Canadian National Report
for the 12h WMO/UNEP Ozone Research Managers Meeting
Geneva, 24-26 April 2024

1. OBSERVATIONAL ACTIVITIES

1.1 Column measurements of ozone and other gases/variables relevant to ozone loss

1.1.1 Canadian Brewer Spectrophotometer Network

Environment and Climate Change Canada (ECCC) continues to operate the Canadian Brewer Spectrophotometer Network at eight main observing sites, monitoring total column ozone and spectral ultraviolet (UV) radiation. Each of the network's mid-latitude stations (Saturna Island, British Columbia; Stony Plain, Alberta; Churchill, Manitoba; Toronto, Ontario; and Goose Bay, and Newfoundland and Labrador) operates two Brewer spectrophotometers, and each Arctic station (Resolute, Eureka and Alert in Nunavut) has three instruments on-site. Since the 1990s, ECCC has been replacing the single monochromator spectrophotometers with double monochromator instruments through network lifecycle management. Currently, one double monochromator Brewer spectrophotometer is operating per station. All Canadian stations have been visited for service, upgrade, and calibration in the fiscal years 2020-2024 with the aim of meeting a two-year cycle maintenance target where possible while considering pandemic travel restrictions. Two double Mark III Brewer instruments were acquired as part of lifecycle management of which one has been deployed (#246) at Alert and the other (#254) at Toronto.

ECCC continues its collaboration with the U.S. National Oceanic and Atmospheric Administration (NOAA), maintaining two Brewer spectrophotometers (one single and one double) at the Mauna Loa Observatory (MLO) in Hawaii and one Brewer instrument at the South Pole Observatory (SPO) in the Antarctic. The two instruments' measurements at MLO were stopped for several months due to the 2022 Mauna Loa volcanic eruption (November 27, 2022 – December 10, 2022). NOAA restarted the Brewer measurements in summer 2023 using off-grid power, but with limited time of NOAA staff's weekly visits and no internet access currently, ECCC has not had the opportunity to assess these instruments' performance. For SPO, there is a continuous record since 2008. The initial instrument (Brewer #085) was at the station between 2008 and 2015 before being replaced with Brewer #021. The current instrument at SPO is Brewer #111 and has been in operation since December 2023. Both Brewers #021 and #111 were operated in parallel for about one month to ensure equivalence prior to Brewer #021 being shipped back to Toronto.

Total column ozone and UV data from the Canadian Brewer Spectrophotometer Network are available at the World Meteorological Organization (WMO) World Ozone and Ultraviolet Radiation Data Centre (WOUDC - World Ozone and Ultraviolet Radiation Data Centre).

1.1.2 Pandora measurement program

Since its operations in 2013, ECCC's Canadian Pandora measurement program focuses primarily on long-term monitoring of air quality and atmospheric composition using Pandora spectral sunphotometers. It has twelve Pandora instruments that measure nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and formaldehyde (HCHO) as well as produce high quality total column ozone data.

ECCC is a research partner to the joint National Aeronautics and Space Administration (NASA)- European Space Agency (ESA) Pandonia Global Network (Pandonia Global Network – Reference Measurements of Atmospheric Composition (pandonia-global-network.org).

ECCC has Pandora instruments operating at seven monitoring sites across Canada (four sites in the Greater Toronto Area; one each in Egbert and Windsor, Ontario; and one in Stony Plain, Alberta). In addition, ECCC deployed a Pandora instrument at Eureka, Nunavut as part of the 2019 Canadian Arctic Atmospheric Chemistry Experiment (ACE) / Optical Spectrograph and InfraRed Imager System (OSIRIS) validation campaign and participated in the next four campaigns (2020-2023). The motivations included investigating tropospheric ozone depletion events and testing Pandora instrument's ability to make observations in the polar region. Total column ozone and other atmospheric composition data (NO_2, HCHO, and H_2O) from ECCC's Canadian Pandora measurement program can be accessed via the Pandonia Global Network (PGN) (https://data.pandonia-global-network.org/).

