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Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe

Working Group on Effects

Seventh joint session
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Item 2 of the provisional agenda
Progress in activities of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe in 2021 and future work
Item 7 of the provisional agenda
Joint thematic session: contribution of scientific bodies to the review of sufficiency and effectiveness of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone
Item 10 of the provisional agenda
Progress in activities in 2021 and further development of effects-oriented activities

2021 Joint progress report on contribution to the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*

Note prepared by the Chairs of the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe and the Working Group on Effects, in cooperation with the secretariat

Summary

The present report was drafted by the Extended Bureau of the Working Group on Effects[a] and the Extended Bureau of the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe[b] in cooperation with the secretariat to the Convention on Long-range Transboundary Air Pollution. The review of recent scientific findings is based on the information provided by the lead countries and the programme centres of the international cooperative programmes, in accordance with the questions listed in the document ECE/EB.AIR/2020/3–

* The present document is being issued without formal editing.

ECE/EB.AIR/WG.5/2020/3 for the preparation of the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol).

[a] Comprising the Bureau of the Working Group; the Chairs of the International Cooperative Programme (ICP) task forces, the Joint Task Force on the Health Effects of Air Pollution; and representatives of the ICP programme centres.

[b] Comprising the Bureau of the Steering Body, the Chairs of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) task forces and representatives of EMEP centres.

I. Introduction

1. The present report was compiled by the Chairs of the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) and the Working Group on Effects, in view of the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol), as amended, launched by the Executive Body at its thirty-ninth session (Executive Body decision 2019/4, Geneva, 9-13 December 2019). The report summarizes the best available information on the observed and projected trends concerning the effects[1] of acidification, eutrophication and ozone pollution, including progress made on emissions, atmospheric transport and integrated assessment modelling. The report is the seventh common report on the work under the EMEP Steering Body and the Working Group on Effects, reflecting the new organization of the two bodies with joint, integrated sessions based on a common agenda. These joint reports represent a further integration of the scientific work under the Convention on Long-range Transboundary Air Pollution (Convention) and should be seen as strengthening the scientific basis for the Convention's policy development.

II. Air pollution effects on health

2. Recent analysis of ozone has showed that reductions in emissions have reduced the peak ozone concentrations, but ozone concentrations have not really decreased in all the countries and rural areas show higher levels than urban areas. In the third quarter of 2021, new World Health Organization (WHO) Air Quality Guidelines (AQGs) are expected to be published, including also new guideline values for ozone (O3). Information about the past and current population exposure to ozone is available from the European Environment Agency (EEA) summarized e.g. in the Air quality in Europe - 2020 report.2 This information is available primarily for the European Union-28, for population in areas exposed to O3 concentrations in relation to the European Union target value threshold and in reference to the WHO AQGs. The estimates of the exposure of total European population (not only urban) in 2018 and changes over time are also available. To extract relevant information, interaction with the EEA will be needed.

3. For fine particulate matter (PM2.5), mortality (premature deaths) estimates are available based on the WHO global ambient air quality database; the most recent estimates are based on 2016 data and include DALYs estimation. New estimates will be generated later in 2021 year, as part of the Sustainable Development Goal (SDG) reporting (indicator on mortality due to air pollution). The estimates of premature mortality and years of life lost are available from the EEA reports. There has been a trend of reduced attributable deaths driven by air pollutants decrease, but there still peaks in some locations, for example for nitrogen dioxide in areas close to traffic. The demographic data and life expectancy data are from Eurostat and the mortality data from WHO; the exposure response relationship and the population at risk follow recommendations from the Health Risks of Air Pollution in Europe (HRAPIE) project. At the twenty-fourth meeting of the Joint Task Force on the Health Aspects of Air Pollution (Task Force on Health; online 10–11May 2021), participants discussed workplan for 2022–2023, including the work on methods for health risk/impact assessment of air pollution and cost benefit analysis, as a follow up to HRAPIE project.

4. With regard to other health metrics, such as morbidity, a new project has been initiated on the estimation of morbidity from air pollution and its economic costs. The project is to deliver a method to estimate costs of morbidity from air pollution (for locations with the available appropriate health statistics) and morbidity-related concentration-response functions. The results are expected in 2022. The Second Clean Air Outlook includes projected trends of morbidity, with data from the EMEP Centre for Integrated Assessment

[1] Extended information on the contributions from the Working Group on Effects to the review of the Gothenburg Protocol is provided in an informal document under agenda item 7.

[2] See www.eea.europa.eu/publications/air-quality-in-europe-2020-report.

Modelling. Follow up actions are needed to check feasibility of getting access to scenarios, in a coordinated effort by several task forces.

5. The main input related to the new scientific evidence will be the publication of the new WHO AQGs, which will contain a set of updated guideline values for PM, nitrogen dioxide, sulfur dioxide (SO2), ground-level ozone and carbon monoxide. Publication of the new WHO AQGs is expected in the third quarter of 2021. Another input would be a technical report on the health effects of polycyclic aromatic hydrocarbons (PAHs), including an overview of emissions and exposure to PAHs, and of both, carcinogenic and non-carcinogenic effects of airborne PAHs. Publication of the report on PAHs is expected in 2021. Areas of new scientific findings that will have impacts are related to the refinement of the work on the shape of the exposure response functions, the importance also of low levels of exposure for health impacts, the issue of the effects not just related to a single pollutant but to multiple pollutants. The work on source apportionment would provide new information to improve burden of disease calculation. Additionally, work on the economic effects of air pollution will benefit from the debate and analysis that are being published by experts.

III. Air pollution effects on materials

6. When looking at observed trends, corrosion and pollution have decreased significantly since the early 1990s and a shift in the magnitude was generally observed around 1997 from a sharp decrease to a more modest decrease or to a constant level without any decrease. SO2 levels, carbon steel and copper corrosion have decreased even after 1997, which is more pronounced in urban areas, while corrosion of the other materials shows no decrease after 1997, when looking at one-year values. When looking at four-year values, however, there is a significant decrease after 1997 for zinc, which is not evident when looking at the one-year values. There are still occurrences of corrosion values above acceptable levels at some places in Europe.

7. For soiling, there is no decreasing trend after 1997 and consequently larger areas in Europe are above acceptable levels, therefore the focus of future development of the programme is on exposure of new soiling materials, for example coil coated materials and stone materials. The main pollutant responsible for soiling of materials is particulate matter.

