

## REVIEW

# Tropospheric ozone assessment report: Missions, developments, and outlook

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The Tropospheric Ozone Assessment Report (TOAR), an activity of the International Global Atmospheric Chemistry Project (IGAC), has become a major international framework for assessing tropospheric ozone as an air pollutant, greenhouse gas, and ecosystem stressor from the surface to the tropopause. This contribution summarizes the evolution, scientific achievements, and remaining challenges of TOAR-I and TOAR-II, and outlines priorities for a possible TOAR-III. TOAR-I established the foundation for global ozone assessment by compiling a harmonized surface ozone database and producing standardized metrics for evaluating ozone distributions, trends, and exposure risks relevant to human health, vegetation, and climate. TOAR-II has expanded this foundation through 16 Focus Working Groups and a broad Community Special Issue, with stronger integration of surface observations, satellites, ozonesondes, aircraft, reanalysis products, and models. Its scientific advances include improved characterization of ozone variability and trends, greater emphasis on attribution to emissions, meteorology, transport, and stratosphere-troposphere exchange, and more explicit assessment of climate, health, crop, and ecosystem impacts. Remaining challenges include sparse long-term observations in the Global South, tropics, oceans, polar regions, and rapidly changing megacities; limited vertical profiling and precursor measurements; uncertainties in ozone deposition, radical chemistry, wildfire influences, and hemispheric transport; and inconsistent methods for trend detection, source attribution, and model evaluation. Future TOAR activities should therefore strengthen observational capacity, harmonize multi-platform data products, improve process-level understanding and predictive capability, and better connect ozone exposure with health burdens, crop yield and nutritional quality, forest carbon sequestration, ecosystem responses, and climate forcing.

**Keywords:** Ozone, Climate, Health, Global, Air pollution

## 1. Overview of Tropospheric Ozone Assessment Report (TOAR) activities

The Tropospheric Ozone Assessment Report (TOAR) is an activity of the International Global Atmospheric Chemistry Project (IGAC) that aims to assess the current state of

knowledge on tropospheric ozone, that is, ozone in the lower part of the atmosphere (surface to about 12 km), and to evaluate the impacts of ozone on human health, ecosystems, and climate. The mission, development and achievements of TOAR are documented at <https://igacproject.org/>

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activities/TOAR. TOAR has evolved into a flagship initiative of IGAC with highly cited papers and substantial uptake by several global stakeholders such as the Intergovernmental Panel on Climate Change (IPCC), the World Health Organization (WHO), and the Global Burden of Disease (GBD).

The efficient work of TOAR comes from four main components: firstly, its governance structure (chairs and a representative steering committee); secondly, the development and curation of the TOAR data infrastructure at the Jülich Supercomputing Centre (<https://toar-data.org>) which has over 100 users and has been used in dozens of studies on atmospheric science, climate change, human health, and crop/ecosystem research as well as the development of deep learning models; thirdly, the working groups formed according to themes and regions; fourthly, the active community engagement expressed through the set of assessment and community special issue papers. Collectively, these efforts provide open, well-documented data resources and standardized analytical methods that enable reproducible research and strengthen the scientific basis for ozone–climate–health assessments.

So far, TOAR activities have been conducted in two separate phases, each with a clear strategy and road map. Upon approval by the IGAC Scientific Steering Committee in 2014, the first phase of TOAR was billed as Tropospheric Ozone Assessment Report (TOAR): Global metrics for climate change, human health, and crop/ecosystem research. Now known as TOAR-I, the activity was defined as an international effort aimed at improving our understanding of tropospheric ozone's global distribution and trends, with research activities conducted over a 5-year period (2014–2019). A major achievement of TOAR-I was the compilation of the world's largest open-access database of surface measurements of ozone and related pollutants (Schultz et al., 2017), which created a common observational foundation for global-scale analyses. Building on this resource, TOAR-I provided harmonized assessments of ozone distribution and trends across urban, rural, and background sites, and consistently calculated widely used exposure metrics relevant to climate change, human health, and vegetation, including MDA8, SOMO35, AOT40, and M7 (Fleming et al., 2018; Gaudel et al., 2018; Lefohn et al., 2018; Mills et al., 2018; Tarasick et al., 2019). These standardized products improved cross-study comparability and accessibility worldwide. TOAR-I also included broader assessments of global-scale model performance and long-term changes in the tropospheric ozone burden and budget, while stimulating additional regional analyses of surface ozone trends in eastern North America, Europe, East Asia, and China (Chang et al., 2017; Young et al., 2018; Archibald et al., 2020; Xu et al., 2020). Collectively, the TOAR-I assessment papers (published in *Elementa: Science of the Anthropocene*, 2020 <https://igacproject.org/activities/TOAR/TOAR-I>) provided a landmark synthesis of global ozone science and established the scientific and data foundation for TOAR-II. TOAR-I provided the first globally consistent, observation-based framework for assessing tropospheric ozone and its impacts on climate, human health, vegetation, and ecosystem services. Its objectives were to harmonize surface ozone observations, establish robust exposure and trend metrics,

