The Network for the Detection of Atmospheric Composition Change at 35 Years: Achievements and Future Strategy.

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Abstract. Since 1991, continuous, consistently calibrated and openly archived ground-based measurements from the Network for the Detection of Atmospheric Composition Change (NDACC) have been collected to investigate processes responsible for decadal-scale changes, anomalies in atmospheric composition, and to validate satellite observations and model simulations. These measurements, from nearly 120 stations, support fundamental research in the area of stratospheric and tropospheric processes impacting ozone chemistry, greenhouse gases, atmospheric radiative forcing, air quality, and interactions with solar radiation and the entire Earth system. NDACC data are supplemented by observations from ~~11~~eleven global Cooperating Networks. The operational principles of Cooperating Networks are well aligned with NDACC objectives and protocols, focusing on data that (a) are high-quality, uniformly processed and traceable to reference standards; and (b) capture short-term (daily to interannual) anomalies and long-term trends. This paper summarizes the NDACC organizational structure. We also review the major accomplishments of NDACC since De Mazière et al. (2018), collaborative research with Cooperating Networks, and interactions with the satellite and modeling communities. Ground-based atmospheric composition monitoring is at a crossroads. Challenges include sustainability of human and financial resources required for complex and intensive data collection, technical issues including aging instrumentation, requirements for FAIR (findable, accessible, interoperable, reusable) data, and lack of data over ~~most~~large parts of Asia, Africa and South America. NDACC is well-positioned to adopt a three-pronged strategy going forward: protecting and modernizing existing stations; promoting the growing use of NDACC data; expanding the number of measured species and network coverage in under-sampled or under-reporting regions.

1 Introduction

As an integral part of the global observing system, the overriding goal of the Network for Detection of Atmospheric Composition Change (NDACC) has been to collect and maintain high-quality ground-based data – both remote-sensing and *in situ* – in order to detect changes and trends in atmospheric composition and to understand the impacts of these changes on the mesosphere, stratosphere, and troposphere. NDACC first emerged as the Network for Detection of Stratospheric Change (NDSC) in the late 1980s and became operational in 1991 (Kurylo et al, 2016). The network was given its present title in 2006, reflecting research support beyond the stratosphere. The network extended selected measurements into the mesosphere to understand its chemical and physical state as well as into the troposphere to study processes impacting air quality and the climate.

As the network extended its vertical domain, ~~the~~NDACC's objectives expanded and are currently:

- Establish long-term databases to detect changes and trends in atmospheric composition and to understand their impacts on mesosphere, stratosphere and troposphere;
- Establish scientific links and feedbacks among changes in atmospheric composition, climate, and air quality;
- Validate and merge atmospheric measurements from other platforms (i.e., satellites, aircraft and ground-based platforms);
- Provide critical data sets to help fill gaps in satellite observations;
- Provide collaborative support to scientific field campaigns and to other chemistry and climate-observing networks;
- Provide validation and development support for atmospheric models;
- Contribute to assessments of the state of the atmosphere (WMO/UNEP, IGAC, IPCC, etc.).

The last objective was added in 2024, following the recognition of its importance as a fundamental contribution to the NDACC since its establishment.

De Mazière et al. (2018) provided a brief history of the network, reviewed major accomplishments during its first 25 years of operation, and discussed recent developments and challenges. Their paper emphasized that NDACC must update its capabilities as new data needs arise. They highlighted developments that could enable NDACC to meet its objectives going forward. In the ~~seven~~eight years since *De Mazière et al.* (2018) the need for the network enhancements has become urgent. *Salawitch et al.* (2025) described a train of unexpected geophysical events, both natural and human-induced, that have led to substantial anomalies in stratospheric composition. They point out that our understanding of the scale, extent, and timing of these disturbances was made possible by robust, comprehensive global-scale observations by the Microwave Limb Sounder (MLS) on the Aura satellite and the Atmospheric Chemistry Experiment-Fourier Transform Spectrometer (ACE-FTS) on SCISAT since the early 2000s. However, our global scale capability to observe upper atmospheric composition will be drastically reduced when the NASA Aura satellite ceases operations in the next year or two. It will take five years or more before new satellites are launched to recover some of that lost capability. Meanwhile the climate system will evolve apace with impacts on ozone recovery and air quality. Significant human-induced changes in atmospheric composition may emerge from experiments referred to as Solar Radiation Management (SRM) and from a projected increase in low-Earth orbit (LEO) satellite and re-entry debris.

The following science questions provide a focus for the work of NDACC in the coming years:

- Which ozone-depleting substances, regulated by the Montreal Protocol or otherwise, will most influence the ongoing stratospheric ozone recovery?
- What are the processes driving atmospheric composition changes in the “Global South”?
- What new stratospheric species require monitoring following atmospheric injections from volcanic eruptions (e.g., Hunga Tonga) and strong wildfires?
- For which atmospheric species and in which regions are enhanced measurement capabilities and precision required for better trend detection and reference data?
- What are the most important factors driving changes in air quality?
- What are the impacts of climate change and extremes on atmospheric composition and vice versa?

NDACC has succeeded for more than three decades because it has leveraged the scarce resources that support its member stations as well as its archival facilities. It is exemplary in channeling technological improvements to meet changing measurement and data requirements. As we enter a period of substantially reduced satellite monitoring of the upper atmosphere – the “data desert” of *Salawitch et al.* (2025) – the scientific community will increasingly rely on the ground-based measurements of NDACC and its Cooperating Networks to bridge data gaps or replace observational methods for some atmospheric species. This challenge is compounded by the prospect of new modalities of atmospheric composition change that require innovative measurement strategies.

This paper reviews NDACC achievements since the publication of De Mazière *et al.* ~~(2018).~~(2018) and serves as an introduction to the special issue "Achievements and perspectives of the Network for the Detection of Atmospheric Composition Change after 35 years of operation”. These are discussed in the light of the seven NDACC cardinal objectives and optimization of its strategy to best address the science questions above. The paper is organized into six sections. Section 2 describes the organization of the network. Section 3 describes NDACC's partnerships and stakeholders. Section 4 summarizes NDACC's achievements in recent years. Section 5 describes technical and scientific challenges facing NDACC. Section 6 looks ahead to prospects for the coming decade and beyond.

2 The organization of NDACC

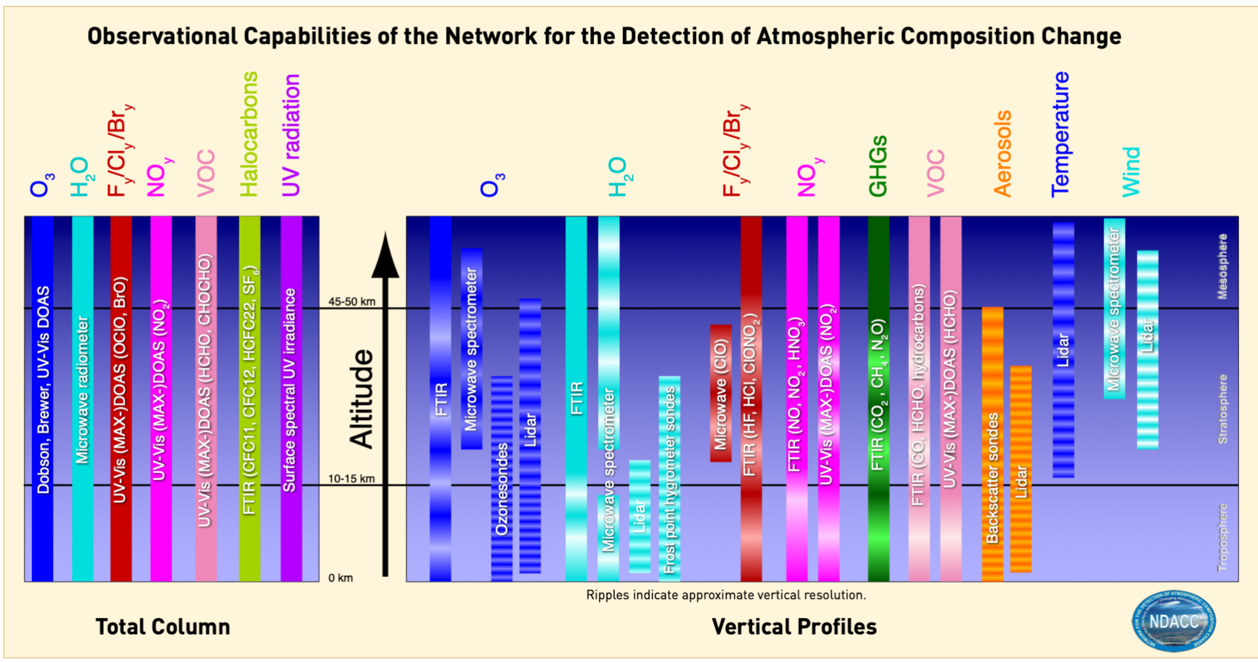


Figure 1: Chart of NDACC observational capabilities is color-coded by observed atmospheric species and parameters with chemical formulas listed at the top. The altitude range of profiles illustrates approximate vertical resolution associated with each measurement technique (light horizontal stripes on vertical columns). Two horizontal dashed lines define approximate levels of tropopause and stratopause.

NDACC collects atmospheric composition data at 118 globally distributed stations with over 170 active instruments. For an interactive map of NDACC stations see https://ndacc.org. Figure 1 shows NDACC's portfolio of long-term and campaign-based measured species and parameters. These include aerosol, BrO, C_2H_2, C_2H_4, C_2H_6, CCl_2F_2, CCl_3F, CH_3OH, CH_4, CHF_2Cl, chlorine, $ClONO_2$, CO, CO_2, COF_2, H_2CO, H_2O and isotopologues, HCHO, HCl, HCN, HCOOH, HF, HNO_3, HONO, N_2O, NH_3, NO, NO_2, OClO, OCS, O_3, PAN, SF_6, temperature, spectral UV irradiance, and wind. NDACC refocuses its objectives as measurement priorities evolve, maintaining high data quality, quick archiving and rapid open data access in compliance with FAIR (Findable, Accessible, Interoperable, and Reusable) data principles. More information about FAIR can be found at e.g. GOFAIR (https://www.go-fair.org/).

Instrument Working Groups (Dobson, Brewer, FTIR, Lidar, Microwave, Sonde, UV/Vis, Spectral UV) oversee instrument and algorithm quality, providing expertise and resources for teams developing new instruments interested in NDACC affiliation. The Satellite Working Group fosters collaboration between NDACC and satellite missions and provides meteorological data to the NDACC database via NOAA/NCEP. The Theory and Analysis Working Group promotes NDACC data use and supplies model output to aid ~~observation~~ interpretation of observations.

NDACC recognizes the value of collaboration with external measurement and analysis networks that operate independently. To foster this partnership, the NDACC offers a "Cooperating Network" (CN) designation. This allows for mutual data access and network representation in the annual meetings while maintaining each network's integrity. Further details on agreements with Cooperating Networks appear in Section 3.

The NDACC Steering Committee is the organizational backbone of the network (see Fig. A1 in Appendix A, and the most up-to-date version in www.ndacc.org > ABOUT > Organizational Structure). Established in 1989, the Steering Committee (SC) includes all NDACC components. In addition to the Co-Chairs, it is composed of representatives from each Instrument Working Group (IWG), the Theory and Analysis Working Group, and the Satellite Working Group. Each CN has representatives on the NDACC SC. The IWGs promote exchange of expertise among NDACC members and the CN and support for establishing new measurement sites or new instrumentation at existing sites. Functional and Ex-Officio SC positions are used for tasking and/or reviewing of specific science matters and for addressing special NDACC-related issues; they ensure that international organizational interests are represented. Emeritus SC Representatives also provide expertise on measurements and science, including historical perspectives on evolving NDACC needs. SC member terms are finite but renewable. The list of current SC members is available on the NDACC webpage (ndacc.org).

NDACC organizational structure ~~(Appendix A, Fig. A1)~~ includes the Data Host Facility (DHF) where the observational and support datasets are archived and made publicly available. The NDACC website provides an easy interface to the DHF and promotes news and information about the network.

The procedures and data quality requirements for affiliating instruments with NDACC are defined in dedicated NDACC Protocols that specify expectations for existing NDACC instrument types and for proposing new techniques. Other protocols stipulate NDACC structure and operating procedures. All protocols are regularly updated to maintain best practices.

3 NDACC partners and stakeholders

Since its inception, NDACC has been endorsed by international agencies and other stakeholders, including United Nations Environment Program (UNEP), the International Ozone Commission (IO3C) of International Association of Meteorology and Atmospheric Sciences (IAMAS) and the Global Atmosphere Watch (GAW) Program of the World Meteorological Organization (WMO). The current landscape of NDACC stakeholders is presented in Fig. 2, grouped in categories: global watch programs, scientific assessments and research programs, cooperating networks, satellite programs, research partners and infrastructures, and operational services. Exchanges with the stakeholders occur through their SC delegates and reciprocally through the participation of NDACC delegates in stakeholder committees or creation of formal agreements.

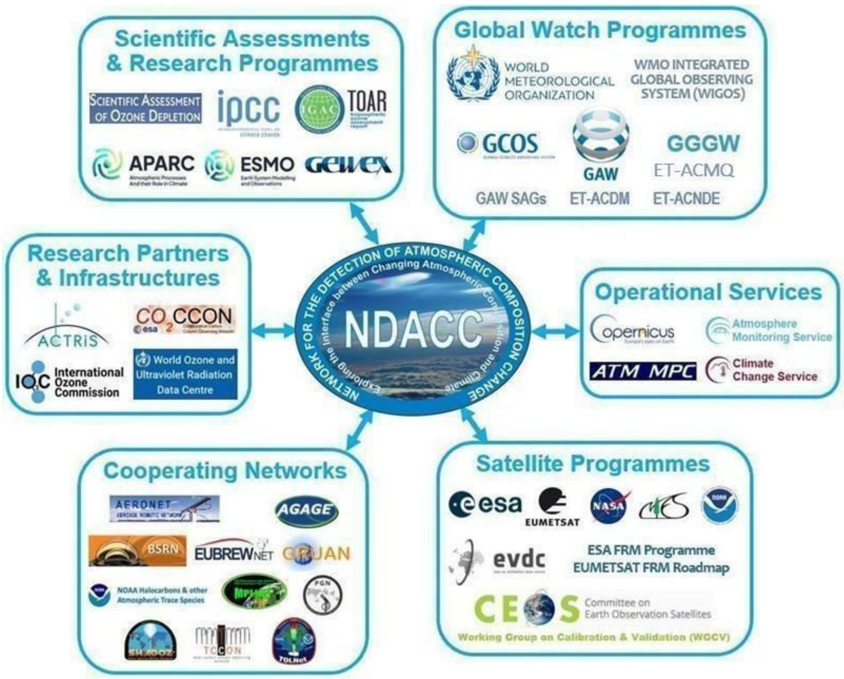


Figure 2. Overview of NDACC stakeholders.

