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Tropospheric Ozone Assessment Report II: Overview

Introduction

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The International Global Atmospheric Chemistry (IGAC) Tropospheric Ozone Assessment Report Phase II (TOAR-II) provides an updated, comprehensive assessment of the global distribution, burden and trends of tropospheric ozone, building on the foundation established by TOAR-I, 2014–2019. Accurate knowledge of tropospheric ozone concentrations remains essential for understanding atmospheric chemistry with far reaching implications for climate radiative forcing, vegetation damage and human health. Here, we present the process and summarize the main conclusions of TOAR-II, 2020–2026. Following TOAR-I, TOAR-II provides updates to trends in ozone concentrations and other metrics and addresses trends in ozone precursor emissions. This was accomplished as a community-driven process by forming Focus Working Groups to continue and expand on TOAR-I topics. Focus Working Group findings were published in a TOAR-II Community Special Issue with 58 review and original research papers. From this Community Special Issue, as well as other relevant literature, seven assessment papers were synthesized and submitted to this issue, along with this overview paper. These papers update the primary themes of TOAR-I: health, vegetation and climate; address unresolved uncertainties and inconsistencies in TOAR-I satellite ozone observations; provide an overdue update on stratosphere–troposphere exchange (STE) and present critical regional assessments for ozone over oceanic and polar regions, and South America. The TOAR-II assessment would not be possible without an extensive data collection and data

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harmonization effort. TOAR-II data are curated under findable, accessible, interoperable and reusable principles, and the TOAR data repository has been certified by the Core Trust Seal. In addition, TOAR-II developed common statistical analysis guidelines for the assessment papers. Although TOAR-II provides an extensive assessment of the current state of tropospheric ozone, many gaps and scientific challenges remain for future assessments. In particular, there is under-sampling of ozone across Southeast Asia and the Southern Hemisphere, especially Africa and Australia/Oceania. Low-cost sensor data and geostationary satellite data for tropospheric ozone, which still require evaluation, should be included. Ozone produced from wildfires and exacerbated by extreme weather events, and attribution of changes in ozone to pollution regulations on precursor emissions require greater attention in future analyses. These topics will be prioritized in the IGAC TOAR-III effort along with incorporating advances in artificial intelligence (AI) and strengthening collaboration with policy-relevant initiatives.

This article is part of the theme issue 'Tropospheric Ozone Assessment Report II'.

1. Introduction

Tropospheric ozone (O_3) is a greenhouse gas that contributes to climate change through its role as a direct short-lived climate forcer (Intergovernmental Panel on Climate Change (IPCC), 2021). It is the main generator of the hydroxyl radical, which controls the oxidative capacity of the troposphere and the removal rates of many chemically and radiatively active trace gases, such as methane (CH_4), carbon monoxide (CO), non-methane volatile organic compound (NMVOCs), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) [1–3].

At the surface, both vegetation [4–6] and human health [7–9] are negatively affected by elevated ground-level ozone concentrations. Surface ozone concentrations and the tropospheric ozone burden are affected by many factors—emissions of ozone precursors (e.g. nitrogen oxides (NOx), CH_4, NMVOCs and CO), their global distribution and trends, weather-driven chemistry and atmospheric transport of ozone and its precursors, stratosphere–troposphere exchange (STE), climate variability and climate change—as broadly illustrated in figure 1 [3,5,10–22].

From 1989 to 2014, coordinated international efforts for assessing the global distribution and trends of ozone primarily focused on the stratosphere, in response to the dramatic ozone losses observed above Antarctica owing to the accumulation of ozone depleting substances in the stratosphere. Scientific assessments of ozone depletion, required by the Montreal Protocol on Substances that Deplete the Ozone Layer, have been published every 4 years since 1989, providing comprehensive updates on the chemical and physical processes that control depletion of the ozone layer and its anticipated recovery (all assessment reports are available at: https://csl.noaa.gov/assessments/ozone). Over the same period (1990–2013), brief observation-based assessments of tropospheric ozone regularly appeared in the first through the fifth assessment reports produced by Working Group I of the IPCC (all assessment reports are available at: https://www.ipcc.ch/reports/). The IPCC assessments were based on information available in the peer-reviewed literature and focused on ozone observations in the free troposphere and at remote surface sites reported as average values, as these data were most relevant to climate change [23]. While IPCC Working Group II briefly assessed published studies regarding the impact of surface ozone on health and vegetation, the report did not provide an observation-based overview of the present-day distribution and trends of surface ozone in terms of metrics relevant to health and vegetation [24]. A common theme across these early (first to fifth) IPCC reports was an acknowledgement of the difficulty in quantifying global ozone trends in both the troposphere and stratosphere owing to the sparse global *in situ* monitoring network, the limited sensitivity and remaining uncertainties in satellite measurements and the heterogeneous nature of ozone distributions and trends. At the time of the fifth IPCC Assessment, brief updates on tropospheric ozone began to appear in the annual State of the Climate reports [25]. However, because these reports