and create an open database for model evaluation, impact assessment, and future research. While TOAR-I established the scientific and data foundation for global ozone assessment, it also revealed important limitations in spatial coverage, metadata completeness, vertical information, precursor measurements, trend attribution, and links to impact-relevant diagnostics. These achievements and remaining gaps shaped the scientific priorities of TOAR-II, as summarized in **Table 1**.

Building on these achievements and remaining gaps, TOAR entered its second phase (TOAR-II) in February 2020. TOAR-II was designed to update the global assessment of tropospheric ozone while moving beyond trend detection toward attribution, multi-platform integration, regional synthesis, and impact-oriented diagnostics. These priorities provided the rationale for the TOAR-II Focus Working Groups (Section 2), which were organized to strengthen observations and harmonization, advance process understanding and attribution, expand regional analyses, and improve linkages to climate, health, vegetation, and ecosystem impacts. As of May 2026, TOAR-II was finalizing a new set of assessment papers and was expected to continue until these had been reviewed and accepted. A key focus in TOAR-II is to move beyond trend detection to attribute observed ozone changes to specific drivers such as precursor emissions (e.g., NO<sub>x</sub> and VOCs), climate variability, long-range transport, and stratosphere-troposphere exchange (STE). TOAR-II has increased the integration of modeling studies with observations, using chemical transport and Earth-system models alongside satellite, ozonesonde, aircraft, and surface datasets to diagnose source-receptor relationships and attribution. The Community Special Issue publishes papers presenting original research (new datasets, methods, evaluations, regional analyses), whereas the forthcoming Assessment Special Issue synthesizes those results with the wider literature into standardized, non-prescriptive assessments (i.e., providing evidence and metrics without prescribing specific policies). Furthermore, the current phase also prioritizes better integration of observing systems and expanded coverage in under-sampled regions, including the Southern Hemisphere, the tropics, and parts of Africa, South America, China, and South/Southeast Asia, as well as oceanic and polar regions. This is achieved by linking satellite, ozonesonde, aircraft, and surface networks through harmonized QA/QC, common data structures, and joint analyses, while also leveraging newer deployments such as geostationary platforms where available. Maintenance and expansion of the TOAR database with high-resolution, quality-assured data continued throughout TOAR-II.

## 2. Key summaries of papers in TOAR-II Community Special Issue

### 2.1. Scientific goals of TOAR-II and structure of the Community Special Issue

Building on the observational and assessment foundation established by TOAR-I, TOAR-II was designed to provide a more integrated, diagnostic, and policy-relevant assessment of tropospheric ozone. Its goals can be grouped into seven areas: (i) updating and expanding the global ozone database; (ii) improving trend detection and attribution;

**Table 1. Summary table of TOAR-I objectives, major achievements, remaining gaps, and implications for TOAR-II**

| TOAR-I Objective                          | Major Achievements in TOAR-I                                                                                  | Remaining Gap After TOAR-I                                                                          | Implication for TOAR-II                                                                             |
|-------------------------------------------|---------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| Establish a global surface ozone database | Harmonized surface ozone observations with quality control and metadata                                       | Sparse coverage in the Global South, remote regions, and complex terrain                            | Expand observations and integrate surface, satellite, aircraft, ozonesonde, and reanalysis products |
| Standardize ozone metrics                 | Consistently calculated health-, vegetation-, and climate-relevant metrics                                    | Some metrics remained weakly linked to biological uptake and impact endpoints                       | Refine exposure metrics for health, vegetation, and assessment applications                         |
| Assess ozone distributions and trends     | Produced coordinated global and regional trend assessments                                                    | Trend interpretation limited by site history, metadata gaps, and meteorology                        | Improve metadata, statistical methods, and uncertainty quantification                               |
| Identify drivers of ozone variability     | Revealed regionally heterogeneous O <sub>3</sub> changes and changing peak/background O <sub>3</sub> behavior | Limited attribution to emissions, transport, chemistry, and stratosphere-troposphere exchange       | Strengthen process-based attribution using observations and models                                  |
| Support model evaluation                  | Provided observational benchmarks for global and regional models                                              | Coordinated model intercomparison and process diagnosis remained limited                            | Develop systematic model evaluation and reanalysis-model-observation comparisons                    |
| Link ozone to impacts                     | Synthesized O <sub>3</sub> effects on health, vegetation, ecosystems, and climate                             | Exposure-impact links remained incomplete, especially in data-sparse regions                        | Strengthen health, ecosystem, crop, and climate impact assessments                                  |
| Establish an assessment community         | Created a shared scientific infrastructure for long-term O <sub>3</sub> assessment                            | Sustained data submission, regional capacity, and cross-platform harmonization remained challenging | Organize TOAR-II Focus Working Groups around data, methods, attribution, and impacts                |