Comparison of the Pandora spectrometer with the World Brewer reference in Toronto showed that the Pandora instrument's accuracy and precision of total ozone column measurements are comparable with those for the Brewer instrument (Zhao et al. 2016). The Pandora instrument's precision is similar or even better than that for the Brewer instrument; however, there is a large dependence on stratospheric temperature for which has to be accounted. In 2022, a PGN Pandora ozone product was developed, which directly retrieves effective temperature of ozone and shows promising results (not published), but still needs further validation and verification.

1.1.3 University of Toronto Atmospheric Observatory and Polar Environment Atmospheric Research Laboratory

University-based measurements of column ozone are made at the University of Toronto Atmospheric Observatory (TAO) and the Polar Environment Atmospheric Research Laboratory (PEARL) by instruments affiliated with the Network of the Detection of Atmospheric Composition Change (NDACC).

At TAO, column ozone is measured by a Fourier transform infrared (FTIR) spectrometer. At PEARL, column ozone is measured by an FTIR spectrometer and two UV-visible grating spectrometers, and by ECCC's Brewer and Pandora spectrometers. Ozone profiles are measured by the Differential Absorption Lidar (DIAL) at PEARL.

Since the end of March 2020, operations and measurements at PEARL have been affected by the COVID-19 pandemic and associated travel restrictions, lack of funding, and the condition of the road to the Ridge Lab, where most of the PEARL ozone-measuring instruments are located. PEARL will be closing if new long-term funding is not secured in 2024.

More details are provided in Section 2 below.

1.2 Profile measurements of ozone and other gases/variables relevant to ozone loss

1.2.1 Canadian Ozonesonde Network

ECCC continues to operate the Canadian Ozonesonde Network at eight main observing sites, making measurements of vertical ozone profiles. Electrochemical concentration cell ozonesondes are launched on a weekly basis across Canada at five mid-latitude sites (Port Hardy, British Columbia; Stony Plain, Alberta; Churchill, Manitoba; Goose Bay, Newfoundland and Labrador; and Yarmouth, Nova Scotia) and three Arctic sites (Resolute, Eureka and Alert in Nunavut). All ozonesonde sites in the network are co-located with the stations of the Canadian Upper Air Observing program where ozonesondes are flown coupled to radiosondes. The Canadian Upper Air Observing program changed to a new supplier of ground systems and radiosondes and consequently ozonesonde interface cards in 2022. In addition, there was a switch in manufacturer for electrochemical concentration cell ozonesondes in 2021, from En-Sci to Science Pump Corporation.

A small number of higher frequency launches were carried out at the Arctic stations during the 2022 Match campaign in collaboration with the Alfred Wagner Institute in Bremerhaven, Germany and at Eureka during the polar sunrise period for the Canadian Arctic ACE/OSRIS validation campaigns (2020 – 2023). All Canadian ozonesonde data are archived in the WMO WOUDC - World Ozone and Ultraviolet Radiation Data Centre.

1.2.2 Canadian satellite data

The Canadian Space Agency (CSA)'s SCISAT satellite and the Canadian OSIRIS instrument onboard the Swedish Odin satellite continue their operations of measuring atmospheric trace gases globally with no major changes to observational parameters. All instruments continue to function nominally with only minor degradation in performance which does not limit continued operations. The SCISAT satellite has two instruments: the infrared ACE-Fourier Transform Spectrometer (FTS) that measures atmospheric profiles of nearly 70 different species and isotopologues, and the MAESTRO instrument focusing in the visible-near infrared to measure profiles of ozone, water vapour, and NO_2. Vertical resolution of ACE-FTS is ~3km (from field of view) and of MAESTRO is ~1.5km. SCISAT/ACE remains in a highly inclined orbit initially chosen to meet the measurement requirements to advance polar ozone chemistry. Mission objectives are reviewed on a regular basis to respond to emerging needs, with data now contributing to studies related to ozone recovery, state of the Earth's climate, and air quality. SCISAT celebrated its 20th anniversary in August 2023 and continuing operations are now funded out to March 2026.

