



HTAP3-OPNS: Ozone, PM, Nitrogen and Sulphur Deposition - multi-model experiments to support the revision of the CLRTAP Gothenburg Protocol

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Abstract. HTAP3-OPNS is a multi-model exercise designed to support the revision of the Gothenburg Protocol under the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP). Using an ensemble of Chemical Transport Models (CTMs) and Chemistry-Climate Models (CCMs), this study investigates the long-range transport and impacts of ground-level ozone, particulate matter (PM), and nitrogen and sulphur deposition across different global regions. The project aims to assess the contributions of regional versus extra-regional emission sources, evaluate the suitability of current models, and project changes in air pollution under future emission scenarios and climate conditions. A series of perturbation simulations will enable the development of an ensemble emulator to explore and evaluate potential mitigation strategies efficiently. This paper outlines the scientific and policy questions motivating the study, describes the experimental design, including input



40 datasets, model configurations, and required outputs, and discusses methodologies for data handling and analysis. The results
41 will provide crucial insights for policy decisions aiming to improve air quality, protect human health, and protect ecosystems
42 worldwide.

43 **1 Introduction**

44 The 1999 Gothenburg Protocol (GP) of the United Nations Economic Commission for Europe (UNECE) Convention on Long-
45 Range Transboundary Air Pollution (CLRTAP) was the first international, multi-pollutant, multi-effect agreement aimed at
46 reducing the negative effects of acidification, eutrophication, and ground-level ozone in Europe and North America. Under the
47 GP, national emission reduction commitments were agreed for sulphur dioxide, nitrogen oxides, volatile organic compounds
48 (VOCs) and ammonia, based on cost-effectiveness considerations. In 2012, the GP was amended to include particulate matter
49 and black carbon, broadening its scope to include human health impacts and climate change co-benefits. A recent review of
50 the GP concluded that current air quality legislation in the UNECE region is insufficient to meet CLRTAP's long-term clean
51 air objectives. Furthermore, the review concluded that global reductions in methane emissions would be necessary to achieve
52 these objectives.. The Executive Body (EB) of CLRTAP decided in its December 2023 session to launch the process of revising
53 the GP and requested that the convention bodies contributing to the revisions specifically consider how methane in its role as
54 an ozone precursor could be included in a future version of the GP.

55
56 The Task Force on Hemispheric Transport of Air Pollution (TF HTAP) was organized under the CLRTAP with the mandate
57 to quantify the long-range (hemispheric to global) influence of distant sources of air pollution (including methane) in the
58 UNECE region. Previous HTAP assessments (HTAP1 (HTAP, 2010) and HTAP2,
59 https://acp.copernicus.org/articles/special_issue390.html) have shown that ground-level ozone is significantly influenced by
60 long-range transport at the intercontinental scale and demonstrated the utility of a large ensemble of models for quantifying
61 these effects and their uncertainty. While the primary policy audience of HTAP assessments is CLRTAP and UNECE member
62 states, the work being organised here is also of scientific and policy significance for other world regions. To support the
63 revisions of the GP, TF HTAP is currently organising a new round of multi-model experiments (HTAP3-OPNS) with the goal
64 of quantifying the long-range contribution to ozone, particulate matter (PM), and the deposition of nitrogen (N) and sulfur (S)
65 in different world regions.

66
67 In this document we describe the motivating science and policy questions, the design of the several different sets of experiments
68 to be conducted to answer these questions, the input datasets to be used in carrying out these experiments, and the requested
69 output data fields necessary for the analysis of the experiments and the answering of the science-policy questions.



70 2 Science-policy questions

71 The design of the HTAP3-OPNS multi-model experiments can be summarised by the following overarching questions.

- 72 • What are the contributions of intra-regional and extra-regional sources to air pollution and its impacts in different
- 73 world regions?
- 74 • How suitable are current models for quantifying these contributions?
- 75 • Can we explain the inter-model differences?
- 76 • How will these contributions change under different realistic future emission scenarios and under potential future
- 77 climate change?

78

79 While these overarching questions have also motivated previous HTAP assessments, there are several new aspects in HTAP3-
80 OPNS.

- 81 • A stronger focus on the **impacts** of ground-level ozone, especially concerning damage to vegetation.
- 82 • A stronger focus on the effects of **methane** on ground-level ozone.
- 83 • A stronger focus on the effects of **wildfires** on long-range air pollution.
- 84 • A stronger focus on **total atmospheric deposition**, in support of the World Meteorological Organization (WMO)
- 85 MMF-GTAD (Measurement-Model Fusion for Global Total Atmospheric Deposition) exercise. MMF-GTAD is
- 86 organised by the WMO and aims to provide comprehensive maps of total atmospheric deposition through the fusion
- 87 of all available deposition measurements with an ensemble of model runs.
- 88 • The use of **free-running future simulations** with atmospheric chemistry-climate models in addition to an ensemble
- 89 emulator based on source-receptor relationships.
- 90 • Calculation of source/receptor relationships for air pollution based on a **future emissions scenario** rather than
- 91 historical emissions.
- 92 • Comparison of **different methods for calculating source-receptor relationships**, such as source perturbation,
- 93 tagging and adjoint techniques.

94

95 We also note that HTAP is currently involved in the organisation of two additional multi-model exercises, which are being
96 coordinated with the HTAP3-OPNS exercise:

- 97 • **MCHgMAP** (Dastoor et al., 2024), organised together with the OESG (Open-Ended Science Group) of the Minamata
- 98 Convention, with a focus on mercury and the first effectiveness evaluation of the Minamata Convention.
- 99 • **HTAP3-Fires** (Whaley et al., 2024), organised in cooperation with International Global Atmospheric Chemistry
- 100 (IGAC) BBurned, with a focus on the impacts of wildfires on multiple pollutants (ozone, PM, Hg, POPs).



101 3 Future emission scenarios for the revision of the Gothenburg Protocol

102 The basis for all assessment of future air quality in HTAP3-OPNS is the Greenhouse Gas - Air Pollution Interactions and
103 Synergies (GAINS) LRTAP future emission scenarios, a set of emission scenarios produced using the GAINS model (Amann
104 et al., 2011) of the International Institute for Applied Systems Analysis (IIASA), which serves as the EMEP Centre for
105 Integrated Assessment Modelling (CIAM) under CLRTAP. Version 2.1 of the GAINS LRTAP scenarios was produced
106 specifically to support the revision of the GP and is available for download (Klimont et al., 2025).

107
108 Model assessments in HTAP3-OPNS will use the “CLE” and “MTFR” scenarios from GAINS, as well as a hybrid “HILO”
109 scenario, which are described in more detail below.

- 110 ● CLE “Current Legislation”: This scenario is based on economic activity data broadly consistent with SSP2-4.5 (Riahi
111 et al., 2017) and includes all current and planned air pollution control measures and their implementation timelines
112 globally.
- 113 ● MTFR “Maximum Technical Feasible Reduction”: This scenario is based on the same activity data as CLE but
114 includes full implementation of all air pollution reduction measures (including methane reduction measures) which
115 have been shown to be technically feasible (regardless of their cost effectiveness). Economic activity and associated
116 CO₂ emissions are still broadly consistent with SSP2-4.5.
- 117 ● HILO: In addition to the CLE and MTFR scenarios from GAINS, we construct an additional scenario for the purposes
118 of HTAP3-OPNS combining the air pollutant emissions from MTFR and methane emissions from the CLE scenario.
119 This hybrid scenario represents a policy pathway with high ambition on air pollution control, but with minimal
120 ambition on methane control. Economic activity and associated CO₂ emissions are still broadly consistent with SSP2-
121 4.5, as for both CLE and MTFR.

122 4 Overview of the requested model experiments

123 The model runs in HTAP3-OPNS are organised into three separate sets of experiments designed to answer the questions
124 outlined above.

- 125 ● **Perturbation experiments** with chemical transport models (CTMs) based on the GAINS LRTAP scenarios for the
126 target year 2040.
- 127 ● **Transient Future Scenario experiments** with chemistry climate models (CCMs) using the GAINS LRTAP
128 scenarios from 2010 to 2050.
- 129 ● **Transient Historical experiments** from 2003 to 2020 using a historical global mosaic emission inventory.

130 Modelling groups are requested to choose the sets of experiments to which they wish to contribute based on their capabilities,
131 resources, and scientific interests.

132



133 **4.1 Perturbation experiments for source-receptor relationships and ensemble emulation**

134 As in previous HTAP assessments, we invite groups using global CTMs and CCMs (with specified dynamics from a reference
135 meteorological base year) to perform source perturbation runs for key species/regions/sectors to allow the construction of
136 source-receptor relationships. A key difference with previous HTAP assessments is that the proposed perturbation runs are
137 based on emissions from a future scenario (CLE 2040 from the GAINS LRTAP scenarios) rather than from a historical
138 reference year. The year 2040 is chosen to be consistent with the target year for air quality under the revision of the Gothenburg
139 Protocol. The use of future emissions for the perturbation runs will enable direct construction of source-receptor relationships
140 based on the future distribution of emissions. The key perturbation runs (species/regions/sectors) target the major Northern
141 Hemisphere anthropogenic emission sources, and the model experiments in this set are described in more detail in Section 7.1.
142 The development of the ensemble emulator is described in more detail in Section 8.2.2.

143
144 In addition to the standard base case and perturbation experiments based on CLE 2040 emissions, this set of experiments
145 includes global model simulations of CLE 2015, MTFR 2040, and HILO 2040 using the same meteorological base year as the
146 standard base case (CLE 2040). This set of four global CTM simulations (CLE 2015, CLE 2040, MTFR 2040, and HILO
147 2040) will provide boundary conditions for a set of regional model simulations using the GAINS LRTAP scenarios.