(iii) strengthening the linkage between observations, models, reanalyzes, and satellite products; (iv) advancing health, vegetation, ecosystem, and climate impact assessments; (v) connecting ozone variability with precursor chemistry, deposition, and photochemical regimes; (vi) developing policy-relevant diagnostics for air-quality management, methane mitigation, crop protection, and transboundary pollution; and (vii) promoting open, reproducible, and community-based assessment. The TOAR-II Community Special Issue was organized around these goals and provides the scientific basis for the forthcoming assessment papers. **Table 2** summarizes how the 58 papers contribute to these goals.

## 2.2. Scientific advances from the TOAR-II Community Special Issue

The TOAR-II Community Special Issue is an inter-journal initiative spanning five Copernicus journals (ACP (lead), AMT, GMD, BG, and ESSD) to connect method, data, modeling, and impact studies under a common special-issue umbrella. The goal of this special issue was to collect new information and individual perspectives on relevant factors from tropospheric ozone drivers to impacts. Through this, the TOAR-II steering group wanted to create a rich body of literature on which the actual TOAR-II assessment can now build. Within TOAR-II, 16 Focus Working Groups provided the backbone for

this effort. They were established to (i) deliver foundational observations and harmonized data/metrics (e.g., HEGIFTOM, Satellite Ozone, Statistics); (ii) advance process understanding and attribution (e.g., Tropospheric Ozone Precursors (TOP), Ozone Deposition, Radiative Forcing, Chemical Reanalysis, Global and Regional Models, Machine Learning); (iii) produce regional syntheses (East Asia, South Asia, Tropics, Oceans); and (iv) assess impacts and applications (Human Health, Urban Ozone), with ROSTEES linking stratosphere-troposphere exchange to tropospheric burdens. This WG structure is mandated by TOAR-II's mission to update the global distribution, trends, drivers, and impacts of tropospheric ozone from the surface to the tropopause.

As of May 2026, the 58 articles in the TOAR-II Community Special Issue ([https://bg.copernicus.org/articles/special\\_issue10\\_1256.html](https://bg.copernicus.org/articles/special_issue10_1256.html)) reflect a systematic progression along the tropospheric ozone knowledge chain from the working groups: from foundational observation and data harmonization, through trend attribution and mechanistic evaluation, to impact quantification, machine learning-based innovation, and finally, policy-relevant scenario analysis. This framework ensures not only scientific coherence but also relevance to climate-air quality policy decision-making. Here, we summarize the key scientific advances across five interconnected thematic areas.