Five mission dataset versions have been released over 20 years of SCISAT data production algorithm development. They illustrate the continuous improvement in data quality complemented by an increasing number of new gases. The mission began with a first release of 18 molecules and over the years has grown to almost 70 species and isotopologues, including ozone depleting substances (ODSs), hydrofluorocarbons (HFCs), air quality gases, and all major greenhouse gases (GHGs). In the most recent v5 release in 2023, HOCl and HFC-32, along with line-of-sight winds have been added as new data products. The v5 raises the upper altitude limits for SO_2 (from 24km to 40km) and ClO (from 30km to 40km), updates the spectroscopy to the most recent information, implements improvements in atmospheric transmittances, and models the contribution of the ACE-FTS field of view in the analysis. The previous v4 data release included the addition of HFC-23, HFC-134a, ClO, CH_3CN, as well as CO_2 below 18km, all as new data products which are maintained in v5.

The Swedish Odin satellite continues to operate with two instruments, one of which is Canada's OSIRIS. The instrument continues to measure ozone, NO_2 and aerosol extinction with a ~2km vertical resolution and good accuracy, and long-term stability of altitude registration over its vertical range of 7-90km. The satellite remains in a sun-synchronous, circular orbit at an inclination of 97.8° to advance mid-atmospheric science. Mission objectives are also reviewed on a regular basis and now include trend analysis of ozone, aerosol, and air quality. OSIRIS on Odin celebrated its 20th anniversary in February 2021 and continuing operations are funded out to March 2025.

OSIRIS mission dataset versions have been regularly released over the past 23 years. The v7.3 Level 2 dataset now comprises aerosols, ozone, NO_2 and a new stratospheric temperature data product. All have been processed through to December 2023. These dataset versions illustrate continuous improvement in data quality complemented by contributions to multiple merged space-based datasets for global trend analysis. The v7.3 dataset has been integrated into the Level 3 merged data products for ozone known as (1) SAGEII / OSIRIS / SAGEIII/ISS (SOS) which includes the v5.3 SAGEIII/ISS dataset and (2) the SAGEII / OSIRIS / OMPS-LP (SOO) which includes the v.1.3.0 OMPS-LP tomographic ozone data product.

OSIRIS ozone profile data also continues to be merged with six other space-based instrument datasets which are known as the UN/SPARC Long-term Ozone Trend and Uncertainties in the Stratosphere (LOTUS) initiative. The OSIRIS time series is the longest currently active set of ozone measurements spanning over two decades and used to extensively bridge

measurement gaps from original to existing occultation instruments. These merged LOTUS project datasets have been included in the 2022/23 UN/WMO Ozone Assessment Executive Summary and Full Report to monitor global ozone profile trends throughout the atmosphere. OSIRIS also contributes its ozone data record to the MErged GRIdded Dataset of Ozone Profiles (MEGRIDOP) dataset. Finally, the aerosol data product from OSIRIS is also merged with data from six other satellite instruments to create the Global Space-based Stratospheric Aerosol Climatology (GloSSAC), a 40+ year continuous data record of stratospheric aerosol in support of CMIP6 efforts.

1.3 UV measurements

1.3.1 Broadband measurements and narrowband filter instruments

Although ECCC does not make broadband observations, there is the collaboration with the United States Department of Agriculture (USDA)'s UV-B Monitoring and Research Program (UVMRP). As part of their measurement program, the UVMRP obtains erythemal-weighted UV-B irradiance using a Yankee Environmental Systems UVB-1 pyranometer. The UV-B instrument is co-located with the Canadian Brewer spectrophotometers at the monitoring site in Toronto. Further information on UVMRP can be found at USDA UV-B Monitoring and Research Program – a program measuring Ultraviolet Radiation and studying its effects on agriculture and the atmosphere (colostate.edu).

