Economic and Social Council

Economic Commission for Europe

Executive Body for the Convention on Long-range
Transboundary Air Pollution

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

Working Group on Effects

Eighth joint session
Geneva, 12–16 September 2022
Item 7 (a) of the provisional agenda
**Joint thematic session: contribution of scientific bodies to
the review of the Protocol
to Abate Acidification, Eutrophication and Ground-level Ozone**

Scientific information for the review of the Gothenburg Protocol

**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**

Summary

The present report was compiled by the Chair of the Working Group on Effects and the Chair of the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) based on the science information provided by the scientific centres and task forces under the Convention. The science information provided in this report is in accordance with the questions listed in document entitled "Preparations for the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone as amended in 2012 (ECE/EB.AIR/2020/3–ECE/EB.AIR/WG.5/2020/3).

The final version of the present document, unofficially referred to as "Annex I", upon approval by the EMEP Steering Body and the Working Group on Effects at their eighth joint session, will be forwarded to the Executive Body for information and will accompany the report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone Gothenburg Protocol as amended in 2012.

Please recycle

I.   Introduction

1.   The present report was compiled by the Chair of the Working Group on Effects and the Chair of the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) based on the science information provided by the Extended Bureaux of the Working Group on Effects[1] and the Steering Body to the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe,[2] in the perspective of the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) as amended 2012, initiated by the Executive Body with its decision 2019/4.[3] The present document aims at synthesizing a detailed survey of tools, outcomes and results achieved in the framework of the Convention for supporting policy decisions, implementation of the Convention protocols and assessing their efficiency.

2.   The Gothenburg Protocol is based on science knowledge to derive a multi-pollutants/multi-effects approach, which sets national emission reduction objectives to reduce acidification, eutrophication and environmental and health effects of air pollution (including ground-level ozone (O_3) and fine particulate matter ($PM_{2.5}$). Emission inventories, atmospheric pollution and deposition measurement and modelling for eutrophying and acidifying compounds, ozone and fine particulate matter, effects monitoring (acidification, eutrophication, impacts of ozone on vegetation, crops and human health and health impacts of PM) and modelling are the core activities of the task forces, international cooperative programmes and EMEP centres. A unique framework has been implemented in the United Nations Economic Commission for Europe (ECE) region to collect data in those various fields that allows assessment of impacts and trends of air pollution and its effects and measurement of the benefits of current policies and the targeting of areas (sectoral, geographical) where additional efforts are needed.

3.   The status of current knowledge is reported in this document to illustrate the statements contained in the Draft report on the review of the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, as amended in 2012 (ECE/EB.AIR/2022/3, forthcoming).

II.   Emissions

4.   Complementing the emissions trends (including black carbon (BC)) detailed in the report on the Gothenburg Protocol review, as amended in 2012, this section contains more information about the inventory and reporting processes and on the quality assurance principles ensuring the reliability and relevance of the data for science and policy support: comparability, completeness, consistency, accuracy and transparency.

5.   Setting up a robust scientific framework to support emissions inventory activities and emission reporting is a major EMEP programme achievement, linking science and policy since emissions inventories are essential as inputs for modelling activities and to assess compliance with the emissions ceiling obligations arising from the protocols to the Convention.

6   The EMEP/European Environment Agency (EEA) air pollutant emissions inventory guidebook ("the Guidebook") is the pillar of this activity, providing comprehensive information on making air pollutant emission estimates. The technical scope of the Guidebook remains focused on including methodologies for pollutants included in Convention reporting commitments and the sources relevant to the countries within the

---

[1] Comprising: the Bureau of the Working Group; the Chairs of the international cooperative programme task forces, the Joint Task Force on the Health Effects of Air Pollution; and representatives of the international cooperative programme centres

[2] 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 task forces; and representatives of Cooperative Programme for Monitoring and Evaluation centres

[3] Available at https://unece.org/decisions.

Convention's geographical extent. However, the Guidebook is recognized worldwide as a key reference manual for supporting air quality pollutant emission inventories.[4]

7   National emission inventories are reported annually by Parties, which also produce informative inventory reports describing assumptions and content of the national inventories. For most of them, methodologies are generally in line with the 2019 Guidebook and reporting is, in most cases, in line with the Guidelines for Reporting Emissions and Projections Data under the Convention (ECE/EB.AIR/125). Evaluation of emission inventories is performed according to a three-stage approach, stage 3 being the most sophisticated ("in-depth" peer review), performed by national emission experts (selected from a roster).

8.   Completeness of reporting has improved significantly in recent years, with 47 Parties submitting inventories in 2022. However, submissions from 9 Parties were incomplete, and 9 Parties did not provide an informative inventory report. Coverage of reporting Parties has increased over the past years to 94 per cent (see figure 1 below).

Figure 1
**Status of reporting (as of 18 March 2022) over past 20 years**
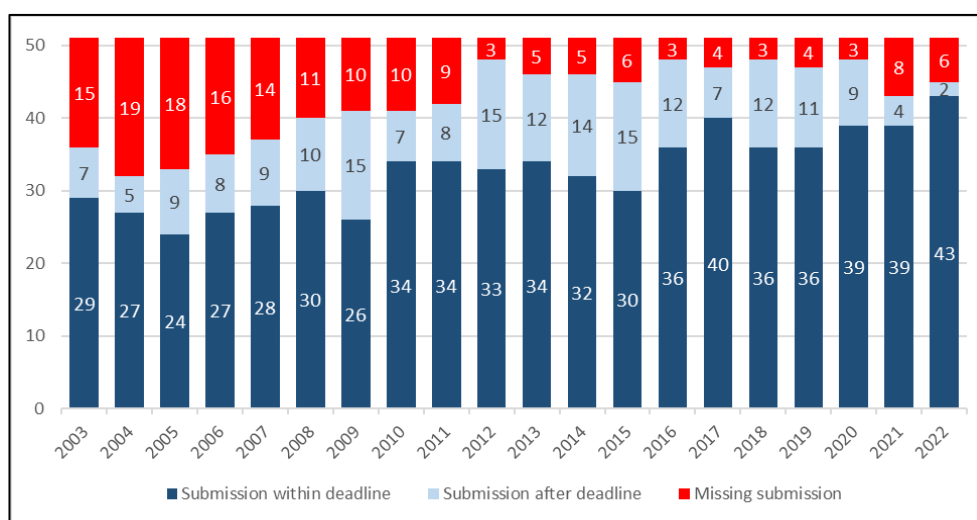
Source: Centre on Emissions inventories and Projections

9.   Completeness remains an issue (see figure 2 below), either because: data are missing; data sets for all priority pollutants are incomplete; full time series are not provided; or activity data are not properly documented.

---

[4]   The Guidebook has also been translated into Russian to improve accessibility to inventory compilers in the United Nations Economic Commission for Europe (ECE) region.

Figure 2
Number of Parties reporting emission data for various groups of pollutants (2010–2021)
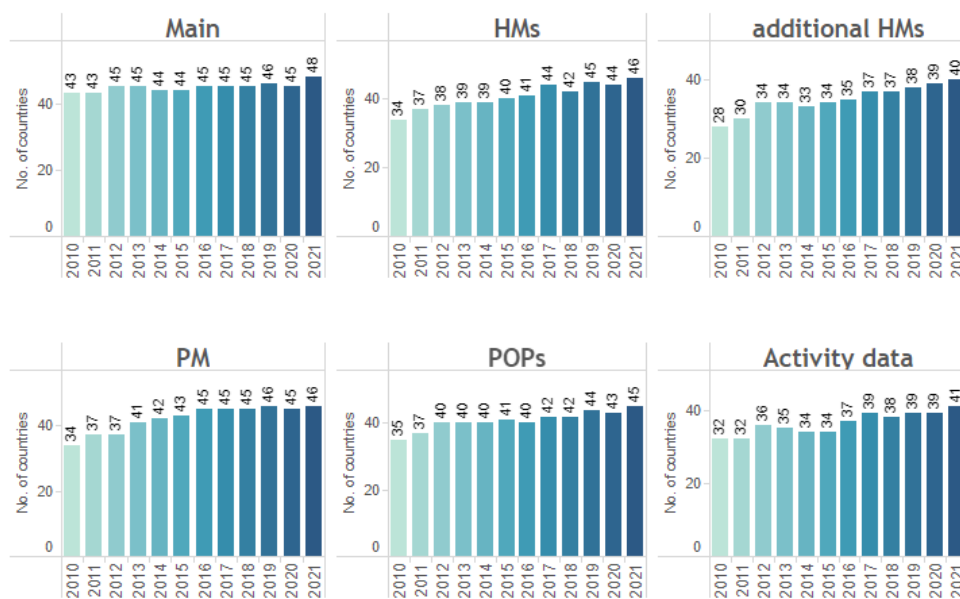
Source: Centre on Emissions inventories and Projections: Data viewer
Abbreviations: HMs, heavy metals; PM: particulate matter, POPs, persistent organic pollutants.

10.   Time series consistency is a question 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. Time series consistency of reported data can be checked via annually updated data viewers.[5]

11.   Generally, accuracy is better for main pollutants and $PM_{2.5}$ than for HMs and POPs. A frequent issue related to accuracy is use of tier 1 methods for a key category. The key element to ensuring good transparency of inventories is good informative inventory reports. However, nine Parties did not provide an informative inventory report in 2021, fewer than in previous years.

