

## **Hemispheric Transport of Air Pollution 2010 Executive Summary**

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### **Prepared by the Co-Chairs of the Task Force on Hemispheric Transport of Air Pollution**

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### **I. Introduction**

1. The Task Force on Hemispheric Transport of Air Pollution was created by the Convention on Long-range Transboundary Air Pollution in December 2004 to improve the understanding of the intercontinental transport of air pollutants across the Northern Hemisphere. Under the leadership of the European Union and the United States of America, the Task Force has organized a series of projects and collaborative experiments designed to advance scientific understanding of the intercontinental transport of air pollution. The Task Force has convened a series of 15 meetings or workshops in a variety of locations in North America, Europe, and Asia, which have been attended by more than 700 individual experts from 38 countries. The Task Force intensively cooperated with the Convention's centres and task forces and other relevant international and regional organizations. This summary, produced by the Task Force Chairs, presents the findings and recommendations of a multivolume assessment produced by the Task Force reviewing the state of the science with respect to the intercontinental transport of ozone (O<sub>3</sub>), particulate matter (PM), mercury (Hg) and persistent organic pollutants (POPs).<sup>1</sup>

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<sup>1</sup> To be printed in the United Nations Economic Commission for Europe (UNECE) Air Pollution Series.

## II. General findings

2. O<sub>3</sub>, PM, Hg, and POPs are significant environmental problems in many regions of the world. For each of these pollutants, observed concentrations or deposition at any given location can be thought of as composed of several different fractions, one of which is related to the intercontinental transport of anthropogenic emissions. Other fractions may be associated with natural emission sources or local and regional anthropogenic sources. Each fraction differs in terms of the emission sources that contribute to it, the temporal and spatial variability of the contribution, and the potential for and sensitivity to emission controls. In most cases, mitigating local or regional emission sources is the most effective approach to mitigating local and regional impacts of these pollutants. However, without further international cooperation to mitigate intercontinental flows of air pollution, many nations are not able currently to meet their own goals and objectives for protecting public health and environmental quality. With changing global future emissions, it is likely that over the next 20 to 40 years it will become even more difficult for nations to meet their own environmental policy objectives without international cooperation to address transboundary and intercontinental flows of air pollution. Furthermore, cooperation to decrease emissions that contribute to intercontinental transport of air pollution has significant benefits for both source and receptor countries.

## III. Main findings on ozone

### A. Observational evidence

3. An increasing trend in O<sub>3</sub> concentrations has been measured consistently at a number of remote sites across the Northern Hemisphere, suggesting an increase in the hemispheric baseline O<sub>3</sub> concentration of a factor of two during the latter half of the twentieth century. It is likely that much of this change is due to increases in anthropogenic emissions of O<sub>3</sub> precursors. More recently, a more rapid increase has been observed taking place downwind of Eastern Asia in the free troposphere, whereas the increases within the boundary layer of Central Europe and North America have slowed down. Measurements at some locations on the western coasts of Europe and North America clearly show that trans-oceanic air flows can carry O<sub>3</sub> concentrations that approach or exceed some air quality standards or objectives.

### B. Global and regional modelling

4. The hemispheric transport of air pollution (HTAP) multi-model experiments have provided the first set of comparable estimates of intercontinental source-receptor relationships from multiple models by examining the impacts of 20% emission reductions of relevant anthropogenic pollutants in four regions, approximately covering the major populated areas of North America, Europe, South Asia, and East Asia. These names are used hereinafter to refer to these rectangular regions, which encompass more than 75% of the anthropogenic emission sources in the Northern Hemisphere and, in some cases, include significant areas of ocean. Specific analyses were also made to quantify the impact in the Arctic of emission changes in these four source regions.
5. The annual average ground-level O<sub>3</sub> mixing ratio averaged across the four regions and the ensemble of participating models is about 37 parts per billion by volume (ppbv) ( $\pm 4$  ppbv standard deviation). This annual average, region-wide O<sub>3</sub> concentration masks large seasonal and geographic variability, and large differences across models. However, it provides a useful point of reference for considering the magnitude of intercontinental transport. Based on estimates in the literature, about 20–25% of this annual average ground-level concentration originates in the stratosphere and a similar fraction is formed from natural emissions of precursors. The remainder is due to anthropogenic sources of precursors from within the region itself and transported from outside the region. The relative contribution of anthropogenic and natural, regional and extraregional sources varies by location, season, and year.
6. Models indicate that for Europe, East Asia, and North America the absolute contribution of intercontinental transport to ground-level O<sub>3</sub> typically peaks in spring and fall, and is smallest during

summer when O<sub>3</sub> concentrations reach their highest maxima due to the peak in production from local and regional emissions. In these regions in winter, intercontinental transport of O<sub>3</sub> may exceed local and regional production. For South Asia, which is largely dominated by the summer and winter monsoon regimes, the absolute contribution of both intercontinental transport and local and regional production of O<sub>3</sub> are largest during the winter monsoon period and the annual contribution of intercontinental transport does not exceed that of local and regional production. Intercontinental contributions to ground-level O<sub>3</sub> in the Arctic are larger than production from local and regional emissions and peak in April through June, with a secondary maximum in October and November. Taken together, these results indicate that decreasing local or regional emissions is more effective at decreasing the highest O<sub>3</sub> levels, but that there is a significant fraction of tropospheric O<sub>3</sub> that is not within the control of local and regional political jurisdictions.

