Questions to TF HTAP for the Review of the Gothenburg Protocol

The review of the Gothenburg Protocol (GP) currently consists of an annotated outline structured into several chapters, each with a different focus. Each chapter consists of several questions assigned to different subsidiary bodies under the LTRAP Convention. Subsidiary bodies have been invited to include additional information in their answers to these questions as appropriate.

TF-HTAP has been assigned to contribute to answers under two different chapters: one chapter with a specific focus on hemispheric transport; and another with a more general focus on measurement and modelling activities contributing to the LRTAP Convention. TF-HTAP will initially focus on providing self-contained answers to all of its assigned questions under the chapter on hemispheric transport.

In this document, the questions assigned to TF-HTAP have been grouped into four topics, around which we plan to structure the GP review chapter focused on hemispheric transport.

Instructions to Readers and Contributors

*Italics*

Notes in italics identify the chapters of the GP review to which topics were assigned, and the subsidiary bodies under the LRTAP Convention that were asked to address each question under those topics. Information from each of the bodies will be integrated to formulate a full answer. Recognizing that other subsidiary bodies may be better positioned to answer aspects of each question, the TF HTAP leadership team has highlighted what aspect of the question we believe the TF HTAP is best suited to address.

- **Bullet Points**
  
  Bullet points are intended to be summary statements that capture the most important points of each answer. The text and citations that follow the bullets are intended to provide further details and references.

**Duplication**

We realize that there is some degree of overlap between these topics and questions. We expect that this duplication will be reduced once all subsidiary bodies of the LRTAP convention have provided their initial input.
Topic 1: Contribution of hemispheric transport to observed trends in air quality and its impacts, and future projections

This topic consists of two questions posed by the WGSR, each assigned to different chapters of the GP review. Question 3.2 was assigned to the hemispheric transport chapter, and question 2.1 was assigned to a chapter on the measurement and modelling activities of the convention. The hemispheric transport chapter of the GP review will begin with an answer to question 3.2 that also answers the elements of question 2.1 concerning hemispheric transport.

Questions under this topic

Question 3.2: What is the current contribution and will be the expected future contribution of emission sources outside the UNECE region to ecosystems and health impacts in the UNECE region, in particular for ozone, PM (and BC)?

This question was assigned to TF HTAP and MSC-W.

Question 2.1:
  a) What are the observed and projected trends in air quality for ozone, SO2, PM (species) and oxidised and reduced nitrogen (in the UNECE region)?
  b) To what extent are these trends associated with emission trends in the region or dependent on transcontinental transport of air pollutants?
  c) What are the observed and projected trends in urban air quality? What is the contribution of long-range transport to air pollutant concentrations in cities? What is the distance to the WHO air quality guideline values (including to updated values, if available on time)?

This question was assigned to MSC-W, TFMM, TF HTAP, TFIAM, and EPCAC. Observed and projected trends at the regional and urban scales in the EMEP region will be addressed best by CCC, TFMM, MSC-W, TFIAM, and EPCAC. Observed and projected trends in North America will be addressed best by the United States and Canada. For purposes of addressing this question, TF HTAP should focus on placing the observed and projected regional trends into the context of observed and predicted trends outside the UNECE region and at the global scale.

Summary of the TF-HTAP contribution to this topic

- The annual average background mixing ratio of ground-level ozone in the UNECE region has risen by about 10 ppb since the availability of reliable measurements in the 1970s, appears to have levelled off since around 2000, and may currently be in a slight downward trend.
- This observed trend in ground-level ozone and its impacts cannot be explained completely by precursor emission trends in the UNECE region. Downward trends of ozone precursor emissions in the UNECE region since around 1990 appear to be at
least partially offset by increasing emissions outside the UNECE region and associated intercontinental transport of ozone.

- Projected future trends in background ground-level ozone in the UNECE region are highly influenced by transcontinental transport. The contribution of emissions of NOx and NMVOCs outside the UNECE region to the impacts of ground-level ozone is expected to decrease in the future due to projected reductions in emissions of these species outside the UNECE region, but these reductions may be at least partially offset by global increases in methane.

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

Further explanation of the TF-HTAP contribution to this topic

Observed Trends

O₃ observations through 2014 collected for the global Tropospheric Observation Assessment Report (TOAR) showed that peak O₃ values strongly decreased in North America and Europe, and strongly increased in parts of East Asia. However, the trends were more mixed for summer daytime average O₃ concentrations in North America and Western Europe, with some sites showing significant increases (Chang 2017; Schultz 2017).