12.   All emissions inventories bear uncertainties. Given that emissions inventories form an important basis for air pollution abatement, it is important that these uncertainties be estimated. Uncertainty information should thus form part of every emission inventory. Furthermore, the Guidelines for reporting emissions and projections data under the Convention require that: "Parties shall quantify uncertainties in their emission estimates using the most appropriate methodologies available, taking into account guidance provided in the EMEP/EEA Guidebook".[6] 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 slow.

13.   The table below shows that there is a 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. Moreover, in some cases, the recalculations observed in the past years are higher than the indicated values of the uncertainty would suggest.[7]

---

[5]   See www.ceip.at/data-viewer.

[6]   ECE/EB.AIR/125, para. 31.

[7]   Sabine Schindlbacher, Bradly Matthews and Bernhard Ullrich, "Uncertainties and recalculations of emission inventories submitted under CLRTAP", Centre on Emission Inventories and Projections (CEIP) Technical Report No. 01/2021 (n.p., 2021).

Analysis of the uncertainties provided with emission data (2021 submission)

Pollutant	Uncertainty range reported by Parties for national total (Percentage)	Number of Parties providing uncertainty estimate for national total	Uncertainty range reported by Parties for emission trend (Percentage)	Number of Parties providing uncertainty estimate for emission trend
NO_x	8.5–59	19	1–31	19
NMVOCs	15–112	19	1.8–32.2	19
SO_x	5–47	19	0.2–103	19
NH_3	9.5–143	19	3.1–364.8	19
$PM_{2.5}$	9.96–96.6	17	3–140	18
BC	27.1–302	7	3.1–67	7

Source: Centre on Emissions inventories and Projections

Abbreviations: NH_3, ammonia; NMVOCs, non-methane volatile organic compounds; NO_x, nitrogen oxides; SO_x, sulfur oxides.

14. In the review, particular attention was paid to shipping – nowadays, a major source of air pollutants. Three Nomenclature For Reporting (NFR) categories concern shipping emissions: NFR 1.A.3.d.i(i) (International maritime navigation); NFR 1.A.3.d.i(ii) (International inland navigation); and NFR 1.A.3.d.ii (National navigation (shipping)). NO_x emissions from international maritime shipping are projected to remain approximately constant or decrease slightly in absolute terms over the twenty-first century, depending on assumptions about growth in international trade and use of emission control technology. The share of global shipping NO_x as a proportion of global anthropogenic NO_x emissions (currently about 30 per cent) is projected to vary from 10–60 per cent by the end of the current century depending on the effectiveness of land-based NO_x emission control. In the transport sector, aviation could also be better estimated (like shipping); nevertheless, it is, by definition, a "cross-boundary" source that is "international". However, a centralized approach to investigating this item would certainly be preferable, since there is a risk that compilation bottom up from each Party would result in gaps, data of variable quality, and, generally, an inconsistent data set.

15. Lastly, in terms of investigating future emission reductions commitments, considering sectors for which methodologies and data were supposed to be too uncertain to be mandatory would be certainly relevant. Thus, NO_x and NMVOC sources from agriculture activities could be better described in the reported inventories in the future. Emissions from livestock and manure activities can be reasonably estimated in national emission reports. Methodologies and emissions factors have been updated in the latest versions of the Guidebook. Emissions from agricultural soils and crops are neither mandatory in the reporting process nor taken into account for national compliance checking. Uncertainties are still high, but considering potential future improvement in the description of those anthropic emission on one side, and their potential contribution on the other side, it seems relevant to include them in future reporting processes.

III. Atmospheric monitoring and modelling

16. The monitoring strategy for EMEP for the period 2020–2029 (ECE/EB.AIR/2019/4) sets up a network dedicated to measurement of background air pollution (concentrations and deposition) in rural areas to catch transboundary fluxes. The network is operated by national experts in the Parties and coordinated and managed by the Chemical Coordinating Centre. The EMEP modelling framework includes chemistry-transport model development, including most recent knowledge about air pollution mechanisms and production of modelling results (assessment maps, source-receptor analysis, scenario runs) that support science and policy. The EMEP monitoring network and EMEP model development have a

long history that allows for consistent trend analysis for records going back more than 20 years. Such results are presented below.[8]

Ozone

17. O_3 is a secondary pollutant, and its observed trends reflect meteorological variability to a much greater extent than trends in precursor compounds. Observed trends in O_3 pollution are largely dependent on the metric considered, with large variability between trends in annual mean concentrations and trends for other metrics relevant to health (SOMO35[9]) and ecosystem exposure, or most intense peaks.[10] The trends are also notably different when considering a diversity of monitoring station typology and geographical area. Trends are affected by titration effects, in which decreasing NO_x emissions can increase O_3, especially in wintertime. Over the period 2000–2018, annual mean O_3 increased as much as 11 per cent, whereas a slight decrease (3 per cent) was observed in rural areas.[11] Such a difference between station typology is driven by the titration effect: the sum of O_3+NO_2 declining by 2 per cent and 13 per cent for urban and rural sites, respectively.

18.   Trends in summertime O_3, and metrics of higher O_3 (maximum daily average 8-hour concentration, sum of mean over 35 parts per billions (SOMO35), are stronger and clearer than those in annual data, though site-to-site variability is large.[12] Using stringent data-capture criteria, median trends in daily maximum O_3 during June–August were 0.6 parts per billion per year (ppb/yr) at EMEP sites (EMEP model -0.4 ppb/yr). Observed trends showed much more variability than modelled trends, with observed trends being more affected by the high O_3 summers of 2003 and 2006 in some regions.

19. O_3 peaks decline systematically (by 11 per cent and 6 per cent at rural and urban sites, respectively), but this range of decline can be considered limited regarding the -47 per cent and -54 per cent changes for NMVOC and NO_x emissions, respectively, over the same time period. This discrepancy expressed in relative trends is largely influenced by O_3 mitigation strategies only effectively reducing – in excess of a certain natural burden that remains difficult to estimate. Additionally, these trends for the period 2000–2018 are still largely influenced by the outstanding 2003 and 2006 O_3 years, even for O_3 peaks. O_3 peaks tend not to show any significant declines for the years post-2007, except in Southern Europe.

20.   Such conclusions are illustrated by figure 3 below, which presents the lowest and highest percentiles of O_3 trends over the last 20 years for North and South areas (over and below 49°N). Increasing trends or stable trends are shown for the lowest concentrations levels when slight decreasing trends are observed and modelled (thanks to O_3 precursors emission reductions) for highest percentiles, especially in the South. Observed and modelled trends are reasonably consistent.

---

[8] For more details see EMEP Status report for 2022 (forthcoming) and EMEP_Status_Report_1_2021.pdf.

[9] Sum of means over 35 ppb (ozone)

[10] https://unece.org/DAM/env/documents/2016/AIR/Publications/Air_pollution_trends_in_the_EMEP_region.pdf

[11] These trend estimates are updated for the period 2000–2018 using the methodology published in a report focusing on the period 2000–2017 (to be further updated in summer 2021 for the period 2000–2019), available at https://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.

[12] Kai-Lan Chang and others, "Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia", *Elementa: Science of the Anthropocene*, vol. 5, art. 50 (2017).