7. To quantify the relative importance of emissions changes outside each of these regions as compared to emissions changes inside each of these regions, we defined the Relative Annual Intercontinental Response (RAIR) metric, which is the sum of the changes in the annual average, regionally averaged concentration within a region due to a 20% decrease in emissions in the three other regions divided by the sum of the changes in concentration within a region due to a 20% decrease in emissions in all four regions. The value of the metric ranges from 0%, indicating no intercontinental influence, up to 100%, indicating that air quality in a region is completely dominated by intercontinental sources. Thus, the RAIR is a measure of how much benefit a region may receive from emission reductions in other regions when emission reductions are coordinated on an intercontinental scale. The RAIR values calculated in the HTAP multi-model experiments for some of the different pollutants or parameters considered are tabulated in the annex to this document.
8. For O<sub>3</sub>, the impact of 20% changes in anthropogenic emissions of nitrogen oxides (NO<sub>x</sub>), VOCs, CO, SO<sub>2</sub>, and primary PM in one region on ground-level O<sub>3</sub> in the other regions varies from 0.07 to 0.37 ppbv O<sub>3</sub> on an annual average, region-wide basis, as estimated by the mean of the model ensemble. These values are significant in comparison to the response of ground-level O<sub>3</sub> to 20% decreases of emissions within the region itself, which vary from 0.82 to 1.26 ppbv. The RAIRs (shown in the annex) indicate that, in all four of the source/receptor regions, at least 30% of the total concentration changes within each region is related to emission changes in the other three regions. The RAIRs are larger for column O<sub>3</sub> than for ground-level O<sub>3</sub>, and the column RAIRs exceed 50% in Europe and East Asia.
9. On an annual average, region-wide basis, the largest source/receptor relationship is the impact of North American emissions on European ground-level O<sub>3</sub>. This is followed by the impact of European emissions on South Asian and East Asian ground-level O<sub>3</sub>. The annual average impact of East Asian emissions on North American ground-level O<sub>3</sub> is similar to the impact of North American emissions on East Asian ground-level O<sub>3</sub>, but with peaks in different seasons. European emissions have the largest influence on Arctic ground-level O<sub>3</sub> followed by North American emissions.
10. Within a region, annual average, region-wide O<sub>3</sub> concentrations are most strongly influenced by changes in emissions of NO<sub>x</sub>, VOCs, methane (CH<sub>4</sub>), and CO, in decreasing order of importance. The intercontinental contributions to annual O<sub>3</sub> concentrations, however, are most strongly influenced by changes in CH<sub>4</sub>, followed by NO<sub>x</sub>, VOCs, and CO. Decreasing anthropogenic CH<sub>4</sub> emissions in a given region was shown to produce roughly the same decrease in intercontinental transport of O<sub>3</sub> to other regions as a similar percentage decrease in NO<sub>x</sub>, VOCs, and CO emissions combined. The O<sub>3</sub> response to changes in CH<sub>4</sub> emissions, however, requires several decades to be fully realized, given the relatively long atmospheric lifetime of CH<sub>4</sub>.
11. The HTAP multi-model ensemble of O<sub>3</sub> simulations was compared to O<sub>3</sub> concentrations observed by selected ground-based networks and sondes (balloons) in North America, Europe, and Asia. At most ground-level sites and for lower and middle troposphere sonde measurements, the model ensemble mean generally captures the observed seasonal O<sub>3</sub> cycle and is close to the observed regional mean ground-level O<sub>3</sub> concentration. Furthermore, the model ensemble mean agrees well with regionally averaged observed values in all regions in spring and late autumn when intercontinental transport

tends to be strongest. This ability gives us some confidence that we can quantitatively represent the key processes controlling the formation, transport and removal of O<sub>3</sub> and its precursors.

12. However, there are notable biases in the model ensemble mean: underestimating ground-level O<sub>3</sub> at high altitude sites, overestimating summertime ground-level O<sub>3</sub> concentrations over Japan and the eastern United States, and high biases for sonde measurements in the upper troposphere and at polar sites.
13. In the HTAP multi-model experiments, the difference between models in terms of the response of O<sub>3</sub> concentrations due to 20% changes in precursor emissions is appreciable in both the source region and at distant receptors; the standard deviation is 20–50% of the ensemble mean response. The differences between models and between models and observations are due to uncertainties in emissions estimates, limitations imposed by the spatial and temporal resolution of the models, and uncertainties in the representation of transport, chemistry, and removal processes.

### **C. Impacts of intercontinental transport**

14. In terms of exceedances of ambient air quality standards, the highest concentrations of O<sub>3</sub> are typically associated with stagnant conditions, when the contribution from transport is low and the contribution of local and regional sources are most important. However, intercontinental transport has increased baseline O<sub>3</sub> concentrations to the point where they exceed thresholds for protection of vegetation in many locations and exceed thresholds for the protection of human health occasionally in some locations. As public health-based air quality standards continue to be tightened based on new health effects research, the contribution of intercontinental transport to exceedances of such standards will continue to increase.
15. There is considerable evidence from experimental human and animal studies and epidemiological studies that exposure to ambient O<sub>3</sub> concentrations causes adverse health effects which range from minor sensory irritation to premature death. Relatively few studies have tried to quantify the human health impacts of intercontinental transport of O<sub>3</sub> specifically. Those studies have focused on the relationship between annual average concentrations and premature mortality and suggest that intercontinental transport can contribute significantly to health impacts of air pollution within a given receptor region. For O<sub>3</sub>, one study based on the HTAP multi-model experiments estimated that intercontinental transport of O<sub>3</sub> contributes 20% to more than 50% of O<sub>3</sub>-related premature adult mortalities in a given receptor region, subject to large uncertainty.
16. The sum of the health impacts of transported pollution in downwind foreign regions can be larger than the health impacts of emissions in the source region itself. Although the impact on ambient concentrations in downwind foreign regions may be much less than in the source region itself, the total population exposed in those downwind regions is much greater. The HTAP multi-model experiments suggest that emission reductions in North America and Europe will avoid more O<sub>3</sub>-related mortality outside these source regions than within the regions themselves.
17. O<sub>3</sub> causes damage to crops, forests, and grasslands, which has important implications for productivity, biodiversity, and food security and may be an important contributing factor to the agricultural yield gap that currently exists across much of Asia. Global yield losses of four staple crops due to exposure to O<sub>3</sub> are estimated to be between 3%–16%, depending on the crop, and are valued at \$14 billion to \$26 billion per year. Based on the HTAP multi-model experiments, intercontinental transport may be responsible for 5% to 35% of the estimated crop yield losses depending on the location, crop and response function used, subject to large uncertainties.
18. O<sub>3</sub> contributes significantly to climate forcing, directly as a greenhouse gas and indirectly by damaging plants and inhibiting their natural uptake of CO<sub>2</sub>. Among O<sub>3</sub> precursors, widespread decreases in emissions of CH<sub>4</sub>, CO, and VOCs better reduce net climate forcing over time than decreasing NO<sub>x</sub>, which increases the lifetime of CH<sub>4</sub> and, thus, increases climate forcing over decadal time scales. Decreasing emissions of CH<sub>4</sub>, which is a greenhouse gas itself, will result in decreases in the direct forcing from CH<sub>4</sub> and the direct and indirect forcing of O<sub>3</sub>, affecting the rate of climate change in the coming decades.