Baseline ozone levels at midlatitude sties on the west coasts of Europe and North America, which reflect the background or in-flow of ozone into UNECE region, show very similar seasonal cycles and long-term trends, increasing before 2000, reaching a maximum in the mid-2000s, and slowly decreasing to the present day (Parrish 2020).
For fine particles, satellite observations over the period 1992-2012 show decreasing trends in North America and Europe and strong increasing trends in South and East Asia (Boys 2014). Analyses of more recent satellite observations have shown decreasing emissions of NO\textsubscript{X} and SO\textsubscript{2} and decreasing PM over East Asia, which have been attributed to the implementation of emissions control policies (Karplus 2018; Liu 2017; Zheng 2018).

**Emissions Trends**

Between 1990 and 2010, anthropogenic emissions of PM increased little globally, but shifted geographically, with a 30% decline in Europe and North America and a 50% increase in Asia (Klimont 2017). Similarly, between 2000 and 2010, global anthropogenic emissions of ozone precursors (NO\textsubscript{X}, CO, and NMVOCs) grew modestly. However, emissions in Europe and North America decreased by 10% to 50% while emissions in South Asia and East Asia and other regions of the world increased by 10% to 50% (Turnock 2018). Globally, anthropogenic CH\textsubscript{4} emissions increased by 17% between 1990 and 2012, with decreases in Europe, little change in North America, and strong increases in East Asia, South Asia, and other regions of the world.
Since 2010, there have been strong decreases in SO2 emissions and significant decreases in NOx, CO, and PM emissions in China. NMVOC emissions have continued to increase outside of Europe and North America, particularly in Africa and Asia. Likewise, NH3 emissions have continued to increase outside of Europe and North America, particularly in East and South Asia (McDuffie 2020).

The changing spatial patterns of emissions globally have shifted ozone precursors into the tropics where ozone production is more efficient. Zhang et al. (2016) suggest that this equatorward shift of emissions has increased the total global ozone burden more than the combined effect of the increase in global methane emissions and the increase in the total mass of non-methane precursor emissions.

Contribution to Observed Trends

Global model simulations of annual average ozone have shown overall declines in Europe and North America since 1990, with overall increases in East and South Asia. In Europe, the contribution of both regional and extra-regional sources declined between 1990 and 2000. In North America, the contribution of regional sources declined, but extra-regional sources remained relatively constant. In both regions, the contribution of methane increased over time offsetting some of the benefits of regional emission control (Wild 2012).
Between 1990 and 2014, in western North America, increases in Asian NOx emissions contributed an estimated 65% to the observed increase in springtime background ozone levels, while increases in global methane contributed an estimated 15%. In summer, increasing Asian emissions approximately offset the benefits of US emission reductions (Lin 2017).

For Europe, ground-level ozone concentrations are more sensitive to anthropogenic emissions outside of Europe than to anthropogenic emissions inside of Europe. This is the case for all European sub-regions, all seasons, and for a range of ozone metrics including annual and seasonal averages, SOMO35, and POD1 (Jonson 2018). The relative influence of these extraregional emissions on ozone in Europe varies by location, season, and ozone metric. Extraregional anthropogenic emissions of NOx and VOCs outside of Europe are estimated to contribute between 2-12 ppb of ozone depending on the season, with an annual average contribution of 4-8 ppb of ozone depending on the model used. The contribution of anthropogenic methane emissions to ozone in Europe is estimated to be about 5-8 ppb (on the basis of 6mDMA1).
For North America, region-wide annual average ozone concentrations appear equally sensitive to anthropogenic emissions outside of North America and emissions inside of North America. Extra-regional anthropogenic emissions of NOx and VOCs outside of North America and changes in global methane, together, are estimated to contribute between 8-13 ppb of ozone in the western United States, 2-12 ppb of ozone in the central United States, and 2-10 ppb of ozone in the eastern United States, depending on the season.