148
149 We also invite groups using alternative source attribution techniques such as tagging (e.g. Butler et al., 2020; Mertens et al.,
150 2020) and adjoint sensitivity (e.g. Choi et al., 2019) to perform equivalent runs with their alternative methods and to contribute
151 to the analysis of the different source attribution methods.

152 **4.2 Transient future scenario experiments**

153 In HTAP3-OPNS we invite modelling groups using atmospheric CCMs to contribute transient simulations for the period 2010-
154 2050 using the GAINS LRTAP future anthropogenic emission scenarios and future fire emissions (Section 5.2). These
155 simulations serve several purposes:

- 156 ● Provide a direct assessment of the GAINS LRTAP scenarios.
- 157 ● Act as a check on the output of the ensemble emulator produced from the Perturbation experiments.
- 158 ● Allow quantification of the effects of climate change on long-range transport of air pollution.

159
160 A minimum of three simulations are requested in total from each modelling group (see Section 7.4 for more details).

161 **4.3 Transient historical experiment**

162 We invite groups using CTMs and CCMs to perform specified dynamics simulations from 2003-2020 using standardised
163 historical emission inventories for anthropogenic emissions and biomass burning. These simulations serve several purposes:



- 164
- Provide an assessment of the models' ability to simulate observed trends and interannual variability.
- 165
- Comprehensive deposition fields from these runs will be provided to the WMO for use in the MMF-GTAD project
- 166
- (<https://community.wmo.int/en/activity-areas/gaw/science-for-services/mmf-gtad>).
- 167
- Provide a baseline simulation for additional experiments in the related HTAP3-Fires exercise (Whaley et al., 2024).
- 168

169 The Transient Historical experiment is described in more detail in Section 7.5.

170 **4.4 Global to regional downscaling**

171 Regional modelling groups are invited to perform simulations for their region of interest using the GAINS LRTAP emission
172 scenarios and boundary conditions from the global CTMs contributing to HTAP3-OPNS through the Perturbation experiments
173 (Section 4.1).

174

175 For the European domain, TF HTAP will organise a common set of model experiments designed to support the revision of the
176 GP in cooperation with the CLRTAP Task Force on Measurements and Modelling (TFMM) and the Copernicus Atmosphere
177 Monitoring Service (CAMS). These experiments are described in more detail in Section 7.3.

178 **4.5 Additional science questions**

179 Some groups may see an opportunity to piggyback on the HTAP3-OPNS multi-model exercise to answer additional scientific
180 questions (e.g., detailed analysis of ozone budgets, deposition pathways, regionally focused assessments, etc...) and to take a
181 leadership role in the associated analysis. These groups are encouraged to discuss their ideas at TF HTAP meetings and
182 potentially recruit other modelling groups to participate by contributing additional runs or model output parameters.

183 **5 Input data sets**

184 All HTAP3-OPNS model experiments will require modelling groups to use standardised emission datasets for anthropogenic
185 and biomass burning emissions for the defined simulation periods. All other aspects of model configuration, such as natural
186 emissions and meteorological forcing will be left to the discretion of each modelling group, as long as these are consistent with
187 the overall climate forcing required for each model run, which is described for each set of experiments below.

188



Model runs	Emission data source				
	Anthro.	Aviation	Ag. Burning	Wildfires	CH ₄ (emis/conc)
Future Transient (2010-2050)	GAINS LRTAP	Corrected CMIP6	GAINS LRTAP	2010-2019 GFAS (w/o ag burning) 2020-2050 Hamilton et al.	GAINS LRTAP / Met.no
Future Perturbation (2040 emis/2015 met)	GAINS (for 2040)	Corrected CMIP6	GFAS4HTAP (for 2015)	GFAS4HTAP (for 2015)	Met.no
Future Regional Models (2040 emis/2015 met)	GAINS (for 2040)	Corrected CMIP6	GFAS4HTAP (for 2015)	GFAS4HTAP (for 2015)	Met.no
Historical Transient (2003-2020)	HTAPv3.2	HTAPv3.2	GFAS4HTAP	GFAS4HTAP	Met.no

Table 1 Summary of the emission datasets to be used in each of the experiment sets in HTAP3-OPNS

Table 1 shows the emission datasets which should be used for each of the different experiment sets in HTAP3-OPNS. The individual datasets are described in more detail below.

5.1 Anthropogenic future emission scenarios

All model experiments in the Perturbation and Transient Future Scenario sets of experiments must use the GAINS LRTAP version 2.1 anthropogenic emission scenarios. This dataset was introduced in Section 3.

The GAINS LRTAP version 2.1 emissions for the CLE and MTFR scenarios are available for download from Klimont et al. (2025) and contain the following emission sectors:

- Energy sector
- Residential combustion (cooking and heating)
- Transportation
- Industry (combustion and processes)
- Solvent use
- Waste management
- Agriculture (livestock and fertilizer application)
- Open burning of agricultural residues
- International shipping

The hybrid HILO scenario is not included in the official GAINS set of scenarios but must rather be constructed by each modelling group by taking methane emissions from the CLE scenario and emissions of all other pollutants from the MTFR scenario. For CTMs and other models using prescribed methane concentrations, methane concentrations are available for all three scenarios (CLE, MTFR, and HILO, see Section 5.5).

The GAINS LRTAP scenarios do not provide emissions for the aviation sector. All sets of experiments in HTAP3-OPNS which use GAINS LRTAP scenarios (the Perturbation and Transient Future Scenarios experiments) should use aircraft emissions from the CMIP6 historical and SSP2-4.5 datasets as appropriate for the simulation period. The vertical distribution



216 should be kept as provided in the emission files (with appropriate interpolation to the vertical levels of each participating model
217 to be performed by each group themselves). The correction described in Thor et al. (2023) should be applied to the CMIP6
218 aircraft emissions. Corrected CMIP6 historical emissions for aviation are available for download from Mertens (2024a).
219 Corrected SSP2-4.5 scenario emissions for aviation are available for download from Mertens et al. (2024b).

220
221 The GAINS LRTAP sector “Open burning of agricultural residues” should be excluded from the Perturbation experiments,
222 which use the historical biomass burning emissions from GFAS4HTAP (Section 5.3), as the GFAS4HTAP emissions already
223 include this source. Conversely, the GAINS LRTAP agricultural burning emissions should be included in the Transient Future
224 Scenarios experiments, as the future fire emissions for this set of experiments do not include managed burning. Table 1
225 provides a summary of the emissions to be used in each set of experiments.

226
227 Modelling groups are free to choose their own chemical speciation profiles, temporal profiles, and injection heights for the
228 GAINS LRTAP scenarios.

229 **5.2 Future fire emissions**

230 All model experiments in the Transient Future Scenario set of experiments (Section 4.2) must use the dataset from Bergas-
231 Massó and Hamilton (2025). Future biomass burning emissions from wildfires in this dataset have been prepared based on the
232 output from an ensemble of ESMs with interactive fire models, bias corrected to present-day GFAS4HTAP emissions (Section
233 5.3). These future fire emission datasets correspond to climates simulated in SSP2-4.5 and will also be considered for use in
234 other related multi-model exercises coordinated through HTAP3-Fires, IGAC-BBURNED, and AMAP.

235
236 For the model spinup and the period 2010-2019, modelling groups should use biomass burning emissions from GFAS4HTAP
237 (Section 5.3). From 2020 onwards, the Bergas-Massó and Hamilton (2025) emissions should be used.

238
239 The Bergas-Massó and Hamilton (2025) dataset does not include burning of agricultural waste. As shown in Table 1, all model
240 experiments in the Transient Future Scenario set of experiments should take emissions from agricultural waste burning from
241 the GAINS LRTAP scenarios (Section 5.1).

242
243 Recommended injection heights for future fires follow Dentener et al., (2006).

244 **5.3 Historical fire emissions**

245 As shown in Table 1, all model experiments performed in the Perturbation and Transient Historical sets of experiments must
246 use all sectors (including agricultural waste burning) from the GFAS4HTAP dataset (Kaiser et al., 2025) which has been
247 developed specifically for HTAP3-OPNS and HTAP3-Fires. To ensure maximum overlap between these related exercises, a



248 common biomass burning emission dataset will be used in both HTAP3-OPNS and HTAP3-Fires. The GFAS4HTAP dataset
249 provides emission fluxes at daily temporal resolution. For HTAP3-OPNS, modelling groups may either use these daily fluxes
250 or aggregate these to monthly mean fluxes.

251 **5.4 Historical anthropogenic emissions**

252 All model experiments in the Transient Historical set of experiments must be based on the monthly mean fluxes for 2000-2020
253 from HTAPv3.2 (Guizzardi et al., 2025), an update to the HTAPv3 global mosaic emission inventory (Crippa et al., 2023).
254 The HTAPv3.2 dataset is available for download from Zenodo (Crippa, 2024).

255
256 Agricultural waste burning emissions from HTAPv3.2 should be excluded from the Transient Historical experiments (Table
257 1), since these are included in the biomass burning emissions from GFAS4HTAP (Section 5.3). Modelling groups are
258 encouraged to use the NMVOC speciation profiles provided with the HTAPv3.2 emission inventory. Modelling groups are
259 free to apply vertical emission profiles to these emissions as they see fit, although HTAP makes no specific recommendation
260 on vertical emission profiles.

261
262 The Historical Transient experiment is the only experiment in HTAP3-OPNS using the HTAPv3.2 emission inventory (Table
263 1). For the historical component of the Transient Future and Perturbation sets of experiments, emissions are taken from the
264 GAINS LRTAP scenarios (Section 5.1).

265 **5.5 Surface methane emissions and concentrations**

266 For the Transient Future set of experiments, anthropogenic emissions of methane are provided in the GAINS LRTAP future
267 scenarios (Section 5.1). Groups with the capacity to perform methane emission-driven simulations should use the GAINS
268 LRTAP anthropogenic methane emission fluxes, along with their own choice of natural methane emissions and any necessary
269 flux adjustment (Folberth et al., 2022).