**Table 2. Mapping of TOAR-II Community Special Issue publications to TOAR-II scientific goals**

| TOAR-II Scientific Goal                                                                        | Community Special Issue Publications Mapped to this Goal                                                                                                                                                                                                                                                                                                                      | Synthesis of Contributions                                                                                                                                                                                                                                                                                                    |
|------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Strengthen observations and harmonized data products                                           | Pope et al. (2023); Orfanos-Chequela et al. (2024); Pope et al. (2024a); Wang et al. (2024); Zang et al. (2024); Björklund et al. (2024); Satheesan et al. (2024); Iturrate-Garcia et al. (2025); Arosio et al. (2025); Van Malderen et al. (2025a); Pennington et al. (2025); Kanaya et al. (2025); Smit et al. (2025); Coldewey-Egbers et al. (2025); Keppens et al. (2025) | Expanded and harmonized satellite, ozonesonde, aircraft, ground-based, oceanic, polar, and precursor datasets; evaluated retrieval bias, instrument consistency, vertical sensitivity, representativeness, metadata quality, and measurement traceability.                                                                    |
| Improve trend detection and attribution                                                        | Gaudel et al. (2024); Stauffer et al. (2024); Chang et al. (2024); Seguel et al. (2024); Donnou et al. (2024); Froidevaux et al. (2025); Chang et al. (2025); Lu et al. (2025); Li et al. (2025); Van Malderen et al. (2025b); Pimlott et al. (2025a); Nelson and Drysdale (2025); Ansari et al. (2025); Thompson et al. (2025)                                               | Quantified surface, free-tropospheric, and column O <sub>3</sub> trends across regions; documented heterogeneous changes in tropical, urban, high-elevation, East/Southeast Asian, South American, African, European, and North American O <sub>3</sub> ; improved statistical treatment of sparse and heterogeneous records. |
| Link ozone variability with process understanding and precursor chemistry                      | Li et al. (2024); Mertens et al. (2024); Elshorbany et al. (2024); Lebourgeois et al. (2024); Huang et al. (2025); Sourì et al. (2025); Nalam et al. (2025); Fadnavis et al. (2025); Gong et al. (2025); Seguel et al. (2025); Okamoto et al. (2026)                                                                                                                          | Connected O <sub>3</sub> distributions and variability with precursor emissions, reactive nitrogen, VOCs, transport emissions, biomass burning, Arctic processes, tropical Atlantic variability, O <sub>3</sub> production regimes, and stratosphere-troposphere exchange.                                                    |
| Assess climate forcing and ozone–climate interactions                                          | Pope et al. (2024b); Collins et al. (2025); Sellitto et al. (2025)                                                                                                                                                                                                                                                                                                            | Updated estimates of tropospheric O <sub>3</sub> radiative effects and evaluated how precursor emissions, vertical O <sub>3</sub> redistribution, future emission pathways, and metric choice influence ozone–climate forcing assessments.                                                                                    |
| Quantify health, crop, forest, and ecosystem impacts                                           | Cook et al. (2024); Pande et al. (2025); Cook et al. (2025); Everett et al. (2025); Karlsson et al. (2025); Turnock et al. (2025); Wang et al. (2025)                                                                                                                                                                                                                         | Linked O <sub>3</sub> exposure with crop phenology, wheat yield, nutritional quality, forest biomass growth, carbon sequestration, health-risk drivers, and uncertainty in health-relevant O <sub>3</sub> exposure datasets.                                                                                                  |
| Develop modeling, reanalysis, statistical, and machine-learning tools                          | Brown et al. (2024); Sekiya et al. (2025); Miyazaki et al. (2025); Hickman et al. (2025); Jones et al. (2026)                                                                                                                                                                                                                                                                 | Evaluated Earth-system models and chemical reanalyses; assessed the value of assimilating satellite O <sub>3</sub> and precursor observations; applied explainable machine learning and reviewed emerging AI applications for ozone research.                                                                                 |
| Use perturbation events, urban sensitivity analyses, and scenarios for policy-relevant insight | Putero et al. (2023); Pimlott et al. (2025b); Cazorla et al. (2025)                                                                                                                                                                                                                                                                                                           | Used COVID-19 emission perturbations, satellite-model analyses, and urban NO <sub>x</sub> /VOC sensitivity studies to diagnose O <sub>3</sub> responses under rapid emission changes and to inform air-quality management in data-limited regions.                                                                            |

### 2.2.1. Ozone observation and data product development

Building on decades of global ozone observations, this theme strengthens the observational backbone by improving accuracy, cross-platform comparability, and precursor data coverage. Several studies provide intercomparisons between satellite (e.g., Ozone Mapping and Profiler Suite (OMPS) and Tropospheric Monitoring Instrument

(TROPOMI)), ozonesonde, and aircraft observations (e.g., In-Service Aircraft for a Global Observing System (IAGOS)), revealing systematic differences related to vertical sensitivity (especially near the surface), sampling/representativeness, and retrieval uncertainty; these differences can influence trend detection and highlight where methodological refinement is needed (Pope et al., 2023; Pope et al., 2024a; 2024b; Gaudel et al., 2024; Wang

et al., 2024). Complementing these are evaluations of chemical reanalysis products, which identify spatial–temporal performance variations and inform targeted improvements (Miyazaki et al., 2025; Jones et al., 2026). A novel strand of this thematic area involves expanding observational networks, especially for ozone precursors such as OVOCs, which are difficult to measure because of their low atmospheric abundance and lack of stable and traceable calibration standards. Beyond well-instrumented regions (e.g., Europe, the USA, and parts of China), significant gaps remain in in situ monitoring of both anthropogenic and biogenic VOCs. Expanding coverage would improve attribution of ozone formation regimes and trend detection. Iturrate-Garcia et al. (2025) emphasize metrological traceability for OVOC measurements, while satellite datasets such as GOP-ECV and OMPS-based (OMPS-NM/OMPS-LP ozone profile and related tropospheric ozone column) products offer enhanced continuity and coverage. More broadly, TOAR surface observations provide an objective reference for evaluating emerging satellite-derived tropospheric ozone products and their ability to inform spatial patterns and trends at the surface, especially where vertical sensitivity is limited (Pope et al., 2023; Gaudel et al., 2024). Collectively, these efforts reinforce the integrity of long-term ozone data for subsequent analysis (Chang et al., 2024).