Although ozone concentrations are more sensitive to extra-regional sources than are PM concentrations, PM concentrations have a larger impact on mortality. Considering PM2.5 and O3 mortality effects together in regional models for Europe and North America, Im et al. (2018) found that a 20% decrease in global anthropogenic emissions of non-methane precursors of ozone and PM would result in a decrease of 54,000 and 27,500 premature deaths in Europe and North America, respectively. In Europe, 87% of the reduced deaths were associated with emission decreases within Europe, 2% were associated with decreases in North America, and 11% were associated with decreases in the rest of the world. In North America, 90% of the reduced deaths were associated with emission decreases in North America, with the remaining 10% due to emission decreases elsewhere.

Liang et. al. (2018) found similar results to Im et al (2018) using an ensemble of global models. In contrast to the findings in HTAP (2010), Liang et al. (2018) found that emission decreases in North American and Europe resulted in more ozone related deaths inside those regions than outside those regions. However, Europe, as well as the regions of Russia and Belarus and the Middle East, had more avoided deaths due to decreases of extra-regional emissions of O3 precursors than decreases in regional emissions.

**Contribution to Projected Trends**

Turnock et al. (2018) found that annual average surface ozone concentrations in 2050 in Europe and North America are expected to be relatively similar to 2010 under a current legislation scenario, despite strong decreases in regional NOx emissions. In both Europe and North America, the contribution of extra-regional sources of non-methane precursors does not change much, but an expected increase in global methane concentrations offsets the decreases in regional emissions. Under a climate policy scenario, the increase due to methane emissions is not as high, North America benefits from decreased regional contributions, and Europe benefits from decreased extra-regional contributions. Under a maximum technically feasible scenario, the contributions of regional, extra-regional, and methane sources are all decreased, with the largest decreases coming from the control of extra-regional sources.
Turnock et al. (2020) describe the changes in ground-level ozone throughout the 21st century from the ensemble of CMIP6 models, based on emissions from SSPs 1, 2, 3, and 5. Surface ozone decreases in the UNECE region under SSPs 1 and 2, and either increases or stays roughly constant (depending on the world region) under SSPs 3 and 5. Short-lived ozone precursors (NOx and NMVOC) generally decrease in SSP5 and increase in SSP3. Increasing ozone in the SSPs is thus linked to increasing methane. A similar result was seen in the CMIP5 model ensemble using the RCP scenarios, in which short-lived ozone precursors decreased in all scenarios, but surface ozone increased in RCP8.5, the only scenario in which methane increased (Young et al. 2013).

References


Young et al. (2013) [https://doi.org/10.5194/acp-13-2063-2013](https://doi.org/10.5194/acp-13-2063-2013)


Topic 2: Projected trends in methane, contribution to ground-level ozone, and mitigation potential

The one question under this topic is assigned to the hemispheric transport chapter of the GP review.

Questions under this topic

Question 3.3: What is the projected future trend in methane emissions? What is the impact on ozone formation? In which regions and in which sectors outside the UNECE region is there potential for emission reductions that have a significant effect on reducing ozone effects in the UNECE region?

This question was assigned to TF HTAP and MSC-W, however input from TFIAM will be essential to providing an answer.

Summary of the TF-HTAP contribution to this topic

- Projected future 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.
- 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.
- Due to the long lifetime of methane in the atmosphere, methane is well mixed. Equal emission reductions in any given regions will lead to the same reductions in global background ground-level ozone.
- The fossil fuel 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 UNECE region there is currently potential for reducing methane emissions from the waste sector in China and the fossil fuel sector in the Middle East.

Further explanation of the TF-HTAP contribution to this topic

Methane concentrations have been increasing at a rate of about 6 ppb per year in 2007-2013 and accelerating to 10 ppb per year during 2014-2018 (Dlugokencky 2020).

Approximately half of global methane emissions are anthropogenic, with the anthropogenic methane emissions being generally better constrained than natural emissions by both bottom-up and top-down methods (Saunois et al. 2020). Projected trends in anthropogenic emissions of methane have been provided for the CMIP5 and CMIP6 exercises in the form of the RCP
(Representative Concentration Pathways) and SSP (Shared Socioeconomic Pathways) scenarios respectively. The SSPs are described and compared with the earlier RCPs by Gidden et al. (2019). Figure 1 shows the projected emissions of methane for the RCP and SSP scenarios until 2100.