270
271 For all groups performing the Perturbation experiments, and for groups performing the Transient Future experiments without
272 the capacity to perform methane emission-driven simulations, surface concentrations of methane consistent with the GAINS
273 LRTAP emission scenarios CLE and MTFR and the hybrid scenario HILO are provided based on the reduced complexity
274 climate model (RCM) simulations run by MSC-W (Met Norway) driven by emissions from the GAINS LRTAP scenarios. In
275 HTAP3-OPNS, these methane concentrations are named as Met.no. The RCM used for this purpose is the Model for the
276 Assessment of Greenhouse-gas Induced Climate Change v7.5.3, MAGICC7 (Meinshausen et al., 2009, 2011, 2020), following
277 the approach described in van Caspel et al. (2024). In this configuration, the MAGICC7 model is run in its 600-ensemble
278 probabilistic mode (Nicholls et al., 2021) to calculate global mean tropospheric methane concentrations as a function of the
279 anthropogenic emission scenarios. Natural emissions are estimated by closing the methane budget with respect to historical



280 observations up to the year 2023 and are kept constant throughout the simulation period. The MAGICC7 model is calibrated
281 to observations from the NOAA network for the historical period.

282
283 Surface methane concentrations for the CLE, MTRF, and HILO scenarios are available for download from Zenodo (van Caspel
284 and Fagerli, 2025). It is important to note that the surface methane concentrations in each of the three scenarios are different.
285 While the HILO scenario uses the same methane emissions as the CLE scenario, the resulting methane concentrations are not
286 identical under CLE and HILO due to the different emissions of NO_x and NMVOC in these scenarios and the consequent
287 effects on ozone, hydroxyl radical, and the methane lifetime.

288
289 For the Transient Historical experiment, historical concentrations of methane are also provided as annual average surface
290 mixing ratio in van Caspel and Fagerli, (2025). For the historical period, these concentrations have been harmonised with the
291 observations from the NOAA Global Monitoring Laboratory (Thoning et al., 2022). Modelling groups should fix the
292 concentration of methane at their lower boundary to these values. Values are provided from 1998 to allow for up to five years
293 of model spin-up.

294 **5.6 Hydrogen**

295 For all model experiments, groups must specify a global average surface mixing ratio of hydrogen of 530 ppb, equivalent to
296 the present-day mixing ratio (Novelli et al., 1999). The GAINS LRTAP scenarios do not include emissions from a potential
297 future hydrogen/ammonia economy, and other future projections of hydrogen emissions are too uncertain at this time.

298 **5.7 Natural emissions and other emissions not specified in this experiment description**

299 A key aim of the HTAP3-OPNS exercise is to minimise barriers to participation for modelling groups. As such, all modelling
300 groups are free to choose whichever datasets are most convenient and appropriate for their model for natural emissions, and
301 any other emissions not specified in this experiment description. We expect that each modelling group contributing to HTAP3-
302 OPNS already has experience running their model and can make a judgement on the appropriate treatment of the emission
303 sources and appropriate datasets required for their model simulations.

304
305 All groups are required to report their total emissions including both natural and anthropogenic emissions using the appropriate
306 fields in the requested output data (Section 6) and additionally provide a description of the emission data sets or online
307 calculations used for natural emissions or other emissions not specified in this experiment description in their simulations.

308 **5.7.1 Emissions of Biogenic Volatile Organic Compounds**

309 Each group is free to choose their own treatment of BVOC emissions. Ideally, BVOC emissions used in each model should be
310 calculated online in a way consistent with the land cover and meteorology used in each model experiment, although we will



311 also accept submissions from groups using offline BVOC emissions. Please note that reporting of both isoprene emissions and
312 total BVOC emissions as model output fields are required in HTAP3-OPNS (Section 6).

313 **5.7.2 Emissions of NO_x from lightning**

314 Each modelling group is free to choose their own treatment of lightning NO_x emissions, including the overall magnitude of
315 the lightning NO_x source. Ideally, groups should use the same treatment of lightning NO_x emissions as they have used in
316 previously published evaluations of their respective models. Please note that reporting of lightning NO_x emissions as a model
317 output field is required in HTAP3-OPNS (Section 6).

318 **5.8 Land cover**

319 There is no requirement in HTAP3-OPNS to use any specific land cover treatment. Each modelling group is free to choose
320 whichever land cover treatment is most appropriate and convenient for their model, as long as it is broadly consistent with the
321 period being simulated in each model experiment (Section 7). All groups are requested to report their land cover using the 16
322 generic land cover types defined for the AQMEII4 project (Galmarini et al., 2021).

323
324 For an offline treatment of land cover, we recommend the use of the LUH2 dataset (Hurtt et al., 2020), which provides detailed
325 land cover patterns from 850-2100, and was used by modelling groups contributing to the CMIP6 model intercomparison
326 project.

327 **5.9 Meteorology and climate boundary conditions**

328 Modelling groups are free to choose whichever meteorological or climate input data is most appropriate and convenient for
329 their model, within the constraints of the relevant experimental specifications (Section 7).

330
331 For CTMs contributing to the Perturbation and Transient Historical experiments, this input consists primarily of archived
332 meteorological fields (specified dynamics) from a reanalysis product. HTAP recommends that CTM groups use meteorological
333 input data which they have previously used in published evaluations of their respective models.

334
335 For CCMs contributing to the Transient Future experiments, this input consists of sea surface temperature and ice cover data,
336 as well as the concentrations of well-mixed greenhouse gases (except for methane, which must be taken from the GAINS
337 LRTAP scenarios as either emissions or concentrations, Section 5.5). Groups are free to choose whichever source of input data
338 is most convenient for their model. HTAP recommends that CCM groups use input datasets for the historical period and SSP2-
339 4.5 corresponding to their own CMIP6 simulations (or equivalent).



340 **6 Requested model output data**

341 The full list of requested model output fields for HTAP3-OPNS is available in the supplement to this manuscript. This HTAP3-
342 OPNS output table is based on the requested output for AerChemMIP (Collins et al., 2017), with several modifications specific
343 to HTAP3-OPNS. All modelling groups are encouraged to provide as many of the HTAP3-OPNS diagnostic fields as possible
344 from their simulations for all sets of experiments in HTAP3-OPNS. Diagnostic fields of particular importance, as well as new
345 fields which have been added for HTAP3-OPNS, are described in this Section below. A table of the full set of requested output
346 fields is provided in the supplementary material to this manuscript. The format in which model output should be provided is
347 described in Section 8.1.

348
349 For climate models contributing to the Transient Future experiments (Sec. 4.2 and 7.4), hourly fields should be saved in the
350 first ten years (2010-2019) and last ten years (2040-2049) of each model run. All other models contributing to all other sets of
351 experiments should save and report hourly fields for the full duration of each model experiment.

352 **6.1 Hourly surface mixing ratio of ozone and other pollutants**

353 In order to calculate policy-relevant ozone impact metrics, all groups are required to provide hourly averaged fields of the
354 surface ozone mixing ratio at the lowest model level for all simulations in all sets of experiments. While this diagnostic was
355 already included in the AerChemMIP output table, and is not new in HTAP3-OPNS, we emphasise the necessity of including
356 this field for all models participating in all HTAP3-OPNS experiments.

357
358 In addition to the hourly mixing ratio of ozone, modelling groups are also strongly encouraged to provide hourly mixing ratio
359 of PM_{2.5} and NO₂ at the lowest model level, which will also be used in health impact assessment.

360 **6.2 Ozone deposition and related fields**

361 Ozone impacts on vegetation will be an important part of the analysis of HTAP3-OPNS. This will be jointly performed by
362 HTAP in cooperation with ICP Vegetation (The International Cooperative Programme on Effects of Air Pollution on Natural
363 Vegetation and Crops), a body of CLRTAP based at the UK Centre for Ecology and Hydrology. Ozone impacts on vegetation
364 (primarily wheat crops and deciduous forests) will be determined using the PODyIAM (Phytotoxic Ozone Dose above
365 threshold y for Integrated Assessment Modelling) metric using the DO3SE model (Emberson et al., 2007; Simpson et al.,
366 2012).

367
368 Modelling groups who have implemented the DO3SE model (or equivalent methods for calculating the PODyIAM metrics)
369 in their systems are encouraged to directly provide daily accumulated values of the relevant PODyIAM metrics. Crop impacts
370 will be calculated from POD3IAM, and forest impacts will be calculated from POD1IAM. A detailed description for the



371 calculation of these metrics is given in CLRTAP (2023). Groups who are able to calculate PODyIAM metrics should provide
372 both POD1IAM and POD3IAM at daily resolution on a longitude/latitude grid.

373

374 All groups (including groups which calculate and provide the PODyIAM metrics) should provide hourly values of the
375 following parameters (where available) as a high priority, which will be used to calculate the PODyIAM metrics offline:

376 • Hourly mean 2D (longitude, latitude) output:

377 o Mixing ratio of ozone at the lowest model level (also requested in Section 6.1).

378 o Ozone deposition flux.

379 o Ozone deposition velocity.

380 o Aerodynamic resistance as used in the deposition calculation.

381 o Near-surface air temperature.

382 o Near-surface relative humidity.

383 o PPFD (Photosynthetic Photon Flux Density).

384 ▪ If this is not available, it can be calculated offline based on location and time.

385 • Daily mean 2D (longitude, latitude) output:

386 o soil_moisture_content.

387 • Monthly mean 2D (longitude, latitude) output:

388 o soil_moisture_content.

389 o soil_moisture_content_at_field_capacity.

390 o Land cover maps including all vegetation types used in the model runs using the generic land cover types
391 defined for the AQMEII4 exercise (Galmarini et al., 2021).