1.3.2 Spectroradiometers

The Canadian Brewer Spectrophotometer Network also makes observations of spectral UV-irradiance at all eight sites. The sites are equipped with double Brewer spectrophotometers that measure UV in the 286-363 nm spectral range. Approximately five UV spectra are obtained each hour. Collected data are used for UV index forecast validation purposes. UV spectral data are available in the WMO WOUDC.

1.4 Measurements of substances controlled under the Montreal Protocol

1.4.1 Flask measurements

ECCC continues to collect samples at Alert in Nunavut for NOAA's Halocarbons & other Atmospheric Trace Species flask sampling program. ECCC also continues to help in the coordination of NOAA's Global Greenhouse Gas Reference Network's aircraft program for two western sites in Canada. For both programs, samples collected are analyzed for a multitude of trace gas species including chlorofluorocarbons, hydrofluorocarbons, and other halogenated trace gases.

1.4.2 Satellite measurements

SCISAT is the only remote sensing satellite to monitor trends of nine long-lived halogenated source gases in the upper troposphere, tropospheric and stratospheric fluorine changes, and stratospheric chlorine changes. These gases include ODSs (CFCs, HFCFs and CCl_4), HFCs controlled under the Montreal Protocol and GHGs (CF_4 and SF_6) covered by Canada's Nationally Determined Contributions (NDCs) under the Paris Climate Agreement. SCISAT global measurements together with more limited global coverage ground-based measurements, show decreasing trends for some of the gases, demonstrating the effectiveness of the Montreal Protocol controls. However, trends of the two GHGs (CF_4 and SF_6) in Canada's NDC continue to increase and trends of very-short lived substances (VSLSs), inferred using HCl and $COCl_2$ data from SCISAT, also continue to increase. VSLSs can contribute to ozone destruction when transported to the stratosphere but are not yet controlled

under the Montreal Protocol. SCISAT can continue to provide long-term trends as input for potential future controls.

Hydrofluorocarbons (HFCs) do not contain ozone-depleting chlorine or bromine; however, they are now controlled through the Kigali Amendment to the Montreal Protocol. SCISAT remains the only space-based instrument to produce 20-year data records of multiple HFCs. HFC measurements from SCISAT were reported in the 2022 Scientific Assessment of Ozone Depletion and compared with NOAA ground-based measurements and model results to illustrate the increasing trends of HFC-134a and HFC-23. With the increasing trends of most HFCs, continuous monitoring of these gases is necessary to assess compliance to the Montreal Protocol and to ensure that the estimated reduction in warming is realized.

In summary, SCISAT continues to monitor the following substances relevant to substances controlled under the Montreal Protocol: (a) CFCs (three of the six major CFCs and all of those with mole fraction > 20 ppt); (b) HCFCs (three out of the six major HCFC's, and all of those with mole fraction > 10 ppt); (c) HFCs (three out of the 11 major HFCs, and three out of five with mole fraction > 10 ppt); and (d) one PFC (one of the four major PFC's, and all with mole fraction > 10 ppt).

1.5 Calibration activities

1.5.1 World Brewer Triad

As the WMO/Global Atmosphere Watch (GAW) Brewer Central Calibration Laboratory, ECCC operates and maintains the world reference standard for Brewer instruments of total column ozone, known as the World Brewer Triad. In addition, ECCC has been hosting the WMO/GAW Brewer World Calibration Centre (WCC) since the 1980s to provide transferable calibration to field instruments at monitoring sites globally. Initially, the World Brewer Triad consists of single monochromator Brewer spectrophotometers (#008, #014 and #015). In 2013, more accurate double monochromator Brewer world reference triad (#145, #187 and #191) was formed to replace the original single Brewer triad. In 2019, an updated assessment of the single triad's performance was carried out along with the first assessment of double triad (Zhao et al.,2021). The findings are: Good long-term stability of the world reference instruments; and both the single and double triads met the WMO requirement of better than 1% precision [0.49% and 0.42% for single triad and double triad, respectively]. After the assessment, the performances of the single and double triads continued to be carefully monitored with ECCC preparing internal annual assessment reports. The reports include detailed maintenance and calibration activities conducted for the world reference instruments, and the findings of their performance from analyses using statistic models and reanalysis data. These internal reports ensure that the status of the world reference instruments is recorded in detail.