8. For projected trends, it should be possible to make analyses based on existing dose-response functions using pollution and climate data for different scenarios. However, this information is not available at the present but, and in anticipation of this data, the International Cooperative Programme on Effects of Air Pollution on Materials, including Historic and Cultural Monuments (ICP Materials) has data from a case study which was performed on five historic and cultural monuments in Italy to evaluate the effects on materials deriving from the reduction of emissions required by the European Union new National Emission Ceiling Directive (NECD) using the air quality projections obtained with the Italian national model AMS-MINNI for the scenario years 2020 and 2030 and existing dose-response functions. Two different emission scenarios were considered: a scenario including all the measures planned by the current national legislation (with measures, WM) and a scenario with additional measures (WAM) to achieve the 2030 objectives. The expected reduction of the concentrations of atmospheric pollutants in Italy by 2030 could lead to a decrease in the limestone surface recession and an improvement regarding the soiling of non-transparent (limestone) and transparent (glass) surfaces, with lengthening of the times between two cleaning operations. Overall, no significant improvement can be expected in the corrosion rate of copper.

IV. Air pollution effects on terrestrial ecosystems

A. Forests

9. Although deposition rates of inorganic nitrogen in throughfall are currently high at many the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) sites, measurements show a clear decrease at most

sites between 2000 and 2015. Significant decreases were observed particularly at the highly polluted sites. The third of sites with the highest initial (2000-2004) rate of throughfall deposition show a median reduction of 24 per cent between 2000 and 2015, whereas the third of sites with the lowest initial rate of throughfall deposition show a corresponding reduction of 16 per cent. Another interesting feature is that on many sites, throughfall deposition of nitrate decreased faster than for ammonium: Nitrate deposition decreased by 26 per cent and ammonium by 18 per cent between 2000 and 2015. The ICP Forests long-term measurements show that there is a long-time lag between emission abatement and changes in soil solution acidity. Moreover, eutrophying or acidifying effects of inorganic nitrogen and sulfur deposition led to imbalances in tree nutrition across Europe as briefly discussed in the following. In many parts of Europe positive tree growth was observed during the last decades. Among other factors, the increased nitrogen deposition contributed to the observed tree growth stimulation. An increased tree growth will result in an increased demand for phosphorus and base cations. On highly nitrogen polluted sites the tree growth is reduced. Moreover, there is evidence that high nitrogen deposition loads affect composition of ground vegetation in forests as well as ectomycorrhizal communities that play a crucial role in providing phosphorus and other elements to trees; high nitrogen load lead to acidification, i.e. depletion of base cations.

10. The analysis of foliar data collected at ICP Forests sites confirmed that due to the enhanced nitrogen deposition, there is a shift from nitrogen limitation to phosphorus limitation in many forests. Furthermore, it is supposed that nutrient imbalances can affect the resilience of the European forests to a changing climate and their carbon sequestration capacity.

B. Forested catchments

11. The International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP Integrated Monitoring) catchments have increasingly responded to the decreases in the emission and deposition of nitrogen (N) in Europe. Concentrations of total inorganic nitrogen (TIN) in runoff water for years 1990-2017 exhibited dominantly downward trend slopes (76 per cent of sites, mean slope -0.48 micro equivalents per liter per year (μeq L−1 yr−1), and for fluxes 69 per cent of the sites (mean slope -0.21 meq m−2 yr−1), respectively. Decrease of nitrate and ammonium (NO3 and NH4) in concentrations was significant at 59 per cent (-0.36 μeq L−1 yr−1) and 36 per cent (-0.05 μeq L−1 yr−1) of the sites, and but the decrease in fluxes was significant only at 25 per cent (-0.18 meq m−2 yr−1) and 31 per cent (-0.04 meq m−2 yr−1) of the sites, respectively. Decreasing trends for sulfur and N emissions and deposition reduction responses in runoff water chemistry tended to be more gradual since the early 2000s. A significant negative correlation was found between the annual change of TIN concentrations and fluxes in runoff, and mean TIN fluxes in throughfall, total N concentrations and N/phosphorous-ratios in foliage and litterfall, and total N concentrations and fluxes in soil water. The results also showed that the most N-affected sites with the highest N deposition to the forest floor and highest N concentrations in foliage, litterfall, runoff water and soil water, showed the most pronounced decreases of TIN in runoff.

12. Twenty-three European forest sites belonging to the ICP Integrated Monitoring, ICP Forests and the European Long-Term Ecosystem (eLTER) networks with high quality long-term data on deposition, climate, soil chemistry, and understory vegetation were used to assess benefits of currently legislated N deposition reductions on forest understory vegetation. A dynamic soil model coupled to a statistical plant species niche model was applied with site-based climate and deposition. Indicators of N deposition and climate warming effects such as the change in the occurrence of oligophilic (favoring nutrient-poor conditions), acidophilic (favoring acidic conditions), and cold-tolerant plant species were used to compare the present with projections for 2030 and 2050. The decrease in N deposition under current legislation emission (CLE) reduction targets until 2030 was not expected to result in a release from eutrophication. Albeit the model predictions showed considerable uncertainty when compared with observations, they indicated that oligophilic forest understory plant species will further decrease. This result is partially due to confounding

processes related to climate effects and to major decreases in sulphur deposition and consequent recovery from soil acidification but shows that decreases in N deposition under CLE will most likely be insufficient to allow recovery from eutrophication. The results also showed that oxidized and reduced N emission reductions need to be considerably greater to allow recovery from chronically high N deposition.

13. ICP Integrated Monitoring studies have shown that a systems approach is useful in addressing the question of future integrated impacts of climate and air pollution on ecosystem processes and biodiversity responses. A chain of models was applied to a combined dataset from 26 ICP Integrated Monitoring, ICP Forests and eLTER forested sites throughout Europe. Key soil properties such as soil solution pH, soil base saturation (BS) and soil organic carbon and nitrogen ratio (C:N) under projected N and sulfur deposition and climate change until 2100 were simulated. Simulated future soil conditions improved under projected decrease in deposition and current climate conditions: higher pH, BS and C:N at 21, 16 and 12 of the 26 simulated sites, respectively. When climate change projections were included, soil pH increased in most cases, while BS and C:N increased in about half of the cases. Hardly any climate warming scenarios led to a decrease in pH. Modelling results also indicated that decreases in N deposition under the CLE current legislation scenario will most likely be insufficient to allow recovery of forest understory vegetation from eutrophication. Oxidized and reduced N emission reductions would need to be considerably greater to allow recovery from chronically high N deposition. These studies illustrate the value of long-term integrated monitoring sites for applying models that can predict soil, vegetation and species responses to multiple environmental changes.