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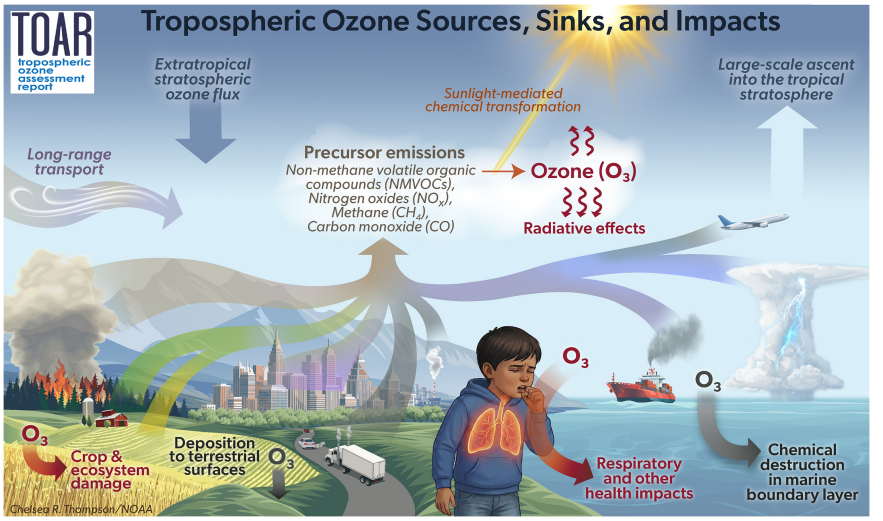


Figure 1. Tropospheric ozone sources, sinks and impacts. Focus is on time scales ranging from seconds/hours (chemical reactions, deposition and short-term health impacts) to days (long range transport) to months (seasonal cycles), and does not address climate variability (several years) or climate change (decades).

focused on anomalies relative to recent conditions (e.g. the 2013 anomaly compared to the previous decade), the analysis relied on a single satellite product available for such applications, together with long-term *in situ* observations.

By 2013, the IPCC assessments (e.g. [26,27]), the Coupled Model Intercomparison Project fifth phase [28] and the Atmospheric Chemistry and Climate Model Intercomparison [29–31] had greatly improved our understanding of tropospheric ozone's evolution from the pre-industrial to the present day. However, the focus remained on climate and relied heavily on model simulations with a present-day period centred on 2000, based on available emission inventories. In addition, other multi-model initiatives, such as The Task Force on Hemispheric Transport of Air Pollution (TF HTAP) [32], were quantifying the impacts of intercontinental and interregional transport on present-day surface ozone concentrations. At the same time, the global ozone observational network was expanding, with deployment of more surface monitors [33–36], ozonesondes [37–42], commercial aircraft [43,44], research aircraft [45–48], lidar instruments [49,50], Fourier transform infrared spectrometers [51] and satellite instruments [52–58]. Ozone records were also becoming long enough that multi-decadal trends could be assessed at multiple locations around the globe [59–61].

Recognizing the need for a coordinated effort to understand the global-scale distribution and trends of troposphere ozone, and to involve scientists from around the world, two international workshops on tropospheric ozone changes were held in Boulder, USA, in October 2009, and in Toulouse, France, in April 2011 [62,63]. In early 2014, the momentum from these workshops and activities led to the creation of a new International Global Atmospheric Chemistry (IGAC) activity called the Tropospheric Ozone Assessment Report (TOAR): global metrics for climate change, human health and crop/ecosystem research [34]. TOAR had a mission to provide the research community with an up-to-date scientific assessment of tropospheric ozone's global distribution and trends from the surface to the tropopause, with two main goals: (i) produce the first TOAR based on all available surface observations, the peer-reviewed literature and new analyses, and (ii) generate easily accessible, documented data on ozone exposure and dose metrics at thousands of measurement sites around the world, freely accessible for research on the global-scale impact of ozone on climate, human health and crop/ecosystem productivity. TOAR was a grassroots effort relying on the voluntary contributions from more than 230 scientists and air quality experts from 36 nations, who developed the research goals and gathered observations for the database. Findings

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from the first phase of TOAR (TOAR-I), were reported in a series of 10 peer-reviewed, open-access publications [4,7,15–17,64–68].

After the successful completion of TOAR-I (2014–2019), a second phase of TOAR (TOAR-II) was launched in 2020 to provide an updated assessment expanding on the analyses performed during the first phase, and an improved data infrastructure. This second TOAR assessment is the content of this special issue with a collection of seven articles together with this overview article. The remainder of this article is structured as follows: §2 provides an overview of the main findings from TOAR-I, §3 describes the TOAR-II process, §4 describes the TOAR-II data sources and data infrastructure, §5 summarizes the main conclusions from this assessment and §6 identifies open science questions for the third phase of TOAR (TOAR-III).