### 2.2.2. Ozone distribution and variability

Building on improved data foundations, this thematic area investigates global and regional ozone patterns, their evolution, and underlying causes. Multiple analyses report post-2000 declines in high-percentile surface-ozone metrics across much of North America, along with short-term COVID-period reductions in Europe and western North America; changes are more heterogeneous for other metrics and across site settings (e.g., urban vs. rural/background) (Putero et al., 2023; Gaudel et al., 2024; Pope et al., 2024a; Chang et al., 2025; Pimlott et al., 2025a; 2025b). Complementary TOAR-II syntheses based on harmonized multiplatform observations (e.g., ozonesondes, IAGOS, FTIR, lidar, and Umkehr) quantify free-tropospheric and tropospheric-column ozone trends and provide additional context and constraints for satellite-based trend estimates (Thompson et al., 2025; Van Malderen et al., 2025a; 2025b). Aircraft observations across the stratosphere-troposphere exchange region show a hemispheric contrast with lower, more stratosphere-like ozone in the Southern Hemisphere, and year-to-year variability tied to stratospheric dynamics, exemplified by the 2019 sudden stratospheric warming (Seguel et al., 2025). The improved Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere (TOST) spanning 1970–2021 provides global seasonal and decadal context and indicates stagnant lower-stratospheric ozone since the late 1990s (Zang et al., 2024). Vertical distribution patterns and upper tropospheric anomalies are also scrutinized through IAGOS and satellite composites. Attribution studies further identify the meteorological and anthropogenic drivers of ozone variability, ranging from  $\text{NO}_x$ /VOC emission trends to STE and biomass burning. Lebourgeois et al. (2024) apply

trajectory diagnostics and tagged tracers to isolate source contributions while modeling studies by Sekiya et al. (2025) and Huang et al. (2025) quantify the precursor influences with reanalysis-informed sensitivity frameworks. This integrative approach bridges observation with process understanding, supporting consistent trend attribution across scales from local to global dimensions.

### 2.2.3. Evaluation of ozone impacts and drivers

Several papers (Pope et al., 2024b; Collins et al., 2025; Everett et al., 2025; Fadnavis et al., 2025; Sellitto et al., 2025) assess the impacts of ozone in the Earth system, as a short-lived climate forcer, an ecological stressor, and a pollutant that affects human health. From the climate aspect, Pope et al. (2024b) update the tropospheric ozone radiative effect ( $\text{TO}_3\text{RE}$ ) for 2008–2017 to  $1.21\text{--}1.26 \text{ W m}^{-2}$  and show a negligible global trend due to offsetting impacts from precursor-emission changes and meteorology; Fadnavis et al. (2025) demonstrate that  $\text{NO}_x$  emission changes dominate  $\text{TO}_3\text{RE}$  responses (with the largest enhancements over South and East Asia); and Sellitto et al. (2025) use IAGOS-constrained offline radiative modeling to show that RF did not decrease between recent periods because of shifts in the vertical distribution of ozone. These analyses frame ozone within the context of short-lived climate forcers and global warming potential. Concurrently, ecosystem impact assessments quantify ozone-induced crop yield and nutritional quality losses and forest productivity reductions in relation to carbon sequestration. Everett et al. (2025) apply crop models to estimate the effect of ozone on irrigated and rainfed crops under current and future climate simulations in India and find that ozone has the potential to offset some of the benefit to yield offered by irrigation. Cook et al. (Cook et al., 2024; 2025) developed crop modeling methods capable of linking surface ozone exposure to nutritional quality declines and yield penalties, and translating ozone impacts into effects on amino acids and dietary protein requirements for human health. Karlsson et al. (2025) estimate ozone-induced biomass losses in managed European forests, and find that carbon sequestration would increase by 31% under the scenarios considered in the absence of ozone pollution (i.e., exposure to elevated near-surface ozone above natural/background levels). Collectively, these studies underline the societal relevance of tropospheric ozone, especially in food and nutritional security and forest carbon sequestration. Finally, Turnock et al. (2025) additionally show that historical increases in peak-season surface ozone and associated health risk were driven mainly by rising anthropogenic precursor emissions, particularly  $\text{NO}_x$  and  $\text{CH}_4$ . For health-relevant exposure metrics, Wang et al. (2025) intercompare multiple global ground-level ozone mapping products and show that differences among datasets are large enough to materially affect estimated population exposure and health impacts.

