries, the enforcement efficiency is largely unknown and remote sensing data shows that burning continues across large areas. Activity and emissions data are more uncertain than for other sectors. It is estimated that an effective ban on open burning could account for about 10 per cent of the total reduction potential for BC emissions. Additionally, agricultural fires often cause forest fires, which are in turn another

important source of emissions. However, there are significant implementation barriers in some countries (e.g., jurisdictional issues in North America).

49. *Shipping.* To encourage the use of best available techniques and accelerate the introduction of cleaner fuels and ships, IMO regulations could be complemented by strict national or regional emission standards and/or by economic instruments, such as emission charges. Additional mitigation may be achieved from sources associated with port activities, for example port electrification.

50. *Industry and power generation.* In relation to other sources, there is only a relatively small potential for further reduction of BC emissions in the industry and power generation sector, with estimates that measures in these sector account for less than 5 per cent of the total potential in the UNECE region. The most important source in this sector are small (<50 MW_{th}) poorly operated old plants, such as those employing small boilers, using coal, oil and biomass.

51. *Flaring.* Although anecdotal evidence suggests gas flares can be a significant source of pollution, the overall magnitude of BC emissions is very uncertain. More effective methods to quantify BC emissions are currently being developed through a Canadian research effort. Additionally, flare improvements programmes are under way (e.g., reducing venting and flaring) in a few countries (e.g., Canada and Norway), but their impact on BC release is unknown. Resources should be made available to better understand activity data and actual BC emissions from this source.

52. *Waste (garbage) burning.* Although open garbage burning has been banned in most countries, the effectiveness is a subject of concern and this source might be locally representing a measurable contribution to BC emissions. Emissions could be reduced by assuring enforcement of this law or introducing such legislation if it is missing.

VI. Options for potential revisions to the Gothenburg Protocol

53. The Expert Group recommends the Executive Body consider options to mitigate BC as a component of PM when making revisions to the 1999 Gothenburg Protocol. A range of options are outlined below.

54. *Monitoring and reporting.* One of the greatest challenges in the overall effort to understand and effectively mitigate the impacts of BC (and other carbonaceous aerosols) is lack of emission and measurement data. At this time, no country has a comprehensive programme to measure and report BC emissions. Given the uncertainties of the inventories, inconsistencies in measurements and the lack of country- and source-specific measurements needed to understand the mixtures being emitted, the Executive Body should consider instituting monitoring and reporting requirements for emissions and air quality specific to BC. This could include specifically listing the constituents of PM, as in EU air quality Directive 2008/50/EC, when including the pollutant in the Protocol language.

55. The Executive Body should also consider tasking specific existing expert groups to recommend the most constructive path forward for gathering and sharing data in the following areas. This may include collaboration with groups working on BC, OC and other co-emitted pollutants outside the auspices of the Convention. The list below offers examples and is not intended to be an exhaustive listing of all possible action, nor should the order presented be interpreted as establishing any priority.

(a) Source measurement and emission factor development:

(i) Characterize and define various carbonaceous aerosol properties (mass, number, size distribution, absorption and scattering coefficients, indices of refraction);

(ii) Identify and characterize missing sources;

(iii) Compile and evaluate all available emissions and activity factors, with guidelines on when they are appropriate to use;

(iv) Identify a central location where emissions test data would be collected, quality assured, and disseminated and establish mechanisms for continuous improvement of emission factors for specific and currently relevant sources;

(b) Emission inventories:

(i) In addition to the obligation to establish inventories for other listed pollutants, add the obligation for each Party to establish a BC/OC emission inventory and a procedure for its regular updating and validation;

(ii) The Task Force on Emission Inventories and Projections should give priority to more work on guidelines for BC inventories with a focus on BC/OC reductions achievable from existing PM control measures/techniques;

(iii) Validate BC inventories against ambient concentrations with an appropriate regular measurement programme;

(iv) Reconcile bottom-up and top-down regional and national inventories;

(v) Evaluate sources and consequences of uncertainties in emissions inventories.