ECCC, World reference Brewer #145, participated in the XVII Intercomparison Campaign of the Regional Brewer Calibration Center-Europe that was hosted by Physical Meteorological Observatory in Davos and World Radiation Center (PMOD-WRC) between Aug 22 to September 1, 2022, at Davos, Switzerland. Results are under review.

Due to the Mauna Loa volcano eruption in late November 2022, instead of calibration at the Mauna Loa Observatory (MLO), Brewer #187 received its absolute calibration at the State Meteorological Agency of Spain (AEMET)'s Izana Observatory (IZO) in Tenerife, Spain during August 2023. The preliminary comparison between the World and European regional reference Brewer instruments shows good consistency. Brewer #187 has been independently calibrated by the ECCC and AEMET teams and its calibration factor was determined to be within requirements (ETC differences within +/-5 R6 unit). The next calibration of triad instruments will be carried out in the summer/fall 2024 and the location depends on whether MLO is accessible.

1.5.2 Brewer calibration site conditions

A research study was conducted to understand the factors that influence Brewer absolute calibration quality at different sites (Zhao et al., 2023). It looked at observations that cover 10 years from 11 Brewer instruments located at four different sites (including MLO, Izana, Toronto, and Davos). Using the MERRA-2 reanalysis data, a new model was developed and validated to provide estimates on Brewer absolute calibration requirements for different sites. The work shows MLO and IZO have the optimum conditions for Brewer absolute calibration, benefiting from these sites' low total ozone variability on a day-to-day basis. For other mid-latitude sites, much longer periods will be needed to achieve similar or comparable results as from these optimum sites. Based on the analyses, recommendations, and requirements (e.g., minimum number of days for the calibration) for Brewer absolute calibration were provided.

1.5.3. Brewer travelling standard

ECCC's Brewer travelling standard #017 has been in service to transfer Brewer calibrations from the world reference standard to field instruments worldwide since 1990s and assures the high-quality column ozone observations from the WMO global ozone monitoring network. In 2020, ECCC performed an assessment on the performance of Brewer #017, in terms of comparison with the Brewer world reference standard (both the single and double triads) and co-located Pandora spectrometers. It was found that Brewer #017's performance from 2010 to 2019 met the WMO/GAW ozone monitoring requirements with a better than 1% agreement with the world reference standard. More detailed analysis on the travelling standard has been planned, which will be published as a science paper.

1.5.4 SCISAT

SCISAT continues to capture a solar spectrum as part of each observation to calibrate individual atmospheric profiles. A reference Solar Atlas is provided to the public on the SCISAT/ACE website (also in Bernath et al. JQSRT 111, 521 (2010)). This long-term reference spectrum continues to find usefulness for calibration of atmospheric composition in other planets and biosignatures in exoplanets.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

2.1 Total ozone variability and trends over the South Pole during the wintertime

Since 2008, ECCC has operated a Brewer instrument at the NOAA South Pole Observatory. In a joint study with NOAA, Dobson and Brewer ozone measurements as well as reanalysis data were used to study long-term trends over the South Pole during the wintertime (Fioletov et al., 2023). It was shown that the recent wintertime ozone values over the South Pole were about 12 % below the pre-1980s level, i.e., the decline there was nearly twice as large as that over southern midlatitudes. Thus, wintertime ozone at the South Pole can be used as an indicator of the ozone layer state.

2.2 Ozonesonde records

The Assessment of Standard Operating Procedures for Ozone Sondes has completed its second phase (ASOPOS-2). The new report, with updated standard operation procedures (SOPs), is published as GAW Report No. 268, Editors: Herman G.J. Smit & Anne M. Thompson, World Meteorological Organization (WMO), August 2021. This includes improved knowledge of measurement uncertainties, and a resultant international collaborative activity to evaluate an apparent small decline in sonde response (Stauffer et al., 2020). The decline has been traced to a change of pump motor and is in the process of being corrected (Tarasick et al., 2023). Improved

understanding of the time-dependent “background current’ has also been a product of this effort (Tarasick et al., 2021; Smit et al., 2023).