V. Air pollution effects on aquatic ecosystems

14. Trends in water chemistry. Major indices of acidification such as acid neutralizing capacity (ANC), pH and toxic aluminium indicate waters demonstrate a process of recovery, based on the International Cooperative Programme on Assessment and Monitoring of the Effects of Air Pollution on Rivers and Lakes (ICP Waters) dataset that includes records since 1990, from circa 500 lakes and rivers in Europe and North America. The observed trends are a response to reduced deposition of acidifying substances, but changes in climate as well as land use are becoming more important as drivers of change. Major perturbances such as wildfires and insect outbreaks are often climate-related and can result in re-acidification of surface waters.

15. Effects of COVID-19 pandemics detected in ICP Waters sites. Long-term data sets of environmental monitoring of alpine and subalpine sites in Italy and Switzerland revealed a distinct reduction in deposition of sulfur and oxidized N in 2020 that deviated from the long-term trend. These deviations result most likely from lower emission of N oxides to the atmosphere because of reduced vehicle traffic during the coronavirus disease COVID-19 pandemic. Some improvements in water chemistry were also noted, especially for nitrate, which suggests that alpine, acid-sensitive sites are extremely well-suited for monitoring freshwater responses to rapid changes in atmospheric chemistry.

16. Biological responses to less acidic waters. Monitoring data from the United Kingdom of Great Britain and Northern Ireland demonstrate biological changes consistent with a response to chemical recovery in several, but not all, recovering acidified waters, while data from high alpine lakes in Italy do not show clear trends. In the United Kingdom, the extent of biological change does not show clear relationship with threshold levels of ANC commonly used to define “critical limits”. Factors that drive the rate of biological recovery are not well understood and it is not always clear which organisms are most acid sensitive. The environments of ICP Waters sites are not only recovering from acidification but are more enriched with reactive nitrogen and becoming warmer as a consequence of climate change. The post-acidification biological community assemblies may be very different from the pre-acidification state.

17. Nitrogen. The deposition of nitrogen has declined less than sulphur and major questions remain concerning the chemical and biological effects thereof. Climate and catchment properties are important determinants of nitrogen leaching, linking air pollution

and effects of reactive nitrogen in surface waters. Although nitrogen is an essential nutrient, phosphorus is often the dominant control of freshwater productivity. However, there is increasing evidence that N derived from N deposition can influence freshwater productivity in nutrient-poor lakes. Leaching of nitrogen deposited from air to surface waters, and downstream to marine ecosystems, can also contribute to marine eutrophication because nitrogen is the limiting nutrient in marine waters. Source attribution of nitrogen in water bodies (i.e., to deposition, agriculture or other source) is important for effect-evaluation of policy to reduce emissions of nitrogen to the environment. Preliminary results in the N report indicate that useful input is being generated, to support the empirical critical load guidance currently being developed under the Working Group on Effects.

18. Monitoring networks of surface waters under various policy instruments (Convention on Long-range Transboundary Air Pollution, NECD, European Union Water Framework Directive (WFD)) benefit each other mutually. In many European countries, surface water monitoring networks deliver data to support several policy instruments, such as the Convention, NECD and WFD. In some countries, the NECD monitoring network is more extensive than the national monitoring network delivering data to ICP Waters, while in other countries, the networks are largely identical. Under the WFD, the suggested minimum lake size is 0.5 km2, which is larger than that of many headwater lakes reported to ICP Waters. Small headwater lakes and streams that are not confounded by local pressures, such as agriculture or point source pollution, are pivotal for the assessment of regional scale pressures (air pollution, climate change) such as under the Convention and NECD.

19. Differences between national classification systems for surface water acidification may limit robust national comparisons of ecological status under the WFD. The physico-chemical definition of the important threshold between good and moderate (i.e. acceptable/non-acceptable) state of water body acidification differs between Norway, Sweden and Finland. A Nordic dataset on chemistry and biology has been used to propose an ANC-based system that can be used to harmonize classification systems.

VI. Critical loads and levels

A. Critical loads

20. The International Cooperative Programme on Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends (ICP Modelling and Mapping) in close collaboration with the Coordination Center for Effects (CCE) and the Centre for Dynamic Modelling (CDM) will perform exceedance calculation for critical loads for acidification and eutrophication in the perspective of the Gothenburg Protocol review process. Updated Critical Loads will be available by mid-summer. Updates may comprise updated national submissions and critical loads calculated with the newly updated background database of CCE. The calculation of exceedances will be based on deposition data provided by the Meteorological Synthesizing Centre-West (MSC-West) and the Centre on Emission Inventories and Projections. This work still needs to be coordinated for data timing specification and availability until September 2021. Its purpose is the comparison of exceedance calculation between years 2000 and 2019.

21. CCE is also leading the review and revision of empirical critical loads for nitrogen. To this aim, the literature review was completed in 2019 and the updating process was carried out from June 2020 until June 2021 through a review work led by 45 authors which are experts in the field. The announced schedule aims at completing the first internal revision in June 2021 and a second review by external experts will be completed by September 2021. The background document will be finalized in 2022 and a draft executive summary will be prepared for formal use in the ECE by April 2022.

22. CDM is leading the work on development of indicators of biodiversity change and methods to set critical loads for nitrogen as a nutrient based on biodiversity. Under its 2020-2021 workplan, CDM is progressing towards a report on dynamic modelling of the air pollution effects on ecosystems carried out under the Working Group on Effects with respect to biogeochemistry and biodiversity.

23. ICP Integrated Monitoring has calculated site-specific exceedances of critical loads (Cls) for acidification and eutrophication and evaluated the link between time-series of CL exceedances and measured site data, using long-term measurements (1990–2017) for bulk deposition, throughfall and runoff water chemistry.[3] The temporal developments of the exceedance of the CLs indicated the more effective reductions of S deposition compared to N at the sites (n = 17). There was a relation between calculated exceedance of the CLs and measured runoff water concentrations and fluxes, and most sites with earlier higher CL exceedances showed larger decreases in both total inorganic nitrogen (TIN) and H+ concentrations and fluxes. Sites with higher cumulative exceedance of eutrophication CLs (averaged over 3 and 30 years) generally showed higher TIN concentrations in runoff. The results confirm that emission abatement actions are having their intended effects on CL exceedances and ecosystem impacts. The results also provided evidence on the link between CL exceedances and empirical impacts, increasing confidence in the methodology used for the European-scale CL calculations.