(c) Ambient monitoring and measurement:

(i) The Executive Body should consider the swiftest possible implementation of the EMEP monitoring strategy for 2010–2019;

(d) Exchange of information and technology:

(i) Add BC (and other carbonaceous aerosols) to the list of pollutants under article 4 of the Gothenburg Protocol;

(e) Control options:

(i) The Expert Group on Techno-economic Issues is developing a new chapter for the technical annex VII to the Gothenburg Protocol on emissions of PM from combustion installation < 50 MW, including domestic appliances burning wood. This chapter will consider BC;

(ii) The Executive Body may consider tasking the Expert Group on Techno-economic Issues to assess the impacts of other annex technologies (e.g, for total suspended particulates (TSP) and dust) on BC as well as identify for the draft technical annex on dust those emission limit values that would also result in a reduction of BC;

(f) Cost effectiveness:

(i) The Executive Body should request the Task Force on Integrated Assessment Modelling to assess the cost effectiveness of mitigation options.

56. The Executive Body should support the initiative by EMEP to define BC or, more accurately, operationally define each component of PM that is important from a climate perspective. This means reaching agreement on how the Parties will define, measure and use different terminology regarding light absorbing (and scattering) carbonaceous aerosols. This could be then included in the definition article of the Protocol.

57. *Preambular language.* A revised Gothenburg Protocol could include language setting out the rationale behind BC reduction so as to highlight the urgency of achieving such reductions. Similar to the rationale in this report, the preamble might mention impacts on the Arctic and other climate effects, public health co-benefits, and ongoing work in other forums.

58. *Environmental objective*. The Executive Body should consider whether to include an objective that gives overall priority to measures that achieve, or are explicitly linked, to climate outcomes or targets. A revised Gothenburg Protocol could establish an environmental objective for BC that could be used to measure progress and for integrated assessment modelling. Options could include either qualitative or quantitative objectives or both. Examples of qualitative objectives are: slow the melting of sea ice in the Arctic; or contribute to slowing the enhanced warming of the Arctic. Examples of quantitative objectives are: reduce the radiative forcing due to BC in the Arctic by a total or percentage reduction in Wm^{-2} by a certain date; or reduce by a certain per cent the amount of deposited BC on snow. Other examples could include impacts on near-term radiative forcing and other appropriate near-term climate metrics.

59. *Country-specific goals*. The ability to establish country-specific goals will depend on how accurately sources of BC emissions can be identified and, ideally, source-receptor relationships established. The country-specific goals outlined below may be for consideration in the medium- rather than near-term, given scientific uncertainties and information gaps.

(a) Emission ceilings are one option for individual countries. Given the variability in priority sectors by country, emission ceilings could be established based on the reduction potential of each Party to the Convention. These may be developed for PM with a focus on sources known to be high emitters of BC. The Executive Body could charge the Expert Group or other Convention body to determine whether existing emission ceilings and implementation timelines are adequate to achieve the stated environmental objectives;

(b) Provisional, indicative ceilings could be established if the Executive Body determines that the inventories and modelling are not yet capable of being used to establish definitive emission ceilings;

(c) Technical annexes are another approach to commitments developed and adopted under the Gothenburg Protocol. Some are mandatory, while others have a status closer to that of guidance documents. This option would require best available techniques (BATs; e.g., here, emission limit values) and best available practices (BAP) to be identified and developed for BC emissions;

(d) The Executive Body may wish to consider charging the Expert Group or other Convention body to develop in greater detail the potential options for using both mandatory and voluntary provisions in a revised Gothenburg Protocol. Mandatory provisions may be more appropriate for actions needed to fill critical information gaps, or for reductions from source categories for which more is known regarding impacts and control options. Voluntary provisions may be more appropriate for actions where less is known or where technologies may be still developing;

(e) The Executive Body may wish to consider charging the Expert Group, or some other Convention body to develop additional options for mechanisms by which Parties who do not ratify the revised Protocol might make verifiable and measurable progress toward the stated environmental objective.

60. *Source-category-specific emission limit values*. Alternatively, or to complement country-specific emission ceilings, the Executive Body could consider implementing emission limit values for those source categories known to emit high amounts of BC.