![Global CH4 emissions](image)

**Figure X: Methane emissions projections from the RCP and SSP scenarios (Gidden et al. 2019, Figure3)**

There is no single projected future trend in methane emissions; the RCP and SSP scenarios span a wide range, depending on assumptions of socioeconomic development and mitigation levels. Methane emissions decrease (compared with the present day) in baseline versions of SSPs 1 and 2, and increase in baseline versions SSPs 3, 4, and 5. In the earlier RCP scenarios, methane emissions increase in RCP 8.5 and decrease or stay roughly constant in all three other scenarios. Trends in projected emissions from the energy and agricultural sectors dominate the projected future trends in methane emissions. Scenarios in which methane emissions decrease can be characterised either by a phasing out of reliance on fossil fuels or stronger mitigation measures. Scenarios in which methane emissions increase are characterised by increasing unmitigated emissions primarily from the energy and/or agricultural sectors.
Figure X: Emission scenarios of anthropogenic methane until 2050 from Höglund et al. (2020).

Butler et al. (2020) recently estimated that methane oxidation contributes to 40% of the annual average present-day northern hemisphere concentration of ground-level ozone. Turnock et al. (2020) describe the changes in ground-level ozone throughout the 21st century from the
ensemble of CMIP6 models, based on emissions from SSPs 1, 2, 3, and 5. Surface ozone decreases in the UNECE region under SSPs 1 and 2, and either increases or stays roughly constant (depending on the world region) under SSPs 3 and 5. Short-lived ozone precursors (NOx and NMVOC) generally decrease in SSP5 and increase in SSP3. Increasing ozone in the SSPs is thus linked to increasing methane. A similar result was seen in the CMIP5 model ensemble using the RCP scenarios, in which short-lived ozone precursors decreased in all scenarios, but surface ozone increased in RCP8.5, the only scenario in which methane increased (Young et al. 2013).

In Europe, changes in emissions outside Europe and global methane concentrations will largely drive future annual average O3 levels. Without additional controls, global methane emissions are expected to grow, increasing O3 mortality in Europe in 2050 by up to 8,000 additional premature deaths compared to 2010 levels. Implementation of mitigation policies, largely outside of Europe, can decrease methane emissions overall and decrease O3 mortality in Europe by up to 2000 premature deaths per year compared to 2010 levels, a difference of 10,000 deaths per year between the highest and lowest global CH4 emissions scenarios. In North America, the difference between the highest and lowest global CH4 emissions scenarios corresponds to a difference of up to 5,000 deaths per year in 2050. The sectors with substantial mitigation potential are fossil fuel production, waste and wastewater management, and agriculture, with the largest emissions in China, followed by Latin America, Africa, India, and North America (vanDingenen 2018).

References


Gidden et al. (2019) https://doi.org/10.5194/gmd-12-1443-2019


Young et al. (2013) https://doi.org/10.5194/acp-13-2063-2013
**Topic 3: Projected trends in international shipping, contribution to ground-level ozone and N deposition, and mitigation potential**

*The one question under this topic is assigned to the hemispheric transport chapter of the GP review.*

**Questions under this topic**

**Question 3.4:** What is the projected future trend in NOx-emissions from shipping? What is the impact on ozone formation and nitrogen deposition? What and where is the potential for emission reductions that have a significant effect on reducing ozone effects in the UNECE region?

*This question was assigned to TF HTAP and MSC-W. MSC-W and TFIAM have done recent work on the impacts of shipping on the EMEP region. TF HTAP can provide additional context from HTAP2 experiments and from the literature. TF HTAP is also performing new analyses that may provide additional insights about the role of shipping activity beyond coastal regions.*

**Summary of the TF-HTAP contribution to this topic**

- 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 shipping NOx as a proportion of global anthropogenic NOx emissions (currently at about 30%) is projected to vary between 10% and 60%, by the end of the century depending on the effectiveness of land-based NOx emission control.

- Projections of the future effects of shipping NOx on ground level ozone and N deposition in the UNECE region are currently lacking. Models show low agreement on the present-day effects of shipping NOx on ground-level ozone, but do agree that extra-regional sources account for up to half of N deposition in coastal regions, strongly indicating a role for shipping NOx.

- Due to the short lifetime of NOx, it seems likely that reduction of emissions of ship NOx near coastlines has a high potential to reduce N deposition. There are some indications that the global springtime maximum in intercontinental transport of ozone is influenced by shipping NOx emitted over the high seas, but further model studies are needed to determine the strength of this influence.