### 2.2.4. Technological innovation

Innovation in ozone research is increasingly driven by machine learning (ML) and data integration technologies. This thematic area encompasses novel uses of AI and statistical learning to enhance model interpretation, trend

attribution, and uncertainty quantification. Miyazaki et al. (2025) employ an explainable machine learning technique to identify bias sources in chemical reanalysis products, while Lu et al. (2025) integrate chemical transport models with neural networks to improve East and South-east Asian ozone trend attribution. Hickman et al. (2025) provide a comprehensive review of recent advances in ML applications for tropospheric ozone research, highlighting progress in short-term forecasting, chemical mechanism emulation, and remote sensing-based ozone estimation. They identify major barriers such as limited model explainability, generalizability, and the need for benchmark datasets, and propose actionable pathways to strengthen the integration of ML into atmospheric chemistry through interdisciplinary collaboration. These approaches offer scalable tools for ozone monitoring and modeling, promising enhanced performance in both global assessments and regional applications.

#### 2.2.5. Perturbation events and policy-relevant diagnostics

The final thematic area addresses how external shocks to the economy and contextual shifts influence tropospheric ozone levels and related policy responses. Several studies exploit the COVID-19 lockdown as a natural experiment: Putero et al. (2023) and Pimlott et al. (2025b) quantify ozone decreases associated with reduced anthropogenic activities, while Arosio et al. (2025) use the event to validate satellite column measurements under altered emission conditions. Beyond the COVID-19 perturbation, other Community Special Issue papers examine ozone responses to heat waves, biomass-burning influences, and tropical dynamical variability, including climate-oscillation-related changes in convection and transport over equatorial Southeast Asia (Lebourgeois et al., 2024; Stauffer et al., 2024; Chang et al., 2025). These events not only demonstrate the non-linear sensitivity of ozone chemistry to rapid change in precursor emissions, meteorology, and fire-related emissions but also offer insights into resilience and control strategies. Scenario and sensitivity modelling further support policy-relevant diagnostics by quantifying how precursor-emission changes affect ozone production, health-relevant exposure, and climate forcing (Cazorla et al., 2025; Collins et al., 2025; Fadnavis et al., 2025; Turnock et al., 2025).

In summary, the TOAR-II Community Special Issue provides a structured synthesis of the global ozone landscape and advances scientific understanding across many areas. The five thematic areas form a coherent research continuum: from rigorous observational groundwork to impact evaluation and policy-relevant modeling. By addressing observational gaps, refining attribution, and quantifying interactions with health, climate, and ecosystems, these studies deliver an integrated and actionable scientific foundation for the next generation of ozone assessment and management.

#### 2.3. Community participation and geographic coverage

The TOAR-II Community Special Issue reflects a broad international effort, with contributions from research

groups across North America, Europe, Asia, South America, Africa, and Oceania. This wide participation is important because tropospheric ozone is shaped by regionally diverse emission patterns, meteorology, chemistry, transport, and exposure settings. At the same time, the authorship and data coverage of the Community Special Issue also illustrate a continuing imbalance in global ozone research capacity. Contributions and long-term observations remain concentrated in Europe, North America, and parts of East Asia, whereas Africa, South America, South and Southeast Asia, the tropics, oceans, and polar regions remain comparatively underrepresented. This imbalance reinforces one of the central conclusions from TOAR-I and TOAR-II: future assessment activities must combine scientific synthesis with sustained capacity building, data rescue, harmonized metadata collection, and stronger engagement with under-sampled regions.