24. The target load concept is an extension of the critical load concept of air pollution inputs to ecosystems (Posch et al. 2019). The advantage of target loads over critical loads is that one can define the deposition and the point in time (target year) when the critical (chemical) limit is no longer violated. This information on the timing of recovery requires dynamic modeling. Target loads on a large regional scale can inform effects-based emission reduction policies. The assessment of Posch et al.[4] suggested that reductions beyond the Gothenburg Protocol are required to ensure surface water recovery from acidification by 2050.

B. Critical levels. Effects of ozone on vegetation

25. The International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) reviewed the impacts of ambient ozone on crops and ecosystems and provided highlights described below.

26. The ozone profile has changed since 1990. The ‘peak’ concentrations have reduced, whereas the ‘background’ concentrations have increased. Concentration-based metrics using relatively high thresholds, such as Accumulated Ozone Exposure over a threshold of 40 parts per billion (AOT40), put greatest emphasis on peak concentrations. Scientific evidence has shown that vegetation responds to cumulative ozone uptake, reflected in the flux-based phytotoxic ozone dose (POD) metrics, and that the response is the same when this is delivered as an ‘elevated background’ or ‘episodic peak’ profile. This means that ozone impacts on vegetation can also be found where the critical level for AOT40 is not exceeded.

27. Analysis of modelled data showed only a small change in wheat yield loss for both 1990-2010 and 2010-2030. Modelling impacts of ozone on wheat yield in collaboration with the European Topic Centre on Air Pollution and Climate Change Mitigation of EEA showed that for Europe, based on the modelled AOT40, calculated wheat yield losses declined significantly from 18.2 per cent to 10.2 per cent between 1990 and 2010, whereas according to the flux-based metric (POD6SPEC) losses did not change significantly, i.e. losses were 14.9 per cent and 13.3 per cent in 1990 and 2010, respectively. The percentage yield loss (based on the flux metric POD3IAM) was similar in Europe and North America (approximately 6.6 per cent and 5.5 per cent in 2010 and 2030 respectively), however, the production loss was higher in Europe due to a double total production of wheat in Europe. Note that the percentage yield losses are different in the 1990-2010 compared to the 2010-2030 assessments due to different flux-metrics used.

28. Individual species vary in their sensitivity to ozone. For crops and trees, the most accurate assessments of predicting impacts should use the species-specific models

[3] See Forsius, M., et al. 2021. Assessing critical load exceedances and ecosystem impacts of anthropogenic nitrogen and sulphur deposition at unmanaged forested catchments in Europe. Science of The Total Environment 753: 141791. https://doi.org/10.1016/j.scitotenv.2020.141791.

[4] See Posch, M. et al. 2019. Dynamic modeling and target loads of sulfur and nitrogen for surface waters in Finland, Norway, Sweden, and the United Kingdom. Environmental Science & Technology 53(9): 5062-5070. https://doi.org/10.1021/acs.est.8b06356.

(POD6SPEC). Crops known to be sensitive to ozone include wheat (which has a species-specific model) and bean (which does not). For semi-natural vegetation the difference in sensitivity to ozone between species means that there could be changes in relative species abundance due to altered competition, and possible impacts on biodiversity.

29. Accurate modelling of ozone impacts to vegetation requires parameterisation of the dose-response relationship for each individual species. This is currently limited by the availability of experimental data to parameterise both the stomatal uptake component and the yield-response component. There are many species (both crop, tree and semi-natural vegetation) for which such information does not currently exist, even for some of the common and commercially important species.

30. Impacts on ecosystems and ecosystem function occur with ozone pollution. Scientific knowledge of cumulative fluxes of ozone (including from low ozone concentrations) shows impacts on crops, trees and ecosystems that include growth and flowering (number and timing).

31. Current risk assessments for impacts of ozone on ecosystems are focused on the vegetation component. Qualitative assessments and information indicate that a much wider breadth of impacts occur in response to ozone pollution, including impacts on soil biota, and both directly and indirectly on other trophic levels including pollinating insects. Effects on ecosystem functioning such as C sequestration in soils, water and nutrient cycling in ecosystems or resource use efficiency are also relevant for risk assessments of ozone impacts.

32. There are interactions between ozone pollution and climate change. Some interactions alter the exposure of vegetation to ozone, such as accelerated phenological development with increasing temperature resulting in bud-break earlier in the year and consequent exposure of the plant to ozone earlier in spring than current models predict. Changes in meteorological conditions and soil moisture due to climate change alter ozone fluxes to vegetation via influence on stomatal opening, however, the direction and extent of change will depend on the difference between perceived conditions and optimum conditions for each meteorological and soil moisture parameter.

33. A comprehensive meta-analysis of available data showed that there was no significant relationship between ozone sensitivity and nitrogen application rate for wheat, indicating that there is no requirement to adjust critical levels for ozone for crops according to nitrogen load. Ozone pollution can reduce the nitrogen use efficiency of some crops e.g. wheat, soybean and rice. As a result of lower nitrogen fertilization efficiency, ozone causes a risk of increased losses of nitrogen from agroecosystems, e.g. through nitrate leaching and nitrous oxide emissions. Tropospheric ozone thus has the potential to cause elevated nitrogen in streams and rivers compared to clean air conditions, but the potential magnitude of this has not been quantified. A similar pattern can be seen for semi-natural vegetation, as the stimulating effect of nitrogen on growth can be progressively lost with increasing ozone concentrations, sometimes with increasing soil nitrous oxide emissions.

34. Large-scale studies conducted at the ICP Forests plots revealed that, despite a slight but significant reduction of ozone levels during the vegetative period, the concentration-based Critical Levels (AOT40) have been exceeded on the majority of the investigated sites, especially in East and Southern Europe. On these sites, foliar injury attributable to ozone has been detected on several species, mostly broadleaves. The level of sensitivity to ozone injury in also depends on species and region (for example in Greece Sorbus torminalis appear to be more sensitive than Fagus Sylvatica). No consistent ozone effect has been detected on growth and defoliation at the ICP Forests sites, regardless the ozone metric adopted. The occurrence and severity of visible ozone symptoms depends not only on ozone levels but also on several other environmental parameters and vegetation characteristics that drive the stomatal uptake. We do expect that interaction with climate change and biotic agents (pests and disease) may substantially alter the above results: this will be however dependent on site-specific condition.