3.1 Engagement with international environmental programs

NDACC data are essential to the global atmosphere watch program data centers operated under the auspices of the WMO, UNEP and the UN Framework Convention on Climate Change (UNFCCC). NDACC contributes most of the atmospheric composition Essential Climate Variables (ECVs) required by GCOS (Global Climate Observing System) and ~~play~~plays an essential role in WMO's Global Greenhouse Gas Watch (GGGW) approved in May 2023. NDACC delegates serve on several GAW Expert ~~Groups~~Teams and participate in WMO's Rolling Review of Requirements process in support of the WMO Integrated Global Observing System (WIGOS). Its responsibilities as a Contributing Network to GAW were laid out in a formal agreement between both Parties in 2022.

3.2 Engagement with scientific assessments and research programs

NDACC is a major contributor to the following assessments: the quadrennial WMO/UNEP Scientific Assessment of Ozone Depletion; the Tropospheric Ozone Assessment Reports (TOAR~~-II~~) under the umbrella of International Global Atmospheric Chemistry (IGAC); Intergovernmental Panel on Climate Change (IPCC) assessments. NDACC also contributes to research programs aimed at understanding links among changes in atmospheric composition, dynamics and transport, and the evolution of air quality and climate. Joint activities include the Atmospheric Processes And their Role in Climate (APARC, formerly known as Stratospheric Processes And their Role in Climate, SPARC) and Global Energy and Water Exchanges (GEWEX) projects sponsored by the World Climate Research Program. The Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS-1 and -2) and Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS) projects rely on NDACC observations to assess ozone and atmospheric composition trends and their uncertainties. NDACC data serve as a reference for climate model development and evaluation in the WCRP core project Earth System Modelling and Observations (ESMO).

3.3 Engagement with Cooperating Networks, research partners and infrastructures and operational services

To widen its scope and foster collaboration on complementary measurements, NDACC has long had agreements with Cooperating Networks (CN, see Figure 2). A list showing colocation of NDACC long-term measurement stations with those of Cooperating Networks (referenced in the table) is available in the ‘Site List’ of the ‘Measurements and Analyses Directory’ in the DATA Tab of the NDACC website (ndacc.org). CN agreements since 2018 have been established with the European Brewer Network (EUBREWNET), the Pandonia Global Network (PGN), and the Tropospheric Ozone Lidar Network (TOLNet). The European Research Infrastructure for Aerosols, Clouds and Trace Gases (ACTRIS), established as a European Research Infrastructure Consortium in 2023 (Laj et al., 2024) supports and shares scientific objectives and user communities with NDACC. To avoid discrepancies among instrument, measurement, and data protocols related to common products, a Memorandum of Understanding between NDACC and ACTRIS defines how the Parties operate to maximize benefits to users through exchange of data and expertise. For example, the ACTRIS Centre for Reactive Trace Gases Remote Sensing (CREGARS) will serve the NDACC community through the maintenance of central data processing units (Section 4.4.2), and the provision of training and consultancy for compliance with ACTRIS/NDACC requirements; the ACTRIS Data Portal (formerly GEOmon data portal) is a gateway to complementary data and services.

Agreements with the Copernicus Atmosphere Monitoring Service (CAMS) facilitate the use of NDACC reference data for independent evaluation of CAMS global and regional data products and reanalysis, and with the Copernicus Climate Change Service to deliver NDACC Climate Data Records of ECVs to the Climate Data Store (CDS). Whereas the NDACC Protocol for Data Providers requires consolidated data archiving in the DHF for public availability within one year after acquisition, a majority of NDACC PIs have moved to faster delivery of controlled quality data, for example, meeting timeliness and quality requirements specific to CAMS Rapid Delivery.

3.4 Engagement with satellite observations

A primary objective of NDACC ~~has always been providing~~remains the provision of high-quality reference measurements to support geophysical validation and evolution of satellite atmospheric composition products. The network helps validate various ~~phases of satellite~~ data reprocessing ~~from~~phases for a vast array of atmospheric composition satellite missions ~~to date as shown in Fig. 3 (~~ranging from limb~~)~~ solar occultation and emission sensors (see Fig. 3) to nadir-viewing platforms (see Fig. 4 ~~(nadir).~~) across the UV-VIS and infrared spectrum.

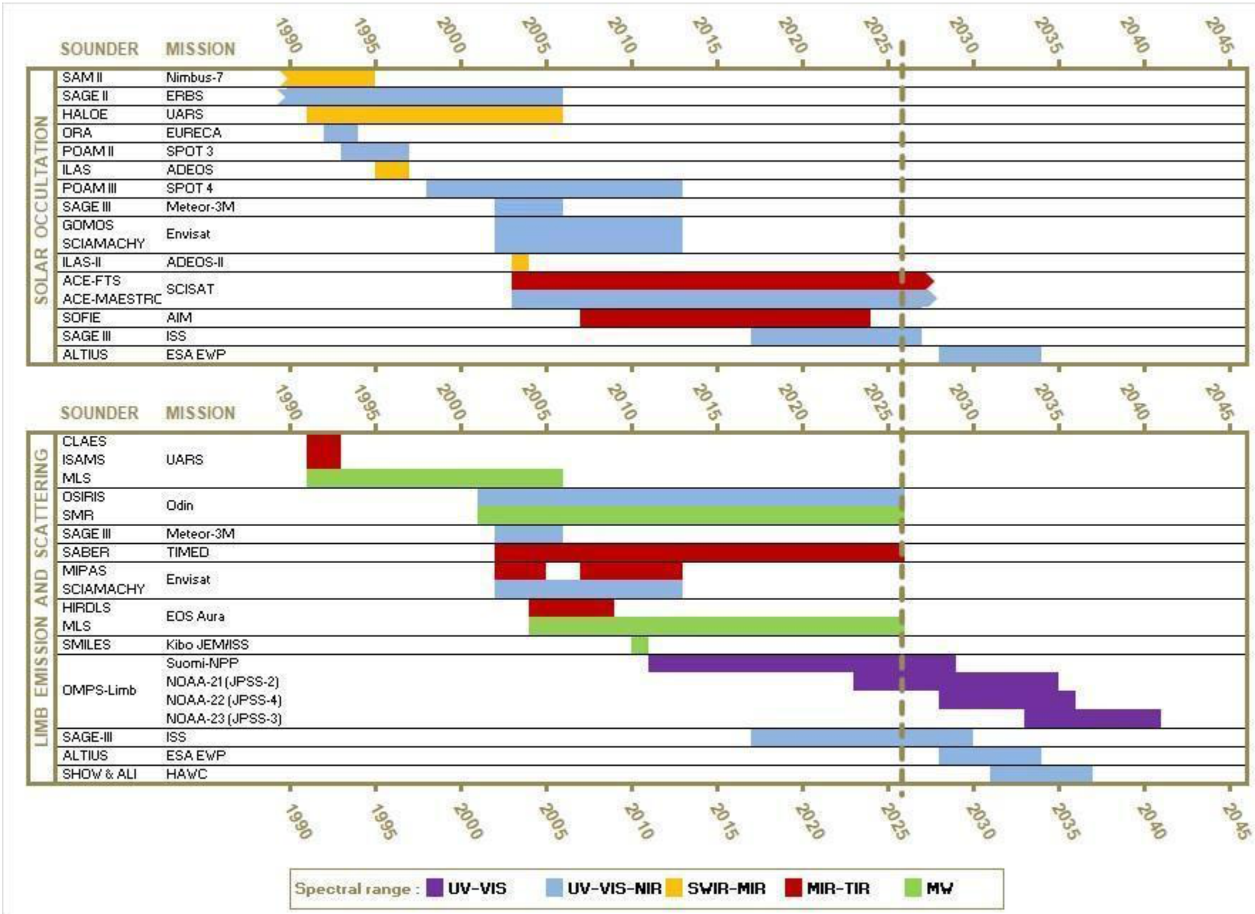


Figure 3. Timelines for limb solar occultation (upper panel) and limb emission (lower panel) satellite sensors that have been, are, or will be supported by NDACC observations.

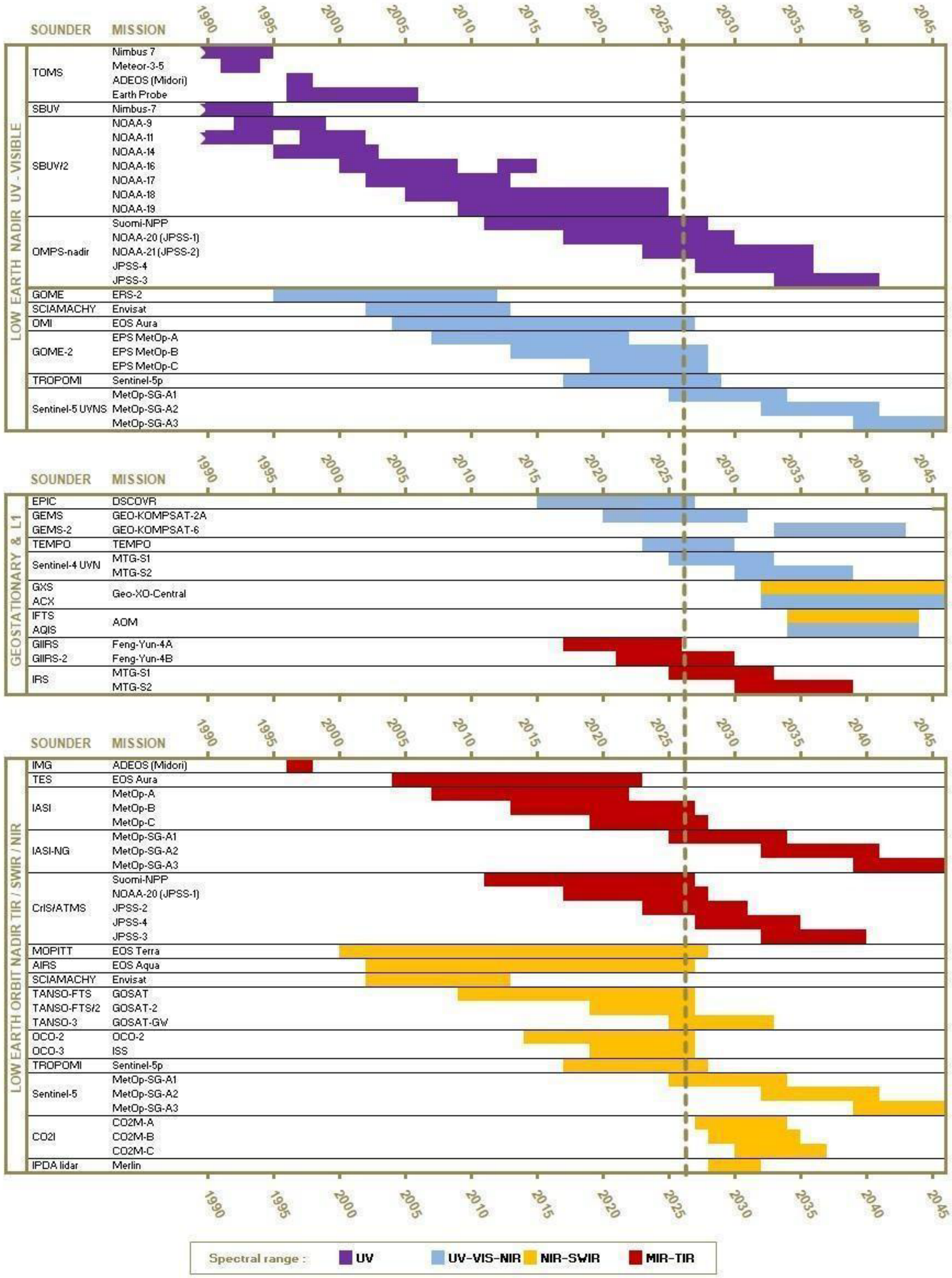


Figure 4. As in Fig. 3 but for nadir-viewing satellite sensors: LEO UV-VIS (upper panel), GEO (geostationary) and L1 (middle panel), and LEO SWIR (Sort Wavelength InfraRed), NIR (near InfraRed) or TIR (Thermal Infrared) (lower panel).

~~Several~~NDACC collaborative efforts are formalized through the representation of several space agencies ~~are represented~~ on the NDACC Steering Committee and Satellite Working Group (WG). ~~A strong level of~~ Enhanced cooperation ~~between NDACC and~~with space agencies ~~at the level~~in support of a Fiducial Reference Measurements (FRM) framework has ~~improved NDACC's response~~allowed NDACC to ~~ever more~~meet increasingly stringent satellite validation requirements for data quality, traceability, uncertainty assessment, cross-network harmonization and timeliness of data access (Goryl et al., 2023). Close links exist with the European Satellite Agency (ESA) Validation Data Centre (EVDC) hosted at the Norwegian Institute for Air Research (NILU) and with NASA's Aura Validation Data Center (AVDC) which both mirror NDACC data to facilitate seamless access for the satellite community.

At the inter-agency level, NDACC ~~is represented on~~promotes exchange of data by contributing to the Committee on Earth Observation Satellites (CEOS) through the Atmospheric Composition ~~Sub Group~~Subgroup of the Working Group on Calibration and Validation (WGCV~~) of the Committee on Earth Observation Satellites (CEOS), an intergovernmental organization ensuring international coordination of civil space-based Earth observation programs and promoting exchange of data to optimize societal benefit.~~
~~In recent years, NDACC has made significant progress towards~~). By advancing the FAIRness of its data~~. As a result~~, NDACC serves as a reference ~~to assess~~for the mutual consistency of the satellites~~ implemented in constellations by the~~, such as CEOS Atmospheric Composition Virtual Constellation (AC-VC) for air quality, for greenhouse gases and for ozone. NDACC ~~also maintains~~ up-to-date ~~content~~involvement in developing satellite validation protocols and ~~guideline documents, and in~~ strategic planning documents~~ defining needs, roadmaps, and frameworks for fit-for-purpose~~, ensures that validation ~~of the international satellite constellations for atmospheric composition monitoring~~frameworks, such as the Quality Assurance Framework for Earth Observation (QA4EO) and FRM principles and maturity matrix, remain fit-for-purpose for evolving global constellations.