Figure 3
Trends in annual percentiles of daily maximum O3 from 2000 to 2019 for Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe observations and model calculations for sites north of 49°N (first and third rows) and sites south of 49°N (second and fourth rows)
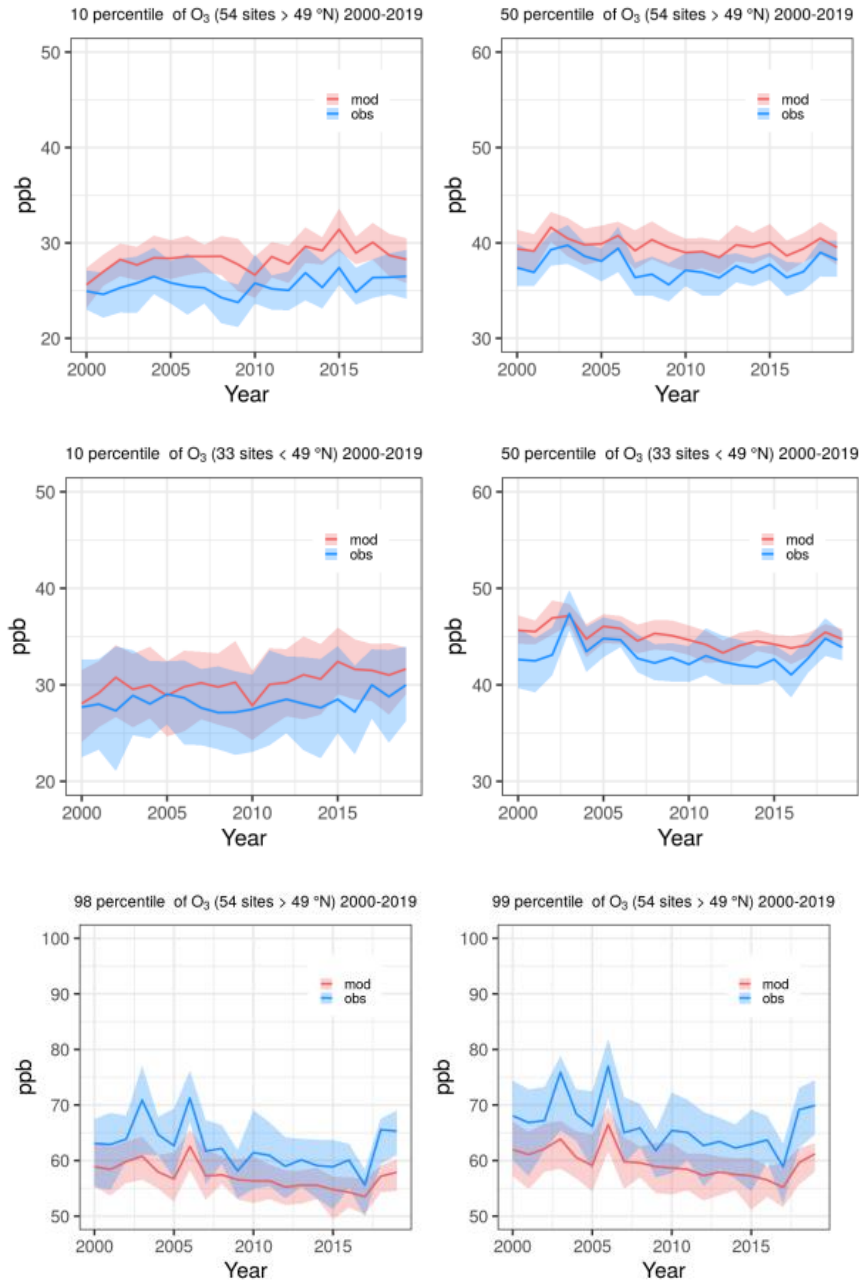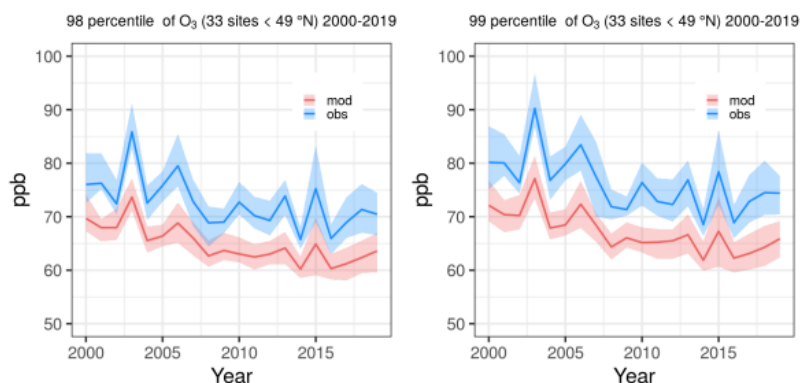
Source: Chemical Coordination Centre

Notes: The solid line indicates the mean, and the shaded area marks the twenty-fifth and seventy-fifth percentile. Only sites located under 1,200 m above sea level and with at least 15 years' worth of data are included.

Sulfur and nitrogen compounds

21.   Annual average concentrations of sulfur dioxide (SO_2) and particulate sulfate, and wet deposition of oxidized sulfur, have been declining since the 1980s. At EMEP background sites, the changes from 2000 to 2018 are, on average, -4 per cent/year(y), -2.9 per cent/y and -3.3 per cent/y for SO_2, particulate sulfate and wet deposition of oxidized sulfur, respectively (EMEP model results: -5.3 per cent/y, -4.0 per cent/y and -4.5 per cent/y, respectively). This is quite in line with the reported 91 per cent downward trend in emission over the period 2000–2018 within Europe and the influence of transcontinental transport is negligible.

22.   From around 1990 onwards, total emissions of NO_x declined significantly in Europe, followed by declining nitrogen dioxide (NO_2) concentrations and total nitrate (nitric acid plus particulate nitrate) in air and reduced oxidized nitrogen (N) deposition at EMEP background sites. From 2000 to 2018, average reductions at long-term EMEP background sites were -1.5 per cent/y, -1.9 per cent/y and -1.7 per cent/y for NO_2 concentrations, particulate nitrate and wet deposition of oxidized N, respectively (EMEP model results: -2.3 per cent/y, -2.3 per cent/y and -2.4 per cent/y, respectively). The trend in observed NO_2 (37 per cent and 28 per cent decline at rural and urban sites, respectively) is, however, much lower than the reported decline in European emissions (55 per cent).

23.   Only modest reductions of ammonia emissions have been achieved since 2000 compared to other pollutants. Consequently, ammonium in precipitation has declined marginally (median of -0.08 per cent/y from 2000 to 2018 at long-term EMEP sites). However, formation of particulate ammonium in air depends on the availability not only of ammonia, but also of nitric acid (formed from NO_x) and sulfate (formed from SO_x). With large reductions in SO_x and NO_x emissions during the last decades, ammonia is, to a large extent, in excess and the availability of nitric acid and sulfate limits ammonia formation, resulting in a decline of ammonium in air of, on average, -2.8 per cent/y at long-term EMEP sites. Total reduced N in air (ammonia + particulate ammonium) is reduced less (-1 per cent/y from 2000 to 2018) as a larger fraction of total reduced N being ammonia (but with a shorter lifetime than ammonium aerosol). The majority of sites for ammonia in air show no significant trend. Figure 4 below synthesizes those conclusions.

Figure 4
Observed and modelled trends of sulfur and nitrogen compounds, compared to emissions trends (first and fifth columns) for atmospheric concentrations and wet deposition over the period 2000–2020
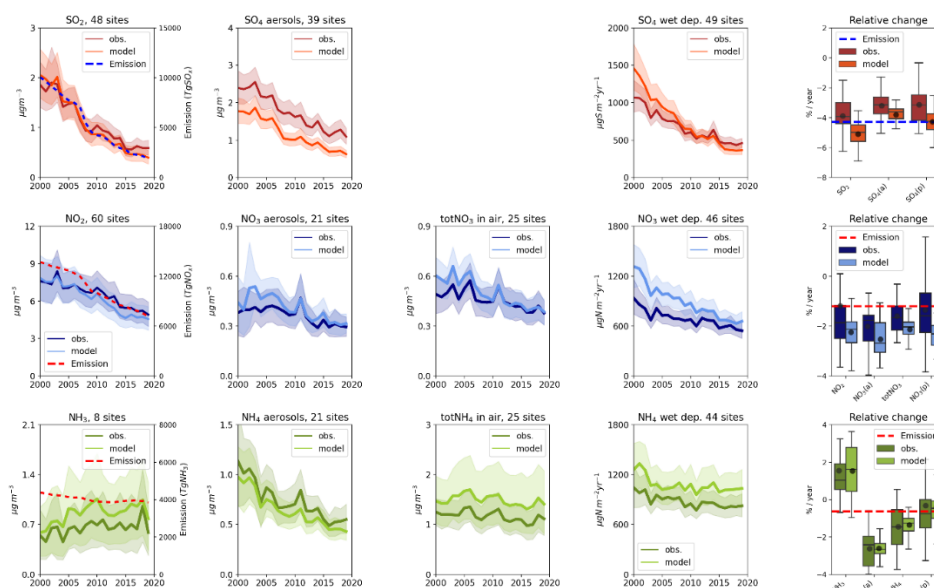

Particulate matter (PM_{10} and $PM_{2.5}$)

24.   Since 2000, there have been significant reductions in PM_{10} and $PM_{2.5}$ (on average -1.7 per cent/y and -2.3 per cent/y, respectively, at EMEP long-term observational sites, and slightly more in EMEP model calculations (-2.0 per cent/y and -2.6 per cent/y, respectively). Secondary inorganic aerosol (particulate sulfate, nitrate and ammonium) has decreased significantly since 2000, with sulfate showing the largest decrease (SO_4: -2.9 (-4.0) per cent/y, NO_3:-1.9 (-2.3) per cent/y, NH_4: -2.8 (-2.9) per cent/y, EMEP model in parenthesis). For the natural components (sea salt and dust), fewer long-term observational sites exist, and only a few of them show significant trends. The trends of PM_{10} and $PM_{2.5}$ exceed the rate of change in emission of primary PM thanks to the additional effect of mitigation measures targeting the precursors of secondary PM. For $PM_{2.5,}$ the average observed decline is -31 per cent compared to -19 per cent changes in emissions (figure 5 below).

25.   For carbonaceous aerosol there are very few sites with long-term, consistent measurements. Figure 6 below shows trends for the shorter period 2010–2019. It shows a 4 per cent/yr decrease in elemental carbon since 2010, indicating a reduction from anthropogenic sources, whereas trends in organic carbon are (more) influenced by natural sources, and are thus more difficult to assess. Seasonal variability is quite high for organic carbon, showing a quite large decrease in winter (not caught by the model) and more stable trends for the other seasons.

Figure 5
PM$_{10}$ and PM$_{2.5}$ observed and modelled trends over the period 2000–2020
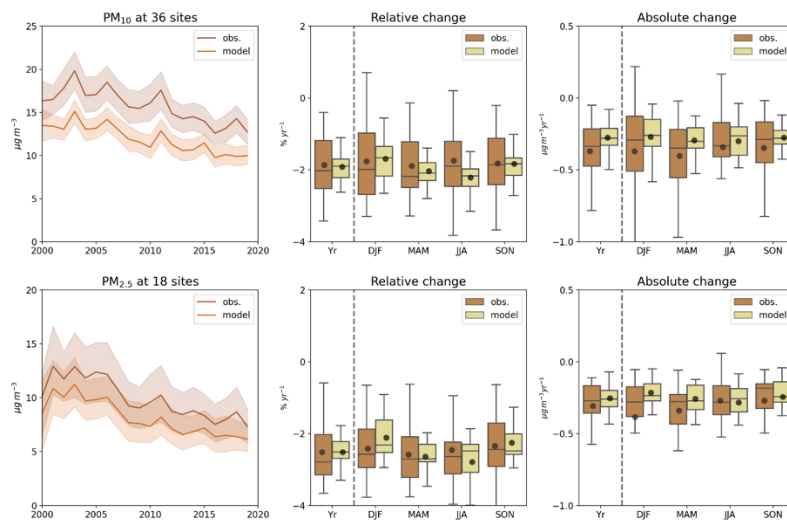
Note: Annual and seasonal trends in relative and absolute changes are also displayed.