2. Main findings from TOAR-I (2014–2019)

A major advancement of TOAR-I was its creation of the world's largest, open-access database of surface measurements of ozone and related pollutants, which was used to assess the long-term trends in ozone levels over a wide range of urban, rural and background sites [66]. These quality-controlled data were contributed by dozens of national air pollution monitoring agencies and by research institutions. Over 30 widely used ozone metrics, designed for health and vegetation exposure studies, and for long-term ozone monitoring applications [65], were calculated consistently for over 9000 time series worldwide, across a range of time scales (e.g. hourly, daily, monthly, season and annual). A Representational State Transfer (REST) interface was implemented to allow interoperable machine access to the TOAR Surface Ozone Database, and pre-compiled metrics datasets for easy use were published at the open-access PANGAEA archive http://doi.org/10.1594/PANGAEA.876108. Results from the extensive quality control of metadata and data that were included in the TOAR database were reported back to international air quality agencies and research data repositories. In many cases, these reports led to improvements in the primary data archives. The TOAR Surface Ozone Database was the foundation for the TOAR-I analyses and has been applied to dozens of independent studies since the completion of TOAR-I.

TOAR-I research based on the TOAR Surface Ozone Database identified regional differences in surface ozone trends (2000–2014), with strong declines in Eastern North America, weak decreases in Europe and increases in most, but not all, regions of Asia where limited data were available [67,68]. A focus on health-based ozone metrics revealed that the present-day (2010–2014) ozone levels were generally greatest in East Asia, followed by North America and then Europe, with the strongest ozone increases found in East Asia (2000–2014) [7]. In terms of ozone metrics focused on vegetation exposure, the highest present-day (2010–2014) ozone values were found in mid-latitudes of the Northern Hemisphere, including Southern USA, the Mediterranean basin, Northern India, North, Northwest and East China, the Republic of Korea and Japan. The lowest metric values were found in Australia, New Zealand, southern parts of South America and some northern parts of Europe, Canada and the USA [4].

TOAR-I broke new ground by conducting the first intercomparison of a range of satellite-detected tropospheric ozone products. While these products all identified Southeast Asia as a hot spot for increasing ozone concentrations, they differed in their estimation of global ozone burden and trends for the 2004–2016 period [15]; this discrepancy became a key focus for subsequent satellite retrieval developments and new TOAR-II research efforts. TOAR-I also produced a retrospective analysis of historical ozone observations to demonstrate that there is no unambiguous evidence in the measurement record back to 1896 that typical mid-latitude background surface ozone values were below about 20 ppbv. However, there is robust evidence for increases in the northern extratropics of 30–70%, between the period of historic observations (1896–1975) and the modern period (1990–2014) [64]. Finally, TOAR-I took advantage of its expert membership to produce an assessment of the advances and limitations of atmospheric chemistry models for ozone

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research [16] and a critical review of changes in the tropospheric ozone burden and budget from 1850 to 2100 [17]. Findings from TOAR-I were reported in a series of 10 peer-reviewed, open-access publications [3,6,14–16,57–61], and these results informed other initiatives such as IPCC AR6 [20,69], Global Burden of Disease (GBD) [70], State of the Climate [71] and the Scientific Assessment of Ozone Depletion: 2018 [72].

3. The TOAR-II process

TOAR-II is an IGAC Activity started in 2020 that built on TOAR-I with updated trends of tropospheric ozone abundance and other metrics, but it also addressed underlying trend drivers, such as changing precursor emissions, as well as resulting impacts and the provision of data and analysis relevant to policy questions. In particular, TOAR-II used a bottom-up, science community-driven approach to identify missing, understudied or inconsistent areas in the assessment of tropospheric ozone from TOAR-I, including limited geographic coverage, lack of consistent vertical profile and tropospheric column information (such as satellite ozone burden and trends), lack of precursor source trends and process attribution. One major objective of TOAR-II was to increase the policy relevance of the assessment by taking further steps to assess tropospheric ozone drivers and impacts. More details of TOAR-II objectives are given in [73].

The TOAR-II effort began with the formation of the TOAR-II Steering Committee (SC) in 2020 followed by a virtual, international kick-off workshop in 2021. Since the inception of TOAR-II was during the COVID-19 pandemic, all meetings of the SC and broader community were virtual in the first years and later hybrid, presenting both challenges and opportunities to engage a wider global community. Working group topics coalesced in a bottom-up way from the kick-off workshop, and leadership teams proposed Focus Working Groups to the SC that met the following criteria: comprise at least six scientists from a minimum of three countries, with the primary goal to synthesize, conduct and/or support the science to be included in the TOAR-II assessment. Each Focus Working Group was assigned one SC member to follow the progress and ensure that linkages were identified and duplication of work was avoided. The Focus Working Groups each conducted regular virtual meetings to coordinate research and write topic-specific articles for the TOAR-II Community Special Issue, sponsored by Copernicus open-access journals (http://acp.copernicus.org/articles/special_issue1256.html). The Community Special Issue was open for contributions by the wider research community and not restricted to papers resulting from the TOAR-II Focus Working Groups, although these form the majority of the Community Special Issue papers. One particular topic that is relevant to TOAR-II but not covered by a Focus Working Group is the response of ozone concentrations to changes in emissions owing to COVID restrictions [74–77]. The Focus Working Groups and the resulting research papers are listed in table 1.