Operational satellites feeding numerical weather prediction and environmental services require a fast response to validation needs. ~~Several~~NDACC currently supports several operational ~~validation~~ systems~~ have been implemented in a staggered approach, product by product, e.g.,~~, including NOAA's Products Validation System (NPROVS) and the ESA/Copernicus Validation Data Analysis Facility (VDAF). ~~Operational validation systems are being developed at EUMETSAT for the recently launched~~As new operational missions (e.g. Copernicus Sentinel-4 and -5 ~~missions and~~or the upcoming Anthropogenic Carbon Dioxide Monitoring constellation~~ (CO2M). While~~), come online, NDACC is ~~already supporting operational programs with rapid~~evolving its data delivery ~~of data, it is anticipated that there will be a need in the near future to develop~~ mechanisms ~~for delivery of~~ to provide near-real-time (NRT) ~~NDACC~~ data on a contractual basis. ~~With the advent of operational satellite missions that – among other goals – serve to provide data to inform~~This evolution is essential for informed international efforts to control emissions of atmospheric pollutants, ~~the appropriate validation protocols and associated requirements for independent validation data must be developed: again, NDACC has~~ thus positioning NDACC for an important role to play in ~~this evolution~~support of modern satellite remote sensing operations.

4 Highlights of NDACC scientific achievements

~~Recent~~Selected recent achievements~~,~~ are described in this section~~,~~. These include discoveries related to both stratosphere and troposphere, synergistic collaboration with satellite observations, and advances in network infrastructure. In all endeavors, NDACC's temporal coverage and ~~emphasis on~~adherence to standardized instruments, data-processing methods and protocols, have been essential in creating the high-quality data required for quantifying chemical composition changes~~.~~ and achieving network science goals. Nearly 500 publications since 2018 attest to NDACC's scientific contribution, ~~e.g.,~~ (https://ndacc.org/publications~~.~~). Highlights of stratospheric and tropospheric research appear in Sections 4.1 and Section 4.2 respectively. ~~Although not exhaustive, the examples feature a range of scientific issues and perspectives.~~ Section 4.3 discusses satellite collaborations~~ and NDACC contributions to validation~~. Section 4.4 illustrates NDACC's advances in instrumentation, technology and archiving infrastructure~~, i.e., those capabilities and practices that make NDACC a uniquely valuable resource for the global atmospheric research community.~~.

4.1 NDACC stratospheric composition observations

As a remote sensing network, the NDSC began with a primary focus on stratospheric composition: ozone, ozone-depleting substances, and water vapor, and that commitment remains to the present.

4.1.1 Stratospheric Ozone Trends.

Section 3.2 described how NDACC is an integral component in SPARC/APARC research focus areas and the quadrennial WMO/UNEP Scientific Assessments of Ozone Depletion. Within APARC/LOTUS, statistical multi-linear regression models were used to detect linear decadal trends in the ground-based (i.e., NDACC, WMO GAW, SHADOZ) and satellite ozone records (Godin-Beekmann et al., 2022) over the 2000–2020 period. The study confirmed significant ozone increase in the upper stratosphere using satellite records averaged in three broad latitude bands, varying from 1.6 to 2.2 % per decade (Godin-Beekmann et al. 2022; 2022 WMO Ozone assessment). Fig. 5 shows longitudinally resolved merged satellite records compared to ground-based data, i.e., from lidars, ozonesondes, Dobson Umkehr, microwave radiometers and FTIR, that confirm the satellite trends. Non-linear behavior in the decline of lower stratospheric ozone (60°S-60°N, below 24 km) during the post-2000 period was first reported by Ball et al. (2018). By applying dynamical linear modeling (DLM) to the Arosa/Davos homogenized Dobson Umkehr record, Maillard Barras et al. (2022) showed that upper stratospheric trends only became significantly positive after 2004, at 0.2-0.5% per year; negative trends persist in the middle stratosphere and were more significant in the lower stratosphere from 2008 to 2018.

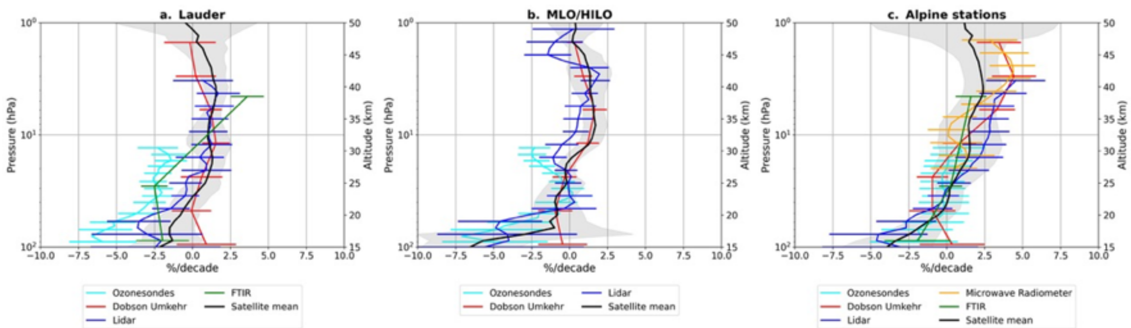


Figure 5. Ozone profile trends post-2000 from selected ground-based NDACC stations: (a) Lauder, Southern Hemisphere station, (b) tropical Mauna Loa and Hilo (ozonesonde) stations, (c) combined Alpine North Hemisphere stations. From Sofieva et al. in review.

APARC OCTAV-UTLS utilizes a dynamical coordinate system (i.e. tropopause, equivalent latitude, etc. derived from MERRA-2 reanalyses) for binning the high-resolution ozone records to separate transport, chemical, and mixing processes in the UTLS region. The method was implemented using several NDACC ozonesonde and lidar high-resolution profiles, aircraft (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container) and satellite (Aura/MLS and ACE-FTS) observing systems (Millan et al., 2023). The result is reduced sampling bias among records, with ground-based and satellite data both revealing patterns of changing atmospheric dynamics (Millan et al, 2024) and a reduction of uncertainties in fitted trends (Millan et al, 2025).

Investigation of the Arctic stratospheric ozone depletion during an unusually strong and stable polar vortex in 2019/2020 winter (Bognar et ~~a. 2020~~al. 2021) relied on long-term observations by NDACC UV-VIS, FTIR, ozonesondes and Brewer instruments located at the Polar Environment Atmospheric Research Laboratory in Eureka, Canada (80°N, 86°W). Cooperating network observations (PGN, Système D'Analyse par Observations Zénithales or SAOZ), non-NDACC lidar and the SLIMCAT model simulations were used to quantify ozone loss. The paper highlighted the importance of combining NDACC measurements with models for attribution of ozone loss processes for predicting ozone recovery.

4.1.2 Ozone-depleting substances, halogenated stratospheric reservoir species and stratospheric circulation

NDACC data were crucial in detecting the unexpected slow decrease of CCl_4, forcing a re-evaluation of missing sources, sinks and atmospheric lifetime (SPARC, 2016; Chipperfield et al., 2016). NDACC data confirmed the unexpected emissions of CFC-11 (CCl_3F) after 2012 (Montzka et. al., 2018, Chipperfield et al., 2021, Pardo-Campos et al., 2022), which resulted in a slowing of its atmospheric decay, potentially delaying ozone recovery.

In the 2022 Ozone Assessment, trends in the Jungfraujoch FTIR time series of CFC-11, CFC-12, HCFC-22, HCFC-142b, CCl_4, CF_4 and SF_6 ~~compared well with those derived from satellite~~support and bridge the trends observed in the high precision in situ ~~surface~~ data and upper troposphere observations from satellites where available (Laube et al., 2022; Chapter 1 in WMO 2022). Work continues with CFC-11, CFC-12, HCFC-22 (Polyakov et. al., 2021) and HFC-23 (Takeda et. al., 2021) using innovative retrieval approaches and water vapor continuum models. A study using data from

16 NDACC FTIR stations quantified decreases in the growth rate of atmospheric HCFC-22 columns derived from harmonized retrievals (Zhou et al, 2024).

Transport of source ODSs to the stratosphere maintains halogen reservoir species. The most abundant chlorine- and fluorine-bearing reservoirs, HCl, $ClONO_2$, HF, and COF_2, are standard NDACC data products. Fig. 6 shows the evolution of total column HCl from several NDACC stations and the evolution of ~~10ºS~~60ºS – 60ºN lower stratospheric HCl from Global OZone Chemistry And Related trace gas Data records for the Stratosphere (GOZCARDS) and ACE-FTS observations. Because only second-order reservoirs are missing, the weighted combination of the respective time series represent budgets of stratospheric inorganic chlorine and fluorine.

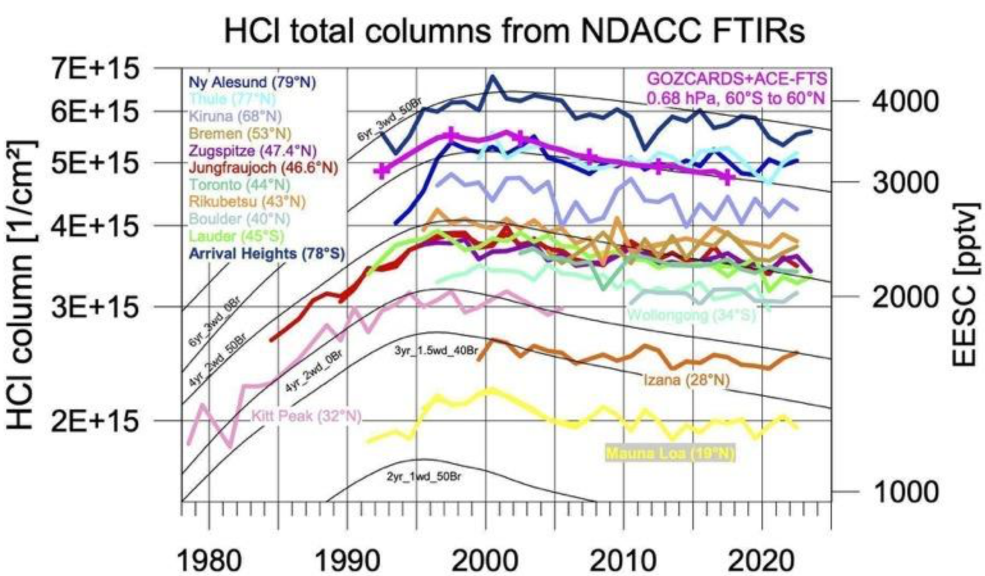


Fig. 6. Total column HCl, the predominant reservoir of Cl, time series from a subset of the NDACC stations representing latitudes from 78ºS to 79ºN, Included is the aggregate satellite time series for 60ºS-60ºN GOZCARDS, augmented with ACE-FTS HCl and Equivalent effective stratospheric chlorine (EESC) model (solid curves represent ODS lifetime and Br efficiency, https://ozonewatch.gsfc.nasa.gov/facts/eesc_SH.html).

NDACC data answer questions about atmospheric change that would otherwise remain speculative. Minganti et. al. (2022) used multi-decade satellite and NDACC data to evaluate WACCM modeled N_2O trends to better understand changes in the Brewer-Dobson circulation. Strahan et al. (2020) used MLS HCl and HNO_3 data, model output from GMI (NASA's Global Modeling Initiative) and measurements from 9 globally dispersed NDACC stations to find (i) a decrease in the age of air of the southern hemisphere lower stratosphere relative to the north by about 1 month/decade and (ii) a 5-7 y variability in both HCl and HNO_3 total columns. The 1994–2018 NDACC record provided more conclusive evidence as it spans 3-plus Solar cycles (11+ years) not available in a single satellite record. The analysis generally supports the finding that the Solar cycle confounds statistical trend regression on the QBO (quasi-biennial oscillation) if not accounted for. Alternatively, N_2O records from the NDACC FTIR stations helped validate the ACE-FTS satellite hemispheric data and global model simulated changes in Brewer Dobson global circulation (Minganti et al, ~~2021~~2022).

4.1.3 Water vapor observations

Detection of small water vapor trends in the upper troposphere, stratosphere and mesosphere is hampered by differences among instruments and sites, as well as natural variability in the troposphere and the large 2022 volcanic water vapor injection into the middle stratosphere. The APARC Water Vapor Assessment II intercomparison of satellite and ground-based microwave measurements, thoroughly investigated trends in water vapor between pressures of 3 hPa and 0.03 hPa (Nedoluha et al, 2017). Agreement between satellite retrievals and ground-based microwave instruments was generally within ±10%. This assessment also included an intercomparison of relative humidity from 19 limb-viewing satellites and the Vaisala RS92 radiosonde coincident with frost point instruments from NDACC (and other) sites between pressures of 300-100 hPa (Read et al., 2022). Agreement of relative humidity in the upper troposphere measured by space-based and frost-point instruments was on average within ±30%, with an additional 30% variability; the Vaisala R92 radiosonde was not recommended for use at pressures below 200 hPa.

4.1.4 Hunga volcanic eruption

On 15 January 2022 the eruption of the Hunga undersea volcano at ~~20S~~20º S injected ~140-150 Tg of water vapor (H_2O) into the atmosphere (Millan et al., 2022; Nedoluha et al., 2024). The bulk of the injection was in the lower stratosphere where it was measured by balloon-borne sondes (Vömel et al. 2022). Not only was the plume injection observed from NDACC stations, a rapid-response team deployed to Réunion Island within one week to make sonde observations (Evan et al., 2023; Asher et al., 2023; Baron et al., 2023). Water vapor from the Hunga plume moved equatorward from its original injection site, where it was first measured in the mid-stratosphere by ground-based microwave instruments at the NDACC station at Mauna Loa, Hawaii (19.5º N) in April 2022 (Nedoluha et al., 2023a). Fig. 7 shows water vapor anomalies at 54 km (just above the stratopause) measured by ground-based microwave instruments at Mauna Loa; Lauder, New Zealand (45.0º S); and Table Mountain, California (34.4º N). In 2022, water vapor mixing ratios at all three sites were unusually large, partly due to dynamical conditions (Nedoluha et al., 2023b). In 2023 water vapor at Table Mountain and Mauna Loa was significantly higher than ever observed in 30+ years of measurements at these (Nedoluha et al., 2024). Lauder showed record-breaking mixing ratios, but short-term weekly anomalies of similar magnitudes can occur during certain seasons due to dynamical variations. Finally, in late 2023/early 2024, ~2 years after the eruption, maximum water vapor anomalies were observed at all three sites at 54 km. These findings are described in more detail in the APARC "The Hunga Volcanic Eruption Atmospheric Impacts Report" (APARC, 2025).