392

393 Groups with the capacity to do so should also provide the soil_moisture_content variables at the vertical resolution of their
394 soil model in addition to the vertically integrated soil moisture variables mentioned above (CF names
395 moisture_content_of_soil_layer and moisture_content_of_soil_layer_at_field_capacity).

396

397 In addition to the requested data, all groups are also requested to provide detailed information about their ozone deposition
398 schemes, in particular about whether and how soil moisture is included in the calculation of the deposition velocity.

399 6.3 Total deposition

400 The WMO MMF-GTAD exercise (<https://community.wmo.int/en/activity-areas/gaw/science-for-services/mmf-gtad>) requires
401 comprehensive information on total atmospheric deposition. Modelling groups contributing to the HTAP3-OPNS experiments
402 are encouraged to fully implement and provide these model diagnostics for all sets of experiments. Total deposition output is



403 required for models contributing to the Transient Historical experiments, since this set of experiments will provide the model
404 output for the MMF-GTAD exercise.

405

406 The requested deposition fields from the HTAP3-OPNS output table (monthly output) are as follows:

- 407 • dry deposition rate of O₃
- 408 • dry deposition rate of dry aerosol total organic matter
- 409 • wet deposition rate of dry aerosol total organic matter
- 410 • dry deposition rate of black carbon aerosol mass
- 411 • wet deposition rate of black carbon aerosol mass
- 412 • dry deposition rate of seasalt
- 413 • wet deposition rate of seasalt
- 414 • dry deposition rate of dust
- 415 • wet deposition rate of dust
- 416 • dry deposition rate of SO₂
- 417 • dry deposition rate of SO₄
- 418 • wet deposition rate of SO₄
- 419 • wet deposition rate of SO₂
- 420 • dry deposition rate of NH₃
- 421 • dry deposition rate of NH₄
- 422 • wet deposition rate of NH₄
- 423 • wet deposition rate of NH₃
- 424 • dry deposition rate of NO_y
- 425 • wet deposition rate of NO_y incl aerosol nitrate
- 426 • dry deposition rate of organic nitrate
- 427 • wet deposition rate of organic nitrate incl aerosol organic nitrate

428

429 Except for the deposition diagnostics for organic nitrates, all the requested deposition fields were already included in the
430 AerChemMIP output tables. The organic nitrate deposition diagnostic fields were added to the HTAP3-OPNS output table at
431 the request of the WMO MMF-GTAD exercise.

432 **6.4 Ozone and other chemical budget terms**

433 The ensemble of models contributing to the various sets of experiments of HTAP3-OPNS represents an opportunity to explore
434 inter-model differences in ozone production and loss terms which may help to explain the inter-model differences in simulated



435 ozone. Modelling groups with the capacity to provide chemical flux diagnostics are encouraged to provide appropriate output
436 which can be used to construct detailed ozone budgets based on the approach described by Edwards and Evans (2017).

437

438 The AerChemMIP output tables already contain variables diagnosing the monthly mean ozone production and loss terms in
439 units of $\text{cm}^{-3}\text{s}^{-1}$. For HTAP3-OPNS we ask for modifications to the ozone loss diagnostic, and several additional diagnostic
440 fields to enable more detailed investigation of the ozone budget and comparison of tropospheric chemistry across participating
441 models:

- 442 • The ozone loss diagnostic `o3loss` should be modified to include Ox loss due to halogen chemistry for models which
443 include this chemistry.
- 444 • An additional diagnostic `primo3loss` is requested for primary ozone loss (as the tendency due to reaction between
445 $\text{O}(^1\text{D})$ and water vapour).
- 446 • Additional diagnostics `do3chm` and `tropdo3chm` are requested for the change in ozone across the chemical timestep.
- 447 • An additional diagnostic `oxprodo2photo` is requested for the production rate of Ox due to the photolysis of molecular
448 oxygen.
- 449 • An additional diagnostic `ohprod` is requested for the total OH production rate, the OH production from all reactions
450 producing OH, including rapid HOx interconversion.
- 451 • An additional diagnostic `ohloss` is requested for the total OH loss rate, the OH loss from all reactions consuming OH,
452 including rapid HOx interconversion.
- 453 • An additional diagnostic `prodco` is requested for the secondary chemical production of CO.

454

455 The standard 2D diagnostics `tropoz` and `toz` are also requested as monthly averages. The variable `toz` is the total ozone column,
456 while the tropospheric ozone column field (`tropoz`) is calculated using a dynamically varying online pressure tropopause (ptp)
457 according to the WMO thermal tropopause definition. Both should be output on the model native lat/lon grid.

458

459 In addition to the extra diagnostic terms, we request all groups to provide a machine-readable file containing their model
460 chemical mechanism to assist in the interpretation of the diagnostic terms. An overview of the planned analyses using these
461 diagnostics is given in Section 8.2.6.

462 **6.5 Boundary conditions for regional models**

463 Since it will not be possible for HTAP to centrally host the large amount of data required for regional boundary conditions,
464 data exchange between global and regional modellers should be organised directly between interested global and regional
465 modellers. HTAP will help with coordination of this exchange. Further details on boundary conditions for regional modellers
466 are given in Section 7.3.1.



467 **6.6 Common radiation calls for Earth System Models**

468 To quantify the effects of the individual emission components on the radiative budget we propose to include additional
469 diagnostic double calls into the CCM model simulations. For aerosols we suggest applying the Ghan method (Ghan, 2013)
470 and include an additional diagnostic ‘aerosol free’ radiation call. Similarly, we propose to include an additional diagnostic
471 radiation call with an ozone climatology instead of the interactive ozone (see Collins et al. 2025). These double calls should
472 be provided for instantaneous radiative forcing (IRF). Models which can also provide a stratospheric adjusted radiative forcing
473 (SARF) are invited to provide these fields in addition. Modellers are encouraged to make this diagnostic output available to
474 allow calculation of ERF as per CMIP6 protocol/experiments for the ESM models.

475

476 **7 Experimental setup**

477 For all experiments in each of the three sets, participating modelling groups have the flexibility to configure their model as
478 they see fit (e.g. grid resolution, meteorological/climate boundary conditions, natural emissions, chemical mechanism, etc...),
479 as long as they adhere to the requirements for the use of specific input datasets as shown in Table 1 and described in Section
480 5, and provision of output fields described in Section 6.

481 **7.1 Perturbation experiments**

482 All experiments in this set consist of year-long model simulations performed by global CTMs or CCMs with specified
483 dynamics, land cover, biomass burning, and natural emissions for a common meteorological base year (2015). Anthropogenic
484 emissions excluding agricultural waste burning for all model runs are based on GAINS LRTAP emissions (Section 5.1).
485 Biomass burning emissions including agricultural waste burning are based on the GFAS4HTAP dataset (Section 5.3). Methane
486 concentrations corresponding with the emissions from the three GAINS LRTAP scenarios (CLE, MTFR, and HILO, Section
487 5.5) are specified as concentration boundary conditions in all runs of this set of experiments. This set of experiments has two
488 primary goals:

- 489 • Direct simulation of single years of the GAINS LRTAP scenarios (2015 and 2040) as a complement to the Transient
490 Future experiments and for the provision of lateral boundary conditions to regional model simulations.
- 491 • Production of source/receptor relationships for hemispheric air pollution in 2040 for the construction of the HTAP3
492 ensemble emulator.

493

494 Model groups should ensure that their model is appropriately spun up in each case. In general, we recommend at least 6 months
495 of spin-up for each run (beginning in July and using the same emissions and meteorology as the simulation itself, if 2014
496 meteorology is not available for spinup then it is acceptable to use 2015 meteorology for the spinup), assuming that initial



497 conditions are chosen appropriately, as recommended below. A good test for sufficient spin-up would be to compare the
 498 December output from the spin-up period with the December output from the delivered model output and to check for the
 499 absence of any chemical drift.

500

501 The runs in this set of experiments are shown in Table 2 and described in more detail below.

502

503

Priorities for HTAP3 Simulations	2015 meteorology / 2040 emissions	Highest Priority	1 or 2					
Base (CLE 2040 emissions)	BASE (CLE2040)	1	n					
Global Perturbations								
Decrease CH4 Conc	CH4DEC	1						
Decrease CH4 Conc and all anthro emissions	CH4ALL	1						
Increase H2 conc	H2INC	2						
Decrease All anthro emissions	GLOALL	1						
Decrease anthro NOX	GLONOX	1						
Decrease anthro VOC	GLOVOC	1						
Decrease anthro CO	GLOCO	1						
Global Scenario Runs								
CLE 2015 emissions	CLE2015	1						
MTR (2040)	MTR2040	2						
HILO (2040)	HILO2040	2						
Regional Emissions Perturbation (2015 meteorology, 2040 CLE emissions)								
		All	NOX	VOC	CO	SO2	NH3	PM
N America	NAM	1	2	2	4			
EMEP Domain	EMEP	1	2	2	4			
EMEP West	EMEPW	3	4	4	4			
EMEP East	EMEP E	3	4	4	4			
East Asia	EAS	1	2	2	4			
South Asia	SAS	1	2	2	4			
South and East Mediterranean	SMD	1	2	2	4			
Middle East	MDE	3	4	4	4			
North Africa	NAF	3	4	4	4			
SE Asia	SEA	3	4	4	4			
Mex/C America/Caribbean	MCA	3	4	4	4			
Rest of World (SAM+SAF+PAN)	ROW	3	4	4	4			
South America	SAM	3						
Southern Africa	SAF	3						
Aust/NZ/Pacific	PAN	3						
International Shipping	SHIP	1						
Aviation (all vertical levels)	AVI	2						
Fires (all fires)	FIRE	3						

504

505 **Table 2 Overview of the perturbation experiments in HTAP3-OPNS.**

506 All model runs should be performed using 2015 meteorology, biomass burning emissions, natural emissions, and land cover.