## **D. Future scenarios for emissions and climate**

19. The significance of intercontinental transport may change in the future due to changes in the magnitude and spatial distribution of anthropogenic emissions. The implications of changes in anthropogenic emissions were explored in the HTAP multi-model experiments by considering a set of global emission scenarios developed to inform the Intergovernmental Panel on Climate Change's fifth assessment report, known as the Representative Concentration Pathways (RCPs). Three of the four scenarios assume some climate change mitigation policy will be adopted, and all four assume that the implementation of air pollution control policies will increase as development and income increase. As a result, all four of the scenarios suggest that between now and 2050, global emissions of NO<sub>x</sub>, VOCs, and CO will eventually decline. However, the regional distribution of emissions in the Northern Hemisphere is expected to shift, with steeper and earlier declines in Europe and North America and shallower declines or actual increases in South and East Asia.
20. The impacts of this redistribution of future emissions and expected changes in future global CH<sub>4</sub> concentrations specified by the RCPs were explored using linear approximations of the intercontinental source-receptor sensitivities determined under current conditions in the HTAP multi-model experiments. To illustrate the range of future levels of air pollution, we assess the RAIRs (provided in the annex) for 2050 under the lowest emissions scenario and for 2030, when global emissions peak, under the highest emissions scenario. For North America ground-level O<sub>3</sub> concentrations, the RAIR is estimated to increase to around 50% under both the high and low emissions scenarios, suggesting that, in the future, changes in emissions of O<sub>3</sub> precursors outside the region may be as important as changes within the region. For Europe, the RAIR for ground-level O<sub>3</sub> increases relatively little under the highest and lowest scenarios, due to simultaneously declining air pollution emissions in North America. For East Asia, the RAIR decreases under a high emission scenario, under which emissions within the region increase, and increases under a low emission scenario, under which emissions in the region decline. For South Asia, the RAIR for ground-level O<sub>3</sub> declines under both the low and high scenarios. Note that the sensitivity to changes in geographical distribution of emissions within a particular region has not been adequately assessed yet.
21. Using the linear approximations of the HTAP multi-model experiments, the influence of changing CH<sub>4</sub> concentrations can be separated from the influence of changing intercontinental transport and local and regional emissions over the historical emission trends and future emission scenarios. Under future scenarios, expected increases in CH<sub>4</sub> concentrations have a large influence on ground-level O<sub>3</sub> changes, in some cases offsetting significant decreases in O<sub>3</sub> formation associated with local and regional emissions.
22. The HTAP multi-model experiments also examined the potential impacts on ground-level O<sub>3</sub> of changes in meteorology and transport patterns expected as a result of climate change. Future changes in climate are expected to increase the effect of precursor emissions over source regions and reduce the effect over downwind receptor regions. However, the impact of these changes on long-range transport is relatively small, and is driven by changes in atmospheric chemistry and not by changes in transport patterns. The effect of natural emission changes and wider climate-related feedbacks have not been evaluated fully yet.

## **IV. Main findings for particulate matter**

### **A. Observational evidence**

23. The most tangible evidence for intercontinental transport comes from satellite images of PM crossing oceans and continents in discrete plumes, often associated with biomass burning or windblown dust events. Within the past few years, satellites have begun to provide quantitative information on intercontinental transport of PM, including estimates of the amount of pollution transported, the altitude of transport and, in some cases, aerosol properties. Ground-based remote-sensing networks and mountain-top measurement sites in Europe, North America and Asia provide large continuous data sets that characterize the frequency of occurrence of PM transport events, the meteorological conditions responsible for them, and important information on aerosol properties. Evidence of intercontinental transport is provided also in the form of long-term trends in ground-based

observations from remote islands, which in some cases compare well with the trends in emissions in upwind areas. Significant air quality and environmental impacts of the long-range transport of PM have been observed, especially in the outflow of the Asian and African continents and in the Arctic.