Examples include a timeline for complete removal of super-emitting vehicles; replacement of older residential heating stoves with pellet stoves, emission limits for categories of road and non-road vehicles on an accelerated schedule; or emission limit values on industrial boilers for which known and cost-effective controls exist.

61. *Financial resources*. The efforts suggested to improve the availability of data on black carbon will require significant resources. The Executive Body may wish to consider how to ensure adequate resources are available to implement this work, including potential ways of cooperation to ensure implementation in all Parties.

62. *Review and amendment provisions.* The scientific knowledge of BC continues to evolve very quickly. At least four major international assessments or reports are under way that will further shed light on the climate and public health impacts associated with BC and other short-lived climate forcers. In addition to the work identified above, for example, ongoing analysis from the International Polar Year will most likely produce a number of important scientific results pertinent to the impacts and control of emissions of BC. To take advantage of this work, the Gothenburg Protocol could include mechanisms for revising the protocol to rapidly take action as a result of further scientific synthesis.

63. As individual countries take action unilaterally or under the Convention, further analysis is needed to ensure these actions are having the intended impact. Provisions could be included to facilitate fast-track amendments to the Protocol to make timely adjustments based on scientific and policy advances.

64. *Non-binding goals.* The Executive Body should consider whether to make a statement outlining even more ambitious non-binding environmental objectives. Examples include potential actions outside the Convention region, or an encouragement to the Parties to swiftly and effectively begin implementation of BC emission reductions to a greater extent than might be agreed by Parties to the revised Protocol. Such a statement could include interested Parties or entities, such as nations that are members or observers of the Arctic Council. The Executive Body could also encourage existing task forces and expert groups to do additional outreach to non-UNECE countries and to be inclusive of BC-related research and mitigation activities.

65. While the Executive Body should prioritize work to ensure development within the Convention region, the Executive Body could also encourage actions outside the UNECE region that may include:

(a) Capacity development for BC emissions monitoring and reporting;

(b) Support for development of institutions and infrastructure for monitoring and reporting;

(c) Transfer of BC reduction technology for key emission source sectors.

66. The Executive Body could consider entering into memoranda of understanding with non-UNECE States that are significant sources of BC emissions transported to the UNECE region and key sensitive regions, such as the Arctic, focusing on sources identified as a priority for BC reduction in the amended Protocol.

67. The Executive Body could consider developing mechanisms such that certain obligations — e.g., cooperation for developing BC monitoring and reporting capacity, building institutions and infrastructure — would be binding upon select non-UNECE States that make an explicit declaration to this end. Alternatively, such a provision could be included into the Gothenburg Protocol.

68. The Executive Body may also wish to consider exchange and capacity development on BC monitoring, reporting and technology transfer with interested nations, such as those

in the Association of Southeast Asian Nations (ASEAN) Agreement on Transboundary Haze Pollution and the Male Declaration.

69. The Executive Body should urge the IMO to enact requirements to reduce emissions of BC from international shipping, especially emissions in those areas that impact on the Arctic climate.

70. *Evaluating progress*. Given the gravity of the task before the Parties, the Executive Body should give serious consideration to how and in what time frames it will evaluate progress under a revised Gothenburg Protocol. With the Arctic and other sensitive regions experiencing negative consequences now, it is likely imprudent to wait until 2020 or 2030 to measure progress and adjust the course of progress. A number of metrics exist for consideration, such as measured extent, age and thickness of sea ice; measured BC deposition in sensitive regions; measured ambient concentrations of BC; and/or measured emission reductions of BC. Each of these examples has limitations, including inter-annual variability and limitations on the understanding of the relationship of these measures to climate impacts of concern. The Executive Body could consider tasking EMEP or other Convention body with identifying appropriate metrics and time frames for inclusion in the Gothenburg Protocol.

71. With several major assessments being issued over the course of 2010 and 2011, the Executive Body could consider charging the Expert Group or other Convention body with synthesizing the results of these assessments to determine what new information is available to inform ongoing development of the Gothenburg Protocol.