**Further explanation of the TF-HTAP contribution to this topic**

Absolute NOx emissions from shipping in the SSP scenarios tend to decrease in the 21st century, at a rate depending on the socioeconomic development pathway assumed (Rao et al. 2017). In SSPs 1 and 3, which are characterised by deglobalisation, NOx emissions decrease faster than in SSPs 2 and 5, which are characterised by increasing globalisation. Shipping NOx
emissions as a proportion of total global NOx emissions decreases in SSPs 1 and 3, stays roughly constant in SSP5, and increases from ~30% to 60% by 2100 in SSP2, due to the combination of high shipping volumes and stronger reduction of land-based NOx emissions in SSP2 (Fig. X).

![Graph showing shipping emissions of NO and their percentage of total global emissions over time](image)

**Figure X:** Absolute emissions of NO from international shipping in the SSP scenarios (left) and ship NO as a percentage of total global emissions (right). Figures prepared by A. Nalam (IASS Potsdam) based on SSP scenario emissions as described by Rao et al. (2017)

We are not aware of any studies specifically examining the effects of ship NOx on ozone or N deposition using the SSP scenarios. Several studies have examined these effects in the present day or recent historical periods.

Butler et al. (2020) noted a strong contribution of ship NOx to the springtime maximum in long-range transboundary ozone in all regions of the northern hemisphere, and a strong contribution of ship NOx to European summer ozone, the latter most likely due to nearby NOx sources. Jonson et al. (2018) compared the predictions of several models for ozone in Europe and found a high degree of variability in the contribution of ship NOx across different models. Representation of chemistry and dilution in ship plumes is currently a weakness of global models (see the answer to Question 2.7).

We are not aware of any studies attributing ozone or N deposition to ship NOx from different world regions using models at the global or hemispheric scales. Butler et al. (2020) and Jonson et al (2020) both suggest that NOx emissions over the high seas have a strong influence on European surface ozone, especially in the springtime.

The sensitivity of the deposition of sulfur (S), oxidized nitrogen (NOy), and reduced nitrogen (NHx) to changes in extra-regional anthropogenic emissions is similar to the sensitivity of PM2.5 concentrations. Using the results of 11 global models, the RERER for S deposition in Europe...
was estimated to be 0.36 averaged regionally, with values of 0.53 for coastal areas and 0.27 for non-coastal areas. The RERER for NOy deposition in Europe is 0.34 (0.48 for coastal areas, 0.27 for non-coastal areas). For NHx deposition, the RERER across Europe in 0.12 (0.22 in coastal areas, 0.09 for non-coastal areas). In North America, the RERERs are smaller and show a similar pattern: for S deposition, 0.17 overall (0.40 in coastal areas, 0.12 in non-coastal areas); for NOy deposition, 0.17 overall (0.43 in coastal areas, 0.12 in non-coastal areas); and for NHx deposition, 0.07 overall (0.31 in coastal areas, 0.05 in non-coastal areas). The larger sensitivity in coastal areas may be due to the location of coastal areas in proximity to upwind sources, including maritime shipping, and differences in deposition processes in coastal regions.

In North America, 83% of S deposition, 83% of NOy deposition, and 93% of NH3 deposition are due to sources within North America. In Europe, the fractions are 64%, 66%, and 88% for S, NOy, and NHx deposition, respectively. However, in the region defined by Russia, Ukraine, and Belarus, only 39%, 41%, and 45% of S, NOy, and NHx deposition, respectively, are due to emissions within the region. The percent of emissions transported and deposited outside each of the priority source regions is shown in Table 2.

<table>
<thead>
<tr>
<th>Source Region</th>
<th>S</th>
<th>NOy</th>
<th>NHx</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>31%</td>
<td>29%</td>
<td>12%</td>
</tr>
<tr>
<td>Europe</td>
<td>40%</td>
<td>34%</td>
<td>17%</td>
</tr>
<tr>
<td>Russia/Belarus/Ukraine</td>
<td>38%</td>
<td>39%</td>
<td>23%</td>
</tr>
<tr>
<td>East Asia</td>
<td>27%</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>South Asia</td>
<td>34%</td>
<td>34%</td>
<td>15%</td>
</tr>
<tr>
<td>Middle East</td>
<td>58%</td>
<td>46%</td>
<td>51%</td>
</tr>
</tbody>
</table>

Table 2. Percent of emissions in a source region transported out of the region and deposited elsewhere (Tan 2018).