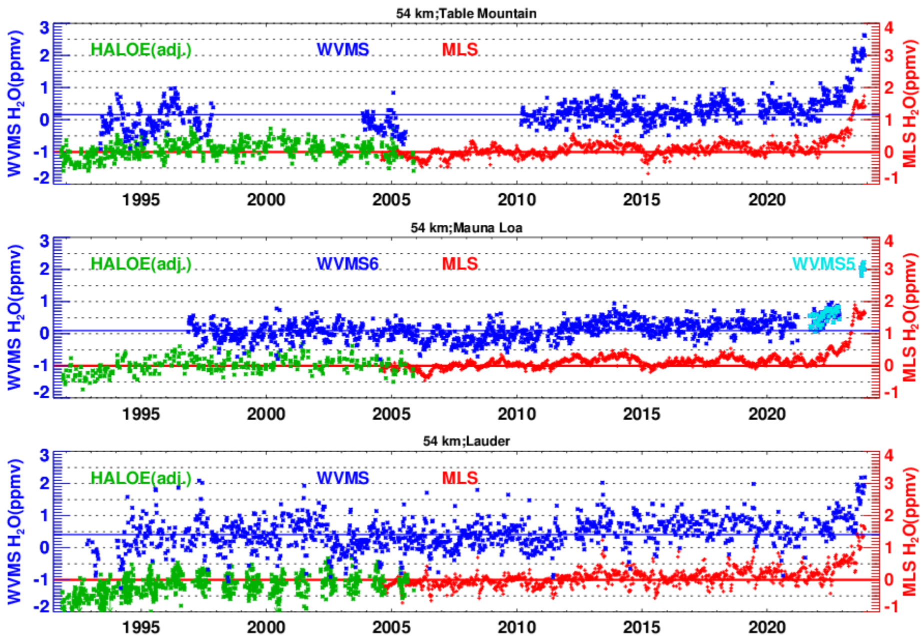


Figure 7. Water vapor volume mixing ratio anomalies at 54 km from ~weekly ground-based microwave measurements at Table Mountain, California (34.4°N, 242.3°E), Mauna Loa, Hawaii (19.5°N, 204.4°E) and Lauder, New Zealand (45.04°S, 169.68°E). The anomaly is calculated relative to a climatology based on Aura MLS measurements from 2004-2021. From Nedoluha et al. (2024).

4.1.5 Extreme Australian wildfires and stratospheric chemistry

In late December 2019 and early January 2020, Australian New Year wildfires injected record-breaking amounts of smoke and aerosol into the southern hemisphere stratosphere. Aerosols were injected up to 32 km, resulting in a bimodal size distribution as was observed in sonde flights launched at Lauder, New Zealand (Asher et al., 2024). Although heterogeneous reactions on stratospheric aerosol surfaces have been known since early analyses of the Antarctic ozone hole, less was known about reactions on black or brown carbon from biomass burning smoke. What NDACC and satellite observations revealed in the post-fire months was unprecedented stratospheric chlorine partitioning (Fig. 8; Strahan et al., 2022) which has important implications for predicting stratospheric ozone in a more wild-fire prone world. Satellite observations of fire-perturbed HCl, $ClONO_2$, HF, O_3, N_2O and NO_2 by NDACC and H_2O, ClO and aerosol extinction were reported by Santee et al. (2022) and Boone et al. (2020). Chemical simulations by Solomon et al. (2023) proposed that chlorine partitioning was caused by oxidized organics and sulfates increasing hydrochloric acid solubility (and associated heterogeneous reaction rates). This is supported by the observed enhanced $ClONO_2$ and decreased HCl, although Strahan et al. (2022) pointed out that definitive ozone loss is not confirmed due to entangled chemistry/transport effects. Ozone losses appear to peak in May-June.

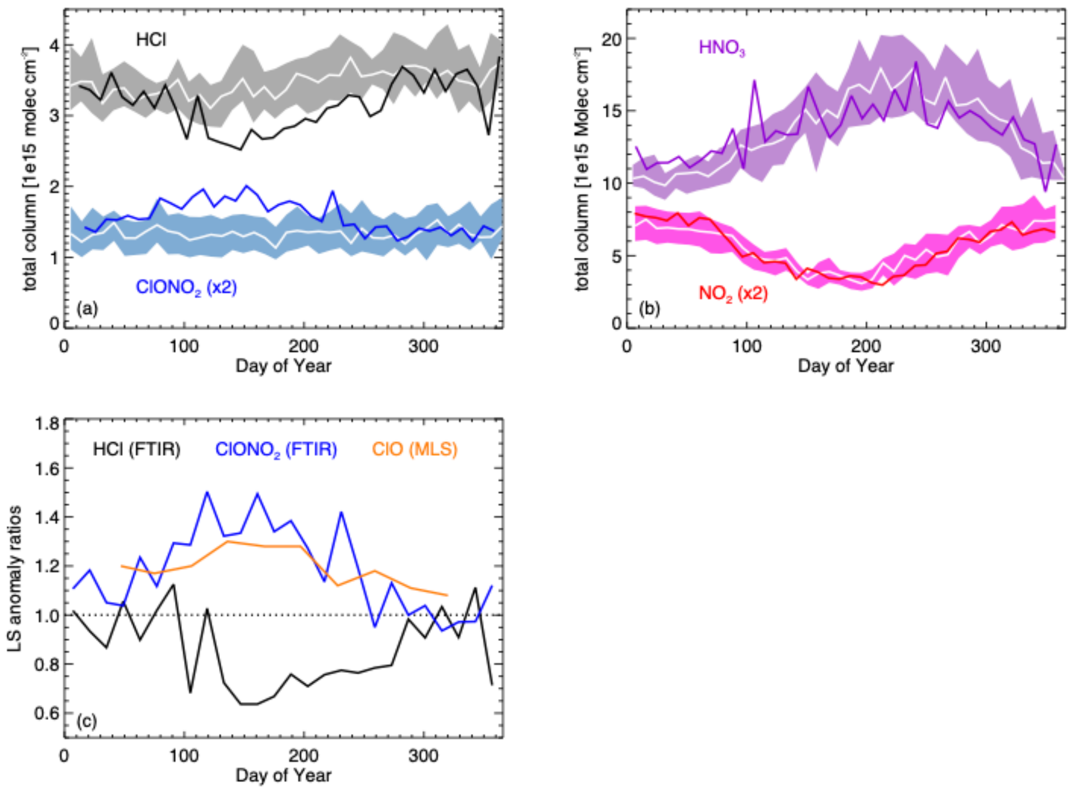


Figure 8. (a) 2020 9-day average of Lauder FTIR total column HCl and $ClONO_2$ (scaled for clarity) along with associated 2010-2019 mean (white) and 1 standard deviation (shaded). (b) Same as (a) but for HNO_3 and NO_2 (scaled for clarity). (c) Lower stratosphere column (LS, ~150-50 hPa, ~12-21 km) 2020 anomalies (9-day average, ratioed to 10-year means, 2009-2019) for HCl and ClO. Total column ClONO2 anomalies are displayed because there is insufficient signal for a $ClONO_2$ LS column. Aura-MLS ClO observations are averaged over 40°-50°S. (after Strahan et al. 2022)

4.2 NDACC tropospheric composition observations

NDACC research in the 2000's has focused increasingly on tropospheric composition and radiation as described below.

4.2.1 NDACC and the Tropospheric Ozone Assessment Report (TOAR)

NDACC played a major role in analyzing global tropospheric ozone trends in the second phase of IGAC's Tropospheric Ozone Assessment Report (TOAR II; see TOAR I reports by Gaudel et al., 2018; Tarasick et al. 2019). Within the HEGIFTOM working group (Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements), records from NDACC and ~~affiliated~~other atmospheric measurement networks for four instruments – FTIR, Lidar, Brewer/Dobson Umkehr, ozonesonde – were reprocessed with absolute reference standards and archived to produce ozone column data with uniform formats with uncertainty estimates and quality flags (Van Malderen et al, 2025a). Fig. 9 shows an intercomparison study at the multi-instrumented Lauder supersite (Björklund et. al., 2024) for both stratospheric and tropospheric columns based on time-series for 2000-2022. More than 50 articles from TOAR II analyses, including those based on HEGIFTOM and other ground-based ~~datas~~data, with satellite products, have been published in a TOAR II special collection (see https://bg.copernicus.org/articles/special_issue10_1256.html).

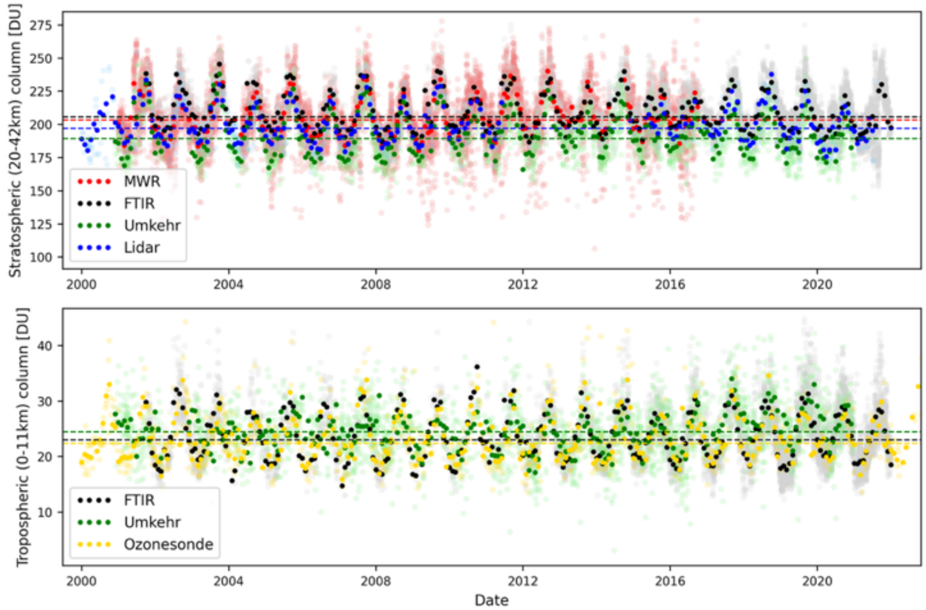


Figure 9. Upper: Time series (2000-2022) ozone columns (20-42 km) in Dobson Units (DU) from four remote sensing techniques at Lauder, New Zealand. Shaded points are all data, highlighted points are monthly means, dashed lines are median of all data by technique. Lower panel shows the tropospheric ozone column (defined as surface to 11km). After Björklund et al., (2024).

Trends for individual station HEGIFTOM/NDACC ozone columns, augmented by landing/takeoff profiles from the In-service Aircraft for a Global Observing System (IAGOS) airports, were calculated following TOAR-II guidelines on metrics, units, time range, and statistical trend model in a series of studies (e.g., Van Malderen et al., 2025a,b; Gaudel et al., 2024; Thompson et al., 2025). A summary of median trends for a tropospheric total column (TrOC, specified as surface to 300 hPa, for 2000 to 2022, based on the HEGIFTOM data, ~~appear~~appears in Fig. 10. Trends are illustrated with 2-σ uncertainties for 55 sites (Van Malderen et al., 2025a) as a function of latitude (Fig. 10, left) and longitude (Fig. 10, right). The HEGIFTOM-derived trends mark a turning point for the tropospheric ozone community~~. Having~~ because it is the first time that a global picture of changes based on consistently processed observations from multiple ground-based ~~ozone trends as~~instruments is available. The outcome is a definitive reference dataset for evaluating still-evolving satellite products, some ~~covering <~~of which cover fewer than 10 years~~, is essential for rigorous evaluation of ozone trends based on satellite data (~~ (Hubert et al., TOAR-II Satellite Ozone Report, 2025). For ozone profile trends in the troposphere, there is no substitute for ozonesondes and aircraft data (Thompson et al., 2025; VanMalderen et al., 2025b).

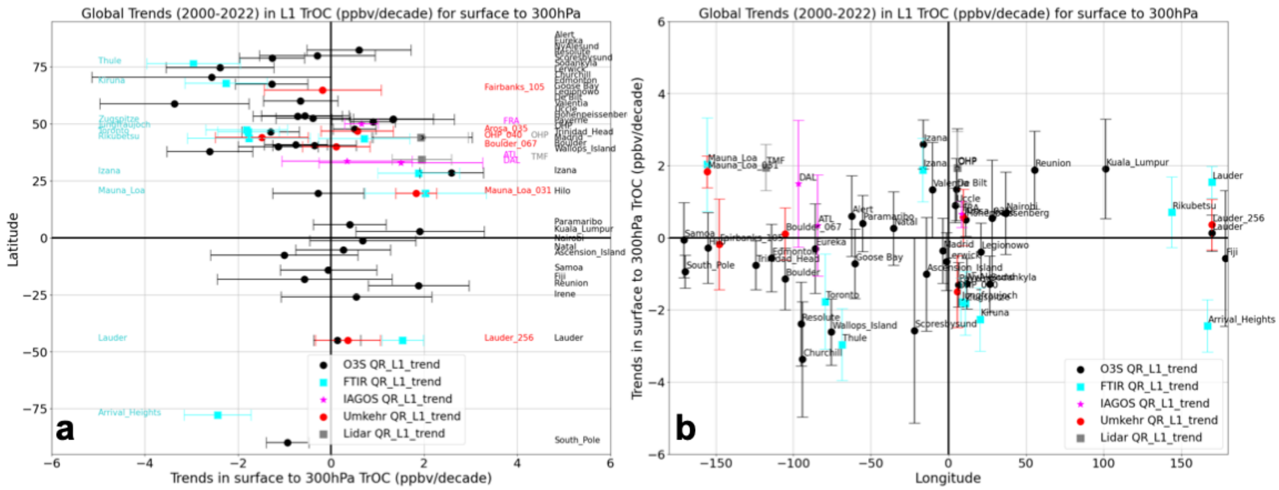


Figure 10. Tropospheric column ozone (TrOC, surface to 300 hPa) trends in ppbv/decade, determined ~~from~~at three IAGOS ~~airport~~airports and for four NDACC instruments: ozonesondes, FTIR, Umkehr, and Lidar. Calculation was made using all data (L1, 2000 to 2022) by Quantile Regression. Uncertainties at ± 2-σ. Most stations exhibit median trends within ± 3ppbv/decade (Van Malderen et al., 2025a). a) trends as function of latitude, b) trends as function of longitude.