507 Recognising that most modelling groups will not have the capacity to perform a large number of simulations, the model runs



508 in Table 2 are prioritised according to their usefulness for constructing the HTAP3 ensemble emulator. There are 14 runs with
509 a priority of 1, and another 10 runs with a priority of 2. Remaining runs are given either priority 3 or 4 or not requested at all.
510 Construction of reliable model emulators requires contribution of results to priority 1 runs and would benefit from results for
511 priority 2 runs; priority 3 and 4 runs provide useful additional information on regional and species contributions but are less
512 essential.

513
514 All groups contributing simulations to this set of experiments are required to perform the base simulation, which uses GAINS
515 LRTAP CLE 2040 emissions and methane concentrations, and another simulation using GAINS LRTAP CLE 2015 emissions
516 and methane concentrations. The CLE2040 simulation will form the basis for all perturbation runs in this set, while the
517 CLE2015 run will be used for model evaluation as well as to evaluate the change in global air quality between 2015 and 2040.

518
519 For the spin-up of the CLE2015 and CLE2040 simulations, we recommend initialising the model with archived 3D
520 concentrations from an existing present-day simulation, but with 3D fields of methane and hydrogen set to the same values as
521 the respective specified surface concentrations from each scenario. We recommend using the same initial conditions as
522 CLE2040 for all other perturbation runs, except where otherwise specified. As mentioned above, we recommend six months
523 of spin-up for each model run, but each group should ensure that their model is appropriately spun-up for each run.

524 **7.1.1 Direct scenario experiments**

525 There are four direct scenario runs requested in this set of experiments: CLE2015; CLE2040; MTFR2040; and HILO2040.
526 These runs will be used to assess future global air quality under the GAINS LRTAP scenarios and as a source of boundary
527 conditions for regional model simulations (Section 7.3.1).

528
529 The CLE 2015 and CLE 2040 runs have priority 1 because they are used respectively for model evaluation and as the base
530 case for source/receptor runs. All groups contributing to the Perturbation experiments should perform these two runs.

531
532 The MTFR2040 and HILO2040 runs have priority 2 because they do not contribute directly to the construction of the HTAP3
533 ensemble emulator. However, global modelling groups providing lateral boundary conditions for regional model simulations
534 should perform both of these runs as a matter of high priority. Other global modelling groups with additional resources and an
535 interest in the assessment of these scenarios are also encouraged to perform these runs as long as they also perform the 14
536 priority 1 runs (Table 2).

537
538 For the spin-up of all direct scenario simulations, we recommend initialising the model with archived 3D concentrations from
539 an existing present-day simulation, but with 3D fields of methane and hydrogen set to the same values as the respective
540 specified surface concentrations from each scenario.



541

542 As noted in Section 3, all emission fluxes except for methane for the HILO scenario are taken from the MTR scenario. As
543 also noted in Section 5.5, methane concentrations for the HILO run in this set of experiments are calculated based on methane
544 emissions from the CLE scenario, but the resulting methane concentrations are not identical between CLE and HILO. Groups
545 performing the HILO2040 run should take care to use methane concentrations from Met.no for the HILO scenario (Section
546 5.5).

547 7.2 Global perturbation experiments

548 Global perturbation runs are performed by decreasing the specified emissions or surface concentrations by 20% relative to the
549 base run, as for previous HTAP assessments. There are six priority 1 global perturbation runs:

- 550 • CH4DEC: The global methane concentration boundary condition is reduced by 20%.
- 551 • CH4ALL: The global methane concentration boundary condition and all anthropogenic (including shipping and
552 aviation) emissions (NO_x , NMVOC, CO, SO_2 , NH_3 , and all PM species) are reduced by 20% globally. Biomass
553 burning emissions (including agricultural waste burning) and natural emissions are not changed.
- 554 • GLOALL: All anthropogenic (including shipping and aviation) emissions (NO_x , NMVOC, CO, SO_2 , NH_3 , and all
555 PM species) are reduced by 20% globally. Biomass burning emissions (including agricultural waste burning), natural
556 emissions, and methane concentrations are not changed.
- 557 • GLONOX: All anthropogenic emissions (including shipping and aviation but excluding agricultural waste burning)
558 of NO_x are reduced by 20%.
- 559 • GLOVOC: All anthropogenic emissions (including shipping and aviation but excluding agricultural waste burning)
560 of NMVOC are reduced by 20%.
- 561 • GLOCO: All anthropogenic emissions (including shipping and aviation but excluding agricultural waste burning) of
562 CO are reduced by 20%.

563

564 In addition to the priority 1 global perturbation runs, there is also a priority 2 global perturbation run H2INC, in which the
565 hydrogen concentration boundary condition is increased by 20%. Groups with the additional resources to perform this run are
566 encouraged to do so, which will allow the HTAP3 ensemble emulator to include the atmospheric response to future changes
567 in hydrogen.

568

569 For the CH4DEC and CH4ALL simulations, we recommend applying the 20% reduction in methane concentrations to the 3D
570 initial conditions as well as to the surface boundary conditions to reduce the need for additional spin-up time. Similarly, for
571 the H2INC simulation, we recommend applying the 20% increase in H_2 concentrations to the 3D initial conditions as well as
572 to the surface boundary condition.



573 7.2.1 Regional and sectoral perturbation experiments

574 There are six priority 1 runs which include regional or sectoral emission perturbations of -20% relative to the base run of all
575 anthropogenic species (NO_x, NMVOC, CO, SO₂, NH₃, and all PM species). The source regions for the perturbation
576 experiments are shown in Figure 1 and are available for download from Zenodo (Butler, 2025). Please make sure to use version
577 4 of this dataset. Since the work has been designed to support the revision of the CLRTAP Gothenburg Protocol, the primary
578 focus is the Northern Hemisphere. For the five regional perturbation runs, only the land-based anthropogenic emission sectors
579 should be perturbed. No perturbation should be applied for aviation emissions, international shipping emissions, biomass
580 burning emissions (including agricultural waste burning), or natural emissions.

- 581 ● NAMALL: Emissions are reduced by 20% over the North American source region.
- 582 ● EMEPALL: Emissions are reduced by 20% over the EMEP source region.
- 583 ● EASALL: Emissions are reduced by 20% over the East Asia source region.
- 584 ● SASALL: Emissions are reduced by 20% over the South Asia source region.
- 585 ● SMDALL: Emissions are reduced by 20% over the Southern Mediterranean source region.

586
587 In addition to the priority 1 regional perturbation runs, we also request with priority 1 the SHIPALL perturbation run, in which
588 all emissions from the international shipping sector (regardless of location) are reduced by 20%.

589
590 There are an additional 10 regional perturbation runs of priority 2 corresponding to the five major source regions with -20%
591 perturbations of anthropogenic emissions (excluding aviation, all biomass burning sectors, and natural emissions) of individual
592 pollutant species (5 NO_x perturbation runs and 5 NMVOC perturbation runs):

- 593 ● NAMNOX and NAMVOC
- 594 ● EMEPNOX and EMEPVOC
- 595 ● EASNOX and EASVOC
- 596 ● SASNOX and SASVOC
- 597 ● SMDNOX and SMDVOC

598
599 For groups which have performed at least the 14 priority 1 runs (Table 2), and ideally also the 10 priority 2 runs, there are an
600 additional 12 priority 3 regional or sectoral perturbation runs which would be of use in constructing the HTAP3 ensemble
601 emulator:

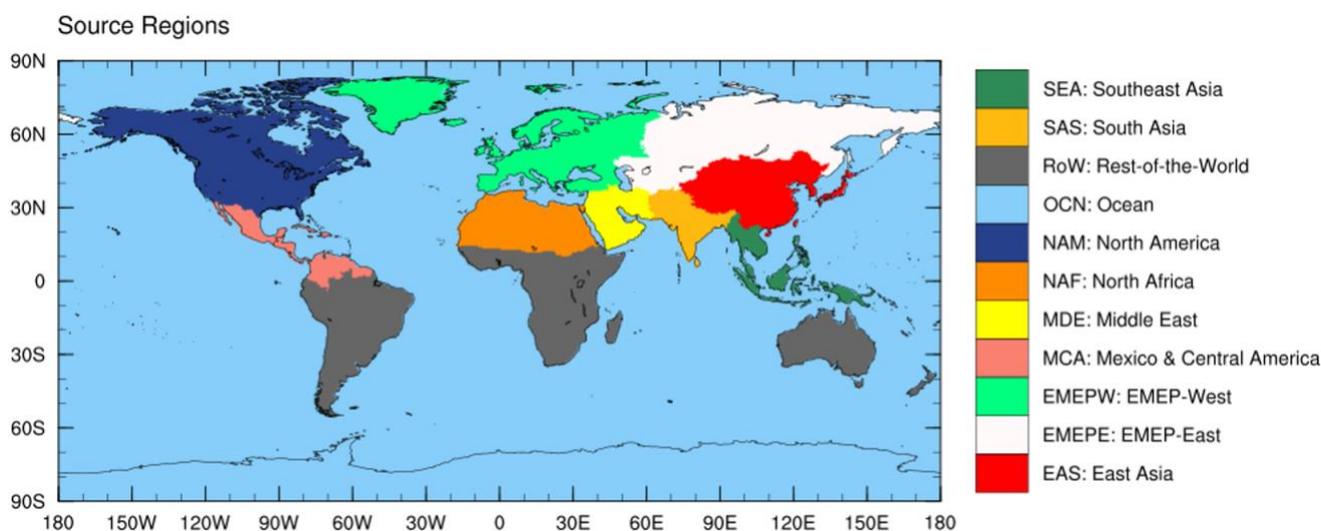
- 602 ● EMEPWALL and EMEPEALL: these runs help with disaggregation of the EMEP source region into its western and
603 eastern parts.
- 604 ● NAFALL and MDEALL: these runs help with disaggregation of the SMD source region into its component parts.
- 605 ● ROWALL, SAMALL, SAFALL, and PANALL: these runs complete the coverage of all global source regions.