The ASOPOS and continuing work on the Ozonesonde Data Quality Assessment (O3S-DQA) have improved ozonesonde precision by a factor of 2 (Tarasick et al., 2021). To date, about 43 stations (including those in Canada) have reprocessed their records.

The Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere (TOST) has been updated to 2021, and comprehensively validated (Zang et al., 2024). Accuracy against independent ozonesondes compares favourably with SAGE and MLS.

Canadian ozonesondes showed significant depletion of stratospheric ozone in the Arctic in spring 2020. The degree of depletion is the largest ever seen, exceeding 50% in total ozone column and reaching more than 95% near 18 km altitude. Profiles taken in late March/early April resemble “classic” Antarctic ozone hole profiles, the first time near-total destruction of ozone has been seen in the Arctic stratosphere (Wilka et al., 2021).

Arctic profile data continue to show ozone decline in the lower stratosphere over the 25 years since peak chlorine (Nilsen et al., 2023). Increases in observed ozone are found at the surface and in the free troposphere during winter in the high Arctic (Law et al., 2023).

The Tropospheric Ozone Assessment Report (TOAR) is well into its second phase, with a number of papers from Working Groups on specific topics (Health, Vegetation, Climate, Stratosphere-Troposphere Exchange, S. America Regional, Africa Regional).

Canada, through Air Canada, joined IAGOS (In-service Aircraft for a Global Observing System). Work is in progress to compare ozonesonde and IAGOS profiles and evaluate their consistency (Wang et al., 2024).

2.3 Results from space-based observations

SCISAT and OSIRIS datasets continue to contribute to the study of the natural variability of ozone to determine the long-term trends of ozone and accurately attribute sources of variability. Four merged datasets that contain data from SCISAT and/or OSIRIS were reported in the 2022 Scientific Assessment of Ozone Depletion (SAGE-OSIRIS-OMPS, SAGE-CCI-OMPS, GOZCARDS and MEGRIDOP). These merged datasets report ozone trends in vertical profiles, time series, altitude-latitude cross sections, and latitude-longitude and altitude-season variation. Although ozone levels in the upper stratosphere show unambiguous increase for 2000-2020 outside of the polar regions and validated the success of the Montreal Protocol, observations and model simulations indicate uncertain and divergent trends in the lower stratosphere. This demonstrates the importance of continuous long-term monitoring of ozone trends in various altitudes to improve model projections ozone recovery.

Researchers discovered the chemical composition of wildfire aerosols for the first time, linking them to activating reactive chlorine species and enhancing ozone loss rates. SCISAT data was used to compare and confirm new wildfire chemical mechanisms within established atmospheric microphysics and Earth System Models. The resulting further depletion of southern mid-latitude ozone increases concerns that more frequent and intense wildfires could delay ozone recovery in a warming world (Solomon et al., 2023). It was also discovered that the Australian wildfires from 2019/20 caused a change in stratospheric winds, leading to a reduction of the stratospheric ozone layer in the Southern Hemisphere. SCISAT data provided strong evidence that the fires increased levels of the ozone depleting substance $ClONO_2$. The impact of such events needs to be understood as climate change is expected to increase both the frequency and intensity of wildfires (Salawitch et al., 2022). Using SCISAT, Canadian scientists measured chlorine and nitrogen containing substances from recent Canadian and Australian wildfires. It was discovered that injected smoke particles produce unexpected and extreme changes in stratospheric gases beyond any seen in the previous 16 years of measurements (Bernath et al., 2022). SCISAT

observations were also used to study wildfires in the southern hemisphere to discover an unprecedented depletion in the main stratospheric chlorine reservoir species (HCl) and thus an increase in ozone-destroying forms of chlorine (Santee et al., 2022). Finally, a group of 17 scientists studied the impacts of wildfire smoke on stratospheric composition and chemistry using four different satellite datasets. SCISAT data was used to contribute to a 17-year data record of NO_x and identify an increase in ozone depleting substances. Multiyear OSIRIS aerosol and NO_x data also contributed to evidence of the important chemistry-climate coupling mechanism that temporarily decreases ozone. It was concluded that when wildfire smoke is found in the stratosphere as the world warms, recovery of the ozone layer under the Montreal Protocol is delayed (Solomon et al., 2022).