VII. Emissions

A. Quality of the emission inventories

35. For most inventories reported by the Parties, methodologies applied are generally in line with the EMEP/European Environment Agency air pollutant emission inventory guidebook (Guidebook) and reporting is in most cases in line with the Guidelines for Reporting Emissions and Projections Data under the Convention on Long-range Transboundary Air Pollution (ECE/EB.AIR/125). Regarding the key quality assurance principles, several conclusions can be drawn as described below.

36. Completeness: In 2020, 48 Parties submitted emissions inventories under the Convention. The coverage of reporting Parties increased over the last years to 94 per cent. For 17 Parties the completeness was not satisfactory in the submission 2020, either because they did not submit any data or they did not provide data for all priority pollutants or they did not provide a full time series or they did not provide activity data.[5]

37. Consistency: Time-series consistency is an issue that is still frequently found in annual in-depth reviews. Usually the early years of the time-series are concerned, and recalculations are often not applied consistently over the years.

38. Accuracy: Accuracy is an issue that is frequently found in the depth reviews. Generally, the accuracy is better for main pollutants and PM2.5 than for heavy metals and persistent organic pollutants (POPs). A frequent issue related to accuracy is the use of tier 1 methods for a key category.

39. Transparency: The key element to ensure good transparency of the inventories is a good Informative Inventory Report (IIR). Eleven Parties did not provide IIRs in the year 2020 and three Parties provided an IIR but did not follow the recommended structure. For these Parties the transparency was not given. However, also for Parties with comprehensive IIRs the in-depth review usually finds issues related to transparency.

40. Black carbon (BC) and condensables in PM remain challenges for emission reporting – policy decisions are needed regarding metrics/reporting requirements. Emissions of heavy metals (HM) and POPs have not been reviewed or updated for many years. This is because they are not considered priorities compared to e.g. nitrogen oxides (NOx) and PM2.5 where higher-profile emission reduction commitments are established but should be kept as sensitive issues. Moreover, co-benefits in the design of emission reduction strategies could be found when focus in on HMs and POPs.

41. Black carbon (BC) emissions are reported on a voluntary basis. The number of countries which provide emission estimates for black carbon has increased since reporting of BC was enabled in 2015. In 2021, 40 countries reported BC emissions for at least one year in their inventory time series. Given that BC is a voluntary pollutant, the extent of reporting appears encouraging. Nonetheless, we have not yet reach complete reporting across all Parties and according to independent BC emissions estimates (e.g. Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model and Emissions Database for Global Atmospheric Research (EDGAR)), some of the non-reporting Parties constitute significant emitters of BC. Furthermore, there are indications that the quality of reported BC emissions data needs to be improved. The "EUA BCA Technical report: Review of Reporting Systems for National Black Carbon Emissions Inventories"[6] review BC inventories reported under the Convention until 2018, and noted significant issues in terms of transparency, accuracy, completeness, consistency and comparability. Although some Parties' BC emissions have been reviewed as part of the stage 3 reviews coordinated by the Centre on Emission Inventories and Projections, there has been no subsequent wide-spread review since then.

42. This year may reveal more about the current quality of reported BC emissions under the Convention. The 2021 review of NCED will for the first time focus in part of BC

[5] See Technical Report CEIP 4/2020.

[6] See www.amap.no/documents/doc/eua-bca-technical-report-2/1780.

emissions of the European Union member States (all of which are Parties to the Convention) and it will also be interesting to note the extent and quality of reporting of gridded emissions of BC, given that 2021 marks the deadline for the next round of four-year reporting of gridded emissions.

43. All emissions inventories bear uncertainties. Given that emissions inventories form an important basis for air pollution abatement, it is important that these uncertainties are estimated. Uncertainty information should be part of every emission inventory. However, less than half of the Parties to the Convention reported uncertainty estimates in their inventory submission in 2021. Usually Parties report the uncertainty for total emissions and emission trends. The availability of uncertainty estimates has increased in recent years although progress has been rather slow.

44. The table below provides some figures to illustrate the uncertainty issue based on from the 2021 submission (they will be updated with resubmissions later in the year). It shows substantial range in uncertainties reported by Parties for most pollutants. It is likely that part of this wide range is due to real differences in the uncertainties of inventories and that also part of the range is due to under-or overestimation of the real uncertainties. It is also observed that in some cases the recalculations observed in the past years are higher than the indicated values of the uncertainty would suggest.

45. It can be concluded that uncertainty estimation is still a topic that receives too little attention in the Informative Inventory Reports of many Parties and that it is currently not possible to estimate the uncertainty of pollutant emissions in the whole EMEP area with the information provided by Parties.

Pollutant	*Uncertainty range reported by Parties for National Total (per cent)*	*Number of Parties providing an uncertainty estimate for National Total*	*Uncertainty range reported by Parties for the emission trend (per cent)*	*Number of Parties providing an uncertainty estimate for the emission trend*
NO_x	8.5 to 59	19	1 to 31	19
NMVOC	15 to 112	19	1.8 to 32.2	19
SO_x	5 to 47	19	0.2 to 103	19
NH_3	9.5 to 143	19	3.1 to 364.8	19
$PM_{2.5}$	9.96 to 96.6	17	3 to 140	18
BC	27.1 to 302	7	3.1 to 67	7

Note: NMVOC – non-methane volatile organic compounds; NH_3 - ammonia

B. Priorities for improving the EMEP/EEA Guidebook

46. The Guidebook is considered to be broadly comprehensive in its scope and content. Simpler (‘Tier 1’) and more detailed (‘Tier 2’) methods are provided for all source categories and pollutants for which emission inventory reporting is currently requested from Parties. However, there are a significant number of improvements which could be made to both the management and the content to benefit all of the emissions inventory and modelling communities. In addition, continued emphasis within the Convention to encourage/require Parties to shift from the simpler methods (which are still often inappropriately being used for important key sources) to the generally-more accurate Tier 2 methods is also an important way in which to improve emission inventory quality.