- AVIALL and FIREALL: these runs help to quantify the response of air pollution to emissions from aviation and biomass burning respectively.

608

609 Runs listed as priority 4 in Table 2 are useful in the construction of the HTAP3 ensemble emulator. Due to the large number
610 of runs of priority 1, 2, and 3, we do not expect many groups to perform runs of priority 4. However, groups with a special
611 interest in priority 4 perturbation runs are encouraged to perform these and submit them to the data archive if they have
612 completed at least the 14 priority 1 runs, and ideally also the 10 priority 2 runs.



613

614 **Figure 1 The HTAP3 source regions.**

615 **7.3 Global to regional downscaling of GAINS LRTAP scenarios**

616 A major motivation for the work in HTAP3-OPNS is the revision of the CLRTAP Gothenburg Protocol, which regulates the
617 emissions of ozone precursors and particulate matter in the UNECE region. Assessment of the GAINS LRTAP scenarios using
618 high resolution regional models for Europe and North America is therefore an important part of HTAP3-OPNS. Depending on
619 interest from regional modellers simulating other domains, there may also be demand for boundary conditions for other regions.
620 For compatibility with global specified-dynamics simulations in HTAP3-OPNS, regional simulations should be performed
621 using meteorological input from the common base year (2015).

622 **7.3.1 Global simulations providing boundary conditions for regional models**

623 Lateral boundary conditions for regional model simulations will be taken from the global simulations of CLE2015, CLE2040,
624 MTFR2040, and HILO2040 (Section 7.1.1). Global modellers performing these four simulations during the course of HTAP3-



625 OPNS are encouraged to save output of key model species at high temporal resolution (at least 6 hourly) and 3D spatial
626 resolution (globally or at the coordinates of regional model boundaries) in a format accessible for regional modellers. Given
627 that HTAP will not have the resources to store these boundary conditions centrally on the AeroCom server, global modelling
628 groups providing boundary conditions for regional models are requested to host these data themselves and make them available
629 to regional modellers.

630
631 HTAP will make efforts to identify regional modellers interested in downscaling the GAINS LRTAP scenarios for their region
632 using boundary conditions from HTAP3-OPNS global runs. HTAP will work to connect regional modellers with global
633 modellers and help to identify the key species which must be saved from global simulations, and the coordinates at which these
634 species should be saved.

635
636 NCAR will perform global simulations with the CAM-chem model and host global 3D 6-hourly output of the species listed
637 here: <https://wiki.ucar.edu/display/camchem/CESM+2.2%3A+Species+saved+in+boundary+condition+files>. These species
638 should be especially suitable for regional models using chemical mechanisms related to the MOZART mechanism as used in
639 CAM-chem.

640
641 The CLRTAP MSC-W will perform global simulations with the EMEP model and host 6-hourly output at the edges of the
642 CAMS and EMEP domains.

643
644 The IFS-COMPO operated within the Copernicus Atmosphere Monitoring Service (Peuch et al., 2023) model will also
645 undertake the core global simulations and make them available. As far as the European domain is concerned, the operational
646 character of CAMS is making the IFS-COMPO a well established and easy to use source of boundary conditions for regional
647 modellers.

648 **7.3.2 Regional model simulations for Europe**

649 Several regional modelling groups with a focus on Europe have expressed an interest in performing simulations through fora
650 such as the CLRTAP Task Force on Measurements and Modelling (TFMM) and the Copernicus Atmosphere Monitoring
651 Service (CAMS).

652
653 European regional modellers are encouraged to perform simulations for the EMEP domain where possible, otherwise for the
654 CAMS domain. Groups performing simulations using the CAMS domain must make sure to simulate the entire geographical
655 extent of the CAMS domain.

656



657 All regional model input data should be harmonised as closely as possible with the descriptions given in Section 5.
 658 Meteorological input data should correspond with the base year (2015) for all simulations. Anthropogenic emissions excluding
 659 agricultural waste burning should be taken from the relevant GAINS LRTAP scenarios (Section 5.1). Regional model
 660 simulations should not specify methane emissions within their simulation domain but rather specify methane concentrations
 661 at their lateral boundaries. Biomass burning emissions including agricultural waste burning should be taken from the
 662 GFAS4HTAP dataset (Section 5.3) for 2015 for all simulations. Natural emissions should also correspond with the year 2015.
 663 All other aspects of model configuration are left to the discretion of the regional modelling groups.

664
 665 A summary of the regional model simulations for Europe is given in Table 3. Five simulations are requested from each
 666 contributing modelling group. Simulations 1-3 use the same emission scenario in both the global and regional models.
 667 Simulation 4 uses MTFR emissions for air pollutants in both the global and regional domains and boundary conditions from
 668 the global HILO scenario. Simulation 5 uses boundary conditions from CLE2040, but emissions from all land-based
 669 anthropogenic emission sectors (excluding aviation and international shipping) in the EMEP West source region (Figure 1 and
 670 Butler et al., 2025) within the regional model domain are replaced with the corresponding emissions from the MTFR2040
 671 scenario. All regional simulations should cover the full meteorological year 2015.

672

Simulation number	Simulation name	Emissions in the EMEP West region	Emissions in all other regions	Boundary conditions from global model
1	CLE2015	CLE2015	CLE2015	CLE2015
2	CLE2040	CLE2040	CLE2040	CLE2040
3	MTFR2040	MTFR2040	MTFR2040	MTFR2040
4	HILO2040	MTFR2040	MTFR2040	HILO2040
5	EMEPWLO2040	MTFR2040	CLE2040	CLE2040

673 **Table 3 Regional model simulations for Europe in HTAP3-OPNS**

674

675 It is anticipated that several different sets of boundary conditions from different global models will be available for these
 676 simulations (Section 7.3.1). Regional modelling groups are free to choose the most convenient dataset and encouraged to
 677 choose the global model output which most closely corresponds to their chemical mechanism. Groups with the resources to
 678 perform additional simulations are encouraged to perform the same set of five regional simulations using alternative boundary
 679 conditions.

680

681 Regional modelling teams should format their model output according to the instructions in Section 8.1 before uploading their
 682 data to the AeroCom server, taking care to include the fields which are indicated to be of high priority for HTAP3-OPNS.



683 **7.4 Transient future experiments**

684 In this set of experiments, transient model simulations will be performed by CCMs with the GAINS LRTAP scenarios (Section
685 5.1) from 2010-2050 and the future fire emissions described in Section 5.2. The 10-year period 2010-2019 will be used to
686 determine the baseline conditions for the present day (corresponding to the year 2015), and the 10-year period 2040-2049 will
687 be used to determine the conditions corresponding to the end of the scenarios. The full transient timeseries of model output
688 will be used to determine the model responses to changing emissions.

689 **7.4.1 Scenarios and prioritisation**

690 All CCM groups contributing to the Transient Future Scenarios experiments are requested to run at least the three core
691 scenarios: CLE; MTRF; and HILO, as described in Sections 3 and 5.1. All three of these scenarios should be run with climate
692 forcing corresponding to SSP2-4.5. Comparison of these three scenarios with each other will directly inform the Gothenburg
693 Protocol revision process with an understanding of future air quality under these three emission pathways. In addition to the
694 three core scenarios, CCM groups with the resources to run an additional three simulations are requested to run the same three
695 core emission scenarios, but with constant fixed climate forcing corresponding to the year 2015. Comparison of the fixed 2015
696 climate forcing simulations with the transient-forcing SSP2-4.5 simulations will allow calculation of the climate penalty on air
697 pollution under the GAINS LRTAP scenarios.

698
699 Modelling groups with the capability of performing methane emissions-driven simulations are strongly encouraged to do this
700 for their contributions to the Transient Future Scenarios experiments. Surface methane mixing ratios for concentration-driven
701 model runs are described in Section 5.5). As noted in Section 5.5, the methane concentration pathways in each of the three
702 scenarios are distinct. Groups may submit both emissions-driven and concentration-driven simulations for each scenario if
703 they wish. A summary of the six requested runs is given in Table 4.

704

Run name	Priority	Transient emissions scenario, including methane trajectory	Climate forcing	Radiation coupling
ssp245-CLE-CH4conc OR ssp245-CLE-CH4emis	1	GAINS LRTAP CLE	SSP2-4.5 transient	Fully coupled with composition
ssp245-MTRF-CH4conc OR ssp245-MTRF-CH4emis	1	GAINS LRTAP MTRF	SSP2-4.5 transient	Fully coupled with composition
ssp245-HILO-CH4conc OR ssp245-HILO-CH4emis	1	Hybrid scenario HILO	SSP2-4.5 transient	Fully coupled with composition



clim2015-CLE-CH4conc OR clim2015-CLE-CH4emis	2	GAINS LRTAP CLE	Constant 2015	Decoupled from composition (no ARI/ACI, all aerosol and GHG forcing fixed at 2015 composition, radiation sees a 2015 stratosphere)
clim2015-MTFR-CH4conc OR clim2015-MTFR-CH4emis	2	GAINS LRTAP MTFR	Constant 2015	Decoupled from composition (no ARI/ACI, all aerosol and GHG forcing fixed at 2015 composition, radiation sees a 2015 stratosphere)
clim2015-HILO-CH4conc OR clim2015-HILO-CH4emis	2	Hybrid scenario HILO	Constant 2015	Decoupled from composition (no ARI/ACI, all aerosol and GHG forcing fixed at 2015 composition, radiation sees a 2015 stratosphere)

705 **Table 4 Chemistry-climate model simulations for the Transient Future experiments in HTAP3-OPNS**

706 **7.4.2 Chemistry-climate model setup**

707 Groups are encouraged to use any version of their model which they think is appropriate, although we recommend that they
 708 use their CMIP6-AMIP configuration. Model output of the fields described in Section 6 in the format described in Section 8.1
 709 should be reported for the years 2010-2050, with the exception of hourly surface fields, which should only be reported for the
 710 first ten years (2010-2019) and last ten years (2040-2049) of each model experiment. Model runs should begin from a
 711 sufficiently spun-up state in the simulation year 2010. We leave the details of model spin-up to each modelling group.