Figure 6
Organic carbon and elemental carbon observed and modelled trends over the 2010-2019 period
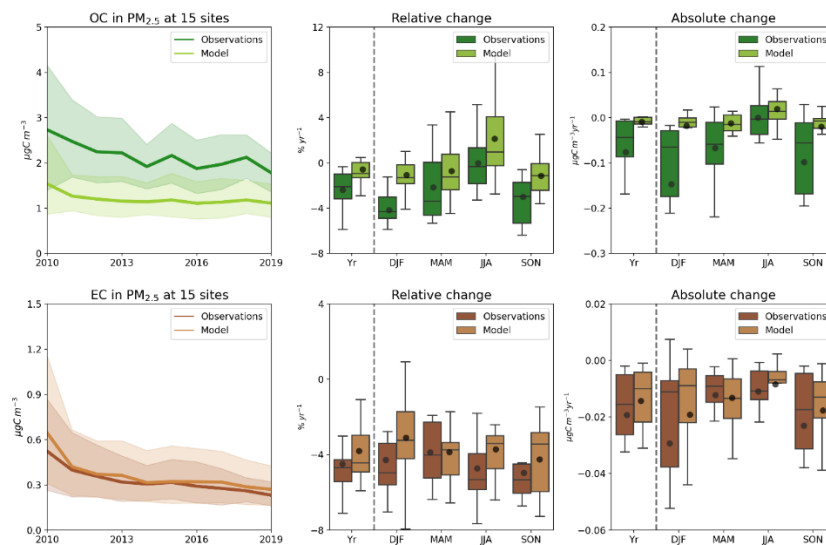
Notes: Annual and seasonal trends in relative and absolute changes are also displayed.

Focus on marine areas

26.   According to Meteorological Synthesizing Centre-West (MSC-W) model calculations, deposition of oxidized N to the Baltic Sea decreased by 37 per cent between 1995 and 2018. The decrease in deposition of reduced N is much smaller (4 per cent), while total N deposition decreased by 25 per cent, mainly due to substantial reductions in NO$_x$ emissions from land-based sources and shipping. For the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) regions covering the North Sea and parts of the North Atlantic, the decrease in oxidized N over the same period amounted to 44 per cent. However, reduced N deposition did not decrease – there were even slight increases in some OSPAR regions. A study on future (2030) effects of the Gothenburg Protocol (and the European Union National Emissions reduction Commitments (NEC)

Directive[13] was conducted for the Baltic Marine Environment Protection Commission (HELCOM). According to MSC-W model results, oxidized and reduced N depositions in 2030 will be lower by about 55 per cent and 14 per cent, respectively, with respect to 2005 values. The results from these calculations are summarized in MSC-W reports for OSPAR and HELCOM and in Gauss and others (2021).[14] Together with waterborne input, the Maximum Allowable Input of N to the Baltic Sea is still exceeded as of 2017.[15]

27.   According to MSC-W model results, deposition of oxidized N on the North Sea, the Mediterranean Sea and the Black Sea decreases by 63 per cent, 28 per cent and 20 per cent, respectively, over the period 2005–2030. Deposition of reduced N decreases by 18 per cent (North Sea) and 5 per cent (Black Sea), respectively, while in the Mediterranean Sea it increases slightly over the period 2005–2030, despite (minor) ammonia emission reductions in the European Union.

Hemispheric transport of air pollution

28.   The intercontinental contribution to ground-level O_3 is larger than the intercontinental contribution to PM or its components due to O_3's longer atmospheric lifetime. The concentration of O_3 experienced at any given location is the combination of O_3 and O_3 precursors transported from distant sources on hemispheric to regional scales and, depending on the photochemical regime, local photochemical O_3 production or local O_3 loss due to titration with nitrogen oxide. Reduction in emissions of O_3 precursors in the ECE region has led to a reduction in peak, short-term ground-level O_3 concentrations associated with local photochemical production, especially in summertime. Reduction of NO_x emissions has also led to a reduction in the titration of O_3 by nitrogen oxide, leading to higher concentrations of ground-level O_3, especially between autumn and spring, at night-time, and in Europe. Both effects have increased the relative influence of background O_3, including O_3 from hemispheric transport, on local concentrations of O_3 experienced in urban areas of the ECE region, especially in Europe.

29.   Peak ground-level O_3 levels in Europe and North America have decreased significantly since 2000, but trends for annual average O_3 levels are mixed, with increases at some sites and decreases at others. Average O_3 levels in the free troposphere above Europe and North America, as measured by aircraft, have continued to increase. Elsewhere in the world, both peak and annual average levels of ground-level O_3 have continued to increase, as have O_3 levels aloft as measured by aircraft.

30.   The mixed or weak trends in annual average O_3 levels belie opposing trends in different seasons. In Europe, in winter (December-January-February) and spring (March-April-May) some sites experienced weak increasing trends and others weak decreases. In summer (June-July-August), however, most European sites had strong decreases over the period 2000–2014. In autumn (September-October-November), most sites saw no trend or a weak decrease. In North America, winter (December-January-February) ground-level O_3 levels increased over the period 2000–2014 and summer (June-July-August) levels decreased. Trends in spring and autumn were mixed, with many sites showing no significant trends.[16]

31.   This observed trend in ground-level O_3 and its impacts cannot be explained completely by precursor emission trends in Europe and North America. Downward trends of O_3 precursor emissions in Europe and North America since around 1990 appear to be at least partially offset by increasing NO_X and VOC emissions outside the ECE region and increasing methane emissions globally.

---

[13]   Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.344.01.0001.01.ENG&toc=OJ:L:2016:344:TOC.

[14]   Michael Gauss and others, "Airborne nitrogen deposition to the Baltic Sea : Past trends, source allocation and future projections", *Atmospheric Environment*, vol. 253 (15 May 2021).

[15]   Baltic Marine Environment Protection Commission (HELCOM), "Inputs of nutrients (nitrogen and phosphorus) to the sub-basins (2017) – Key message", HELCOM Indicators, HELCOM core indicator report (n.p., 2019).

[16]   Chang, "Regional trend analysis".

32.   The contribution of anthropogenic emission sources outside the ECE region to PM species and their associated impacts within the ECE region are 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.

33.   If NO_x and VOC emissions were reduced everywhere by the same percentage, emission reductions outside of Europe would have a bigger impact on European O_3 levels than emission reductions within Europe. For North America, equal percentage emission reductions of NO_x and VOC outside of North America would contribute significantly to decreases of O_3 in North America, but not more than if the equivalent percentage emission reductions were made in North America itself.

34.   Due to the long lifetime of methane in the atmosphere, methane is well mixed. Decreases in surface O_3 arising from methane emission control are largely independent of source location; i.e. equal reductions in methane emissions in different regions will lead to similar reductions in background ground-level O_3 in a given location. However, the local response to global methane reduction is stronger in locations where local NO_x emissions are high and O_3 formation is VOC-limited.

IV.   Effects on human health, materials and the environment

Human health

35.   The Joint World Health Organization (WHO)/Convention Task Force on Health Aspects of Air Pollution brings together environmental and public health experts representing Parties to the Convention. In 2015, a report entitled *Residential heating with wood and coal: Health impacts and policy options in Europe and North America* was presented,[17] which summarized evidence linking wood/coal heating emissions to serious health effects (e.g., respiratory and cardiovascular mortality and morbidity). Wood/coal burning also emits carcinogenic compounds and, each year, an estimated 61,000 premature deaths are attributable to ambient air pollution from residential heating with wood and coal in Europe, alongside an additional 10,000 attributable deaths in North America. The report concluded that it would be difficult to tackle ambient air pollution without addressing wood biomass heating as a major source of harmful air pollutants, especially PM.

36.   Landmark WHO global air quality guidelines were published in 2021,[18] providing quantitative, health-based, evidence-informed recommendations for air quality management, expressed as long- or short-term concentrations for several key air pollutants. The new WHO guidelines provide air quality guideline levels for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 and carbon monoxide, and interim targets, as well as good practice statements about several types of PM, such as black/elemental carbon, ultrafine particles and sand and dust storms. Ultimately, the guidelines' goal is to guide policies and actions to help reduce air pollutant levels in order to decrease the enormous health burden resulting from exposure to air pollution worldwide, including in the ECE region.

37.   For $PM_{2.5}$, 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 disability-adjusted life years estimation. The estimates of premature mortality and years of life lost are available from EEA reports[19]. There has been a trend of reduced attributable deaths driven by a decrease in air pollutants, but there still peaks in some locations, for example, for NO_2 in areas near 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 project.

---

[17] World Health Organization (WHO)/European Environment and Health Process (Copenhagen, 2015).