47. There are some selected activities within existing source categories for which there are no methodologies (e.g. burning of garden and domestic waste). But these are generally smaller sources.

48. Improving the quality of the GB content is hampered by the funding mechanism. EMEP provides no resources, and the Task Force on Emission Inventories and Projections

relies entirely on in-kind contributions from Parties. Past updates of the Guidebook have been supported by a small number of Parties for specific chapters, and with funding from the European Union (i.e. European Environment Agency, European Commission). This causes some significant issues:

(a) There are substantial constraints on the amount of time that can be spent on the Guidebook improvements, which does not allow effective planning ahead;

(b) When in-kind contributions are provided by the Parties, it is not necessarily possible to use it for items that are considered priorities. Priorities could be given by the Parties which provide the budget.

49. One of the most significant challenges is that there are not strong enough links between the emission inventory experts managing the content of the Guidebook, and research groups undertaking new emission measurements. Significant improvements could be made to the Guidebook if domestic emissions measurement research being conducted by national authorities in countries also ensured a link between their project and the Task Force on Emission Inventories and Projections/Guidebook.

50. The most important improvements are improving the accuracy of existing methodologies by improving the accuracy/representativeness of default emission factors (EFs). This is not straightforward and typically requires new measurement data. Use of “regional” EFs to improve the accuracy of default EFs for sources where we know that there is substantial variation across regions (particularly the case for member States of the European Union vs. other locations) should be explored in the future.

51. There remains a number of emission factors in the guidebook that are based on literature that sometimes dates to e.g. the 1990s. Such emission factors may no longer be representative of current emission rates. Such instances are typically in source categories that provide only a small contribution to the overall national inventories and so are not prioritised for updating when the limited budget for updates does become available.

52. Emissions methodologies in the Guidebook need to better account for climate change i.e. to better take into account the relationships between changing climatic conditions and emission factors. This is starting to be investigated for the agriculture sector, but ambient temperatures and behaviour changes will need to be taken into account when updating the information the Guidebook, and particularly for supporting projection calculations.

53. There are some sources which may be better estimated centrally rather than by each Party – for example shipping and aviation. This would ensure consistency across the full geographical extent and would ensure high quality emission estimates were available for sources which can be challenging for individual Parties to estimate.

54. There are increasingly new types of data becoming available which have the potential to support emission estimates e.g. satellite-based measurements, near real-time activity data, and Artificial Intelligence projections. Many of these data types are most likely to be used in verification studies rather than directly in emissions inventory calculations.

VIII. Monitoring and modelling

A. Observed and modelled trends analysis

55. Ozone is a secondary pollutant, and observed trends reflect meteorological variability to a much greater extent than trends in precursor compounds. Trends are also affected by titration effects, in which decreasing NOx emissions can increase ozone, especially in wintertime. Trends in summertime O3, and metrics of higher ozone (daily maximum 8-hour ozone (MDA8) and annual sum of ozone means over 35 parts per billion (ppb; SOMO35)), are stronger and clearer than those in annual data, though site to site variability is large. Using stringent data-capture criteria, median trends in daily maximum ozone during June-August were -0.6 ppb/year(y) at EMEP sites (EMEP model -0.4 ppb/y). Over the 2000-2018 period, annual mean ozone increased as much as 11 per cent, whereas a slight decrease (3 per cent)

is observed in rural areas.[7] Observed trends showed much more variability than modelled trends, and observed trends being more affected by the high ozone summers of 2003 and 2006 in some regions. Ozone peaks decline systematically (by 11 per cent to 6 per cent at rural and urban sites, respectively), but this range of decline can be considered limited with regards to the -47 per cent and -54 per cent changes for non-methane volatile organic compounds and NOx emissions, respectively, over the same time period.

56. Annual average concentrations of sulphur dioxide and particulate sulphate, and wet deposition of oxidized sulphur, has been declining since the 1980s. At EMEP background sites, the changes from 2000-2018 is on average -4 per cent/y, -2.9 per cent/y and -3.3 per cent/y for sulphur dioxide, particulate sulphate and wet deposition of oxidized sulphur, respectively (EMEP model results: -5.3 per cent/y, -4.0 per cent, -4.5 per cent/y). Overall, the trends of sulphur and nitrogen compounds in air and precipitation follow the emission trends within Europe and the influence of transcontinental transport is negligible.

57. From around 1990 onwards, the total emissions of NOx declined significantly in Europe, followed by declining nitrogen dioxide concentrations and total nitrate (nitric acid plus particulate nitrate) in air and reduced oxidized nitrogen deposition at EMEP background sites. From 2000-2018, the average reductions at long term EMEP background sites have been -1.5 per cent/y, -1.9 per cent/y and -1.7 per cent/y for nitrogen dioxide concentrations, particulate nitrate and wet deposition of oxidized nitrogen, respectively (EMEP model results: -2.3 per cent/y, -2.3 per cent, -2.4 per cent/y).

58. Only modest reductions of ammonia emissions have been achieved since 2000 compared to other pollutants. As a result, ammonium in precipitation has declined marginally (median of -0.08 per cent/y from 2000-2018 at long term EMEP sites). However, the formation of particulate ammonium in air depends not only on the availability of ammonia, but also on the availability of nitric acid (formed from NOx) and sulphate (formed from SOx). With large reductions in SOx and NOx emissions during the last decades, ammonia is to a large extent in excess and the availability of nitric acid and sulphate limit the formation of ammonium, resulting in a decline of ammonium in air of on average -2.8 per cent/y at long term EMEP sites. Total reduced nitrogen in air (ammonia + particulate ammonium) is reduced less (-1 per cent/y from 2000-2018), as a larger fraction of total reduced nitrogen being ammonia (but with a shorter lifetime than ammonium aerosol). The majority of sites for ammonia in air show no significant trends.

59. Since 2000, there has been significant reductions in PM10 and PM2.5 (on average -1.7 and -2.3 per cent/y at EMEP long term observational sites, and slightly more in EMEP model calculations (-2.0 and -2.6 per cent/y). The secondary inorganic aerosols (SIA, particulate sulphate, nitrate and ammonium) has decreased significantly since 2000, with sulphate showing the largest decrease (SO4: -2.9 (-4.0) per cent/y, NO3:-1.9 (-2.3) per cent/y, NH4: -2.8 (-2.9) per cent/y, EMEP model in parenthesis). For the natural components (sea salt and dust), less long-term observational sites exist, and only few of them show significant trends. For carbonaceous aerosol there are very few sites with long term, consistent measurements. One study shows a 4 per cent/y decrease in elemental carbon since 2001, indicating a reduction from anthropogenic sources, whereas trends in organic carbon is (more) influenced by natural sources, and thus more difficult to assess.