712 **7.4.3 Climate forcing data**

713 Climate forcing data for each run consists of the following fields:

- 714
 - Sea surface temperatures.



- 715
- Ice cover.
- 716
- Land cover (unless using a dynamic land model).
- 717
- Concentrations of long-lived greenhouse gases (except for methane, which should be specified from the GAINS
- 718
- LRTAP scenarios).
- 719
- Ozone depleting substances.

720

721 For the “ssp245” runs, the climate forcing fields should be taken from the CMIP6 SSP2-4.5 forcing data. Fields not directly
722 specified in SSP2-4.5 (SST and ice cover data) could be taken from a previous run of a fully coupled ESM forced with SSP2-
723 4.5. As the SSP2-4.5 forcing data begins in 2015, modelling groups will need to perform the first part of their ssp245
724 simulations up until 2014 (including the spin-up) with historical forcing data. We recommend that groups begin their spin-up
725 by branching from an existing CMIP6 historical simulation of their model, substituting the GAINS LRTAP scenarios from the
726 branching year. The choice of branching year for sufficient spin-up is left to the judgement of each modelling group.

727

728 For the “clim2015” runs, the climate forcing fields, CO₂ concentrations, other long-lived GHG (apart from methane), and
729 ozone depleting substances should be taken from the year 2015 of an appropriate SSP2-4.5 dataset and kept constant throughout
730 the entire simulation (including sufficient spin-up). All aspects of radiative forcing should also be kept constant at 2015 levels;
731 this means that the evolving simulation of atmospheric composition (including methane, ozone, particles, and stratospheric
732 composition) in response to the GAINS LRTAP scenarios should be decoupled from the model radiation scheme in the
733 clim2015 simulations, with the model radiation seeing 2015 composition. SST and ice cover data should be taken from a 10
734 year (2005-2014) average of a previous fully coupled historical run of a fully coupled ESM. Land cover data should be kept
735 constant in the clim2015 runs.

736

737 We note that the updated versions of the GAINS LRTAP scenarios will diverge from one another from the year 2025. Where
738 appropriate, modelling groups are advised to branch their future simulations from this year to save storage and computational
739 resources.

740 **7.5 Transient historical experiment**

741 This run should be performed with specified dynamics, the HTAPv3.2 global mosaic anthropogenic emissions (Section 5.4),
742 the GFAS4HTAP biomass burning emissions (Section 5.3), and surface methane concentrations from the NOAA network
743 (Section 5.5) for the period 2003-2020. Groups not in the position to perform the full time series should focus on the latter part
744 of the period and include at least the year 2015 in their simulation. Groups performing this simulation are required to include
745 total deposition output in their data submission (Section 6.3), as this will be provided to the WMO MMF-GTAD exercise.



746 **8 Data handling**

747 **8.1 Initial delivery of data**

748 Model output from HTAP3-OPNS as specified in the data request (Sec. 6) will be stored on the AeroCom server
749 (<https://aerocom.met.no>). All groups contributing model output to HTAP3-OPNS must request an account on this server linked
750 to the HTAP3-OPNS project. Data must be uploaded to the AeroCom server on a regular lat/lon grid. Model grids based on
751 other projections or unstructured grids should be regridded by each modelling group to a regular lat/lon grid before being
752 uploaded to the AeroCom server.

753
754 Data must be submitted in the CF-compliant netCDF format with file names based on the following convention:

- 755 • `htap3opns_<ModelName>_<ExperimentName-PerturbationRealisation>_<DataRequestSheet>_<VariableName>_<Period>.nc`

756
757 Where:

- 758 • `<ModelName>` should be chosen such that model name, model version, and possibly the institution can be identified.
759 No underscores (`_`) are allowed in `<ModelName>`, use (`-`) instead. Restrict `<ModelName>` to max 20 characters.
- 760 • `<ExperimentName>` = will either be `TransientHistorical`, or follow the naming conventions introduced for each
761 experiment in Sections 7.1, 7.3, and 7.4. For the various emissions perturbation runs, `PerturbationRealisation` will
762 be 5-8 letters (3-5 indicating the region of perturbation and 2-3 indicating the pollutants or sector decreased) based
763 on the experiment matrix in Table 2. For example, `CLE2040-GLOALL` is used to indicate a 20% decrease in
764 anthropogenic emissions globally; `CLE2040-NAMNOX` is used to indicate a 20% decrease in anthropogenic NOx
765 emissions from North America; and `CLE2040-EMEPWVOC` is used to indicate a 20% decrease in anthropogenic
766 NMVOC from the EMEP West region.
- 767 • `<DataRequestSheet>` refers to the name of the sheet in the data request in which the variable was requested = `aerfixed`,
768 `aermonthly-3d`, `aermonthly-2d`, `aerdaily`, `aerhourly`, `aerzonal-vert`, `aerzonal`, `ModelLevelAtStations`.
- 769 • `<VariableName>` = are the HTAP variable *short* names in the requested output spreadsheet discussed in Section 6
770 above. An example of a variable *short* name is: `vmro3`
- 771 • `<Period>` = year of simulation

772 **8.2 Analysis of model experiments**

773 During the analysis phase of HTAP3-OPNS, access to the submitted model output will be restricted to users of the AeroCom
774 server who have requested access to the HTAP3 project. Groups who have not contributed model output, but who are interested
775 in contributing to the analysis are welcome to contact the HTAP leadership team. The HTAP leadership team will organise
776 regular meetings for all participants in the project to gauge the progress of model simulations and to coordinate the associated
777 analyses. A non-exhaustive summary of some expected analysis is given below in this Section.



778 **8.2.1 Model evaluation**

779 Comparison of model results with observations is vital for determining the degree to which models are capable of simulating
780 the historical past and providing confidence in their ability to make future projections. The requested model output fields in
781 HTAP3-OPNS (Section 6) include hourly surface (2D) values of ozone, NO₂, PM₁₀, PM_{2.5}, and other species which are
782 routinely measured at surface sites. With its focus on the impacts of air pollution on human health and ecosystems, the
783 evaluation of model results against surface observations will be of high priority. In addition to hourly surface concentrations,
784 the requested model output also includes other fields which can be used in model evaluation, such as Aerosol Optical Thickness
785 (AOT) at different wavelengths, deposition fields, and monthly mean 3D concentrations. Results from the CLE2015 CTM
786 experiment (Section 7.1.1), the first 10 years of the transient future experiment (Section 7.4), and the full transient historical
787 experiment (Section 7.5) will deliver output suitable for evaluation.

788 **8.2.2 Source-receptor relationships and emulator development**

789 The source-receptor relationships from the perturbation experiments (Section 7.1) will allow the construction of an ensemble
790 emulator for rapid assessment of alternative future emission scenarios. Previous HTAP assessments have demonstrated the
791 value of this approach for quantifying surface concentration changes across a wide range of future scenarios along with an
792 estimate of the associated uncertainty as represented by the spread of responses across contributing models (Turnock et al.,
793 2018; Wild et al., 2012). The approach allows incorporation of the nonlinearity in model responses and provides a valuable
794 tool to guide policy development. Use of a 2040 baseline will allow exploration of source-receptor relationships under future
795 conditions, permitting a more robust assessment of the effectiveness of mitigation measures around this policy-relevant target
796 year. Groups are encouraged to submit results for as many of the runs as they can, but to focus in particular on runs defined as
797 high priority to permit reliable emulation of their model.

798 **8.2.3 Assessment of future air quality**

799 An assessment of the air quality under the GAINS LRTAP future scenarios is a fundamental goal of HTAP3-OPNS. The
800 transient future experiments (Section 7.4) will provide a direct assessment of future air quality using state-of-the-art Chemistry-
801 Climate Models both with and without the effects of climate change. The direct scenario experiments (Section 7.1.1) will add
802 to this with Chemical Transport Model simulations of air quality in 2040. The CTM ensemble emulator (Section 8.2.2) will
803 also allow the attribution of future air quality to specific source regions. Analyses of future air quality using results generated
804 in HTAP3-OPNS will be coordinated by TF-HTAP and a synthesis report will be written by the TF-HTAP leadership team
805 for presentation to the Convention on Long-Range Transboundary Air Pollution.



806 **8.2.4 Ozone impact on health**

807 The collection of hourly surface ozone mixing ratio from all participating models (Section 6.1) will allow the calculation of
808 health impact metrics based on the MDA8 (Maximum Daily 8-hour Average) ozone mixing ratio at the year and seasonal
809 levels to compute the appropriate exposure indicators (e.g. peak season ozone, SOMO35). Such metrics will be used to estimate
810 premature mortality, years of life lost attributable and other health outcomes attributable to ozone exposure by means of
811 concentration-response functions (Huangfu and Atkinson, 2020; Murray et al., 2020, Kasdagli et al., 2024) associated with all-
812 cause or specific causes of mortality (e.g. respiratory disease or chronic obstructive pulmonary disease). In this way it will be
813 possible to link the measures and assumptions in the studied scenarios, especially those concerning the influence of methane
814 emissions on ozone concentrations, with their implications for health. The information about regional emissions and activity
815 sectors will be used to provide insights about the allocation of health impacts to their sources (Belis and Van Dingenen, 2023).
816 In addition, the health impacts of other pollutants such as PM_{2.5} and NO₂ and their implication for this analysis will be also
817 explored.