## **B. Global and regional modelling**

24. PM is comprised of different chemical components, some of which are directly emitted as particles by natural or anthropogenic sources (primary PM) and others have their origin in gases that are transformed through chemical and physical reactions and adsorbed on particles (secondary PM). Both primary and secondary PM play a role in intercontinental transport. Conceptually, the components of PM can be separated into those of natural origins (including volcanic eruptions, oceans, wind-blown soil dust), open biomass burning (which can be both natural and anthropogenic), anthropogenic emissions that have been transported on intercontinental scales, and local and regional anthropogenic emission sources.
25. The HTAP multi-model experiments suggest that, in the four regions studied, ground-level concentrations of wind-blown soil dust from deserts in Africa, Asia, and the Middle East can be a factor of 1.5 to almost 20 higher than that from anthropogenic and open biomass burning sources on a region-wide, annual average basis. Of the ground-level PM concentration originating from anthropogenic and open biomass burning sources, intercontinental transport of anthropogenic emissions accounts for between 5% and 35% on a region-wide, annual average basis.
26. As is the case with O<sub>3</sub>, annual average, region-wide statistics mask significant variability between seasons, within a given region and across models. The seasonal cycles of PM concentration and intercontinental transport vary by chemical component and by region. However, there are substantial differences between the seasonal cycles in ground-level concentration predicted by models participating in the HTAP multi-model experiments. The model differences are larger for wind-blown soil dust than they are for sulphate, black carbon and particulate organic matter, and are larger for the Arctic than for the mid-latitude regions. The differences between models reflect large uncertainties in emissions and atmospheric processes represented in the models. Despite the substantial differences in estimated absolute concentrations, there is much closer agreement between the participating models in terms of source attributions on an annual average, region-wide basis.
27. As shown in the annex, the RAIRs estimated in the HTAP multi-model experiments indicate that decreases in intercontinental transport would contribute 5% to 20% of the decrease in region-wide, annual average, ground level PM concentrations that results from decreasing anthropogenic emissions by 20% in each of the four regions studied. The influence of intercontinental transport is larger for aerosol optical depth (AOD) (17–25% for non-soil dust components) and total column loading (24–37% for sulphate), reflecting the importance of transport above the boundary layer and implying more significant contributions to visibility and radiative forcing impacts.
28. Ground-level PM concentrations or deposition in the Arctic are most sensitive to emission changes in Europe. However, total column loadings of PM over the Arctic are equally sensitive to changes in emissions from Europe or Asia, due to the fact that Asian emissions have a stronger tendency to be lifted and transported aloft than do European emissions.
29. Ground-level PM concentrations generally respond linearly to changing emissions from both local and upwind source regions. However, sulphate and some fraction of particulate organic matter are not directly emitted, but are formed in the atmosphere through oxidation, and can be affected by non-linear systems of chemical reactions. Thus, changes in the intercontinental transport of O<sub>3</sub> and its precursors can affect downwind PM concentrations, underscoring the multifaceted consequences of a rising background of pollution levels in the Northern Hemisphere on local pollution levels.
30. Many of the same limitations and sources of uncertainty faced in estimating O<sub>3</sub> concentrations apply to current models for PM, although there are additional challenges as well. In the HTAP multi-model experiments, the range of predicted concentrations is about a factor of two for sulphate ground-level concentrations in the mid-latitude continental regions, whereas the model differences approach a factor of four for black carbon and particulate organic matter ground-level concentrations, and a factor of seven for soil dust ground-level concentrations. For the Arctic region, where PM levels are very

low, the relative spread of modelled concentration estimates is much greater. A detailed comparison between the HTAP-participating models reveals a factor of four difference in the atmospheric lifetime of sulphate calculated by the different models.

31. A comprehensive comparison of HTAP multi-model estimates with PM observations has not been conducted. However, available observational data to support such an evaluation are being compiled and some comparisons have been conducted for sulphate wet deposition.

### **C. Impacts of intercontinental transport**

32. Intercontinental transport of wind-blown soil dust can cause exceedances of ambient air quality standards for PM and, in western North America, is likely to interfere with the attainment of visibility goals. Intercontinental transport of PM components other than wind-blown dust is not usually sufficient to exceed health-based ambient standards. However, there is no threshold for adverse health effects from exposure to PM.
33. Based on the HTAP multi-model experiments, the intercontinental transport of PM has influences on human mortality that are comparable to O<sub>3</sub>. While O<sub>3</sub> is transported between regions more efficiently, the relationship between PM and mortality is stronger. Consequently, the estimated mortalities attributable to PM within each source region are much higher, and the contributions of the three foreign regions to the mortality in a given home region range from 3% to 5%. Of the total mortalities associated with emissions from North America and Europe, 15% and 12%, respectively, are estimated to be realized outside of these source regions.
34. PM deposition also damages a variety of different ecosystems, including forests and grasslands, through acidification. Similarly, eutrophication is damaging to biodiversity in sensitive ecosystems of low nutrient status. PM can benefit ecosystems by increasing the diffuse solar radiation; however, the contribution of long-range transport to these effects is very uncertain and may be relatively small.
35. PM is a significant contributor to climate forcing; intercontinental transport influences the distributions of PM and, therefore, the extent and magnitude of its forcing. PM is a mixture containing components that mainly cool, including sulphate and organic aerosols, and black carbon that warms. Anthropogenic emissions of black carbon, CH<sub>4</sub>, CO, and VOCs are estimated to have caused a climate forcing since 1750 roughly as large as that from anthropogenic CO<sub>2</sub>. Reductions in PM would improve air quality, but for cooling aerosols, including sulphate, nitrate and particulate organic matter, this would generally increase warming. Reductions in black carbon would typically benefit both air quality and climate.
36. The Arctic is experiencing rapid climate change. Arctic climate is affected by O<sub>3</sub> and PM that are transported into the Arctic from other regions, as well as by the climate forcing of O<sub>3</sub> and PM outside of the Arctic. Deposition of black carbon on snow is understood to be an important positive forcing (warming) in the Arctic.