60. At EMEP regional sites, exceedances of the WHO AQGs for PM10 and PM2.5 are in the later years seen at around ⅓ and ½ of the observational sites respectively. EMEP MSC-West model simulations show a decrease in the area with (rural and urban background) daily PM10 and PM2.5 exceedances of WHO AQGs from 2000 to 2018.

[7] These trend estimates are updated for the period 2000-2018 using the methodology published in report focusing on the 2000-2017 period, which will be further updated in the summer 2021 for the 20 years between 2000 and 2019: www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-16-2019-air-quality-trends-in-europe-2000-2017-assessment-for-surface-so2-no2-ozone-pm10-and-pm2-5-1.

B. Improving monitoring and modelling

61. Additional measurements of nitrogen deposition in sea areas (islands or on ships) would be beneficial for better monitoring of eutrophication trends in marine ecosystems and to evaluate/constrain model

62. There are hardly any (long-term) EMEP observations in the Eastern Europe, the Caucasus and Central Asia and Western Balkan areas. Combined with the lack of consistent, high quality (and long term) emissions for countries in the eastern part of the EMEP domain, it is very difficult to assess and project air pollution and its effects in these areas.

63. Condensable organics have been highlighted as one such problem and so-called intermediate volatility organics may also emerge as an important issue. Further discussion is needed between the EMEP Task Forces, Parties, and in conjunction with the Guidebook.

64. There are also issues with the consistent inclusion or exclusion of some other emission components, e.g. emissions from agricultural soil-nitrogen oxide, waste-burning, or volatile organic compound emissions.

65. The improved resolution in the EMEP model results (and in the emissions) has in general improved the comparison to observations, especially for the primary components. While model results in the old resolution (50km x 50km) were representative for the regional background, the model results in the new resolution can represent urban background scale as well. As model results now better represent smaller scale areas with higher concentrations (typically sub-urban areas), it will by definition have a tail of higher concentrations that it did not have in lower resolution. Based on model calculations in 0.1° x 0.1° or 50km x50 km alone, the higher resolution results will result in somewhat higher exposure and larger distance to WHO target.

66. Exceedances of critical loads are slightly higher in the high-resolution model results (0.1° x 0.1° grid) than in the old 50km x 50km grid results for acidification. The overall exceedances of eutrophication critical loads are slightly smaller under the 0.1° x 0.1° depositions. A reason for this could be that the high-resolution deposition resolves the population centres much better. These areas generally have higher depositions but less (semi-)natural ecosystems. This may be an additional argument for the use of high-resolution depositions for exceedance calculations. Overall, the changes are small, e.g. 5.28 per cent vs. 5.25 per cent area exceeded for acidification and 62.5 per cent vs. 61.2 per cent for eutrophication for Europe for 2015 (Based on EMEP Status Report 1/2017).

67. The overall differences in source-receptor matrices due to different model resolutions for the country-to-itself contribution are small for depositions (a few percent), but somewhat larger for PM and ozone (up to 11 per cent). For the individual transboundary contributions, differences can be larger, especially when the pollution is transported across mountain areas and/or is very small. A new and more accurate country border data set was introduced at the same time as the increased resolution. Overall, the differences using a new country border data set were as large as the differences due to the different model resolutions. None of the two changes introduced consistent changes in one way (e.g. it did not consistently increase or decrease country-to-itself or country-to-country source-receptor matrices).

C. Influence of international shipping

68. Projections of future emissions from international shipping in Europe have been made by the International Institute for Applied Systems Analysis (IIASA) and the Finnish Meteorological Institute (FMI). According to the FMI projections, NOx emissions from shipping in Europe will continue to decrease, despite the growth in traffic volumes. IIASA projects NOx emission reductions by up to 40 per cent in 2030 and 79 per cent in 2050, with respect to 2015 emissions.

69. At the global scale, NOx emissions from international shipping are projected to remain approximately constant or decrease slightly in absolute terms over the 21st century, depending on assumptions about growth in international trade and the use of emission control technology. The share of global shipping NOx as a proportion of global anthropogenic NOx

emissions (currently at about 30 per cent) is projected to vary between 10 per cent and 60 per cent, by the end of the century depending on the effectiveness of land-based NOx emission control.

70. Based on a single model study roughly 10 per cent of the ozone in Europe of anthropogenic origin can be attributed to international shipping. Regulations of NOx emissions from shipping in emission control areas are likely to reduce ozone levels by 2030. Exceptions are regions with very high NOx levels, where reductions in NOx emissions can lead to increases in ozone during wintertime. However, as ozone levels are low during winter, this will not have a major effect on exceedances of AQGs.

71. According to IIASA, the designation of the Mediterranean as a NOx emission control area (NECA) would be efficient in reducing PM2.5, and related premature deaths, especially in the southern parts of the ECE region. Some studies conclude similarly for Northern Europe that the number of premature deaths due to shipping emissions can be significantly reduced by 2050 through a heavy fuel oil ban in addition to the sulphur emission control regulations.

72. Critical loads of nitrogen depositions are exceeded in much of Europe. In particular, in countries with long coastlines, a substantial portion of the nitrogen deposition is from shipping. Shipping emissions contribute to critical load exceedances in land areas but that this contribution will decrease due to emission regulations, in particular in emission control areas as already implemented in the North Sea and the Baltic Sea.

IX. Designing future impact of emission reduction strategies

73. According to the New Clean Air Outlook for European Union 27, with additional national plans (NAPCPs) NECD's national emission reduction obligations for 2030 will be met for NOx, SO2, VOC and primary PM2.5, with only few exceptions. Increased ambition of European Union's climate policies will also help achieving compliance. Meeting the emission reduction obligations for ammonia appears to be most challenging. Additional ammonia measures are required, which need - in some cases - to include non-technical measures. The ammonia assessment report[8] shows that there are options available at lower costs than the costs of inaction.

74. There are significant transboundary health and ecosystem benefits of coordinated European Union policy. With current policies in 2030, nearly 15 per cent of the population in the European Union-27 will be exposed to higher pollution levels than the (current) WHO air quality guidance value. Further health benefits can be reached with a combination of local, national and internationally coordinated policy measures. At the local scale, the international component of air pollution still proves to be significant.