4.2.2 Long-term trends in whole atmosphere carbonyl sulfide.

Carbonyl sulfide (OCS), the reservoir sulfur species in the free troposphere, is a product of anthropogenic, biogenic and oceanic emissions, a tracer for CO_2 uptake by the biosphere and the largest source of sulfur transported to the stratosphere during periods of low volcanic emissions, helping maintain the lower stratospheric sulfate aerosol layer. Despite these important roles, it remains under-observed. NDACC FTIR OCS measurements are unique in having near-global coverage for 3+ decades. Hannigan et al. (2022) derived trends in the lower free troposphere and the lower stratosphere, showing distinct trends over discrete time periods since 1986. ~~Regression~~They showed that regression models ~~and~~using available geophysical proxies of varying time periods~~, attribute~~ could not adequately explain the ~~varying trends in Fig. 11 are due primarily~~multi-decadal OCS variability. For the longest time series through to 2012 the highest correlations to the free tropospheric NDACC time series was with the gridded, bottom up anthropogenic emissions from Zumkehr et. al., 2018. Shown in Fig. 11, between 46% to 77% of the variability can be attributed to anthropogenic sources at stations between 76ºN and 80ºS.

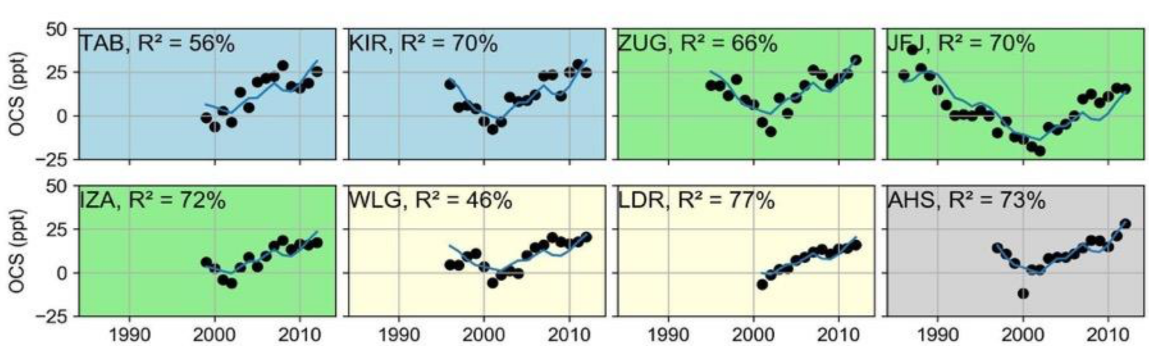


Figure 11. Fit of the annual anthropogenic emissions inventory from Zumkehr et al. (2018) (blue line) to annually averaged FTIR OCS data (black dot) from stations with the longest running data records. The emissions inventory is interpolated to the station location. From Hannigan et al. (2022). TAB: Thule Air Base 76ºN, KIR: Kiruna 67ºN, ZUG: Zugspitze 47ºN, JFJ: Jungfraujoch 46ºN, IZA: Izana 28ºN, WLG: Wollongong 34ºS, LDR: Lauder 45ºS, AHS: Arrival Heights 79ºS.

4.2.3 Surface UV radiation: Monitoring, impacts, and research

Surface UV radiation is a crucial indicator of atmospheric change, capturing the combined effects of aerosols, clouds, ozone, and ~~dynamics.~~other atmospheric composition changes driven by natural and anthropogenic sources, transport and atmospheric mixing. Its reach extends to public health, impacts on terrestrial and aquatic ecosystems and the degradation of materials like plastics into microplastics. Regular high-precision NDACC spectral UV observations are conducted at 12 globally distributed stations, strategically located to cover diverse environments (polar, mid-latitude, tropical) to ensure data collection across Earth's UV regimes. In Antarctica, continuous monitoring since 1990 has shown a slight decline in overall UV exposure since the early 2000s (Bernhard & Stierle, 2020), consistent with ozone layer recovery. However, ground-based measurements still record extremely high UV levels like persistent ozone holes (Cordero et al., 2022). These observations have greatly advanced our knowledge of public health impacts from spatial and temporal variability in UV doses (Brogniez et al., 2021). Cumulative, low-dose UV exposure has significant health implications, leading to advocacy for a more nuanced understanding of UV benefits and risks (McKenzie & Lucas, 2018; McKenzie et al., 2022).

4.3 Satellite validation and collaboration

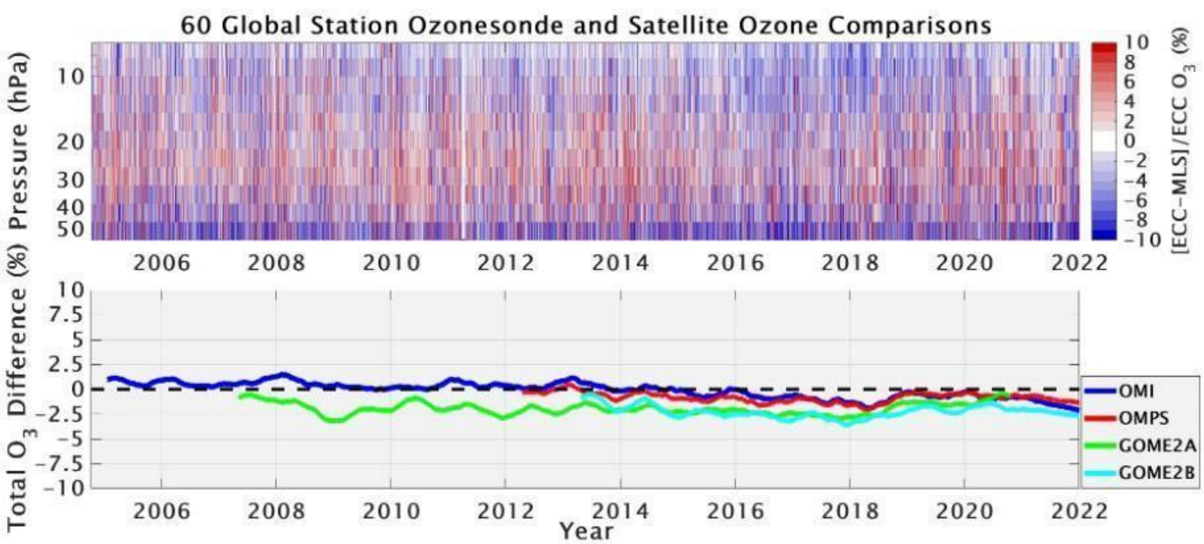
There is considerable synergy between NDACC, with its focus on remote sensing measurements, and the satellite observations community for initial validation of new space-based instrumentation, detection of long-term drifts, and collaborative research. Selected highlights follow. More examples with publications appear in Table C1 in Appendix C~~,~~ ~~Table C1~~.

4.3.1 Detection and quantification of long-term satellite drifts

Without long-term ground-based observations, detection of drifts or steps in satellite data record is difficult. The MOPITT instrument aboard NASA's EOS-Terra satellite launched in 2000 measuring near-global CO has exceeded initial specifications. Buchholz et. al. (2017) used data from 14 latitudinally distributed NDACC FTIR stations to determine drifts over the first 17 years. Co-located data carefully matched using the vertical sensitivity (averaging kernels) to account for the respective response of each FTIR examined three MOPITT retrieval schemes. Mean bias for all sites was determined to be 2.4 % for TIR-only, 5.1 % for TIR–NIR, and 6.5 % for NIR-only. The MOPITT long-term bias drift is calculated to be within ±0.5 % yr^{-1}. Aura MLS has also operated past its programmed lifetime. NDACC water vapor sonde data at Lauder, Hilo and Boulder were used to evaluate, determine and correct for drifts over 15 years, 2005 to 2020 (Livesey et. al., 2021).

Stability of ground-based records themselves can be compromised by instrumental artifacts, e.g. ~~”~~“drop-off” in ozonesonde records due to manufacturing changes (Stauffer et al., 2020), which are often detected through calibration and multi-instrument intercomparison activities (Thompson et al., 2019) and by adherence to NDACC observational protocols. Processing satellite and ground-based (GB) data by identical statistical methods minimizes biases in trend detection while illustrating potential inconsistencies among records (Petropavlovskikh et al, ~~2024~~2025).

Over the past 25 years, members of the NDACC ozonesonde community have been part of the WMO/GAW ASOPOS (Assessment of Standard Operating Procedures for Ozonesondes) activity to optimize sonde data quality through specification of standard operating procedures (SOP) including data processing (Smit et al., 2024). Roughly ~~half~~2/3th of the 60 global sonde stations have reprocessed their records. For ozonesonde data since mid-2004, satellite measurements are used to evaluate the sonde profiles as shown in Fig. 12. Total column and stratospheric ozone from the sondes were compared to overpass readings from ~~satellite~~satellites (Aura OMI and MLS, S-NPP OMPS, GOME-2A and -2B) from mid-2004 through 2021 to determine stability in the sonde measurements. Overall, the ozonesonde data show remarkable agreement compared to satellite instruments. Total column ozone derived from the sondes is on average within ±2% of the Aura OMI over the last 18+ years (Fig. 12), and the ozone profiles match Aura MLS to within ±5% in the mid-stratosphere up to 10 hPa (Stauffer et al., 2022). The excellent agreement is achieved even with a known instrumental bias at several stations (Stauffer et al., 2020). These comparisons underscore the success of the ozonesonde data reprocessing and homogenization effort (Smit et al., 2021). In the 1990s, ozonesonde data uncertainty was on the order of 20%, and biases near 10% in total column ozone were common. Today, data uncertainties approach 5%, with total column ozone biases < 2%.



4.3.2 Figure 12. Coincident ozonesonde and satellite comparisons (% difference) for 60 global ozonesonde stations. (Top) Time series comparisons among all ozonesonde and Aura Microwave Limb Sounder (MLS) ozone profiles ([ECC-MLS/ECC]) where ECC signifies the sonde value. Red (blue) colors indicate where the sonde ozone is greater (less) than MLS. (Bottom) Ozonesonde and satellite total ozone comparisons in % difference ([ECC-satellite]/ECC) for OMI (blue), S-NPP OMPS (red), GOME-2A (green), GOME-2B (cyan).

4.3.3 Operational validation of HCHO and NO_2 for Sentinel-5P

The operational validation service of Sentinel-5P TROPOMI relies on the fast delivery of correlative measurements acquired by most of the NDACC sub-networks and several cooperating networks. Total and tropospheric ozone column and profile data products are quality assessed by an operational validation server (https://mpc-vdaf.tropomi.eu) using Brewer, Dobson, FTIR, lidar, ozonesonde and Zenith-Sky DOAS measurements acquired from pole to pole and under a variety of measurement conditions and influencing parameters (Garane et al., 2019; Hubert et al., 2021; Keppens et al., 2024).

The quality assessment of NO_2 total and partial columns relies on a holistic approach combining validation of TROPOMI stratospheric NO_2 with respect to NDACC Zenith-Sky DOAS columns, tropospheric NO_2 with respect to MAX-DOAS columns, total NO_2 with respect to PGN total columns (Verhoelst et al., 2021) and cloud parameters validation using the ACTRIS-Cloudnet network of lidars and radars (Compernolle et al., 2021). Harmonization of NDACC FTIR NO_2 (Vigouroux et al., 2025), provides a new global dataset for TROPOMI validation (see S5P Quarterly Validation Reports at https://mpc-vdaf.tropomi.eu). Stratospheric NO_2 columns measured by NDACC FTIR, Zenith-Sky DOAS and PGN at pristine stations (i.e., without tropospheric NO_2 pollution) give mutually consistent validation results, showing e.g. a similar station-to-station 1-sigma scatter of the bias with TROPOMI of ~5%.

Although not a standard NDACC product, harmonized HCHO FTIR data were produced by the network (Vigouroux et al., 2018) and used for the first TROPOMI HCHO validation (Vigouroux et al. 2020). TROPOMI HCHO products were shown to be biased high over clean regions by ~26% but underestimated by ~31% in polluted conditions. The robust linear relationship between TROPOMI and NDACC data is shown in Fig. 13 across a range of HCHO concentrations. These data are used in inverse modeling studies to correct TROPOMI and OMI products before inverting them (Oomen et al., 2024; Müller et al., 2024). The high internal consistency of FTIR-based HCHO is illustrated; HCHO is now archived as a standard NDACC species. The HCHO FTIR data set has been employed in other satellite ~~validation~~validations (Lee et al., 2024; Kwon et al., 2023; Ayazpour et al., 2025; Müller et al., 2024) and for characterizing errors in satellite-based HCHO/NO_2 ratios (Souri et al., 2023) and for TEMPO validation over North America.

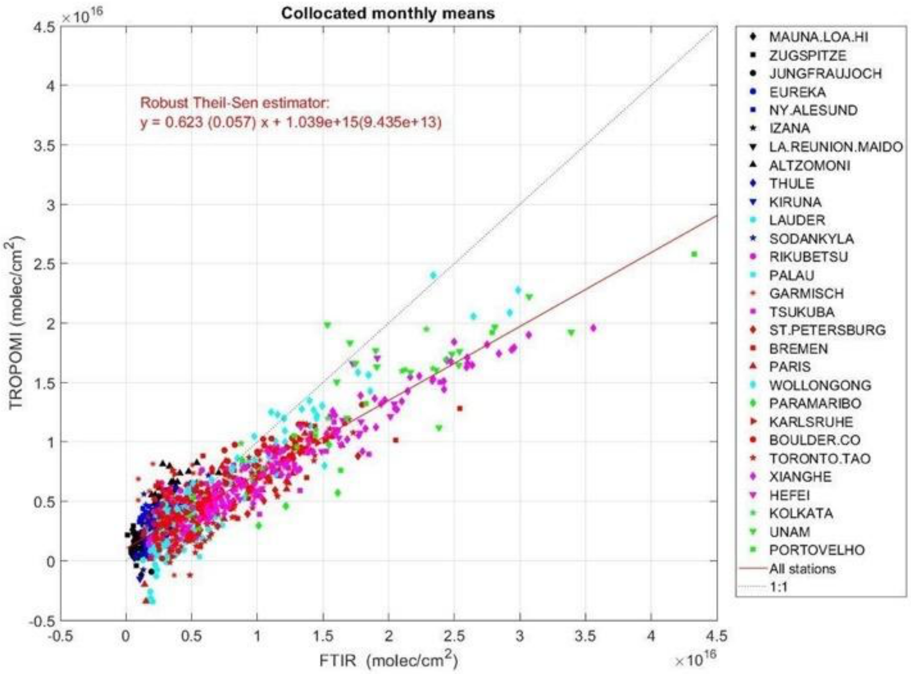


Figure 13. Scatter plot of NDACC FTIR and TROPOMI HCHO data, after Vigouroux et al. (2020).