The IGAC TOAR-II Focus Working Groups collectively advanced a coordinated, community-based assessment of tropospheric ozone by integrating observations, models and emerging analytical approaches across regions and themes. Regional groups evaluated ozone distributions and trends in key areas, such as Africa, East Asia and South Asia. Satellite, ground-based and chemical reanalysis efforts improved data integration, validation and coverage in observation-poor regions. Modelling and precursor-focused studies strengthened attribution of ozone variability to emissions, chemistry and transport, while process-oriented groups improved understanding of deposition, oceanic influences, tropical variability and urban ozone. Additional efforts reported impacts on human health and climate, and advances in statistics and machine learning provided new tools for trend analysis and interpretation.

As the Focus Working Groups' activities were culminating in papers submitted to the TOAR-II Community Special Issue, the TOAR-II SC began the coordination of author teams for the assessment papers, and the organization of this Phil. Trans. A Special Issue was initiated. Hybrid meetings were held in Cologne, DE (March 2023), Boulder, CO, USA (July 2024) and York, UK

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Table 1. TOAR-II Focus Working Groups and journal articles in the Community Special Issue.

TOAR-II Focus Working Group	references
Africa	[78]
Chemical Reanalysis	[79–81]
East Asia	[82–84]
Global and Regional Models	[85,86]
Harmonization and Evaluation of Ground based Instruments for Free Tropospheric Ozone Measurements (HEGIFTOM)	[87–93]
Human Health Impacts of Ozone	[94,95]
Machine Learning for Tropospheric Ozone	[80,96]
Ozone Deposition	[97–101]
Ozone over the Oceans and Polar Regions	[102,103]
Ozone and Precursors in the Tropics (OPT)	[104,105]
Radiative Rorcing	[106–108]
The Role Of STE in the Earth System (ROSTEES)	[109]
Satellite Ozone	[110–119]
South Asia	[83,84]
Statistics	[120,121]
Tropospheric Ozone Precursors (TOP)	[122–130]
Urban Ozone	[131]
additional contributed articles	[74,75,132,133]

(June 2025) to discuss the topics and scope of the assessment papers among the TOAR-II SC and the designated lead authors. A set of guidelines was adopted to maintain coherence and consistency among all assessment papers. First drafts of the assessment papers were submitted to the full TOAR community (over 350 subscribed members) for review and comments in September 2025. The author teams incorporated the community suggestions, and replies to the community comments were archived before the articles were submitted in December 2025 and January 2026.

The TOAR-II assessment papers draw from the Community Special Issue, alongside TOAR-I, IPCC AR6 and other articles recently published in the broader peer-reviewed literature. Brief summaries of the assessment papers collected in this special issue are given in §5.

4. TOAR-II data

The open and findable, accessible, interoperable and reusable (FAIR) [134] provision of air quality monitoring data, and especially of ozone observations, is the second key objective of TOAR-II besides the scientific assessment. TOAR-II adopted a free and open data access policy, requiring all data providers to agree that all data that are needed to reproduce the assessment results be shared with a Creative Commons - By Attribution (CC-BY 4.0) license. This license provides

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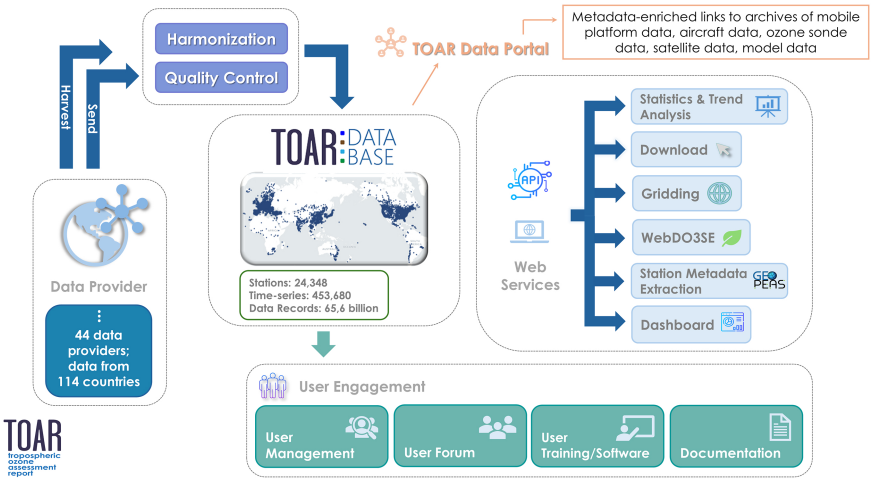


Figure 2. Summary of key features of the TOAR-II database of surface station observations.

the necessary flexibility for users to perform any kind of analysis, aggregation or other operations on the data, while still requiring them to clearly attribute the data originators and providers in any publication so that the data use can be tracked and due credit is given to all people and institutions who are involved in the laborious undertaking of atmospheric composition measurements. We understand FAIR data provision as an objective not only to enable the use of TOAR-II data, but to employ modern software technology in an effort to make discovery and analysis of TOAR data as easy as possible, including complete documentation of all processing steps. To facilitate the discovery of tropospheric-ozone-related datasets that have been used in the context of TOAR, we developed a simple data portal (http://toar-data.org). The TOAR data portal provides a standardized layout with brief descriptions of several dozen datasets, and it redirects users to the original data repositories for the actual data access.