75. The Centre for Integrated Assessment Modelling (CIAM) and MSC-West have developed a fine scale modelling methodology to assess air quality trends and health impacts in countries in Eastern Europe, the Caucasus and Central Asia and the Western Balkans, which clearly show the high concentrations and health risks in urbanized and industrialized regions and the benefits of reducing air pollution in such polluted regions, in combination with coordinated measures to reduce transboundary pollution. Implementation in the GAINS model will be completed in 2021, along with the extension of the GAINS model domain to include also all countries in Eastern Europe, the Caucasus and Central Asia.

76. The Task Force on Integrated Assessment Modelling and CIAM have identified measures to abate primary PM-emissions that are also effective to reduce black carbon emissions and thus could help to increase the synergies between reducing health risks and limiting radiative forcing. Limiting solid fuel burning in households, phasing out old vehicles and limiting agricultural waste burning are among the key measures that effectively reduce PM and BC.

[8] https://unece.org/fileadmin/DAM/env/documents/2020/AIR/WGSR/Final_Assessment_Report_on_Ammonia_v2_20201126_b.pdf.

77. For end-of-pipe measures, regulation via emission limit values is an effective policy instrument, but for promoting structural changes in production processes and behavioral changes, economic incentives would work better.

78. CIAM has analysed the potential synergies of climate policy measures and the reduction of air pollution. According to the Clean Air Outlook for European Union-27, additional climate measures would deliver almost halve of the health and ecosystem improvements in the period 2030-2050. Globally, with a combination of additional air pollution abatement measures, energy and climate measures and agricultural and food policy measures, the number of people exposed to higher levels than the WHO AQG-value can be reduced from 5.5 bn to 1 bn by 2040.

79. Methane proves to be the main driver behind increasing background ozone levels. CIAM has identified cost-effective measures to reduce methane emissions in world regions. In Europe, measures in the waste sector have the largest potential. In eastern Europe and central Asia, measures in oil and gas sector, and in the US measures in (unconventional) gas production can deliver most of the abatement potential. In all regions, emissions from agriculture (especially from cattle) tend to be a source with a low technical abatement potential. United Nations Environment's Global Methane Assessment estimates that reduced dairy and meat consumption could give a significant contribution to avoiding warming, ozone related deaths, morbidity as well as crop losses.

X. Hemispheric transport of air pollution

80. The hemispheric contribution to ground-level ozone is larger than the hemispheric contribution to PM or its components due to ozone's longer atmospheric lifetime. The concentration of ozone experienced at any given location is the combination of ozone and ozone precursors transported from distant sources on hemispheric to regional scales and, depending on the photochemical regime, local photochemical ozone production or local ozone loss due to titration with nitrogen oxide. The relative influence of background ozone increased, including ozone from hemispheric transport, on local concentrations of ozone experienced in urban areas of the ECE region, but especially in Europe.

81. The contribution of anthropogenic emission sources outside the ECE region to PM species and their associated impacts within the ECE region is negligible compared with the impact of local anthropogenic sources. Wildfires and wind-blown dust emanating from outside the ECE, however, do influence PM levels and deposition in the ECE region and are sensitive to changes in climate.

82. The absolute contribution of NOx and VOC emissions outside the ECE region to annual average ground-level ozone in Europe and North America is not expected to change significantly under a business as usual scenario to 2050. Expected increases in global methane are expected to more than offset projected reductions of NOx and VOC emissions in Europe and at least partially offset reductions of NOx and VOC emissions in North America.

83. If NOx and VOC emissions were reduced everywhere by the same percentage, the emission reductions outside of Europe would have a bigger impact on European ozone levels than the emission reductions within Europe. In North America, equal percentage emission reductions of NOX and VOC outside of North America would contribute significantly to decreases of ozone in North America, but not more than the equal percentage emission reductions in North America itself.

84. Projected trends in anthropogenic methane emissions span a very wide range, between a factor of two smaller or a factor of two larger than present-day emissions by the end of the century, depending on assumptions made about economic development and the use of emission control technology.

85. Ozone formation is strongly influenced by the atmospheric methane burden, with model studies consistently showing that higher mixing ratios of methane lead to higher background mixing ratios of ground-level ozone.

86. Due to the long lifetime of methane in the atmosphere, methane is well mixed. Decreases in surface ozone arising from methane emission control are largely independent of source location, but the local response to global methane reduction is stronger in locations where local NOx emissions are high. Equal emission reductions in any given regions will lead to the same reductions in global background ground-level ozone.

87. The fossil fuel (production and distribution) and waste sectors have the highest technical potential for reduction of methane emissions. The agricultural sector is a major source of methane emissions but has a low technical potential for reductions in methane emissions. Outside the ECE region there is currently potential for reducing methane emissions from the waste sector in China and the fossil fuel sector in the Middle East.

88. Multi-model intercomparisons show a very large spread in simulated surface ozone, which has not improved over the last decade despite higher spatial resolution and other model developments. As an ensemble, global models tend to overestimate available surface observations.

89. The source/receptor relationships for ground-level ozone from the Hemispheric Transport of Air Pollution (HTAP2)[9] multi-model exercise was not significantly different from that of the HTAP1 exercise, despite developments in individual models and closer harmonization of the model inputs.

90. Global models disagree strongly on the magnitude of the pre-industrial to present-day trend in ground-level ozone and tend to underestimate the magnitude of the observed trend. Projection of the contribution of hemispheric background ozone to the attainment of future targets using current models remains highly uncertain.

91. Technical challenges for improved global simulations of ground-level ozone for the ECE region include more accurate simulation of the global methane lifetime, better resolution of the NOx chemistry of ship exhaust plumes, and better representation of ozone deposition to vegetation. Model intercomparison studies such as HTAP, Chemistry-Climate Model Initiative (CCMI) and Aerosol Chemistry Model Intercomparison Project (AerChemMIP) exercises play a vital role in assessing the adequacy of state-of-the-art emission inventories, global models, and measurement data for informing the Convention on the impacts of extra-regional emission sources on ozone impacts in the ECE region.

92. In addition to model development, ongoing provision of high-quality emission inventories and expansion of the global network of ozone observations for model evaluation are required.

[9] See http://htap.org/. and http://htapold.kaskada.tk/.