### **D. Future scenarios for emissions and climate**

37. As for O<sub>3</sub>, the impact of future emission changes on the intercontinental transport of PM was examined by considering the RCP scenarios up to 2050. All of the scenarios assume some implementation of air pollution control policies as development and income increase. By 2050, global anthropogenic emissions of SO<sub>2</sub> are expected to have declined between 30% and 70%. European and North American emissions are expected to continue to decline from their current levels. East Asian emissions are expected to continue rising for a while before declining dramatically by 2050. For black carbon emissions, global emissions are expected to decline between 15% and 50% by 2050, with dramatic declines in East Asia, which currently has the largest share of black carbon emissions. Thus, both the magnitude and composition of the intercontinental transport of PM is likely to change in the future.
38. Climate change is expected to impact PM concentrations through changes in temperature, humidity, precipitation patterns, and atmospheric chemistry and dynamics, as well as changes in emissions from wind-blown dust, natural forest fires, and biogenic hydrocarbons. The overall impact of these changes on the intercontinental transport of PM has not been fully evaluated.

## V. Main findings for mercury

39. Hg differs from other major atmospheric pollutants (e.g., O<sub>3</sub> and PM) primarily because its environmental and health impacts are not directly related to atmospheric mercury burden. While the major redistribution pathway of Hg is atmospheric transport, its primary environmental and health impacts are in aquatic systems and for aquatic organisms and their consumers. Atmospheric Hg that is transferred to aquatic systems through dry and wet deposition mechanisms is converted from an inorganic form to methylmercury (MeHg) by microbes in the water and sediments of wetlands, lakes, reservoirs, rivers, estuaries and oceans. Unlike other forms of Hg, MeHg biomagnifies in aquatic food webs. Consumption of fish or other aquatic organisms with elevated MeHg concentrations is the primary route of exposure for humans and other freshwater and marine fish-eating wildlife.
40. Hg is emitted into the atmosphere as elemental Hg<sup>0</sup> in gaseous form or/and as oxidized, ionic Hg<sup>2+</sup> in gaseous form or/and bound to suspended particulate matter. Hg<sup>0</sup>, which has an average atmospheric lifetime of six months to a year, dominates atmospheric loading and is typically the form in which Hg is transported long distances. Ionic Hg is removed from the atmosphere very quickly through dry deposition and wet removal processes. For purposes of apportioning deposition and subsequent impacts back to emission sources, Hg deposition can be divided into Hg that was released originally from natural sources; legacy Hg that was released from anthropogenic sources originally, was deposited, and subsequently re-emitted; newly-released Hg that was released from anthropogenic sources primarily as Hg<sup>0</sup> and transported on intercontinental scales; and newly-released Hg that was released from local and regional anthropogenic sources primarily as ionic Hg and quickly deposited locally and regionally.

### A. Observational evidence

41. The long atmospheric lifetime of Hg<sup>0</sup> results in baseline concentrations of 1.5 to 1.7 ng m<sup>-3</sup> Hg<sup>0</sup> in the Northern Hemisphere and 1.1 to 1.3 ng m<sup>-3</sup> Hg<sup>0</sup> in the Southern Hemisphere (at sea level). This inter-hemispheric gradient has been observed consistently in ship-borne observations and is reproduced by current global models. Intercontinental transport of Hg has been observed in episodic events of elevated Hg<sup>0</sup> concentrations recorded at remote mountain-top sites and during aircraft measurement campaigns. Long-term changes in the atmospheric Hg burden have been derived from chemical analysis of lake sediments, ice cores, and peat deposits, and observed in firn air samples, and suggest that Hg deposition has increased about threefold since pre-industrial times. Decreasing deposition trends observed in Europe and North America are consistent with documented regional emission reductions; however, global trends in concentrations and deposition are ambiguous and may indicate offsetting effects between emission trends in Asia and the other parts of the world, and significant recycling of Hg between environmental components.

### B. Global and regional modelling

42. Based on the HTAP multi-model experiments, natural and re-emitted Hg account for about 35% to 70% of total Hg deposition on region-wide, annual average depending on the region, whereas intercontinental transport of newly-released anthropogenic Hg emissions accounts for about 10% to 30% of total Hg deposition, on an annual globally-averaged basis. East Asia, which accounted for almost 40% of total global newly-released mercury in 2000, is the most dominant among the four HTAP source regions accounting for 10% to 14% of the annual Hg deposition found in other regions, followed by contributions from Europe, South Asia, and North America. However, where deposition is highest, local and regional anthropogenic emission sources are the dominant sources of Hg deposition.
43. The Arctic has no anthropogenic emission sources within the region, so anthropogenic Hg that is deposited there comes from intercontinental transport. A large fraction of transported Hg is deposited in springtime during polar sunrise in atmospheric mercury depletion events, during which Hg<sup>0</sup> is rapidly oxidized by photochemical reactants that have built up over the dark winter.
44. The global Hg models participating in the HTAP multi-model experiments provided relatively consistent estimates of the impact of one source region on another despite significant differences in emissions and chemistry in each model. The RAIR (see annex) for East Asia is low, suggesting that

emission controls within East Asia are much more important for deposition levels in that region than are changes in intercontinental transport into the region. For Europe and South Asia, the RAIRs are 35% and 43%, respectively, suggesting that intercontinental transport makes a significant contribution to deposition within these regions. For North America, the RAIR is greater than 50%, suggesting emission reductions in East Asia, Europe and South Asia decrease region-wide deposition more than emissions reductions within North America itself. In the Arctic, Hg deposition could be the most effectively controlled by emission reduction in East Asia and Europe due to their proximity to the Arctic, prevailing atmospheric circulation patterns and significant contribution of these regions to global anthropogenic emissions.

45. Current global atmospheric Hg models reproduce the observed ground-level Hg<sup>0</sup> concentrations to within 20% of the sparse observations that are available. The agreement between models and observations for Hg wet deposition is weaker, with differences between observed and modelled values up to 100%, mainly due to uncertainties in Hg emission rates, Hg oxidation chemistry and estimated precipitation rates.