The TOAR-II assessment would not be possible without an extensive data collection and data harmonization effort. At the centre of many TOAR-II papers is the TOAR database of surface station observations with its associated web services [135]. Building on the experiences gained with databases in TOAR-I [66], the TOAR-II database was completely redesigned at the Jülich Supercomputing Centre with maximum usability and performance in mind (http://toar-data.fz-juelich.de). Figure 2 presents an overview of the key features of this database. For more information, please consult the online documentation at https://toar-data.fz-juelich.de/subpages/documentation.html. To document our commitment to FAIR data and enhance trust in the TOAR database infrastructure, the database team obtained a Core Trust Seal certificate in 2023 and 2026.

Other *in situ* datasets, which were used in the assessment, include: (i) the collection of mobile platform data [103,136] for the assessment of ozone in marine and polar regions [137], (ii) aircraft measurements on board commercial airliners from the IAGOS programme (http://www.iagos.org/iagos-data/), and (iii) ozonesondes from the World Ozone and UV Data Centre (http://www.woudc.org/en/) and Southern Hemisphere Additional Ozone Sondes (http://tropo.gsfc.nasa.gov/shadoz/) networks. The TOAR-II assessment on satellite-detected tropospheric column ozone [138] describes, interprets and integrates the collection of new satellite datasets that were generated after TOAR-I identified several inconsistencies in the distribution and trends of earlier products. These datasets have now been used in the TOAR-II assessments of ozone interactions with climate [139] and ozone across South America [140].

Compared to TOAR-I, TOAR-II increased the participation of numerical modellers and also included new artificial intelligence (AI) models [80,96]. We refer to the *Models and Data* sections of

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the respective publications for accessing these results, and many of these links are also available through the TOAR data portal http://toar-data.org.

TOAR-II has succeeded in creating and documenting the world's most comprehensive collection of datasets relevant for assessing the distribution, burden and temporal trends of tropospheric ozone. Nevertheless, in particular with respect to surface and aircraft observations, several gaps remain, in particular over Africa, Australia/Oceania, South America and Southeast Asia. Not all of the blank areas on maps [139,141] are due to non-existing observations. In some cases (for example, Australia), data were available in TOAR-I but could not be updated, because the data providers did not react in time to our requests for releasing their data under the CC-BY 4 license. In other cases (for example, Southeast Asia), we started negotiating with the environmental agencies, but we could not reach an agreement in terms of open data sharing. Then, there are regions, where we know that data exist, but where it was impossible in the TOAR-II time frame to establish the relevant contacts. Owing to the absence of funding and limited available person-power, the TOAR database team had to concentrate on easily accessible data sources. Clearly, a stronger effort will be needed in the future to close the remaining gaps in the TOAR database (more on this below).

Intensive efforts were made to use data from the OpenAQ network (http://openaq.org/) to fill at least some gaps. However, in spite of various scripting, metadata retrieval and data curation activities, various data quality issues (large data gaps, obvious calibration or unit errors, etc.) prevented the use of OpenAQ data in this assessment. Also, because of open questions concerning calibration, sensor locations and data stability, no data from low-cost sensor networks have been included in the analyses.

5. Main conclusions from this assessment

TOAR-II builds on TOAR-I to provide a more comprehensive assessment of how and why tropospheric ozone is changing, and of its impacts on climate, health and vegetation. This has been informed by a refined and unified approach to statistical analysis [142]. The assessment papers in this issue can be categorized as topical and regional assessments. The main conclusions from the topical articles can be summarized as follows:

Vegetation: Emberson *et al.* [143] report that ozone flux-based metrics have improved functionality compared to concentration-based metrics and allow other environmental change factors (e.g. climate change) to be incorporated in vegetation impact assessments. Flux-based metrics suggest greater potential for damage and higher levels of risk under present-day conditions when compared to concentration-based metrics; both suggest that ozone damage is occurring at well over 60% of TOAR sites globally for sensitive crop and forest species. Both metrics suggest similar global trends with the greatest decreases in North America followed by Europe. However, the flux-based metrics suggest more limited declines. The Asian region shows both increasing and decreasing trends though limited spatial coverage of sites makes robust conclusions challenging. Reducing surface ozone for air quality will probably improve food supplies of staple crops and carbon sequestration by forest trees.

Climate: Szopa *et al.* [139] provide an assessment of tropospheric ozone interactions with climate change, with a focus on new findings since IPCC AR6. Model estimates based on long-term emissions datasets of ozone precursors confirm the substantial ozone burden increases since the pre-industrial era, which leads to an estimated radiative forcing from total column ozone of 0.50 (0.25 to 0.75) W m^{-2}. All precursors (NOx, CH_4, NMVOCs and CO) have had important influences on ozone increases over the historical period. The disparity between positive trends in the tropospheric ozone burden and decreasing observed ground-level ozone in some regions of the world is partly explained by the redistribution of ozone precursor emissions towards the equator, which has been more important than changes in emissions magnitude in driving the rise in tropospheric ozone, and leads to greater ozone accumulation in the tropics and subtropics compared to northern mid-latitudes. Future ozone changes will not only be influenced by emission changes of

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precursors owing to climate change and air pollution control policies, but also by climate change, in particular through land-biosphere feedbacks.