[18] Available at https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y.

[19] https://www.eea.europa.eu/publications/air-quality-in-europe-2021/

38.   Regarding other health metrics, a project has been initiated to deliver a method for estimating morbidity from air pollution and its economic costs (for locations with appropriate health statistics available) and morbidity-related, concentration-response functions (results expected in 2022). The Second Clean Air Outlook[20] includes projected trends of morbidity, with data from the Centre for Integrated Assessment Modelling. Follow-up actions are needed to check the feasibility of gaining access to scenarios, in a multi-task force coordinated effort.

Materials

39.   Looking at observed trends (see figure 7 below), corrosion and pollution have decreased significantly since the early 1990s and a shift in magnitude was generally observed around 1997 from a sharp to a more modest decrease or to a constant level without any decrease. SO_2 levels and carbon steel and copper corrosion decreased even after 1997, a trend which is more pronounced in urban areas, while corrosion of other materials shows no decrease after 1997, when looking at one-year values. For 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.

Figure 7
(Left) Trend in decreasing of yearly corrosion loss of zinc at all test sites during period 1987–2018. (Right) Trend of corrosion loss of carbon steel exposed to rural, urban and industrial sites with average values during period 1987–2018
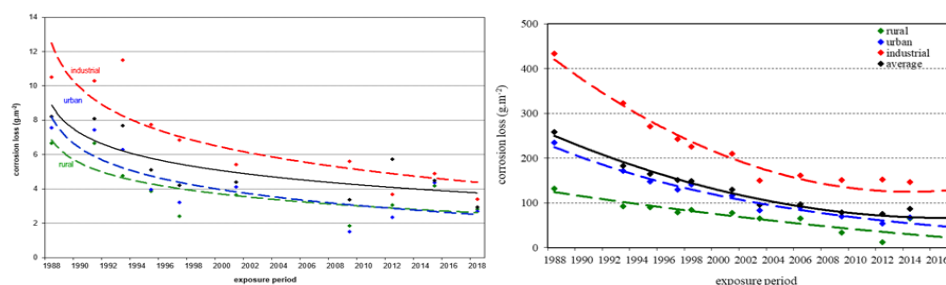
40.   For soiling, there is no decreasing trend after 1997 and, consequently, larger areas in Europe are above acceptable levels; therefore future development of the programme is focused on exposure of new soiling materials, for example, coil-coated materials and stone materials. The main pollutant responsible for soiling of materials is PM.

Environment

Forests

41.   Although deposition rates of inorganic N 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. Interestingly, on many sites, throughfall deposition decreased faster for nitrate (by 26 per cent) than for 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 N and S deposition led to imbalances in tree nutrition across Europe. In many parts of Europe, positive tree growth was observed during the last decades. Among other factors, increased N deposition contributed to the observed tree growth stimulation and increased carbon sequestration, but on non N-limited sites, additional N deposition may lead to nutrient imbalances including phosphorus deficiency, nitrate leaching, acidification and

---

[20] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0003&from=EN.

loss of base cations, and increased sensitivity to pests or pathogens. High N deposition can therefore have divergent effects and potentially reduce forest growth.[21]

Forested catchments

42. The International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems (ICP Integrated Monitoring) catchments have increasingly responded to decreases in emission and deposition of N in Europe. Concentrations of total inorganic nitrogen (TIN) in run-off water for the period 1990–2017 exhibited dominantly downward trend slopes (76 per cent of sites), and, for fluxes, 69 per cent of sites. Decrease of nitrate (NO_3) and ammonium (NH_4) in concentrations was significant at, respectively, 59 per cent and 36 per cent of the sites, but the decrease in fluxes was significant only at 25 per cent and 31 per cent of the sites, respectively. Decreasing trends for sulfur and N emissions and deposition reduction responses in run-off water chemistry have tended to be more gradual since the early 2000s. A significant negative correlation was found between: annual change of TIN concentrations and fluxes in run-off, 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, run-off water and soil water, showed the most pronounced decreases of TIN in run-off.

43. Twenty-three European forest sites belonging to the ICP Integrated Monitoring, ICP Forests and Integrated European Long-Term Ecosystem, Critical Zone and Socio-Ecological Research Infrastructure (eLTER-RI) 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 change in occurrence of oligophilic (favouring nutrient-poor conditions), acidophilic (favouring 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. Although 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 sulfur 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.

44. 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.[22] A chain of models was applied to a combined data set 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 N 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

---

[21] W. de Vries and others, "Impacts of acid deposition, ozone exposure and weather conditions on forest ecosystems in Europe: an overview", Plant and Soil, vol. 380, No. 1–2 (2014), pp. 1–45; and Sophia Etzold and others, "Nitrogen deposition is the most important environmental driver of growth of pure, even-aged and managed European forests", Forest Ecology and Management,vol.458 (15 February 2020).

[22] Thomas Dirnböck and others, "Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests", *Environmental Research Letters*, vol. 13, No. 12 (17 December 2018); and Maria Holmberg and others, "Modelling study of soil C, N and pH response to air pollution and climate change using European LTER site observations", *Science of the Total Environment*, vols. 640–641 (1 November 2018), pp. 387–399.

climate warming scenarios led to a decrease in pH. Modelling results also indicated that decreases in N deposition under the CLE 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.

Rivers and lakes

45. Major indices of acidification such as acid neutralizing capacity (ANC), pH and toxic aluminum indicate 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) data set that includes records since 1990 from approximately 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 and land use are becoming more important as drivers of change. Major perturbations such as wildfires and insect outbreaks are often climate-related and can result in reacidification of surface waters.

46. Deposition of N has declined less than sulfur and major questions remain concerning the chemical and biological effects thereof. Climate and catchment properties are important determinants of N leaching, linking air pollution and effects of reactive N in surface waters. Although N is an essential nutrient, phosphorus is often the dominant control of fresh-water productivity. However, there is increasing evidence that N derived from N deposition can influence fresh-water productivity in nutrient-poor lakes. Leaching of N deposited from air to surface waters, and downstream to marine ecosystems, can also contribute to marine eutrophication because N is the limiting nutrient in marine waters. Source attribution of N in water bodies (i.e., to deposition, agriculture or other source) is important for effect-evaluation of policy to reduce emissions of N to the environment. Preliminary results in the N report indicate that useful input is being generated to support empirical critical load guidance currently being developed under the Working Group on Effects.

47. 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 noted, especially for nitrate, suggesting that alpine, acid-sensitive sites are extremely well-suited for monitoring fresh-water responses to rapid changes in atmospheric chemistry.

48. 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 of Great Britain and Northern Ireland, the extent of biological change does not show a 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 N and becoming warmer as a consequence of climate change. The post-acidification biological community assemblies may be very different from the pre-acidification state.

49. In many European countries, surface-water monitoring networks deliver data to support several policy instruments (e.g., the Convention and the European Union NEC Directive and Water Framework Directive (WFD).[23] In some countries, the NEC Directive 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 km^2, 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

---

[23] Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060.

of regional scale pressures (air pollution, climate change) such as under the Convention and the NEC Directive.

50. Differences between national classification systems for surface-water acidification may limit robust national comparisons of ecological status under the WFD. The physicochemical 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 data set on chemistry and biology has been used to propose an ANC-based system that can be used to harmonize classification systems.

Effects of O_3 on crops and vegetation: Critical Levels

51. The O_3 profile has changed since 1990. "Peak" concentrations have reduced, whereas "background" concentrations have increased. Concentration-based metrics using relatively high thresholds, such as the accumulated O_3 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 O_3 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. Thus, O_3 impacts on vegetation can also be found where the critical level for AOT40 is not exceeded.

52. Analysis of modelled data showed only a small change in wheat yield loss for both 1990–2010 and 2010–2030. Modelling impacts of O_3 on wheat yield in collaboration with the EEA European Topic Centre on Air and Climate Change Mitigation 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. 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, production loss was higher in Europe due to a double total production of wheat in Europe. The percentage yield losses are different in the 1990–2010, compared to the 2010–2030, assessments due to the different flux-metrics used.

53. Accurate modelling of O_3 impacts to vegetation requires parameterization of the dose-response relationship for each individual species. This is currently limited by the availability of experimental data to parameterize 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.

54. Impacts on ecosystems and ecosystem function occur with O_3 pollution. Scientific knowledge of cumulative fluxes of O_3 (including from low O_3 concentrations) shows impacts on crops, trees and ecosystems that include growth and flowering (number and timing).

55. Current risk assessments for impacts of O_3 on ecosystems are focused on the vegetation component. Qualitative assessments and information indicate that a much wider breadth of impacts occur in response to O_3 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 O_3 impacts.

56. O_3 pollution can reduce the N use efficiency of some crops (e.g., wheat, soybean and rice). As a result of lower N fertilization efficiency, O_3 causes a risk of increased losses of N from agroecosystems (e.g., through nitrate leaching and nitrous oxide emissions). Tropospheric O_3 thus has the potential to cause elevated N 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 N on growth can be progressively lost with increasing O_3 concentrations, sometimes with increasing soil N_2O emissions.