### **C. Impacts of intercontinental transport**

46. To better evaluate the main impact that international emissions controls will have on MeHg exposure over intercontinental scales, it is necessary to understand the overall chain of human exposure, including the linkages between atmospheric and oceanic Hg transport, Hg methylation in marine and freshwater ecosystems, exposure to and biomagnification of MeHg in freshwater and marine fish, the international trade of fish and fish consumption patterns. These linkages are poorly quantified at present.

### **D. Future scenarios for emissions and climate**

47. Several recent studies have developed global emission projections for anthropogenic Hg emissions in the years 2020 and 2050. Both studies conclude that significant increases in global Hg emissions, up to 25% in 2020 and 100% in 2050 as compared to 2005, can be expected if no major changes in emission controls are introduced. However, both studies also conclude that the implementation of known emissions control technology could maintain or decrease global Hg emissions. The intercontinental source-receptor relationships under these future scenarios are not significantly different from the source-receptor relationships estimated for current emissions. The large contribution of Hg released from aquatic and terrestrial ecosystems (primary natural sources plus re-emissions of previously-deposited mercury) to the overall atmospheric deposition dampens the relative response of Hg deposition to changes in new anthropogenic emissions, reinforcing the long-term benefit of decreasing the amount of Hg recirculating in the environment by decreasing Hg emissions globally.
48. The impacts of climate change on intercontinental transport of Hg were not explicitly addressed in the HTAP multi-model experiments, and there is large uncertainty about how climate change will effect natural and recycled emissions of Hg, as well as the atmospheric chemistry and transport of Hg. Climate change effects on temperatures, frequency of forest fires, plant growth and decomposition will significantly impact the terrestrial-atmospheric exchange of Hg. Likewise, ocean-atmosphere exchange of Hg will be affected by changes in temperature, wind speeds and storm frequency, as well as changes in atmospheric oxidant and aerosol concentrations. The net effect of these changes, however, has not been adequately studied yet.

## **VI. Main findings for persistent organic pollutants**

49. By definition, POPs have long lifetimes in the environment, often cycling between different environmental compartments (i.e., air, water, soil, vegetation, snow and ice). Thus, through direct emission and transport or repeated cycles of emission, transport, deposition and re-emission, POPs can end up in the environment far from their emission source. The overall potential and dominant mechanisms for intercontinental atmospheric transport vary between individual POPs, since these have widely different chemical characteristics.

## A. Observational evidence

50. Evidence for intercontinental transport is provided from observations in remote locations far from emission sources and in elevated levels in plumes observed at high altitude sites in mountains and during an aircraft campaign. Concentrations of POPs are often correlated with other anthropogenic pollutants. Existing atmospheric monitoring programmes provide adequate spatial coverage of atmospheric concentration information for most POPs in the United Nations Economic Commission for Europe (UNECE) region. However, only a few monitoring programmes also analyse POPs in precipitation from which total deposition can be estimated. Some long-term air monitoring programmes have observed decreasing concentration trends for some POPs subject to international emissions controls (e.g., technical Hexachlorocyclohexane or HCH). For other POPs (e.g., p,p'-Dichlorodiphenyltrichloroethane or p,p'-DDT), at the Arctic stations of Alert and Pallas, observed trends show slow or no significant decline in air concentrations in response to international emissions controls.

## B. Global and regional modelling

51. Most POPs do not have natural sources, so observed POPs concentrations or deposition can be apportioned into re-emitted POPs that were originally released from anthropogenic sources, newly-released POPs that were released from anthropogenic sources and have been transported on intercontinental scales and newly-released POPs that were released from local and regional anthropogenic sources. The relative importance of each of these fractions varies depending on the individual compound of interest and the location of the receptor relative to sources. Apportioning re-emitted POPs back to their original sources requires estimating historical emissions and simulating the behaviour of POPs in other environmental media over long time periods. As primary emissions are decreased or ceased as a result of emission control measures, re-emission becomes increasingly important.
52. As part of the HTAP multi-model experiments, the transport of several POPs (Polychlorinated biphenyl-28 or PCB-28, PCB-153, PCB-180, and  $\alpha$ -HCH) covering a range of different physical and chemical properties was simulated by three models using different approaches to describe pollutant transport through environment compartments and different spatial resolutions. Despite their differences, the models provide estimates of annual average atmospheric concentrations, the major transport pathways of selected POPs and the response to primary emission changes that are within a factor of two to three of the ensemble mean.
53. Differences in the estimated RAIR for POPs presented in the annex are primarily a function of the uneven spatial distribution of emissions between regions and the transport characteristics of the pollutant. The largest effect on intercontinental transport is seen for a 20% reduction of new  $\alpha$ -HCH emissions in South Asia, which decreases concentrations in other regions between 2% to 6%. Decreases in PCB emissions in Europe produce similar levels of response across the other regions. The lowest response in other regions is produced by the reduction of  $\alpha$ -HCH in East Asia and North America, and for PCBs in East Asia, due to their relatively low contributions to the global emissions of these pollutants.
54. Arctic pollution is mostly sensitive to the changes of emissions in Europe (for all simulated POPs) followed by North America (for PCBs) and South Asia (for  $\alpha$ -HCH).
55. The regional differences in the effectiveness of atmospheric POPs transport alone was explored by simulating the transport of selected POPs assuming an equal mass of emissions in each source region. In contrast to the results with regionally different emissions, the uniform emissions produced the same level of response to emission changes for all source-receptor region pairs.
56. Current POPs models vary widely in the level of detail represented. Model simulations for a subset of POPs have been conducted and are typically able to reproduce observed annual concentrations to within a factor of three or four, enabling identification of major transport pathways. The POPs that have been successfully modelled and evaluated include PCB-28, PCB-153, PCB-180, and  $\alpha$ -HCH. In some cases, however, the differences between model estimates and observed values can be much

greater indicating fundamental uncertainties both in emission inventories and in modelling approaches.