#### 3. TOAR-II assessment papers: Overview and review

Building on the community special issue publications, TOAR-II is now developing several assessment papers focused on climate, health, and vegetation impacts, while extending TOAR-II focus areas beyond TOAR-I to include regional syntheses and an up-to-date assessment of stratosphere-troposphere exchange processes. Thus, the health assessment efforts align with improving assessments of ozone exposure in developing regions where data are sparse, using GBD (Global Burden of Disease), and newly developed models. In terms of Ozone and Ecosystem Impacts, emphasis has been placed on strengthening links between ozone exposure and impacts on crops and forests, as well as applying more biologically relevant metrics that reflect cumulative ozone uptake and damage to vegetation. The climate assessment will focus on analyzing feedback among ozone, climate change, and greenhouse gases, and on quantifying ozone's radiative forcing and its co-benefits/risks in climate mitigation strategies. In line with this, the assessment will support global assessments, such as reports by the IPCC and WMO with updated tropospheric ozone data. The regional assessments are vital because coverage in the Global South remains sparse in both TOAR-I and TOAR-II. Significant gaps persist across Africa, South America, Central and Southeast Asia, and the Pacific and Southern Oceans, which we identify as priority targets for future capacity-building and assessment updates. Most surface ozone data come from Europe, North America, and East Asia, limiting global representativeness. Thus, the TOAR-II assessment papers aim to bridge this gap with a focus on these key geographic regions such as South America, Africa, the oceans, and the polar regions. Methodologically, TOAR-II delivered a clear step forward by standardizing trend and uncertainty methods and harmonizing units and exposure metrics, thereby improving reproducibility and cross-study comparability across the assessment.

Although the TOAR-II Community Special Issue has now been completed, the TOAR-II assessment papers remain in preparation and/or under review. In drafting the assessment papers, several remaining or newly identified knowledge and data gaps have emerged. Some of the key limitations

of TOAR-II that were discussed at the TOAR Writing Team Meeting in York, UK in July 2025, are listed in **Table 3**. They point toward future research priorities: expanded monitoring networks, improved chemistry in models, harmonized remote sensing techniques, robust statistical frameworks, and deeper mechanistic understanding, which may form the basis for a TOAR-III continuation.

4. TOAR-III in planning

TOAR-III is currently being planned and is intended to address underexplored or emerging areas that were only partially covered in TOAR-I and TOAR-II. The potential focus areas summarized in **Table 4** are motivated by the limitations identified in **Table 3**—for example, strengthening observing capacity and harmonization, improving model chemistry and process representation, and advancing the linkage between in situ data and remote sensing for trend attribution. In particular, **Table 4** priorities can be viewed as three connected thrusts: (i) expanding and harmonizing observations (including in developing regions) to reduce spatial gaps and improve measurement comparability; (ii) improving process understanding, attribution methods, and model representation to better attribute trends and extremes; and (iii) strengthening the translation from ozone exposure metrics to climate, health, and ecosystem-relevant outcomes. These thrusts directly respond to **Table 3** limitations by pairing data needs with methodological advances and by clarifying where new observing strategies, evaluation frameworks, and cross-program coordination can accelerate progress. Stronger links are expected to be pursued with other

Table 3. Key areas of limitation within TOAR-II analysis

| Gap Area                        | Specific Needs                                                                                         |
|---------------------------------|--------------------------------------------------------------------------------------------------------|
| Geographic and Vertical Data    | More stations in tropics, Global South, vertical profiles, GEO satellites                              |
| Chemical Processes              | Organic peroxy radical (RO <sub>2</sub> ) chemistry, reactive nitrogen chemistry, aerosol interactions |
| Model/Reanalysis Accuracy       | Fix hemispheric biases, replicate trends                                                               |
| Statistical Methods             | Standardized trend/uncertainty tools                                                                   |
| Attribution Studies             | Apportion drivers of ozone trends (emissions, meteorology, STE)                                        |
| Satellite Retrieval Consistency | Harmonize data from different instruments                                                              |
| Urban and Extreme Events        | Cover wildfire, convective influence                                                                   |
| Ecosystem Metrics               | Evaluation of stomatal uptake-based indicators and associated effects                                  |
| Model Benchmarking              | Deep intercomparison and process diagnosis                                                             |

Table 4. Potential focus areas for TOAR-III

| Underexplored Focus Area               | Potential Contribution in TOAR-III                                                                                                                                       |
|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Air-Quality-Climate-Health Integration | Cross-sector policy evaluation and co-benefit analysis, including health records and demographic sensitivity                                                             |
| Climate Effect Management              | Improve international accountability and emissions policy, for example, “what reductions in precursor emissions would achieve a 0.1 K reduction from O <sub>3</sub> RF?” |
| Biosphere Feedback                     | Link ozone with global carbon–water cycle                                                                                                                                |
| Wildfires and Biomass Burning          | Impact of wildfires and wildland-urban interface fires on O <sub>3</sub>                                                                                                 |
| Real-Time Forecasting                  | Expanded use of AI                                                                                                                                                       |
| Data Fusion                            | GEO observations for diurnal observations of ozone and precursors (NO <sub>x</sub> and VOCs)                                                                             |
| Evolving Satellite Observing System    | Leverage new GEO/LEO missions and ensure continuity as legacy platforms phase out; improve cross-sensor harmonization and long-term trend robustness                     |
| Supersites and Radical Chemistry       | Advance process understanding and modeling                                                                                                                               |

related international science programs including HTAP (Hemispheric Transport of Air Pollution), CCAC (Climate and Clean Air Coalition), and AQMx (Air Quality Management Exchange Platform) (**Table 4**). To strengthen the focus on developing regions, the TOAR steering committee has already appointed Dr Rodrigo Seguel from Universidad de Chile as the first co-chair to lead TOAR-III.