References


Topic 4: Sufficiency of atmospheric modelling for understanding hemispheric transport of air pollution, and the main requirements for improving simulation of hemispheric transport

Both questions under this topic are assigned to a chapter in the GP review devoted to the measurement and modelling activities of the convention. TF-HTAP will also cover the hemispheric aspects of this topic in the chapter on hemispheric transport.

Questions under this topic

Question 2.6: What has been the influence of improved atmospheric modelling (e.g. the higher spatial resolution) on the effectiveness of emission reductions for air quality improvement and deposition? Did this increase the challenge to meet environmental quality and health targets?

This question was assigned to MSC-W and TF HTAP. MSC-W is best equipped to comment on how improvements in the EMEP model have changed estimates of source-receptor relationships and the estimated effectiveness of emission reductions at the regional scale. TF HTAP should focus on how model improvements have changed estimates of intercontinental transport and the contribution of extra-regional emissions sources to impacts within the UNECE region.

Question 2.7: Is the monitoring and modelling system of the Convention sufficient to observe, assess and project air pollution and its effects related to the Gothenburg Protocol in the UNECE region? If not, what are the main challenges and what is needed to meet them?

This question was assigned to all of the bodies under WGE and EMEP. TF HTAP should focus on the sufficiency of available models, emissions inventories, and observational data at the global scale to provide estimates of the impact of extra-regional emission sources on impacts in the UNECE region.

Summary of the TF-HTAP contribution to this topic

- For simulation of background ground-level ozone, global models have not improved significantly in the last decade. Multi-model intercomparisons show a very large spread in simulated surface ozone, which has not improved with higher spatial resolution and other model developments. As an ensemble, global models tend to overestimate available surface observations.
- The source/receptor relationships for ground-level ozone from the HTAP2 multi-model exercise were not significantly different from those of the HTAP1 exercise, despite developments in individual models and closer harmonisation of the model configurations involved.
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.

Regional ozone models generally performed better in comparison to observations than did global ozone 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.

Technical challenges for improved global simulations of ground-level ozone for the UNECE 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 the CCMI, AerChemMIP, and HTAP 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 UNECE region.

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.

Further explanation of the TF-HTAP contribution to this topic

Sufficiency of atmospheric models for understanding hemispheric transport

In HTAP2, the differences in predictions of particulate matter concentrations from different models decreased relative to the HTAP1 but this was not the case for ozone concentrations. The lack of improvement in model agreement for ozone was surprising given that all HTAP2 models used the same emissions inputs, whereas in HTAP1 emissions inputs were not harmonized. More work is needed to understand the processes contributing to the spread in model predictions, but analysis to date suggests that differences in the vertical transport and deposition processes between models may be resulting in this spread. Higher resolution regional models generally performed better in comparison to observations than did the coarser resolution global models. However, the best performing global models compared better to observations than did the worst performing regional models (Solazzo 2016, Solazzo 2017).

A large inter-model spread in modelled surface ozone was also noted by Young et al. (2013) from the ACCMIP study (their Fig. 3). More recently, Turnock et al. (2020) also noted a large spread in surface ozone from models contributing to CMIP6 (their Fig. 4, reproduced below as Fig. X).

Parrish et al. (2014) provides a detailed comparison of observed and modelled long-term trends for the northern mid-latitudes. Models tend to underestimate the long-term (multi-decadal) changes in surface ozone. Turnock et al. (2020) showed that the CMIP6 models disagree
strongly on the modelled pre-industrial to present-day trend of surface ozone (their Fig. 9 reproduced below as Fig. X).

Lin et al (2015) found that sampling frequency and distribution of ozone profile observations may account for some of the differences between observed and model estimates of ozone trends in western North America. When corrected for the uncertainty in data representativeness, the observational trend estimate and modeled trend estimate overlapped.

Figure X: Figure 4 from Turnock et al. (2020) showing CMIP6 model ensemble comparison with TOAR observations.