Similarly, harmonization of NDACC FTIR NO_2 (Vigouroux et al., 2025), provides a global network dataset for TROPOMI validation (Quarterly Reports at https://mpc-vdaf.tropomi.eu). The NDACC FTIR and Zenith-Sky DOAS NO_2 columns are characterized by excellent internal consistency, showing a similar station-to-station 1-sigma scatter of biases with TROPOMI of ~5% (Verhoelst et al., 2021).

4.3.4 Correlative observations of new species

Some of the most exciting advances in satellite observations are due to advances in retrieval algorithms providing data products for new species. Species like methanol, ethane, ethene, ethyne and isoprene (CH_3OH, C_2H_6, C_2H_2, C_2H_4, C_5H_8 respectively) have been observed with the Cross-track Infrared Sounder (CrIS) (Wells et al., 2022, Wells et al., 2024, Brewer et al., 2024). These species, primarily originating from biogenic and anthropogenic sources, are important as ozone precursors, traceable to emissions sources. NDACC has developed new retrievals for these species, in some cases providing the only validation data. The Infrared Atmospheric Sounding Interferometer (IASI) has produced a formic acid (HCOOH) data product that Franco et al. (2020) validated with global NDACC FTIR data. Other new species observed by NDACC are PAN ($CH_3C(O)O_2NO_2$) (Mahieu et. al., 2021, Wizenberg et. al., 2022) and ammonia (NH_3) (Dammers et al, 2015; Lutsch et. al., 2019, Yamanouchi et. al., 2021, Herrera et. al., 2022). See Table A1 (Appendix B) for the list of species validated by NDACC observations.

4.4 Advances in instrumentation, data processing and archiving infrastructure

Since its inception, the NDACC mission has been to observe the atmosphere with the precision and accuracy required to answer the key science questions of the day, hence the focus on state-of-the-art, calibrated, certified instrumentation. Instrumentation techniques, data acquisition, and signal-to-noise specifications have greatly improved over the last three decades while data processing and analysis techniques have evolved to deliver larger, better characterized, versioned datasets with improved uncertainty budgets. These complex and versatile datasets are used by a more diverse research community. Simultaneously, the geographical, temporal, representativeness, precision requirements of the research and monitoring communities have increased. Some examples of how NDACC has responded to this new environment follow.

4.4.1 Instrumental: Automation, compactness, mobility

The Jet Propulsion Laboratory (JPL) Atmospheric Lidar Team has developed a compact, more affordable class of tropospheric ozone differential absorption lidar (DIAL) systems. The Small Mobile Ozone Lidar (SMOL) is compact enough to be readily deployed for rapid air quality measurement campaigns at 10 to 50% the cost of most existing tropospheric ozone lidars (~~Choza~~Chouza et al., 2025). In June-August 2023 JPL deployed two SMOL instruments in the Los Angeles Basin to participate in the NOAA-led AEROMMA-2023 campaign and in the NASA-led STAQS Mission for the validation of TEMPO. By June 2024, two more SMOL instruments had been built, enabling unprecedented deployment configurations for field campaigns, e.g., within a tight spatial grid for air quality studies, or at a larger, synoptic scale to study long-range transport and stratospheric intrusions.

In 2024, a version optimized for stratospheric ozone (SMOL-X) was designed and successfully tested. SMOL-X can measure vertical profiles of ozone between 5 km and 35 km altitude with a precision better than 10% for a 3-hour averaging time. Because of its affordability and ease of deployment, this new class of stratospheric ozone DIAL provides opportunities for NDACC deployment in remote areas, such as Antarctica, the Arctic, Asian or Africa providing the opportunity to fill critical measurement gaps. NDACC continues to evaluate new measurement techniques and target variables. For example, in 2020, the UV-VIS Working Group updated the instrument and validation protocols for including MAX-DOAS-type instruments, several of which have been NDACC-certified since then. Wind lidar joins microwave wind instruments to extend NDACC’s meteorological observational capability. The Steering Committee is also evaluating the addition of temperature data measured by microwave instruments.

4.4.2 Migration towards central processing

NDACC ensures a high standard of data quality as well as a high degree of homogenization and consistency across instruments and platforms. Centralized data processing with network-wide scrutiny is a powerful tool to achieve quality, consistency, and homogenization.

~~The~~Several NDACC ~~Lidar~~Instrument Working ~~Group recently built its initial~~Groups made significant efforts towards the development of centralized ~~lidar~~ data ~~processor~~processing. The Global Lidar Analysis Software Suite (GLASS~~). Initially~~) was initially developed to retrieve stratospheric ozone, temperature, aerosol, tropospheric ozone, and water vapor for the four NASA/JPL lidars~~, GLASS~~. It was ~~soon~~then expanded to process the raw data of more than a dozen ~~other~~ lidar instruments contributing to NDACC, TOLNet and GRUAN (GCOS reference Upper Air Network). GLASS is used to support several NDACC-contributing stations on a routine basis and ~~also serves~~has served as a transfer standard during campaigns (e.g., the SCOOP and STOIC campaigns in 2016 and 2024 respectively). A second centralized lidar data processor named LIDAR Ozone ACTRIS was also installed at ACTRIS for the analysis of several European NDACC lidars. It has been integrated in the ACTRIS Centre for Reactive Trace Remote Sensing Central (CREGARS).

Within the ESA FRM4DOAS consortium, a Centralised Data Processing System (CDPS) dedicated to the retrieval of tropospheric and stratospheric trace gas data products from MAX-DOAS and zenith-sky light DOAS instruments has been developed In BIRA-IASB (Van Roozendael et al., 2024). In its current demonstration, the FRM4DOAS system generates total ozone, stratospheric NO_2 profiles, and tropospheric columns and profiles of NO_2 and HCHO from approximately 20 stations~~ worldwide~~. Retrieval algorithms are selected through community consensus, resulting in quality-controlled data products being delivered daily to the NDACC rapid delivery (RD) repository and mirrored at the ESA Validation Data Centre (EVDC) to serve as ~~Fiducial Reference Measurement (FRM) for satellite validation. Like the FTIR CDPS (see below) this system is also integrated within the ACTRIS Centre for Reactive Trace Remote Sensing Central Facility.~~an FRM for satellite validation.

An FTIR CDPS has also been developed to ingest infrared spectral data from standard NDACC high-resolution, moderate and low-resolution instruments to accommodate ~~rapidly~~rapid delivery for Sentinel 5P and CAMS validation systems. Key features are the easy integration of additional instruments and open source. For more than a dozen FTIR instruments, the system provides NDACC retrievals for selected species and the capacity for both instruments and species is increasing. ~~Processing these spectra demonstrates~~

The above systems for Lidar, DOAS and FTIR instruments demonstrate the advantages of the CDPS:

- High level of harmonization of retrieval results e.g. uncertainty budgets, regularization
- Traceability of processing: e.g. registration of retrieval strategy, spectroscopy data, ensures FAIR adherence
- Responsiveness to changes, e.g. prior data, spectroscopy, algorithm, reporting and guidelines (GEOMS or NDACC DOI generation),
- Automated rapid delivery data to NDACC DHF or other destinations,
- Decreased operational workload for instrument PI, and
- Uniform quality assurance across all instruments and all data levels (L0 - L2).

The CDPS has created advanced visualization tools for L0, L1 and L2 data accessible to the public at (https://actris-ftir.aeronomie.be/actrisvisualizer?view=visualize). The ~~system is~~FRM4DOAS and FTIR CDPS are integrated into the ACTRIS CREGARS FTIR facility (https://actris-ftir.aeronomie.be/) and used by ACTRIS National Facilities. The ACTRIS ~~FTIR~~ CDPS ~~follows~~are aligned with NDACC~~ IRWG~~ retrieval procedures to maintain consistency with NDACC.

4.4.3 Data Handling Facility: GEOMS, versioning, licensing, DOIs

~~Fundamental issues affecting large data~~The NDACC maintains a leading-edge Data Host Facility (DHF) designed to address the complex challenges of managing large scale geophysical archives~~ include documentation of data, tracking of data versions and reprocessing, consistency of data content when shared to multiple archives, use of formatting standards, including appropriate reporting of error estimates, associated auxiliary variables and metadata, safe storage of raw data, availability of data~~ . Central to ~~the public, acknowledgement of data used in publication, data licensing, and durability and discoverability of datasets.~~

NDACC requiresits mission is assurance of long-term measurement traceability and stability; via change management is critical to NDACC's mission. The DHF has leveraged . The GEOMS metadata standard to introduceis used to enhance interoperability with partner networks. Recent enhancements to GEOMS have improved data versioning capabilities (i.e. identifyingallowing the identification of data processed bywith distinct algorithms, data with varying integration times, data correspondingor linked to a specific publication, centrally-processed and/or in-house-processed data products).publications.

NDACC data are publicly available, findable and searchable at the DHF, i.e., accessible. NDACC relies on the Digitalsupports the FAIR principles: Findability, Accessibility, Interoperability, and Reusability through its use of GEOMS metadata; the use of data protocols guiding public archive and general rules for use of data; and the incorporation of Data Object Identifiers (DOI)). Creation of DOIs, offered to enhance the likelihood of a dataset discovery, to promote data interoperability (i.e. through metadata), and to allow data records to be cited directly (often a requirement of scientific journals). EVDC provides a mechanism to publish DOIs for NDACC data providers. Restrictions or openness of use of a dataset is defined by the data provider as stated in the metadata file. by EVDC, allows direct citation of data records in scientific literature, a frequent requirement for many peer-review journals. The data protocols stipulate details on the public accessibility of NDACC data. As well, GEOMS and NDACC recommend Creative Commons licensing (creativecommons.org)(creativecommons.org) which dictates how data can be used and reused.

The DHF stores model output fromThis transparency ensures that the legal and technical requirements for data reuse are clearly communicated to the global research community.

Beyond primary observational data, the DHF archives high-resolution atmospheric model output to provide broader auxiliary context at the location of NDACC measurements. These include the Global Modeling Initiative (GMI) extracted at the location of NDACC stations. Extracted GMI). chemical transport model (CTM) datasets are available for dating back to 1985 to 2022. Output extracted at NDACC station locations is also available from a and GEOS-GMI simulation simulation run in replay modesimulations (Orbe et al, 2017) tothat constrain the meteorology to the MERRA-2 reanalysis through 2023 (Gelaro et al., 2017). GEOS-GMI utilizes the GMI chemical mechanism (, Duncan et al., 2007; Strahan et al., 2013; Nielsen et al., 2017) as part of the GEOS atmospheric general circulation model (, Molod et al., 2015). The GEOS-GMI simulation, described in Fisher et al. (2024), has higher horizontal resolution than the GMI CTM simulation. The GEOS-GMI datasets are currently available for 1996 to 2022 and Replay datasets up to 2023 with plans to continue with years. Results from Lagrangian transport simulations using theAdditionally, Chemical Lagrangian Model of the Stratosphere (ClaMS; e.g. Pommrich et al., 2014 and references therein), which was originally developed for stratospheric ozone research, are available to NDACC researchers for joint project studies. CLaMS can be used as a conceptual trajectory model, as an offline, reanalysis-driven chemistry transport model, or online as part of a climate model (e.g. Charlesworth et al., 2023; Vogel et al.,)2023). Various CLaMS products, such as pure trajectory calculations, artificialregional model tracers to tag air masses (e.g. of

surface- origin tracers,and age of air), as well as upper tropospheric and stratospheric chemical trace gases, can be provided (e.g. -of-air simulations (e.g. Ploeger et al., 2021; Graßl et al., 2024; Grooß Vogel

et al., 2025~~; Vogel et al., 2025).~~
), are available to NDACC researchers for joint project studies. Physical locations of the NDACC DHF and website are at NASA Langley Research Center (LaRC), ensuring continuity of infrastructure central to the network's functioning. In addition, NILU provides a mirror of the NDACC DHF and a backup of the website content. The recent move of the DHF from its NOAA (Maryland) home at NASA LaRC (Virginia) provided an opportunity for a full redesign of the interface for both data providers and users. While preserving the integrity of data quality and interfaces with partnering organizations, the data ingestion now allows for interactive and programmatic upload. ~~Tools are available for checking files prior to full archiving.~~ The query of data using the database tables is available to the public via an intuitive interface, allowing for data access with identification of statistics on the data, e.g., number of files, submission dates and more.

5 NDACC Challenges and opportunities

The structure of NDACC and how it meets the principal goal of providing the highest quality atmospheric composition data were detailed in Sections 2 and 3. Section 4 illustrates major discoveries and accomplishments focusing on NDACC observations since 2018. The network is not without challenges (Section 5.1). At the same time, NDACC seeks to expand measurements to address emerging areas that require high-quality ground-based observations (Section 5.2).

5.1 Challenges

5.1.1 Technical challenges

There are two general types of challenges facing NDACC. First, there are technical challenges (Section 5.1.1.1), i.e., incorporating new instruments, maintaining reference standards and consistent calibrations, and adapting to every-changing archives and formats. Second, infrastructure challenges (Section 5.1.2) include sustained funding, adapting to new scientific priorities while maintaining long-term measurements, changing expectations on data availability and re-posting on an ever-growing population of secondary and tertiary data platforms.

5.1.1.1 Instrument and IT issues

NDACC researchers often push instruments to their limits, dedicated to collecting consistently high-quality data as instruments age, spare parts dwindle, the cost of maintenance increases, and some instruments are replaced with newer technology.

Total column ozone instruments, a mainstay of satellite calibration and cross-calibration, have been deployed globally for 6-7 decades. Many of the Dobson spectrophotometers used in NDACC are more than 50 years old. There are no dedicated suppliers for replacement parts. Mechanical and optical properties ~~aren't~~are not well documented. Furthermore, the manufacturer of the NDACC Brewer instruments has recently discontinued production.

Simpler, automated and less expensive instruments have been developed, e.g., Pandora or BTS array spectrometers for total ozone and UV measurements (Herman et al., 2015; Zuber et al., 2021) or moderate spectral resolution mid-IR interferometers (e.g., Sha et al., 2020). Some newer instruments are still being evaluated for accuracy and multi-decade stability. An example (Fig. 14) compares total ozone columns measured by a new BTS spectrometer and an NDACC

Brewer. When slant ozone columns are large and the sun is lower in the sky, the BTS instrument reports lower values, presumably due to straylight effects that will need to be corrected.