57. Large-scale studies conducted at the ICP Forests plots revealed that, despite a slight but significant reduction of O_3 levels during the vegetative period, the concentration-based Critical Levels (AOT40) have been exceeded on the majority of the investigated sites,

especially in Eastern and Southern Europe. On these sites, foliar injury attributable to O_3 has been detected on several species, mostly broadleaves. The level of sensitivity to O_3 injury in also depends on species and region (e.g., in Greece, *Sorbus torminalis* appears to be more sensitive than *Fagus sylvatica*). The occurrence and severity of visible O_3 symptoms depends not only on O_3 levels but also on several other environmental parameters and vegetation characteristics that drive stomatal uptake. It is expected that interaction with climate change and biotic agents (pests and disease) may substantially alter the above results: this will, however, be dependent on site-specific condition.

58.   There are interactions between O_3 pollution and climate change. Some interactions alter the exposure of vegetation to O_3, such as accelerated phenological development with increasing temperature resulting in bud-break earlier in the year and consequent exposure of the plant to O_3 earlier in spring than current models predict. Changes in meteorological conditions and soil moisture due to climate change alter O_3 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.

Critical Loads

59.   The concept of Critical Loads (CLs) was developed to estimate the amount of harmful deposition that, if not exceeded, does not lead to adverse effects on ecosystems. As soon as the estimated deposition exceeds the CLs, ecosystems are considered to be at risk.

60.   As indicated in the maps (see figure 8 below), CLs of acidity are exceeded on 14 per cent (2000) and 4.4 per cent (2019) of the ecosystem area. By contrast, CLs for eutrophication are exceeded in large parts of the model domain in all years (see figure 9 below), with 75 per cent in 2000 and going down to 64.3 per cent in 2019.

Figure 8:
Critical Load exceedance for acidification for the years 2000, 2005, 2010, 2015 and 2019
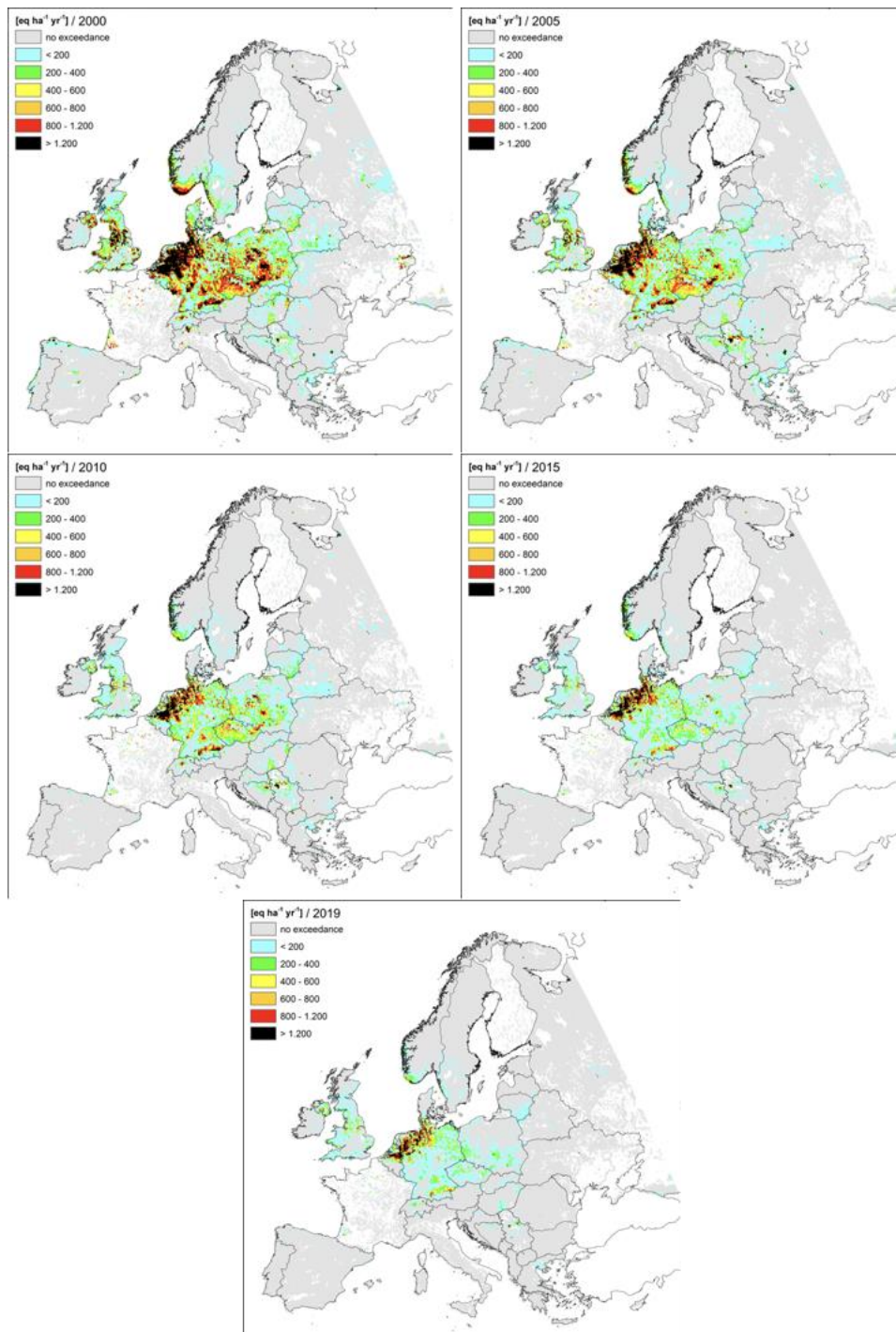
Source: Deposition data from EMEP-MSC-West; CL data from Coordination Centre for Effects (CCE).

Figure 9:
**Critical Load exceedance for eutrophication for the years 2000, 2005, 2010, 2015 and 2019**
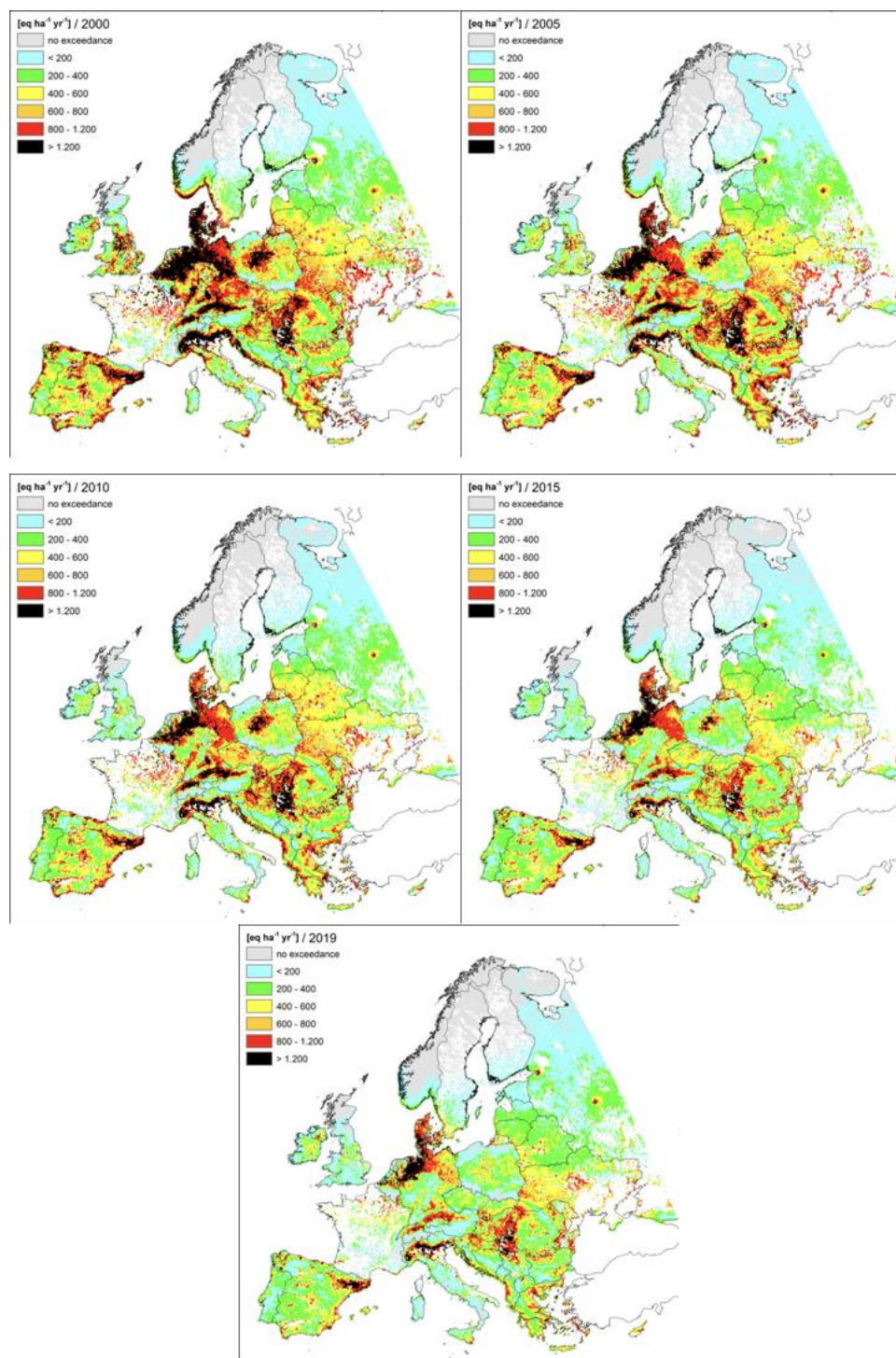
Source: Deposition data from EMEP-MSC-West; CL data from Coordination Centre for Effects.