Health: Kerr *et al.* [141] synthesize global ozone observations and estimates of global ground-level ozone from recent studies to characterize global ozone distributions and trends. They identify South Asia, Eastern China and parts of the Middle East and North Africa as having the highest 2016–2020 concentrations. From 2000 to 2020, ground-level ozone decreased most in Southeastern North America and parts of Eastern Europe, while it grew most quickly in South Asia and sub-Saharan Africa. The paper further summarizes current understanding of ozone health effects and studies that estimate global ozone-related health impacts. These studies suggest about 500 000 premature deaths annually owing to chronic obstructive pulmonary disease (COPD) attributable to long-term ozone exposure, with additional mortality and morbidity from other health endpoints (beyond COPD) and short-term exposure. Despite uncertainties in estimating ozone, especially in un- or under-monitored parts of the Global South, the assessment highlights that most regions (14 of 21 GBD-defined world regions) have experienced increasing ozone-attributable mortality rates over the past two decades.

Satellite data: satellite observations provide a unique and powerful capability for monitoring tropospheric ozone globally and over decadal time scales. To address limitations in the satellite datasets available for the TOAR-I assessment, particularly for regional patterns and decadal trends, Hubert *et al.* [138] harmonized and integrated 15 satellite records. This produced a more robust estimate of the present-day tropospheric ozone burden (336 ± 6 Tg) and its changes since 2005. The analysis reveals strongly nonlinear ozone changes, with increases of 2–4.5% per decade during 2005–2019 over about 20% of the globe, especially in Asia, followed by widespread declines after 2020 linked to drivers such as the COVID-19 pandemic. The assessment also demonstrates that ozone variability is strongly shaped by both dynamical and episodic drivers, including El Niño-Southern Oscillation, extreme wildfires and the COVID-19 pandemic. Sustained and coordinated satellite measurements remain essential for tracking long-term changes in tropospheric ozone.

STE: STE is an important source term in the tropospheric ozone budget and, under certain conditions, can influence near-surface ozone. While STE processes and impacts were discussed by TOAR-I [17], the last comprehensive review of STE was published in 2003 [144]. The TOAR-II STE assessment by Keeble *et al.* [145] synthesizes observational, reanalysis and model estimates to quantify the magnitude, variability and trends of STE across present-day conditions, the recent past and future projections. Present-day global STE is estimated at 380 (350–450) Tg O_3 yr^{-1}, reflecting downward transport from the extratropical stratosphere into the troposphere, partially offset by upward transport from the tropical troposphere into the stratosphere. Analyses indicate a decline in STE of 2.7% per decade during the late twentieth century, driven by stratospheric ozone depletion and partially offset by changes in large-scale circulation. Future projections suggest that STE will increase by around 4.7% per decade as stratospheric circulation responds to climate change and stratospheric ozone recovers.

The two 'regional' assessment papers in this issue can be summarized as follows:

South America: Seguel *et al.* [140] employ satellite products, atmospheric reanalyses and model simulations to identify enhanced tropospheric column ozone over the mid-latitude west coast and subtropical east coast of South America during 2005–2021. Tropospheric column ozone trends varied across the region, reflecting substantial subregional and partial columns variability. Satellite products suggest a low-certainty negative trend in tropospheric column ozone, whereas two chemical transport model reanalyses show high-certainty positive trends of +0.85 (±0.70) and +0.55 (±0.85) nmol mol^{-1} per decade. Attribution analysis indicates that global background methane is the dominant contributor to the regional ozone burden (41%, 17 of 42 nmol mol^{-1}), followed by anthropogenic nitrogen oxides.

Ozone over the oceans and polar regions: Sommariva *et al.* [137] assessed the spatial and temporal variability of tropospheric ozone over the oceanic and polar regions using ship, buoy, aircraft, sonde and surface data filtered to minimize continental influences [103]. They found that trends

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in lower tropospheric ozone from the mid-1970s to present day are modest (less than or equal to nmol mol^{-1} per decade), although sparse and intermittent sampling limits confidence—especially over the Indian Ocean and, in general, in the extrapolar Southern Hemisphere. Nonetheless, ozone trends can be determined with more confidence since 2000 and are found to be negative over the Arctic, northern mid-latitudes and tropical Pacific with significant seasonal decreases in boreal spring (March, April, May) overwhelming more modest increases in boreal winter (December, January, February), whereas in the Antarctic, southern mid-latitudes and tropical Atlantic trends are positive, especially in austral winter (June, July, August). Global models can reasonably capture the main spatial and seasonal features but also show significant disagreement between each other and do not reproduce the variability of observations. An overview of the state of knowledge for possible drivers of these trends is given, but further work is needed for attribution of the observed trends and to address limitations from divergent seasonal patterns within regions, especially in the tropics.