Other challenges include the scarcity and/or cost of supplies, e.g., helium for launching sondes, gases used in lasers, and the phase-out of certain technologies. The latter case is illustrated by the need to replace the HFC coolant (R23) in frostpoint water vapor sondes. R23, a powerful greenhouse gas, is banned in accordance with the Montreal Protocol Kigali Amendment.

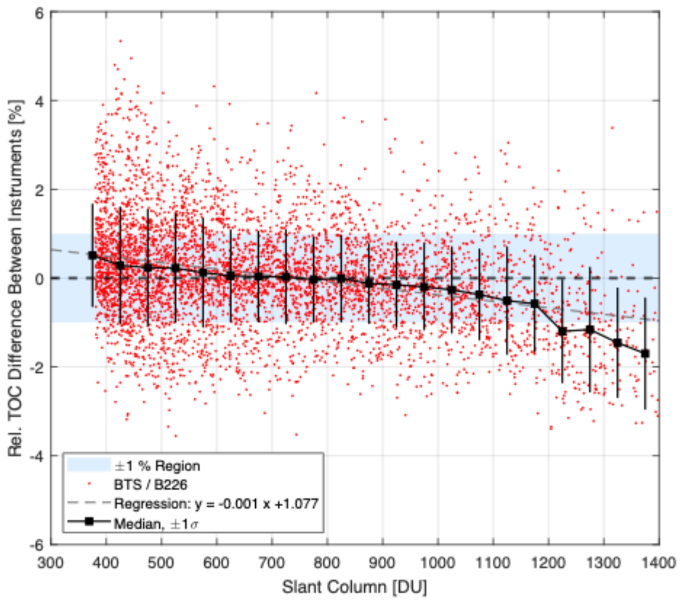


Figure 14. Relative difference between total ozone columns (TOC) measured by a modern CCD-based spectrometer (Gigahertz BTS) and the NDACC Brewer double-monochromator #226, shown as a function of slant TOC for observations at Hohenpeißenberg from November 2021 to December 2025.

Figure 15 shows profiles of water vapor from paired launches of NOAA frost point hygrometers (FPHs) using 1) dry ice and ethanol (DIA) and 2) liquid nitrogen (LN2). Although significant progress has been made transitioning away from R23, further intercomparisons with alternative cryogens are ongoing.

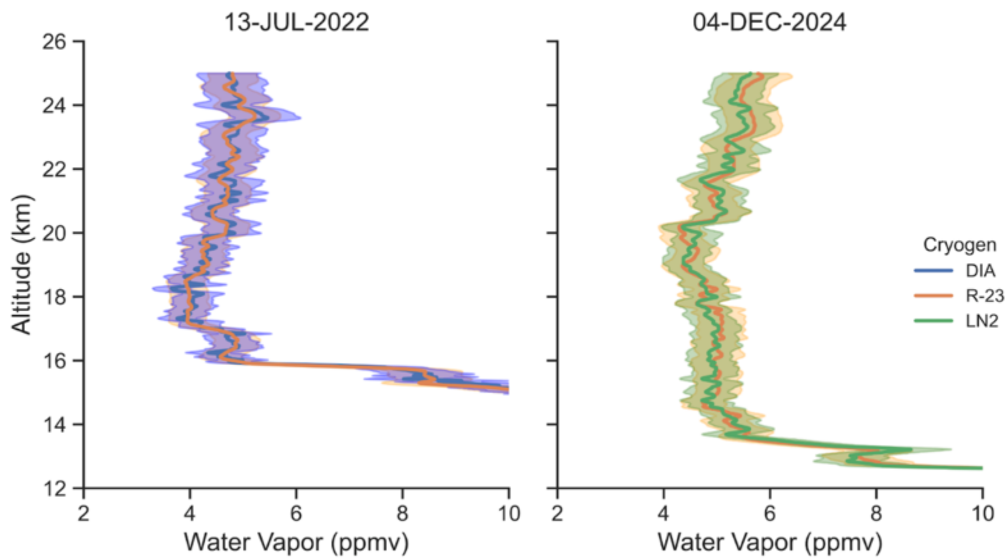


Figure 15. Near simultaneous launches from Boulder with NOAA R-23 and NOAA DIA FPHs on July 13, 2022 and with NOAA R-23 and NOAA LN2 FPHs on December 4, 2024. Shown are the 1-second gaussian filtered water vapor data products and total calculated uncertainties of each, derived using sources of error in the frost point temperature measurements and the reported uncertainty of the iMet-54 radiosonde pressure.

Many NDACC instruments come from small manufacturers with limited staff. This limitation makes it difficult to track unintentional manufacturing changes in ozonesonde production, for example, that have contributed to inconsistencies in ozone profile time series (Stauffer et al., 2022). The NDACC and WMO-sponsored Assessment of Standard Operating Procedures for Ozonesondes (ASOPOS) activity is standardizing procedures for ozonesonde operations and data processing (WMO Report 268; Smit et al. 2024) with the idea of homogenizing long-term records using an absolute ozone standard.

Recent problems with Raman lidar water vapor measurements illustrate an unusual challenge. Their data in regions affected by UT/LS biogenic aerosols from extreme wildfires (Khaykin et al., 2020a) are contaminated by aerosol fluorescence (Chouza et al., 2022). The measurements can be corrected, but with reduced signal-to-noise ratio, compromising reliable trend detection. Raman lidar observations performed at 532 nm are an alternative.

Ongoing changes in IT, lasers, spectrometric systems, components, etc., across 40 years or more is a challenge that requires expertise and costly efforts to digitize historic data and to upgrade to new systems. To guarantee trend-worthy data, parallel operation of old and new systems, sometimes over years, is essential and required by NDACC protocols. Remote access to and/or automatic operation of instruments is increasingly available. This reduces staffing requirements and cost, although in some cases internet security limits remote access.

5.1.1.2 Traceability, fiducial reference measurements, changing calibration

Validating satellite observations and numerical models has been a primary objective of NDACC since its inception. Over the past 35 years, the fleet of satellites and their validation needs have evolved significantly. NDACC data meet many of the requirements but not always all.

Challenges to the FRM process include outdated standards for uncertainty budgets, e.g., Basher (1982) for Dobsons. For Brewers, calibration relies on several entities: International Ozone Services (IOS), the RBCC-E (Regional Brewer Calibration Center - Europe), and Environment and Climate Change Canada. All three organizations participate in calibration campaigns, publishing results in WMO/GAW reports. There is a high level of agreement, typically 0.5% to 1% or better (Zhao et al., 2023), but it is time-consuming to specify data and metadata to ensure reproducible calibrations and efficient reprocessing. The methods developed for more reliable uncertainties (Redondas et al., 2024) are difficult to implement but they represent an opportunity for data format transition, e.g., from NASA Ames to GEOMS-HDF.

Spectroscopic reference databases (e.g., HITRAN used in IRWG) are typically updated every 4 years. ~~IWG tracks~~Instrument Working Groups track the effect of changes on NDACC data records to decide on whether to reprocess historical records. An example of ensuring accurate data comes from ozone absorption cross sections used to derive traceable ozone values that have changed several times over ~60 years, i.e., over the lifetime of the Dobson network. NDACC and the larger community have yet to complete the transition to new temperature-dependent cross sections (Serdyuchenko et al., 2014; Weber et al. 2016), approved a decade ago by the International Ozone Commission (Orphal et al., 2016) because implementation requires reprocessing of large archives (Voglmeier et al., 2024). NDACC and WMO/GAW are coordinating the update at the World Ozone and UV Data Center (woudc.org).

5.1.2 Programmatic and infrastructure challenge

5.1.2.1 Funding challenges

Long-term consistency and continuity are emblematic of NDACC. However, "continue to do for the next five years what was done over the last five years" is not attractive for ~~funders who~~funding organizations that are oriented toward innovation. NDACC research is heavily driven by instrument PIs and staff who need to diversify their work while also maintaining and expanding their NDACC activities. This is a challenge when funding decreases or when staff move on or retire. ~~With staff changes, institutional~~Institutional priorities may change and a research group is disbanded. NDACC is proactive in overcoming obstacles. NDACC engagement with WMO scientific advisory groups, expert teams and technical conferences, with satellite groups, and with evolving observation strategies, provides support for projects that leverage NDACC measurements as well as for helping individual stations. NDACC's letters to sponsors have prevented station closures. Instrument working group meetings promote visibility of PIs and staff to program managers. NDACC's advances in creating and promulgating standard operating procedures and processing and reprocessing software helps maintain operations as personnel and instruments change.

5.1.2.2 Enhancing network efficiency and expanding NDACC

The focus of NDACC has been on general coordination, and scientific and technical support. Central processing, or very rigid or intrusive requirements, have not been part of NDACC's strategy, although they might make some things more efficient. Over the years, instruments and operating procedures have, however, become more standardized and simpler to operate. NDACCs FTIR stations, for example, use nearly all the same instrument, as well as common traveling calibration standards and operation procedures, which allows processing and species retrieval with a common software and in a central facility for PIs interested in this option. Benefits are more cohesive network-wide data products (e.g., Hannigan et al., 2022), more timely deposits to data centers, more rapid data reprocessing, retrieval of an increased number of species with greater efficiency, and a reduced burden on station PIs.

Another aspect, also from FTIR, is extension of the very high quality but sparse NDACC network to lower quality stations to give better coverage. The standard NDACC high-resolution FTIR interferometers are expensive and require substantial expertise. As a consequence, important portions of the globe are not monitored. Lower cost, moderate spectral resolution (e.g., 2 to 4.5 cm OPD) mid-IR interferometers (Sha et al., 2020), that require little maintenance can provide a solution, especially for tropospheric species or total column abundances (e.g., Zhou et al., 2023). Hardware and software that enable autonomous operation are used. In Kolkata, India, a lower-resolution FTIR instrument provides good quality data for species like HCHO.

A "tiered system" might be considered within the NDACC once the recently developed (and future) mobile observational systems will be incorporated in the NDACC (i.e. SMOL, and compact FTIRs). The new set of requirements will be designed for the short and long-term data obtained with these instruments. Depending on the outcomes of the ongoing assessments of these mobile, more cost-effective instruments, they will be fully integrated into NDACC or integrated along the concept of tiered system. NDACC is open to partner with other networks to discuss the needs for further harmonization, integration and cost-effectiveness. Such efforts are initiated in the European CARGO-ACT project (https://www.cargo-act.eu/) in which NDACC is represented.

A world-wide homogeneity among similar instruments within, but also outside NDACC, should be a high priority, e.g., for global satellite validation and long-term variability analyses. NDACC's ozonesonde community, for example, seeks to increase collaboration with China (e.g., Beijing and Hong Kong) and India (e.g., Pune and Trivandrum), stations that collect a significant number of profiles. However, they use ozonesonde models for which instrumental errors are not fully characterized, e.g. at the World Calibration Centre for Ozone Sondes in Jülich, Germany.

More challenging is a lack of homogeneity among different instrument types or networks, e.g., for column NO_2, O_3 and HCHO data from NDACC DOAS UV-visible instruments, NDACC FTIRs, and the PGN (Pinardi et al.,2025) or for CH_4, N_2O and CO column data from NDACC FTIR and TCCON (e.g., Zhou et al., 2018; 2019).

Easy access to data remains a challenge. The NDACC Data Handling Facility provides access to all NDACC measurements, but formats and versions change over time, and the granularity of data packaging is not always user-friendly. Data archived in multiple centers, in various formats, and with various overlaps among the centers are difficult to use. Examples include ozonesonde data, archived in eight archives (NDACC, WOUDC, SHADOZ, NOAA, EVDC, AVDC, HEGIFTOM, CDS) in different data formats. This leads not only to inconsistencies in data and metadata stored across archives, but also between stations in one archive, and even in the data record of one given site. It is expected that transition to unified metadata and data formats, e.g., GEOMS-HDF, will facilitate better coordination among archives. The goal is always to provide simple, friendly access to users, incorporating FAIR principles.

5.2 Scientific opportunities and technical challenges

Challenges and unexpected findings represent new opportunities for NDACC as the following examples illustrate.

5.2.1 Ozone recovery and climate change

Mandates based on the Vienna Convention for the Protection of the Ozone Layer and the associated Montreal Protocol provided the scientific motivation for NDSC in the early 1990s. Following the success of the Montreal Protocol and its subsequent amendments (WMO, 2014), there is a common perception that stratospheric ozone depletion is a "solved problem". However, ozone depletion is still substantial and ozone layer recovery is more complex than a decade ago (WMO, 2022), partially due to unexpected increases in very short-lived ODSs into the UT/LS from Asian emissions (e.g., Adcock et al, 2021, Lauther et al., 2022, Pan et al, ~~2024~~2022). These species are only tracked from NDACC ground-based instruments. The need for these data is greater than ever.

Related to the need to maintain ODS monitoring for ozone recovery is the impending loss of the MLS water vapor and ClO coverage as well as reduced viewing of Arctic ozone depletion events, volcanic and/or wildfire injections of material into the stratosphere. Springtime stratospheric ozone depletion in polar regions continues to be highly variable year to year (e.g., Manney et al., 2020; Bognar et al., 2021; Pazmino et al., 2023; Shi et al., 2023), making long-term NDACC measurements of ozone-related species important for tracking future changes.

5.2.2 Unexpected events

Unexpected events, such as recent extreme wildfires (Khaykin et al., 2020a; John et al. 2021; Wizenberg et al. 2023; Tickl et al., ~~2924~~2024, Flood et al., ~~2925~~2025, Khaykin et al. 2025) and or the Hunga volcanic eruption (Nedoluha et al., 2023) sharply modified stratospheric composition and perturbed predictions of future stratospheric composition (Strahan et al., 2022; Solomon et al., 2023). Modeling is required to assess impacts of potential injected sulfate particles to the stratosphere, an action designed to counteract global warming. Ongoing climate change has modified the trajectory of ozone recovery (WMO, 2022). Whereas anthropogenic ODS defined NDACC's original measurement portfolio, increasing emissions of GHGs like CO_2, CH_4 and N_2O are re-defining some NDACC priorities. Also relevant are changes in air quality, atmospheric aerosol loading, and cloud cover, for example, affecting surface UV (Cordero et al., 2014; Cordero et al., 2023). Extreme UV events still occur from Antarctic ozone loss, e.g. over Patagonia and the Antarctic peninsula (de Laat et al., 2010; Cordero et al., 2022).

5.2.3 Candidates for expanding NDACC measurements

Generally, as some satellite capabilities decrease and others emerge, NDACC's ground-based measurements remain vital. Examples of expansion opportunities follow.