61. The areas with exceedance of the CL for eutrophication were also evaluated in terms of the amount of total N deposition and the contribution of the different N species to the total deposition for the year 2019. Figure 10 below shows that deposition of reduced N on CL relevant receptor areas (green line) is always higher than deposition of oxidized N (yellow line). This pattern is less pronounced in areas of no CL exceedance (negative values on the x-axis), while the share of reduced N to the total N deposition increases significantly with rising CL exceedances. Especially in areas with very high CL exceedances (> 800 equivalents per hectare per year (eq ha-1 year-1), deposition of reduced N accounts for more than 2/3 of

total deposition. However, as the cumulative distribution function shows (red line), those areas account for only about 3 per cent of the total receptor area.

Figure 10
Exceedance of Critical Loads for Eutrophication (2019) and different species of nitrogen deposition
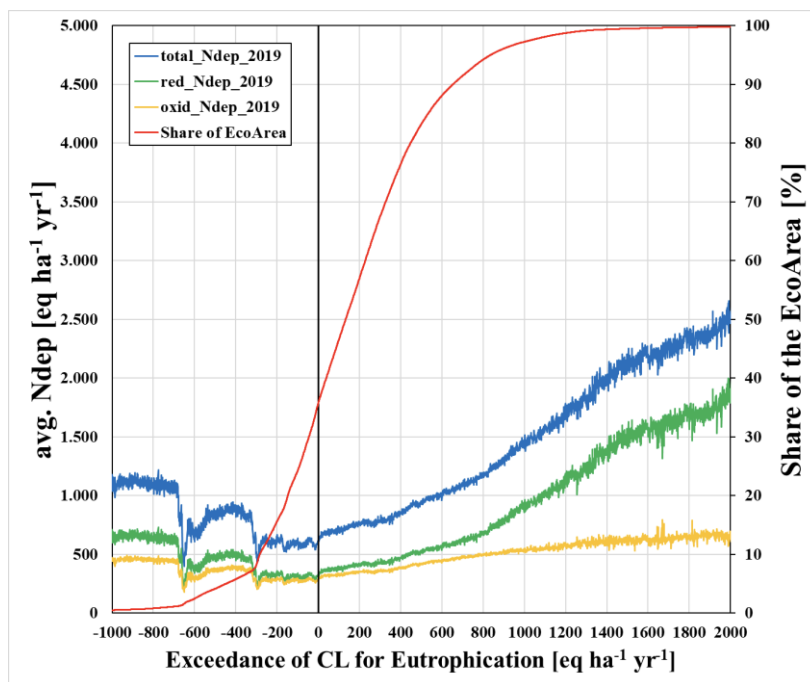
Source: Coordination Centre for Effects

62.   The deposition of reduced N on the areas at risk for eutrophication in general dominates the eutrophying deposition, however, also oxidized N at all areas at risk contributes to it in the order of 30 per cent to roughly 50 per cent. Therefore, in order to effectively reduce the areas affected by eutrophication, a combined reduction of oxidized and reduced N is urgently required.

Effects monitoring networks

63.   Long-term monitoring under the Working Group on Effects has provided scientific evidence that air pollution reduction measures have their intended effect, i.e. ecosystem recovery, reduced corrosion of materials and reduced burden of disease. Many lakes, rivers and catchments have recovered from acidification, although some areas remain acidified, with slow recovery. In highly intensive monitoring sites, interaction between air pollution and climate change, as well as effects on forests, soil and water have been observed, and a greater understanding of these complex relationships gained.

64.   Long-term monitoring under the Working Group on Effects is a valuable resource for model development and validation in the Convention, as these data have been used to understand the cause-effect relationship between air pollution and effects and provide data to evaluate predicted responses to cleaner air. Additionally, the ecosystem data have also been used to evaluate combined effects of clean air and climate change, and effects of N on carbon sequestration.

65.   However, monitoring networks under the Working Group on Effects should be improved by extending those networks to less well covered areas, with the participation of all Parties to the Convention, the inclusion of a broader range of ecosystem types and the development of specific monitoring methodologies for these ecosystem types. This will provide data to detect recovery, assess efficiency and sufficiency of control measures, and identify new impacts.

V. New challenges

66.   The Convention's science bodies will have to address several issues to improve their expertise and the tools developed in support of policy decision.

67.   Improving the quality, completeness, accuracy and transparency of emissions reported by the Parties is a top priority since it drives all interpretations of trends in air pollution and its effects. Good emission inventories are essential to support the preparation and evaluation of emission reduction policies and measures (including setting of emission reduction targets).

68.   Regular updates of the Guidebook, which must be maintained through sustainable funding and support from national experts in the Parties, are vital in this regard. Securing such resources for the Guidebook will be a real challenge in future years.

69.   Data reported by the Parties on international shipping are not sufficiently consistent for use in the gridded data set used in modelled assessments. As mentioned in paragraph 15 above, agricultural sources of NO_x and NMVOCs could be better described in the reported inventories. The issue is similar for emissions from natural sources, primarily forests but also other non-agricultural vegetation. The information provided by the Parties is not sufficiently complete, consistent, or accurate to meet modelling community needs.

70.   A first study using a pragmatic approach to assess the risk of eutrophication through atmospheric N deposition was conducted by the Ad hoc Group on Marine Protection under the Convention in cooperation with HELCOM experts. It concluded that there is widespread, albeit relatively low, exceedance of critical atmospheric inputs, an analogue to CLs. The study has so far focused on the open Baltic Sea, whereas the most sensitive areas with respect to eutrophication are the coastal zones, which should therefore be included in future work. Also, the cost-effectiveness of control options for each input category including aquatic sources should be considered for reduction strategies in future.

71.   Lastly, one highly sensitive aspect of emission compiling and reporting activities is improvement of knowledge and accuracy of particulate emissions and particulate compounds. Estimating the condensable part of organic PM remains a sensitive challenge that the Convention will have to face, since it can have an impact on policy decision (compliance with emission objectives, objectives in emission ceilings, sector priorities).

72.   Regarding the tools developed by the Convention's science bodies, accuracy and reliability of the models, including improved resolution, remain recurrent questions solved progressively with improved knowledge of physicochemical processes, better description of emissions (and their spatial distribution) and higher computing capacities. Nowadays, multiscale modelling systems can be implemented and will play an important role in future development priorities. Moreover, within the Convention framework, consistency and interoperability between air pollution and effect models must be further developed.

73.   Lastly, to increase the Convention's visibility and confidence in the scientific work carried out thereunder, thanks to new information technologies and high interest of the users in the Parties, tools and data developed under the Convention framework must be compliant with open science objectives, linking researchers, institutional and policy stakeholders, and sometimes the general public. Even though some initiatives have already been implemented by EMEP and Working Group on Effects bodies to facilitate access to their models, simulations and observations, a strategy to further develop open access to Convention products will have to be formalized.

Issue of condensables

74.   Condensable primary organic aerosol emissions are a class of organic compounds that are vapour phase at stack conditions, but that undergo both condensation and evaporation processes as the stack air is cooled and diluted upon discharge into ambient air. Emission factors measured in or close to the high-temperature high-concentration exhaust stack or pipe may misrepresent, and even miss, the amount of PM or gas that actually enters the atmosphere, depending on the filters, dilution and sampling conditions of the emission measurement. In current emission reporting to EMEP/the Convention, it is unclear whether condensable organics are included and, if so, to what extent.

75.   The current situation regarding reporting of PM emissions and condensables can lead to different health estimates and different reduction obligations between countries per unit of wood burned, since, for the same activity, very different PM emission factors are found in national reporting from different countries. Assumptions behind these national emission estimates are often not transparently documented, and methods can change from year to year, since no clear guidelines have been provided in the Guidebook, at least for the residential sector – a major contributor to PM emissions. There is an historical background linked to the fact that current product emission standards for residential heating are defined in regulations linked to the environmental performance of residential heating systems (e.g., in the eco-design regulation in European Union, tested in laboratory conditions and are not fully representative for emissions (including condensables) at real use of the appliance.

76.   A large part of current uncertainties in PM emissions relate to the way condensable fractions are or are not taken into account. Estimation and measurements of emission factors with condensable (for which no standard holds currently in Europe) is a part of the question; evaluation of activity data (fuel use, types and ages of appliances, description of use and practices) is the other challenge. Furthermore, numerous uncertainties remain regarding geographical distribution of wood firing emissions.

77.   In 2020 and 2022, brainstorming workshops respectively supported by the Nordic Council of Ministers and the European Commission allowed the definition of a stepwise approach based on the following principles:

        (a)   For modelling purposes, and particularly in the perspective of possible future revision of protocols, it is essential to use PM emission data accounting for the condensable fraction. Neglecting this component could lead to misinterpretation in the actual assessment of sectors' contributions in the countries themselves (and the part of residential heating compared to other sectors), and the relative impacts of neighbouring countries for a given location (source-receptor matrices). It would also result in a less optimal allocation of new emission reduction targets;

        (b)   For modelling purposes, an alternative emission inventory is used. It is based on a mix of official reported PM emissions when they include condensables, and science expert estimates when they do not include condensables. Expert estimates are based on a meta-analysis of the literature, updated statistics and surveys and interactions with national experts. Expert estimates should be gradually replaced by official reported emissions as they improve;

        (c)   To improve knowledge about the condensable part of PM emissions in the various countries, scientific projects and measurement fields campaigns will develop and their results will be gathered and discussed by the EMEP communities to support information-sharing. A database compiling emission factors issued from the meta-analysis carried out in 2021 will be elaborated by the EMEP Centre on Emission Inventories and Projections;

        (d)   Parties that currently do not report information on the condensable component need guidelines and support to help them identify available sources of activity data. A recommendation to help Parties gather activity data through surveys and statistics could be established;

        (e)   The Guidebook will be regularly updated with new knowledge about the condensable component (emission factors and activity data) to support dissemination of good practices in emissions compiling.