Researchers from seven countries discovered that the Hunga Tonga volcano eruption in 2022 injected material up to 58km in the atmosphere, created a plume that circumnavigated the Earth in one week, and went pole-to-pole in three months. Canada's SCISAT satellite data was used to measure a 275% increase in water content from the direct injection of seawater into the stratosphere. This remarkable climatic event has initiated a new era in stratospheric chemistry and particle microphysics (Khaykin et al., 2022). SCISAT data was also used as part of a global database to establish seasonal and annual trends of H_2O in the stratosphere prior to the Hunga Tonga eruption. Given the potential high-impact consequences of such injections, it is critical to quantify the role of volcanoes on the Earth's climate (Millan et al., 2022).

Since the last reporting period, SCISAT data has also been used to record the first infrared transmittance spectra of Polar Stratospheric Clouds (PSCs) associated with the Antarctic ozone hole. This enabled an improved characterization of PSCs and the discovery of a new PSC type, supercooled nitric acid (Lecours et al., 2023). Infrared transmittance spectra of stratospheric sulfate aerosol plumes from volcanic eruptions have also allowed the composition (weight percent of sulfuric acid) to be reliably determined. This has implications for climate change predictions because sulfate aerosols cool the surface of the Earth (Bernath et al., 2023). Finally, the combination of infrared transmittance spectra from SCISAT/ACE and co-incident optical extinction spectra from the SAGE-III/ISS instrument has greatly improved the characterization of stratospheric sulfate aerosols. In particular, a bimodal particle size distribution was necessary to reproduce the observations (Boone et al., 2024).

In support of the UN/SPARC Observed Composition Trends and Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS) activity, ozone climatologies were generated from 14 years of measurements made by three Canadian limb-viewing satellite instruments (ACE-FTS, MAESTRO, and OSIRIS). The objective was to address the need for UTLS-focused climatologies produced with the aim to minimize the effects of geophysical variability and address the influence of disparate sampling patterns. To characterize the differences between the datasets, the Canadian Middle Atmosphere Model 39-year specified dynamics (CMAM39-SD) model output dataset was used as a consistent comparison reference for the analysis. The model analysis was sampled at times and locations of the instrument measurements to generate subsampled model climatologies which permits the sampling-related differences between the datasets to be explored free from the influence of any retrieval biases between instruments. For ozone, the average absolute relative difference between the model and two ACE-FTS dataset versions agreed to within 2% overall, and the OSIRIS ozone climatology agreed to within 10%. The MAESTRO ozone climatologies differ from these two instruments by 30-35% and 25% respectively, albeit with regions of better agreement within the UTLS. It was found that this set of Canadian limb sounders yield generally similar ozone distributions in the UTLS, with some exceptions for MAESTRO depending on the season and gas species. The work was conducted in collaboration between researchers from ECCC, Canadian and American academia, and NASA/JPL. (Jeffery et al., 2022)

2.4 Polar Environment Atmospheric Research Laboratory (PEARL)

The Polar Environment Atmospheric Research Laboratory (PEARL) is a Canadian Network for the Detection of Atmospheric Change (CANDAC) facility for atmospheric research in the High Arctic, located at Eureka, Nunavut (80° N) near ECCC's Weather Station. It began measurements

in 2005-2006 and continues to carry out research on large number of atmospheric constituents, including the partial and total column measurements of trace gases, although there are gaps in some of the datasets since 2000 due to the pandemic and funding constraints. The PEARL instrument suite is being used to examine trends in halogen-containing species and other atmospheric constituents / parameters that control both the ozone budget. These measurements are being used to quantify the contributions from dynamics, chemistry, and climate change to stratospheric ozone depletion and recovery, and to study the tropospheric ozone budget.