Figure 4 – Individual and multi-model (5 CMIP6 models and HTAP_param) monthly mean surface \( \text{O}_3 \) concentrations across different world regions compared with the regional monthly values from all the TOAR observations within the region for the period 2005-2014. The number of observations within a region is shown in parenthesis. The shading shows variability in observations across all sites within the region.
Main requirements for improved simulation of hemispheric transport

Models can simulate European rural background ozone sufficiently with ~15x15km resolution (Schaap et al. 2015). Regional chemical transport models for Europe are commonly run at this resolution or even higher. Simulation of intercontinental transport requires the use of global models, which are not commonly run at resolutions finer than the order of about 100km resolution. In the HTAP1 multi-model exercise, models were run with resolutions of about 200x200km, and in the subsequent HTAP2 exercise, the finest resolution for a global model increased to about 50x50km. There is still scope for improvement in the spatial resolution of global models for the simulation of background ozone.

Given the possible importance of NOx emissions from shipping for long-range transport of ozone into the UNECE region in springtime (see Topic 3), global models require improved treatment of the chemistry of ship exhaust plumes to sufficiently assess and project the impact
of ship NOx emissions. The relatively coarse resolution of global models is not sufficient to
resolve the small scale of ship exhaust plumes (Kasibhatla, 2000, von Glasow 2003). In effect,
ship NOx emissions in global models are instantaneously diluted into large grid cells which are
otherwise relatively low in NOx. This increases the modelled lifetime of NOx and the ozone
production over the oceans, leading to overestimation of the effect of ship NOx on ozone
production. Approaches have been developed to account for the high-NOx chemistry of ship
exhaust plumes in the otherwise clean marine boundary layer (eg. Vinken et al. 2011), but these
have not been widely implemented in current generation global models.

Given the importance of methane oxidation as a precursor for ground-level ozone (see Topic 2),
the large spread in modelled tropospheric methane lifetimes in the current generation of global
models is another challenge. This spread has been around 7-10 years in several recent model
intercomparison exercises (Saunois et al. 2020). Such a spread in modelled methane oxidation
rates could be expected to lead to a large uncertainty in modelled ozone production due to
methane oxidation in these models, but no model intercomparison exercise has yet quantified
this uncertainty.

The mechanistic representation of the multiple pathways of ozone deposition and associated
atmosphere-vegetation feedbacks is currently highly simplified in current global models (eg.
Sadiq et al. 2017, Lin et al. 2019, Clifton et al. 2020). Ozone deposition to vegetation is also a
major cause of damage to crops and ecosystems (Emberson et al. 2013). Improvement of the
representation of ozone deposition processes in models will lead to improved estimates of
ozone impacts on both vegetation (through improved deposition flux estimates) and human
health (through improved concentration and exposure estimates).

Model intercomparison exercises are an important method for understanding the uncertainties in
state-of-the-art models, and thus their limitations for assessment and projection of air pollution
and its effects. Such exercises can reveal deficiencies in models and point the way towards
improvements. A regular cycle of model intercomparison exercises allows the tracking of
improvements in models and how these translate into better assessment and projection of air
pollution and its effects. Intercomparison exercises may be ongoing exercises with a focus on
process representation and model evaluation (eg. CCMI, Duncan et al. 2016), may focus on
chemistry-climate interactions and periodically feed into IPCC assessments (eg. Lamarque et al.
2013, Collins et al. 2017), or may be specifically designed to quantify intercontinental transport
of air pollution and feed into the processes and timelines of the LRTAP Convention (HTAP
2010, Dentener et al. 2017). Ongoing and coordinated model intercomparison exercises are
vital for continuous assessment of the sufficiency of state-of-the-art models for informing the
LRTAP convention on air pollution and its effects related to the Gothenburg Protocol in the
UNECE region.

Accurate emission inventories are vital for accurate model assessment of air pollution and its
impacts. For assessment of intercontinental transport of ozone, emission inventories must be
accurate both within and outside the UNECE region. Mosaic inventories such as the EDGAR-
HTAPv2 inventory (Janssens-Maenhout 2015) combine detailed regional inventories in a
consistent global framework and are especially useful for assessment and projection of intercontinental transport of air pollution.

Global models do not currently produce all features of the observed distribution and trends in ground-level ozone (see the answer to Question 2.6). Ongoing efforts to collect, synthesise, and distribute ozone observations and associated metrics for model evaluation both within and outside the UNECE region such as the TOAR project (Schultz et al. 2017) are vital for continued evaluation and improvement of models.

References


Parrish et al. (2014) https://doi.org/10.1002/2013JD021435


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