78.   Exchanges between modellers, the inventory community and the emission measurement community showed that the process that has been tackled now will be a long stepwise approach, to improve, incrementally, knowledge and tools to deal with the issue of condensables. However, it is accepted by all the Parties. Modelling results provided by MSC-W and the International Institute for Applies Systems Analysis have already improved, with alternative emission inventories accounting for a condensable component. Uncertainties in modelling results are acceptable if they are understood and if the evaluation process is kept transparent and comparable.

79.   The United States of America has already implemented a countrywide approach of harmonized reporting, which does not distinguish between condensable and filterable but

specifies conditions of measurements. A residential wood combustion emission reporting tool, with standardized activity data and emission factors (for 22 types of appliances), has been developed to support this approach and could inspire further developments under the Convention.

Improvements in modelling and monitoring

80.   The improved resolution used over recent years 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 also represent urban background scale. 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 $0.1° \times 0.1°$ or 50km x 50km gird alone, the higher resolution results will result in somewhat higher exposure and larger distance to WHO target.

81.   The overall differences in "blame matrices" due to different model resolutions for the country-to-itself contribution are small for depositions (a few per cent), but somewhat larger for PM and O_3 (up to 11 per cent). For individual transboundary contributions, differences can be larger, especially when 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.

82.   Considering hemispheric transport assessments, it should be noted that global models still disagree strongly on the magnitude of the pre-industrial to present-day trend in ground-level O_3 and tend to underestimate the magnitude of the observed trend. Projection of the contribution of hemispheric background O_3 to the attainment of future targets using current models remains highly uncertain.

83.   Regional O_3 models generally performed better in comparison to observations than did global O_3 models, which generally have lower spatial resolution than regional models. However, the best performing global models compared better to observations than did the worst performing regional models.

84.   Technical challenges for improved global simulations of ground-level O_3 for the ECE region include more accurate simulation of the global methane lifetime, better resolution of the NO_x chemistry of ship exhaust plumes, and better representation of O_3 deposition to vegetation.

85.   Model intercomparison studies (e.g., the Hemispheric Transport of Air Pollution, the Chemistry-Climate Model Initiative or the Aerosol Chemistry Model Intercomparison Project 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 extraregional emission sources on O_3 impacts in the ECE region.

86.   In addition to model development, ongoing provision of high quality emission inventories and expansion of the global network of O_3 observations for model evaluation are required.

87.   Regarding the EMEP monitoring network, the major problem is that there are hardly any (long-term) EMEP observations in Eastern Europe, the Caucasus and Central Asia and the Western Balkans. 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.

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

Open access to data and visibility

89.   Data infrastructures are increasingly governed by general service providers managed by FAIR principles (Findable, Accessible, Interoperable and Reusable data) and open data

sharing should become the default for the results of European Union-funded scientific research. Open access to models, model results and observations should develop into the Convention to stimulate use of this material for research activities and national assessments and support improvement of those tools. Moreover, Convention achievements could be a source of inspiration for other regions and conventions, especially regarding the work of the future task force on international cooperation on air pollution. However, such objectives raise several questions related to the data and intellectual property rights, reuse of data and tools, responsibility and licensing that are not completely resolved. Setting up a robust and efficient framework for supporting open access to Convention tools will take up an important part of the scope of the Convention's future science strategy.

VI. Canada and the United States of America

90.   Canada and the United States of America have assessed the human health and environmental effects of air pollution and have developed regulatory programmes and voluntary measures that have significantly reduced emissions. Accordingly, concentrations of $PM_{2.5}$ and O_3 have declined, as well as sulfur and N deposition.

91.   Emissions from both Canada and the United States of America affect air pollution in the border region. In order to quantify the exposure-related effects of transboundary O_3 and $PM_{2.5}$, the technical review and analysis of the Canada - United States Air Quality Agreement will show an assessment of the population-weighted concentration of O_3 and $PM_{2.5}$, which indicates that O_3 and $PM_{2.5}$ concentrations have declined in the border region.

92.   Emissions of ammonia are of concern in Canada and the United States of America, as atmospheric ammonia is a key precursor to $PM_{2.5}$ formation and contributes to acid deposition and eutrophication. Both countries have a long history of cooperation on monitoring and assessment of acid deposition, including under the 1991 Canada - United States Air Quality Agreement. While much progress has been made in the last two decades in reductions of other precursors to $PM_{2.5}$ such as NO_x and SO_2 (with the reduction in the latter leading to continued reduction of sulfur deposition, see figure 11 below), ammonia emissions and concentrations have continued to rise in both countries, with the agricultural sector being the dominant source of ammonia (see figure 12 below). Recent measurements and modelling in the United States of America have also shown that sensitivity of $PM_{2.5}$ to ammonia varies significantly by region. One ammonia workshop (Ottawa, 10 October 2018), involving participants from Canada, the United States of America and Europe, generated key messages regarding health and environmental impacts of ammonia, as well as tools and approaches available for mitigation. More detailed assessments are needed to quantify these impacts and assess opportunities for abatement. Both countries have continued to reduce SO_2 emissions, leading to continued reduction of sulfur deposition (see figure 12 below).

93.   For further information on the Canadian/United States of America approach to addressing transboundary air pollution, see the Review and Assessment Report of the Canada - United States Air Quality Agreement (expected in late 2022/early 2023).
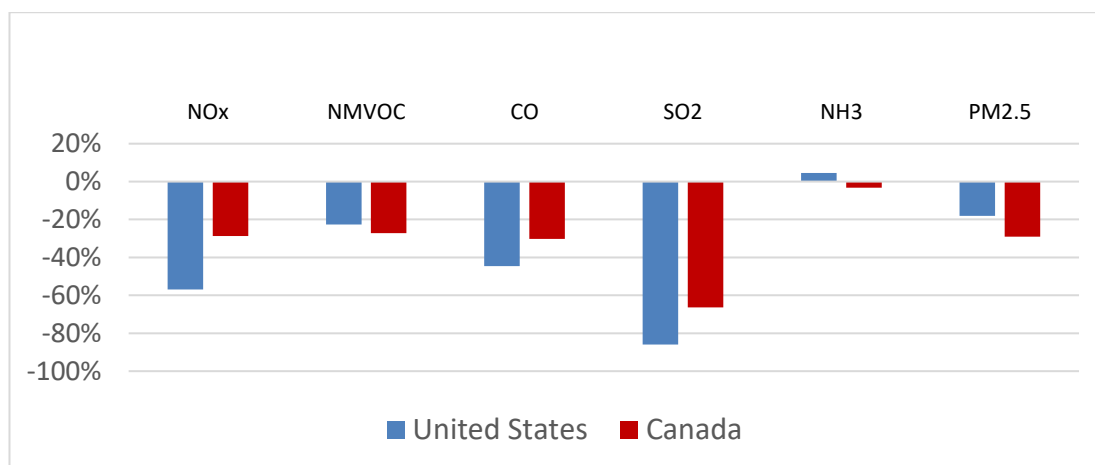
Figure 11
Reduction in SO₂ emissions by Canada and the United States of America, 1990 compared to 2019
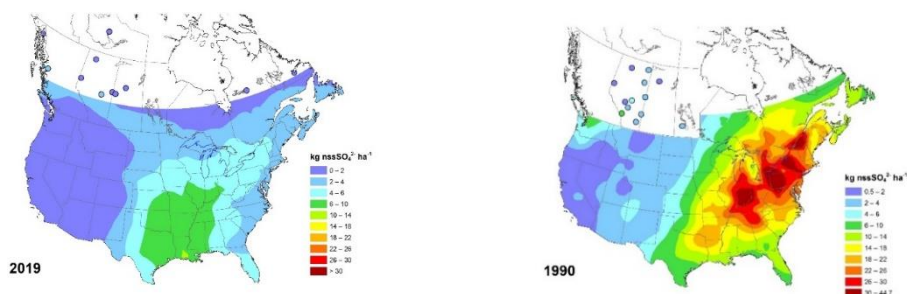
Source: Canada-United States Air Quality Agreement Progress Report, 2020-2022

Figure 12
United States of America (blue) and Canada (red) national emissions, change from 2005 to 2019, as reported
(Percentage)

Source: Centre on Emission Inventories and Projection, Data viewer. Available at www.ceip.at/data-viewer.[24]

Notes: The trend in reported NH_3 emissions of the United States of America is uncertain due to methodological changes during the period 2005–2019. For $PM_{2.5}$, the information provided for Canada reflects the obligations for which Canada has made commitments under the Protocol.

---

[24] https://www.ceip.at/data-viewer and Canada's Air Pollutant Emissions Inventory Report 1990-2022 https://publications.gc.ca/collections/collection_2022/eccc/En81-30-2020-eng.pdf.