In addition to improving the characterization of long-term trends, TOAR-II research expanded our understanding of the abrupt response of ozone to the COVID-19 pandemic [138,139]. During 2020, surface ozone increased in some urban regions, while widespread decreases were observed at remote sites and in the free troposphere. These changes were linked to reductions in precursor emissions during mandatory or voluntary restrictions to limit the spread of the COVID-19 virus [74–77,146]. Continued and enhanced monitoring from both ground-based and satellite observations is needed to assess the possibility of a post-COVID ozone rebound and to determine COVID-19's impact on long-term trends associated with economic activity and natural processes such as wildfires. The assessments also highlight where monitoring is lacking in terms of spatial coverage, record continuity and measurements of ozone precursor emissions, with overall recommendations for future integrated observation and modelling systems.

6. Open questions for TOAR-III

This TOAR-II overview concludes with a set of ideas for consideration by the research community as it develops the scope of TOAR-III, scheduled for 2027–2032. These include:

Africa regional assessment: although the Focus Working Group on ozone observations and trends in Africa made significant progress [78], an Africa regional assessment paper was not possible in the TOAR-II time frame. This delay highlights the need for more local and global support for scientists in Africa, which will be a critical issue for TOAR-III.

Geostationary satellite observations: although low Earth orbit satellite observations of tropospheric ozone are assessed in this report [138], there is much promise in recently launched geostationary (GEO) instruments for observing ozone and precursors including the Geostationary Environment Monitoring Spectrometer (launched 2020), the Geostationary Interferometric Infrared Sounder (launched 2021), Tropospheric Emissions: Monitoring of Pollution (launched 2023) and Sentinel 4 (launched 2025). These instruments provide coverage and diurnal information over much of the Northern Hemisphere for tropospheric ozone and some ozone precursors. However, we note that satellite observations of ozone in the atmospheric boundary layer or near the surface are especially challenging owing to sensitivity limitations of the measurements. Nonetheless, these observations can constrain models and improve near-surface ozone forecasts, especially if combined multi-spectrally (e.g. [58,147,148]). In general, more experience with tropospheric ozone retrievals from the GEO platforms is needed to assess the added skill for quantifying ozone near the surface.

Evolving satellite observing systems: even though the assessment of satellite observations of ozone [138] made significant progress in harmonizing existing satellite data records, extending and updating long-term ozone trend analyses from satellites remains essential. Continuous evaluation is needed to ensure that observed trends reflect real atmospheric changes rather than artefacts of evolving datasets, methodologies or observational coverage. The satellite constellation used

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to observe tropospheric ozone and its precursors is rapidly changing, with instrument degradation, mission discontinuities and the introduction of new sensors. Ensuring that long-term ozone records over multi-decadal time scales are consistent requires careful harmonization of these datasets. Integrated approaches, including chemical data assimilation and machine learning-based fusion, will play a key role in addressing these challenges. Such efforts will also support ongoing community activities to harmonize observational datasets, particularly satellite products, in coordination with initiatives such as the CEOS Atmospheric Composition Virtual Constellation.

Small sensors: as noted in §4, no data from small sensors were included in the analysis for TOAR II. While calibration, sensor siting and data quality are all valid concerns and challenges that will need to be addressed, small sensors also provide an opportunity for improved coverage, especially in data sparse areas where traditional regulatory monitoring networks may not be feasible for various reasons (e.g. cost, space and infrastructure). Opportunities for responsibly incorporating small sensor data in a way that accounts for some of the fundamental differences in small sensor versus reference instrument data, such as underlying measurement principle, associated measurement uncertainty and deployment locations, should be considered in the future, especially in locations where little to no other ground-based measurement data exist. That said, to provide reliable data, evaluation of small sensors against research-grade instruments is needed, through regular collocation of the sensors in analogous locations, a hybrid set-up or similar [149]. Otherwise, there is a strong risk that the sensors are providing measurements that are not reasonable or even indicative of the actual concentrations. Ideally, the research-grade instrument would also be connected to world calibration standards via reference instruments and standards [150]. Small sensors also provide complementarity to, for example, satellite data or more sparse ground-based measurements, and when used together, these data sources can provide improved data reliability of small sensors, along with improved coverage and improved insights into air quality [151]. Assessments of small sensors, such as those from the World Meteorological Organization, can provide guidance on appropriate applications, data quality and data communication [151,152].

Future TOAR data system: TOAR-II witnessed a substantial upgrade of the underlying data infrastructure for collecting, providing and analysing air quality surface observations from around the world. As described in §4, this data infrastructure follows highest standards with respect to functionality, FAIRness and performance. On the other hand, it had to be recognized that the effort of collecting and quality-controlling all data could not be managed by a single group and that the lack of regional data managers made it difficult in some cases to obtain data with the necessary metadata and publishing license. Therefore, if the effort of maintaining a central global archive of global observations is to continue, the leadership of the next phase of TOAR must reorganize and regionalize the data collection and data curation efforts. There is some potential to further expand the TOAR data infrastructure in the future. In particular, (i) support for generating AI-ready data from the database can be enhanced, and (ii) the database can be extended to include mobile platform data, for example, from ships [136].