57. As with Hg, POPs models must not only simulate the behaviour of pollutants in the atmosphere, but they must also simulate the exchange between the atmosphere and other environmental media (such as water, soil, snow, ice and vegetation) and the transport and transformations that occur in those other media. Observational data from inter-media exchange and transport and transformation studies are limited, making it difficult to evaluate models and characterize uncertainties.

### **C. Impacts of intercontinental transport**

58. Similar to Hg, POPs are widely distributed through atmospheric transport, but their primary environmental impacts are realized through the contamination of food webs. Through processes of bioconcentration, bioaccumulation, and biomagnifications, humans and other animals may be exposed to much greater concentrations of POPs than observed in the air, water or soil. There is little information about long-term trends of POPs in food or human media outside of Western Europe, North America and Japan, making it difficult to characterize the global impacts of POPs. The traditional diet of indigenous Arctic people, which is high in locally caught fish and game, combined with the atmospheric and oceanic transport of POPs into the Arctic and accumulation in the Arctic food web results in elevated POPs exposures in native Arctic populations. Studies have demonstrated elevated exposures to PCBs in native Arctic populations and have estimated that exposures to toxaphene, chlordane, DDT, HCH, dioxins and other dioxin-like POPs can be above levels of concern for adverse health effects. Moreover, there is concern about new POPs, which are currently in commerce and now just starting to be addressed by international agreements, including Pentabromodiphenyl ethers (PBDEs), Perfluorooctane sulfonate (PFOS), and Perfluorooctanoic acid (PFOA), that have been detected in Arctic environments, in some cases in increasing amounts. The risks of chronic exposure to these chemicals are not well characterized.

### **D. Future scenarios for emissions and climate**

59. Over the next 40 years, emissions and patterns of intercontinental transport of some POPs will continue to decrease and shift as a result of national and international regulations. For those POPs whose use has been banned or strictly limited, shifts may occur as re-emission of legacy pollution results in migration or dispersion of the pollutants. For POPs that are still in use as chemicals or are unintentionally released from combustion or other industrial processes, differences in regulations or economic activity may lead to shifts in the spatial distribution of emissions. In Europe and North America, full implementation of the POPs Protocol to the Convention on Long-range Transboundary Air Pollution and the Stockholm Convention on Persistent Organic Pollutants is expected to decrease emissions by more than 90% for Hexachlorobenzene (HCB) and PCB, more than 60% for Polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs) and 30% to 50% for Polycyclic aromatic hydrocarbons (PAHs).
60. For POPs that are still in commerce and have yet to be addressed by national and international regulations, intercontinental flows are expected to increase as continued emissions contribute to the stock of the pollutant circulating in the environment.
61. Climate change may further alter the magnitude and patterns of emissions and intercontinental transport of POPs in a variety of ways. Similar to Hg, climate change may significantly alter the exchange of POPs between the atmosphere and water, soil, vegetation, sediments, snow and ice. There is evidence that climate change phenomena, e.g., elevated temperatures and sea-ice reduction, and extreme climate-change induced events, such as forest fires, flooding and glacial melting, will remobilize POPs previously-deposited in sinks, e.g., forest soils and vegetation, ocean and lake sediments and glaciers. Climate change may also alter the exposures of individuals and populations and their vulnerability to chemical exposures. However, our ability to understand the influence of these processes is limited by a lack of measurements and organized monitoring of POPs in media other than air.

## VII. Main recommendations

62. Our current understanding of the magnitude of intercontinental flows of air pollution is sufficient to conclude (a) that such flows have a significant impact on environmental quality throughout the Northern Hemisphere and (b) that coordinated international actions to mitigate these flows would yield significant environmental and public health benefits. However, our current ability to quantify accurately and precisely the contribution of intercontinental flows on air pollution concentrations or deposition at any given location or the effect of international emissions controls on pollution levels and their environmental or public health impacts is limited.
63. To quantify better the impacts of intercontinental flows of air pollution and the effects of international controls, additional efforts are needed to improve further the coverage and resolution of our observational systems, the accuracy and resolution of our emissions inventories and projections, the fidelity and performance of our models of chemistry and transport and the scope and detail of our impact assessments.
64. Moreover, we need to shift the goal of the science activity from simply developing knowledge to a goal of informing action. A programme of monitoring, research, and analysis activities is needed that is:
  - (a) Intentional, making source attribution on global to intercontinental scales an explicit objective of ongoing and future efforts, including efforts to:
    - (i) Maintain and expand long-term observational systems for monitoring trends in intercontinental transport, air pollution concentrations and characteristics above the boundary layer, and contamination in other environmental media;
    - (ii) Conduct intensive field studies to improve model descriptions of transport processes, quantify the fluxes of pollutants between environmental media (including re-emission to the atmosphere) and evaluate emissions inventories;
  - (b) Innovative, employing novel techniques and developing new methods where needed, including efforts to:
    - (i) Quantify transport through the observation of chemical or isotopic fingerprints;
    - (ii) Develop new methods for measuring dry deposition, re-emission fluxes and the composition of reaction products (e.g., for Hg oxidation);
    - (iii) Characterize the relevant properties and environmental chemistry of new chemicals and their potential for intercontinental transport;
    - (iv) Compare emission estimates to ambient observations using inverse modelling;
    - (v) Use adjoint and other advanced modelling techniques for understanding current and future source-receptor relationships;
  - (c) Integrated, generating new insights by combining and comparing information within disciplines and across disciplines, as well as across different pollutants, including efforts to:
    - (i) Improve our understanding of environmental transport and fate of air pollutants by bringing together information from emissions, observations, and models for multiple pollutants;
    - (ii) Co-locate monitoring sites for multiple pollutants, different environmental media and human and wildlife exposure;
    - (iii) Extend modelling and analysis frameworks to include the fate of air pollutants in other environmental media, the exchange between environmental media (including re-emission processes), and the exposure to and impacts of transported pollutants;
  - (d) Inclusive, engaging a broader community of scientists and air quality management officials in developed and developing countries throughout the Northern Hemisphere;