5.2.3.1 More species from FTIR

NDACC FTIRs at nearly two dozen stations provide clear-sky high-resolution solar absorption measurements for 13 key air quality, ozone, ozone precursors, and greenhouse gases. A strategic aim is to expand this list to more constituents important in climate change, global pollution, and ozone depletion. Potential molecules, already retrieved and archived on the DHF for some FTIR sites, include ammonia (NH_3), ethylene (C_2H_4), methanol (CH_3OH), peroxy-acetyl nitrate (PAN), and hydrofluorocarbons (HFCs) that are regulated by the 2016 Kigali Amendment of the Montreal Protocol. Retrieval of the two most abundant HFCs, HFC-134a and HFC-23, has been demonstrated at a few NDACC stations (Pardo Cantos et al., 2024).

5.2.3.2 Wind

Wind data are vital for weather forecasting and for understanding global circulation, but upper air wind data are scarce. For a short period, the space-based AEOLUS lidar provided global upper atmospheric wind data, greatly improving weather forecasts (Rennie et al. 2021; Garret et al., 2022). Ground-based wind-lidars, a recent NDACC addition (Khaykin et al., 2020b), were instrumental in validating AEOLUS (Ratynski et al., 2023). Microwave radiometers also measure upper atmospheric winds (Hagen et al., 2018). A network of ground-based wind instruments could also validate a space-based wind lidar.

5.2.3.3 Water vapor

Water vapor, the most important greenhouse gas, affects radiation and dynamics, cloud formation and atmospheric chemistry. Climate models show a substantial moist bias in the lowermost stratosphere (Stenke et al, 2007; Charlesworth et al, 2023), a sensitive climate-feedback region. NDACC profiles of water vapor are essential for improving models. NDACC measures high resolution water vapor profiles with balloon-borne FPH and water vapor Raman lidars in the troposphere and (lower) stratosphere (Vömel et al., 2016; Hall et al., 2016; Leblanc et al., 2012; Hicks-Jalali, 2020), as well as coarse resolution profiles in the (upper) stratosphere and mesosphere with microwave radiometers (Nedoluha et al., 2021; 2023). Water vapor measurements for stratospheric needs are usually adequate with monthly or bi-weekly observations.

Natural stratospheric water vapor sources, i.e., CH_4 and H_2 oxidation, may be augmented by overshooting convection and subtropical monsoonal circulations. Looking ahead, NDACC has created a water vapor strategy: (https://ndacc.org under sites/default/files/2024-01/NDACC_WaterVaporStrategy_20220119.pdf).

5.2.3.4 Aerosols and climate interventions

The stratospheric aerosol layer impacts radiation and chemistry, but stratospheric aerosol is variable, routinely perturbed by small and moderate volcanic eruptions and increasingly by large wildfires (Solomon et al., 2022; Solomon et al, 2023; Peterson et al., ~~2021~~2022). Typical stratospheric aerosol, concentrated between the tropopause and 25 km, is composed of sulfuric acid particles from SO_2 and OCS oxidation, mixed organic sulfate particles that enter from the troposphere, and meteoric particles (Murphy et al., 1998, 2014). Particles from rocket emissions (Katich et al., 2022) and satellite re-entry (Murphy et al., 2023) are likely to increase in the coming decades. The Asian Tropopause Aerosol Layer (Vernier et al., 2011), occurring during boreal summer, contributes up to 15% of Northern Hemisphere aerosol (Yu et al., 2017). Recent NDACC aerosol measurements show that the Asian summer monsoon is a weak but a measurable source of ~~Arctic~~ stratospheric aerosol even in the Arctic from late summer to early autumn (Graßl et al., 2024). Routine measurements of stratospheric aerosol, a key capability of NDACC, are essential, particularly if climate intervention leads to enhanced particle injections (Asher et al., 2023) and large wildfires (Asher et al., 2024). Because size distributions are not directly observable from space, measurements of particle composition are frequently carried out during aircraft campaigns. NDACC proposes to add routine balloon-borne measurements of aerosol size distributions with optical particle spectrometers, e.g., the Portable Optical Particle Spectrometer (POPS; Todt et al., 2023) in the next 3-5 years.

6 Outlook

This article has reviewed the fundamentals of NDACC, its rationale, mission and the success of the highest quality instruments in monitoring atmospheric composition and contributing to major assessments. NDACC's Working Groups have been exemplary in promulgating standards and best practices. Similar approaches have been employed by NDACC's 10 Cooperating Networks. NDACC has been active in research and scientific service programs, especially within the European Union and North America, and within international satellite projects where its data are essential to algorithm and model development and validation. NDACC is operating within the framework of the latest developments in data distribution and management practices.

NDACC's impact on solving major problems in atmospheric composition and climate has been highlighted. For example, long-term monitoring has been foundational in tracking the health of the stratospheric ozone layer and more recently, the evolution of air quality and climate pollutants. Exceptional events, such as volcanic eruptions, are captured with NDACC observations, which can measure impacts on a scale too small for satellites. With a decreasing satellite constellation for stratospheric composition, the need for NDACC observations could not be greater. NDACC is at a crossroads as resource pressures on ground-based monitoring programs increase. With data archiving and distribution activities diverting resources from data collection in some networks, strategic planning is essential to strengthen NDACC and its Cooperating Networks.

Based on specific recommendations in prior sections, NDACC is well-positioned to adopt a three-pronged strategy: protect existing stations and data streams; promote greater usage of NDACC data; and expand NDACC's coverage geographically and in species-parameter space.

Protect Existing Stations and Data streams. As described above, current NDACC observing infrastructure and resources (instruments, data, and people) must be sustained. With many stations operating for three to four decades, their records are increasingly indispensable as the value of a dataset increases with its longevity. NDACC and cooperating partners are actively engaging a younger generation of scientists and technical professionals, with a specific focus on expanding representations from underrepresented areas. The goal is to evolve infrastructure so that expertise and projects are transferred, that capacity is built, and that innovative ideas and insights emerge. An important element of this effort is the ongoing development of more cost-effective and automated instruments, with centralized data acquisition and processing. Adding new observations at existing stations, leveraging infrastructure and personnel, is another approach to strengthening the networks.

Promote Greater Usage of NDACC Data: It is important to advertise and promote the usage of the NDACC data with network stakeholders and throughout the global scientific community. Due to its roots in stratospheric ozone research, including development and validation of satellite products, there is a dedicated data user group worldwide that extends to atmospheric dynamics and air quality. NDACC is currently extending data impact through cross-disciplinary initiatives in climate and carbon cycle research, climate intervention, etc. The efforts of NDACC and cooperating networks to distribute data more rapidly and more ~~accessibly~~accessible, conforming to the latest data practices (e.g., FAIR), are widening impact even more, as are data sharing initiatives with WMO and other organizations. The CAMS assimilation system that relies on NDACC observations as an independent reference is another sign of network impact.

The TOAR II HEGIFTOM activity, with data reprocessing from four NDACC instrument types, marks a major milestone. The HEGIFTOM ~~archive, which will be entirely harboured on~~homogenized dataset is moved to the NDACC DHF and other historical archives, and is now a gold standard, supplying reference data for evaluation of satellite products and global model output. More active collaboration with satellite and modeling communities will further promote applications of NDACC data.

Expand NDACC's coverage in two ways:

Geographical Coverage. NDACC's coverage is still poor in Africa, Asia, South America and the Mediterranean region, partly due to shortage of resources for equipment and of skilled personnel or expertise. In other cases, high-quality data are collected but they are not shared. The latter situation is expected to improve over time as more journals publish links to data archives. NDACC needs to engage with organizations that have infrastructure and expertise. An NDACC affiliation is a path to greater visibility and access to unique expertise and support.

Collaborations within Cooperating Networks, WMO/GAW, and other agencies can be leveraged to augment NDACC stations. Finding a means of incorporating data from environmental and air quality agencies is an approach to consider. ~~Note the success of the TOAR tropospheric ozone archive.~~ A compelling rationale for expanding NDACC to more urban stations is that researchers evaluating satellite products for air quality and emissions estimates are a growing user community for our data.

Coverage of Species and Parameters (Variables Space). NDACC needs to add measurements of species that are coming to greater prominence~~,~~ or that may not have existed or been measurable decades ago. Selection criteria must include the added-value and complementarity with existing observations at a given station. NDACC instrument working groups, laboratory spectroscopists, and instrument developers can support this work. With the advent of constellations of nadir-looking satellites focusing on air quality pollutants and greenhouse gas observations, including those from geostationary platforms, and the NRT assimilation of their data in forecast systems, we must ensure that observations are carried out and assimilated as continuously as possible. The increasing automation and rapid distribution capacity of NDACC observations is a must for these operations. NDACC is ready to face its future evolution and is confident that the network will maintain and even strengthen its relevance provided that the required resources can be leveraged.

NDACC has faced, and will continue to face, challenges. However, the combined experience and substantial know-how of NDACC's PIs, instrument working groups, and its associated networks should overcome these challenges, develop new opportunities, and secure the continuation of the 35+ years of high-quality, long-term measurements that NDACC is known for. Ground-based data remain irreplaceable for documenting key aspects of atmospheric composition in a warming troposphere and a cooling stratosphere.

Appendix A. NDACC Organizational structure.

Figure A1. Organizational structure of NDACC.

Appendix B. Spectral Range of NDACC observations.

Table B1. Definition of Solar spectral range used in the NDACC observations. See full instrument description at https://ndacc.larc.nasa.gov/instruments.

Name & Spectral Range	Working Group & *Cooperating Network*	Instrumentation
UV (Ultra-Violet) 200 - 400 nm VIS (Visible) 400 - 700 nm	Brewer, Dobson, UV Spectroradiometer, UV/Vis Spectrometer *AERONET, BSRN, EuBrewNet, MPLNet, PGN, TOLNet*	Dobson, Brewer, SAOZ, MAX-DOAS, SUV-100, SUV-150B, JYHD10, Bentham (DTM300, DTMc300, DTM300V, DM150), UV (5, 6, 7), Lidar (DIAL, Rayleigh, Raman)
NIR (Near IR) ~700 nm - 2 µm	*COCCON, TCCON, AERONET*	Bruker 120HR, Bruker EM-27
MIR (Middle Infra-Red) ~2.0 - 14.3 µm	IRWG	Bruker (120, 120M, 125M, 120HR, 125HR), JPL MkIV, Bomem (DA2, DA3, DA8), EOCOM, McMath FTS

MW (Microwave) 13.47 mm - 1.08 mm	MWWG	MIAWARA, MIAWARA-C, GROMOS, GROMOS-C, SOMORA, WIRA, WIRA-C

Appendix C. List of satellite validation work and collaborative effort.

Table C1. recent and current satellite missions for which NDACC provides validation data and / or collaboration effort. Sect. 3.4 gives more details on present and upcoming missions.

Satellite / Sensor	Product	NDACC Group	Reference paper
SAGE III / ISS	H_2O	Lidar, ~~O3sonde~~Ozonesonde	Davis et al., 2021 Wang et al., 2020
	O_3	Lidar, ~~O3sonde~~Ozonesonde	Johnson et al., 2024, Mettig et al., 2022, Mettig et al., 2021
Terra/MOPITT	CO	IRWG	~~-~~Gaubert et. al., 2023, 2024 ; Lutsch et. al., 2022 ; Buchholz et. al., 2017 ; Jalali et al., 2022
TEMPO	HCHO	IRWG~~, UV-VIS~~	~~Souri~~ Ortega et al~~., 2023~~ (Accepted to ESS)
	O_3	Lidar	Johnson et al., 2018
TEMPO+GEMS	O_3 (tot)	Brewer/Dobson	Zhao et al., 2025
GEMS	HCHO	IRWG, UV-VIS	Lee et al., 2024
NPP/CrIS	CH_3OH, C_2H_2, C_2H_4, C_5H_8, HCN	IRWG	Wells et al., 2022, Wells et al., 2024, Brewer et al., 2024 Wells et al. 2024
IASI	N_2O	IRWG	Barrret et al., 2021 Vandenbussche et. al., 2022
	CO	IRWG	Langerock et al., 2023
	HNO_3	IRWG	Langerock et al., 2023
	CH_4	IRWG	Dils et al., 2024
	PAN	IRWG	Mahieu et al., 2021; Wizenberg et al., 2022; Wizenberg et al., 2023
	HCOOH	IRWG	Franco et al., 2020; Franco et al., 2021
	H_2CO	IRWG	Kwon et al., 2023
Aura/MLS	T	Lidar; MWG	Chen et al., 2023; Navas-Guzman et al, 2017
	O_3	MWG	Maillard Barras et al, 2020; Sauvageat et al, 2022
	ClO	MWG	Nedoluha et al., 2025
	H_2O	MWG	Nedoluha et al., 2022; Bell et al, 2025

		SWG, MWG	Livesey et al., 2021
SCISAT/ACE	N_2O	IRWG	Minganti et al, 2022
	inorganic fluorine	IRWG	Prignon et al., 2021
AURA /OMI	O_3	SWG	Huang et al., 2017, Bak et al., 2024
	NO2	IRWG, UV-VIS	Souri et al., 2023
	HCHO	RWGI, UV-VIS	De Smedt et al. (2021); Ayazpour et al., 2025; Müller et al., 2024; Souri et al., 2023
SAGE III/ISS	O_3, WV	Lidar, O3sonde	Wang et al., 2020
	Aerosol	Lidar	Knepp et al., 2020
	H_2O	SWG	Davis et al., 2021
GOME-2	OClO	UV-VIS	Pinardi et al., 2022
FengYun-3E/HIRAS-II	CO, HCOOH, PAN	IRWG	Hua et al., 2025
Copernicus S5P	H_2CO	IRWG, UV-VIS	De Smedt et al. (2021), Oomen et al., 2024, Müller et al., 2024, Vigouroux et al.2020
	CH_4	IRWG	Sha et al (2020)
	O_3	IRWG, SWG	Keppens et al., 2024
	NO_2	UV-VIS	Verhoelst et al., 2021
GOSAT/TIR	CH4	IRWG	Olsen et al, 2017

Data Availability

The NDACC data used in this paper are archived at the Data Host Facility (DHF) that is hosted at NASA Langley Research Center (LaRC). DHF is serving as a central archive and access point for atmospheric data, offering tools for scientists to query and download datasets related to ozone, aerosols, and other atmospheric components: https://www-air.larc.nasa.gov/missions/ndacc/

Author contributions

MD, JCL, IP and JW conceptualized the paper. IP, MD, JW, AT, HS, JWH, RH, WS and JCL led the paper preparation. All authors contributed to the writing of the paper and/or provided figures either from their published papers or updated published figures.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Disclaimer

The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce.

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