Contributions to tropospheric ozone from wildfires: the increasing occurrence of Northern Hemisphere wildfires will impact downwind ozone production [153]. Ozone precursors could be further enhanced by emissions from structure fires as the wildland-urban interface expands [154]. New airborne measurements are needed to assess the impacts of convection of fire plumes with their elevated concentrations of reactive organic species on gas-phase and particle composition in the upper troposphere to lower stratosphere. IGAC's newly formed Biomass Burning Uncertainty: ReactioNs, Emissions and Dynamics activity [155] coordinates research for understanding fire emission uncertainties and could be an essential partner in TOAR-III.

Extreme events and variability: climate change is expected to alter the frequency and intensity of extreme meteorological conditions that can strongly influence ozone formation. Monitoring ozone extremes at regional scales and improving their representation in chemical transport models and machine learning-based prediction systems remain critical challenges. Addressing these issues is particularly important for advancing public health applications, where extreme ozone events often drive the largest impacts.

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Coupling of ozone to Earth system: in terms of ozone deposition, TOAR-II focused on the biosphere, with attention to stomatal uptake by crops and natural vegetation. However, tropospheric ozone also couples to the hydrosphere, cryosphere and geosphere, and TOAR-III would benefit by taking an Earth system approach to ozone deposition processes and impacts.

Attributing changes in ozone to pollution controls: this attribution remains challenging because ozone is not directly emitted and responds nonlinearly to changes in precursor emissions [156]. As precursor emissions continue to increase in many parts of the Global South, the relative contributions of different regions to the global ozone burden are evolving and require continuous reassessment. In addition, recent advances in ozone chemistry modelling, for example, improved understanding of ozone chemical regimes that incorporate interactions with particulate matter [157], need to be adopted for improved understanding of ozone changes owing to pollution controls.

Expanded use of AI: since TOAR-II was designed and implemented in 2020, the world has seen a rapid development of AI tools and methods. In 2020, it still seemed implausible to most geophysical scientists that AI models could one day complement or even replace traditional numerical models [158]. Only 4 years later, at least three AI models for weather forecasting demonstrated skills that were on par or exceeded the best numerical weather models in operation [159–161]. As described in [96], progress in AI modelling for atmospheric composition and air quality has been somewhat slower, even though quite a number of promising results have emerged. With the latest trend to build large transformer-based foundation models for atmospheric dynamics (e.g. [162–165]), new possibilities emerge to exploit the vast amount of meteorological and atmospheric composition information from observations and models and obtain a consistent, high-quality representation of atmospheric states leading to high-quality analyses and predictions (e.g. the WeatherGenerator project; http://weathergenerator.eu/). We anticipate that these models will mature over the next few years and will provide novel information relevant for a new tropospheric ozone assessment. As one preliminary step, Kelp *et al.* [166] proposed to organize a curated collection of ozone datasets for training and benchmarking machine learning models.

Beyond these open questions and new opportunities for science, the TOAR-II steering committee also recognized the need for closer interaction with various global or regional initiatives at the nexus of science and policy. While TOAR-II has interacted with the TF HTAP, the Climate and Clean Air Coalition, the IPCC, GBD and others, in-person exchanges were difficult in the first years of TOAR-II owing to the COVID-19 pandemic. Strengthening these linkages in TOAR-III would further increase the impact of our unique global initiative.

Data accessibility. This article has no additional data.

Declaration of AI use. We considered AI summaries of the assessment papers in this issue to assess completeness in this overview paper, but did not include AI-generated text.

Authors' contributions. H.M.W.: conceptualization, methodology, project administration, writing—original draft, writing—review and editing; M.S.: conceptualization, data curation, formal analysis, methodology, project administration, writing—original draft, writing—review and editing; O.C.: conceptualization, formal analysis, investigation, methodology, project administration, writing—original draft, writing—review and editing; L.E.: conceptualization, formal analysis, investigation, methodology, writing—original draft, writing—review and editing; J.W.K.: conceptualization, methodology, project administration, writing—review and editing; Y.K.: conceptualization, data curation, methodology, project administration, writing—original draft, writing—review and editing; K.L.: conceptualization, methodology, project administration, writing—review and editing; R.M.: conceptualization, methodology, project administration, writing—review and editing; G.P.: conceptualization, methodology, project administration, writing—review and editing; E.v.S.: conceptualization, methodology, project administration, writing—original draft, writing—review and editing; R.S.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, writing—original draft, writing—review and editing; B.S.: conceptualization, methodology, project administration, writing—review and editing; J.J.W.: conceptualization, investigation, methodology, project administration, writing—original draft, writing—review and editing; P.G.: formal analysis, investigation, methodology, writing—original draft, writing—review and editing; D.H.: formal analysis, investigation, methodology, writing—original draft, writing—review and editing; J.K.: formal analysis, investigation, methodology, writing—original draft, writing—review and editing; G.H.K.: formal analysis, investigation, methodol-

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