- (e) Supported by institutions and information networks, fostering and facilitating cooperation between experts within and across disciplinary and community boundaries.
65. As we move from developing knowledge to informing collective action, the costs and availability of controls for emission sources and how they differ across and between continental source regions also need to be assessed further. In future work, the implications of sector-based control strategies in different regions need to be examined holistically in terms of their multiple impacts on public health, ecosystems and climate change at the local, regional and global scales.
66. The availability of forums for pursuing further international cooperation to mitigate sources of intercontinental transport differs depending on the pollutants of interest. The Stockholm Convention on POPs and the recently opened negotiations under the United Nations Environment Programme (UNEP) on a global instrument on Hg provide forums for furthering global cooperation to mitigate sources of POPs and Hg.
67. For O<sub>3</sub> and PM, however, there is no such global agreement, although several regional agreements, in varying states of evolution, address at least some of the sources of transported O<sub>3</sub> and PM. A range of approaches have been suggested for establishing global or hemispheric scale cooperation on mitigation of O<sub>3</sub> and PM, including a global confederation between existing regional efforts building on existing organizational infrastructures and intergovernmental relationships. Such a confederation, or interregional partnership, could facilitate information exchange, capacity-building and technology transfer between regions, and greatly facilitate connections between the regional air quality agreements and other existing global agreements, global institutions and the global scientific community. Thus, a global confederation of regional cooperative programmes on air pollution could help develop a better and globally-shared understanding of air pollution problems and their solutions at the local, regional and global scale while maintaining autonomy and flexibility for regions to develop policies and programmes appropriate for their circumstances. Such a confederation may be created as a new institution or organized under an existing global institution, such as UNEP, the World Meteorological Organization (WMO), or a joint UNEP-WMO venture, as in the case of the Intergovernmental Panel on Climate Change (IPCC).
68. As a subsidiary body of the UNECE Air Convention, the Task Force can continue to play a leadership role in bringing together different expert communities and connecting different regional and global institutions. For the Convention, continuing and expanding such efforts is important to decrease the impact of sources outside the Convention and to meet the Convention's own goals. Irrespective of the future role of the Task Force, the potential for a more formal global confederation of regional cooperative programmes on transboundary air pollution should be explored.

## Annex

### Relative Annual Intercontinental Responses

The Relative Annual Intercontinental Response (RAIR) is based on the HTAP multi-model experiments in which emissions were decreased by 20% in each of four regions approximating North America, Europe, South Asia and East Asia. The RAIR metric is the sum of the changes in the annual average, regionally averaged concentration within a region due to a 20% decrease in emissions in the three other regions divided by the sum of the changes in concentration within a region due to a 20% decrease in emissions in all four regions. Thus, the RAIR is a measure of how much benefit a region may receive from emission reductions in other regions when emission reductions are coordinated on an intercontinental scale.

| Scenario          | Pollutant/Parameter <sup>a</sup>              | Receptor Region |        |            |           |
|-------------------|---|-----------------|--------|------------|-----------|
|                   |   | North America   | Europe | South Asia | East Asia |
| 2001              | O <sub>3</sub> Concentration                  | 32%             | 43%    | 32%        | 40%       |
| 2001              | O <sub>3</sub> Total Column Burden            | 39%             | 62%    | 38%        | 60%       |
| 2001              | Particulate Matter Concentration <sup>f</sup> | 7%              | 5%     | 20%        | 9%        |
| 2001              | SO <sub>4</sub> Deposition                    | 8%              | 9%     | 24%        | 12%       |
| 2001              | Black Carbon Deposition                       | 4%              | 1%     | 12%        | 3%        |
| 2001              | Reactive Nitrogen Deposition                  | 3%              | 4%     | 13%        | 7%        |
| 2001              | Aerosol Optical Depth <sup>b</sup>            | 17%             | 13%    | 25%        | 17%       |
| 2001              | SO <sub>4</sub> Total Column Burden           | 25%             | 25%    | 37%        | 24%       |
| 2001              | Hg Deposition                                 | 61%             | 35%    | 43%        | 10%       |
| 2001              | α-HCH Deposition                              | 82%             | 9%     | 6%         | 63%       |
| 2001              | PCB-28 Deposition                             | 9%              | 3%     | 48%        | 56%       |
| 2001              | PCB-153 Deposition                            | 11%             | 2%     | 32%        | 50%       |
| 2001              | PCB-180 Deposition                            | 11%             | 4%     | 36%        | 56%       |
| 2001 <sup>c</sup> | O <sub>3</sub> Concentration                  | 32%             | 42%    | 33%        | 40%       |
| 2030 <sup>d</sup> | O <sub>3</sub> Concentration                  | 53%             | 45%    | 20%        | 30%       |
| 2050 <sup>e</sup> | O <sub>3</sub> Concentration                  | 49%             | 44%    | 14%        | 41%       |

<sup>a</sup> Concentrations are at ground-level.

<sup>b</sup> Aerosol Optical Depth calculated for the sum of sulphate, black carbon and particulate organic matter. Soil dust was not included.

<sup>c</sup> Calculated from linear approximations of a subset of models participating in the HTAP multi-model experiments.

<sup>d</sup> Based on Representative Concentration Pathway 8.5, a high emissions scenario.

<sup>e</sup> Based on Representative Concentration Pathway 2.6, a low emissions scenario.

<sup>f</sup> Estimated based on the sum of sulphate and particulate organic matter.