818 **8.2.5 Ozone impact on vegetation**

819 This analysis was briefly introduced in Section 6.2. HTAP and ICP Vegetation will calculate the PODyIAM metrics using a
820 standardised land cover dataset. The land cover provided by the modelling groups will be used to better understand the provided
821 deposition fluxes and as a consistency check with the standardized dataset used by ICP Vegetation. This calculation will also
822 use the provided hourly temperature, humidity, and PPFD where available. The availability of daily average soil moisture
823 output will provide additional flexibility for the PODyIAM calculation. Impacts of ozone deposition on vegetation co-occur
824 with effects of changing climates (e.g., higher temperatures and in some regions more frequent and intense drought events).
825 The proposed simulations will allow us to unravel interactions between changing climatic conditions and ozone deposition
826 and their impacts on vegetation.

827 **8.2.6 Ozone budget analysis**

828 Several analyses are planned using the additional chemical diagnostics requested in Section 6.4. The addition of halogen loss
829 reactions for ozone will help with closing the ozone budget. The addition of the primary ozone loss term, which is driven by
830 photolysis, will help to separate the role of model physics from the role of model chemistry in ozone loss. The addition of the
831 OH production term will enable comparison of primary and secondary OH production across models (the primary OH
832 production is equal to the primary ozone loss) and thus provide insight into inter-model differences in chemistry. The addition
833 of the OH loss term enables calculation of the OH lifetime, which can be compared with available measurements, for example
834 from the ATom field measurements (Wofsy et al., 2018).



835 **8.2.7 Climate forcing of air pollution**

836 The CLRTAP Gothenburg Protocol controls emissions of PM and ozone precursors over large parts of the UNECE region in
837 order to improve air quality. These pollutants, along with methane, which is being considered for inclusion in the revised
838 Gothenburg Protocol also exert a radiative forcing on the climate system. The model experiments in HTAP3-OPNS will allow
839 the calculation of the radiative forcing due to these air pollutants, providing CLRTAP with information on the expected climate
840 impact of potential future emission control measures.

841 **8.2.8 Deposition of air pollutants**

842 Detailed fields of total atmospheric deposition are requested in all experiments under HTAP3-OPNS, allowing interested
843 groups to perform their own analyses. In particular, the deposition fields requested from the transient historical runs (Section
844 7.5) will be used in the WMO MMF-GTAD (Measurement-Model Fusion for Global Total Atmospheric Deposition) along
845 with available deposition measurements to produce deposition maps of nitrogen, sulphur, and ozone (Fu et al., 2022).

846 **8.3 Archiving of data**

847 Once the initial set of analyses is completed, the access to the HTAP3 data on the AeroCom server will be opened up to any
848 user with an account on the server. Due to the expected large volume of raw model output stored on the AeroCom server,
849 permanent archiving of the full set of contributed data is not feasible. Permanent archiving of subsets of the contributed data
850 which have been used in the production of scientific publications will be a condition of using data from HTAP3-OPNS in
851 scientific publications. Suitable data repositories with version control and the assignment of DOIs include Zenodo
852 (<https://zenodo.org>) and GFZ Data Services (<https://dataservices.gfz-potsdam.de/portal/>).

853 **9 Links with other multi-model activities**

854 **9.1 HTAP1 and HTAP2**

855 The design of the perturbation runs will be based on the experience gained during previous HTAP multi-model exercises. It
856 will be important to limit the number of perturbation runs (source regions and emitted species) so that modelling groups are
857 not overwhelmed by the number of runs to perform. The design of the perturbation runs is being done in close cooperation
858 with the group responsible for the development of the ensemble emulators to ensure that the ensemble emulator is as useful as
859 possible.

860
861 An important difference between the HTAP3-OPNS set of runs and previous HTAP multi-model assessments will be a focus
862 on policy-relevant ozone metrics. Whereas in previous HTAP assessments, most models delivered monthly mean fields, in
863 HTAP3 we will be asking for hourly mean surface (2D) fields of ozone mixing ratio and deposition fluxes. These hourly



864 surface fields are required in particular to allow the calculation of the impacts of ozone on vegetation and will also enable more
865 flexible and consistent calculation of human health impact metrics.

866 **9.2 HTAP3-Fires and IGAC BBurned**

867 To avoid duplication of work and to provide as large a set of model runs as possible for both projects, the base runs in the
868 HTAP3-OPNS set are being harmonised as much as possible with the work being co-organised with the IGAC BBurned
869 activity (Whaley et al., 2024):

- 870 • Common (or overlapping) base years for historical simulations.
- 871 • Use of the HTAPv3 anthropogenic emissions.
- 872 • Use of the same historical and future fire emission datasets.

873

874 The HTAP3-Fires activity is expected to continue well beyond the 2024-25 CLRTAP workplan, while HTAP3-OPNS is
875 expected to be largely completed by 2027.

876 **9.3 MCHgMAP**

877 Where possible, model runs done for MCHgMAP (Dastoor et al., 2024) will be set up as closely as possible to the HTAP3-
878 OPNS set of runs. A priority here will be the use of common fire activity data between MCHgMAP, HTAP3-Fires, and the
879 HTAP3-OPNS runs.

880 **9.4 AerChemMIP and CCMI**

881 We invite participation from the chemistry climate modelling community using models with interactive tropospheric chemistry
882 and aerosols for the simulation of future emissions scenarios. Modelling groups are requested to use their CMIP6 model
883 configurations with fixed SSTs based on SSP2-4.5 for simulations of the LRTAP CLE and MTR future emission scenarios.

884 **9.5 MethaneMIP**

885 There is some small overlap between the future scenario CCM runs requested in the HTAP3-OPNS set and work being planned
886 under MethaneMIP (<https://wcrp-cmip.org/mips/>), as both efforts include an analysis of methane mitigation measures. Based
887 on the current planning for both exercises however, this overlap does not warrant merging both activities.

888

889 A primary objective of MethaneMIP is to isolate the climate impact of methane mitigation, with air quality impacts being a
890 secondary objective. MethaneMIP builds on the existing SSP2-4.5 base runs that modelling groups have already performed
891 for CMIP6. This determines the MethaneMIP experimental design of fully coupled (including oceans) transient sensitivity
892 runs with only methane being changed from the SSP2-4.5 base case.

893



894 In contrast, HTAP3-OPNS aims to perform an assessment of air quality under the GAINS LRTAP future emission scenarios,
895 including the effects of all precursor emission changes (including methane but also NO_x, NMVOC, etc...) and the effects of
896 the changing climate on the air quality response. This determines our experimental design, which only calls for prescribed
897 SSTs and CO₂ forcing from SSP2-4.5 (CLE and MTR scenarios) in the transient free running cases.

898 **10 Summary**

899 The HTAP3-OPNS multi-model exercise has been designed by the Task Force on Hemispheric Transport of Air Pollution
900 (TF-HTAP) to provide scientific input to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) in support
901 of the current revision of the Gothenburg Protocol, the CLRTAP protocol to abate acidification, eutrophication, and ground-
902 level ozone. Using an ensemble of Chemical Transport Models and Chemistry-Climate Models, along with future emission
903 scenarios specifically developed to support the revision of the Gothenburg Protocol, this exercise will deliver information on
904 the long-range (intercontinental) transport of multiple pollutants across the Northern Hemisphere.

905
906 Building on previous assessments by TF-HTAP, a major focus of this exercise will be ground-level (tropospheric) ozone.
907 Results from the exercise will inform CLRTAP about the relative contributions of locally emitted ozone precursors and ozone
908 precursors emitted in remote source regions to the impacts of ground-level ozone on human health and ecosystems, both inside
909 and outside the UNECE region. These results will inform CLRTAP on options for mitigation of ground-level ozone through
910 controls on emissions of ozone precursors, including controls on methane emissions. In addition to the usefulness for
911 policymakers, the results from this study will deliver information about the suitability of current models for quantifying
912 ground-level ozone and its impacts and point the way to future model improvements.

913
914 A set of perturbation simulations using Chemical Transport Models and pre-existing emission scenarios will allow the
915 construction of detailed source/receptor relationships which will be used to develop an ensemble emulator, which will be used
916 to explore mitigation options in more detail. Transient simulations with Chemistry-Climate Models will be used to explore the
917 impact of climate change on future air quality under policy-relevant air pollution control scenarios. Simulations of the recent
918 historical period using a state-of-the-art global mosaic emission inventory will aid in model evaluation and provide a basis for
919 connecting this exercise with other concurrent exercises focusing on total atmospheric deposition and the impact of wildfires
920 on air quality. The HTAP3-OPNS multi-model exercise is open to all interested modelling groups, and all other groups wishing
921 to contribute to the analysis of model output datasets.



922 11 Data availability

923 GAINS anthropogenic emissions are available via <https://doi.org/10.5281/ZENODO.14748815> (Klimont et al., 2025).
924 Historical aviation emissions are available via <https://doi.org/10.5281/ZENODO.13911489> (Mertens et al., 2024a). Future
925 aviation emissions are available via <https://doi.org/10.5281/ZENODO.13257451> (Mertens et al., 2024b). Future fire emissions
926 are available via <https://doi.org/10.5281/ZENODO.17644150> (Bergas-Massó and Hamilton, 2025). Historical fire emissions
927 are available via <https://doi.org/10.5281/ZENODO.13753451> (Kaiser et al., 2025). HTAPv3.2 anthropogenic emissions are
928 available via <https://doi.org/10.5281/zenodo.7516360> (Crippa, 2024). Surface methane concentrations are available via
929 <https://doi.org/10.5281/ZENODO.14980849> (van Caspel and Fagerli, 2025). Source region definitions are available via
930 <https://doi.org/10.5281/zenodo.12654036> (Butler et al., 2025). Further details on these input datasets and how they are to be
931 used in HTAP3-OPNS are provided in the text of this manuscript. Model output data will be published as described in Section
932 8; model output (as delivered by modelling groups, Sec. 8.1) will be made available to all groups interested in contributing to
933 analyses after registration, and output datasets used in the production of scientific publications will be permanently archived
934 with version control and DOIs assigned.

935 12 Acknowledgements

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