5. Conclusions and outlook

This IGAC anniversary contribution provides a guided overview of TOAR-I and TOAR-II activities and the TOAR-II Community Special Issue, which collectively advance tropospheric ozone science along an observation-to-impact knowledge chain. Key advances include (i) improved harmonization and intercomparison of ozone observations across platforms; (ii) more robust characterization of regional patterns and changes, including improved attribution of drivers; (iii) integration of models, reanalysis, and emerging machine-learning tools to quantify uncertainties and evaluate mechanisms; and (iv) strengthened linkages to climate, health, and ecosystem impacts through standardized exposure metrics. Continued progress will require expanding high-quality observations in under-sampled regions, sustaining open data infrastructures, and further integrating surface observations with profiling and satellite capabilities to support trend attribution and assessment use. The priorities under consideration for TOAR-III (**Table 4**) are designed to address these needs and to strengthen connections to allied international assessment activities.

Appendix A. List of abbreviations

| Abbreviation    | Full Term                                                                                         |
|-----------------|---------------------------------------------------------------------------------------------------|
| AOT40           | Accumulated ozone exposure over a threshold of 40 ppb                                             |
| AQMx            | Air Quality Management Exchange Platform                                                          |
| CCAC            | Climate and Clean Air Coalition                                                                   |
| CTM             | Chemical transport model                                                                          |
| ESM             | Earth system model                                                                                |
| ESSD            | Earth System Science Data                                                                         |
| FTIR            | Fourier-transform infrared spectroscopy                                                           |
| GBD             | Global Burden of Disease                                                                          |
| GEO             | Geostationary Earth orbit                                                                         |
| GMD             | Geoscientific Model Development                                                                   |
| HEGIFTOM        | Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements |
| HTAP            | Hemispheric Transport of Air Pollution                                                            |
| IAGOS           | In-service Aircraft for a Global Observing System                                                 |
| IGAC            | International Global Atmospheric Chemistry Project                                                |
| IPCC            | Intergovernmental Panel on Climate Change                                                         |
| LEO             | Low Earth orbit                                                                                   |
| M7              | Mean daytime 7 h ozone mixing ratio                                                               |
| MDA8            | Maximum daily 8 h average                                                                         |
| ML              | Machine learning                                                                                  |
| NO <sub>x</sub> | Nitrogen oxides                                                                                   |
| OMPS            | Ozone Mapping and Profiler Suite                                                                  |
| OVOC            | Oxygenated volatile organic compound                                                              |
| QA/QC           | Quality assurance and quality control                                                             |
| RF              | Radiative forcing                                                                                 |
| ROSTEEs         | Role of Stratosphere-Troposphere Exchange in the Earth System                                     |
| RO <sub>2</sub> | Organic peroxy radical                                                                            |
| SOMO35          | Sum of ozone means over 35 ppb                                                                    |
| STE             | Stratosphere-troposphere exchange                                                                 |
| TO3RE           | Tropospheric ozone radiative effect                                                               |
| TOAR            | Tropospheric Ozone Assessment Report                                                              |
| TOAR-I          | First phase of the Tropospheric Ozone Assessment Report                                           |
| TOAR-II         | Second phase of the Tropospheric Ozone Assessment Report                                          |
| TOAR-III        | Planned third phase of the Tropospheric Ozone Assessment Report                                   |
| TROPOMI         | Tropospheric Monitoring Instrument                                                                |
| TOST            | Trajectory-mapped Ozone dataset for the Stratosphere and Troposphere                              |
| VOC             | Volatile organic compound                                                                         |
| WMO             | World Meteorological Organization                                                                 |
| WHO             | World Health Organization                                                                         |

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Competing interests

The authors declare no competing interests.

Author contributions

KL, HW, and MS conceptualized this work. KL and RM drafted this manuscript. All authors commented on drafting and revision of this manuscript during both the in situ and online TOAR workshops.

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