PEARL-based observations have been used to validate multiple SCISAT/ACE and Odin/OSIRIS data products, as well as data from many other satellite missions, including TROPOMI on ESA's Sentinel-5 Precursor. The ozone Differential Absorption Lidar (DIAL, also known as the Eureka Stratospheric Ozone Lidar, SOLID) was refurbished several years ago and made measurements in winter/spring 2017-2020 as part of the Canadian Arctic ACE/OSIRIS Validation Campaigns. DIAL measurements since March 2020 have been limited due to COVID-19 travel restrictions, laser failure, and lack of on-site personnel; some measurements were made in October-November 2021 and November 2023. Other instrumentation includes UV-visible and Fourier transform infrared (FTIR) spectrometers that measure ozone and related species (e.g., hydrochloric acid, hydrofluoric acid, chlorofluorocarbons, bromine monoxide). The two UV-visible spectrometers (PEARL-GBS and UT-GBS) continue to operate nominally and were not significantly affected by the pandemic. However, the FTIR data record has been interrupted by the pandemic and instrument issues, exacerbated by lack of on-site personnel. The UV-VIS, FTIR, and DIAL data are contributed to the Network for the Detection of Atmospheric Composition Change (available via https://ndacc.larc.nasa.gov/stations/eureka-canada) and the ozone Rapid Delivery data from all three instruments are also contributed to the Copernicus Atmospheric Monitoring System (CAMS) through a partnership with the Royal Belgian Institute for Space Aeronomy (BIRA-IASB). Data from an in-situ surface ozone analyzer (from a NOAA instrument installed at PEARL) and ECCC ozonesondes also provide information about ozone at Eureka.

PEARL data continue to be utilized for satellite validation, scientific studies, instrument development and demonstration, as seen in the publications listed in Section 4.3. For example, since 2020, PEARL measurements have been used to investigate springtime bromine explosions and tropospheric ozone depletion events (Bognar et al., JGR 2020; Yang et al., ACP 2020), the severe stratospheric ozone depletion in spring 2020 (Bognar et al., JGR 2021), trends in polar ozone loss (Pazmino et al., ACP 2023), and evaluation of tropospheric ozone columns from models that were part of the 2021 Arctic Monitoring and Assessment Programme (AMAP) report on short-lived climate forcers (Flood et al., ACP 2024).

Efforts to secure new long-term funding for PEARL have not yet been successful despite many positive reviews and recommendations. For example, the importance of PEARL was recognized in the report "Northern Research Leadership and Equity" released on 4 December 2023 by the Council of Canadian Academies Expert Panel on the Future of Arctic and Northern Research in Canada (Box 5. "Non-Place-Based Arctic and Northern Research Infrastructure", page 89; https://cca-reports.ca/reports/the-future-of-arctic-and-northern-research-in-canada/). A request for funding over the next six years has been submitted to the federal government; PEARL will be closing if new long-term funding is not secured in 2024. If PEARL closes, Canada will lose a unique High Arctic presence and perspective on the changing atmosphere and be unable to provide critical information about ozone, climate, pollution, and weather in this region.

2.5 The University of Toronto Atmospheric Observatory (TAO)

The University of Toronto Atmospheric Observatory (TAO) houses a Bomem DA8 high-resolution FTIR spectrometer that has been operational since 2002. This instrument acquires solar infrared absorption spectra for long-term measurements of stratospheric and tropospheric trace gases. The TAO FTIR is an NDACC instrument and regularly measures ozone (see https://ndacc.larc.nasa.gov/stations/toronto-tao-canada). TAO data have contributed to validation of ACE-FTS, SCIAMACHY, and OSIRIS, the first detection of NO in the mesosphere and lower thermosphere using ground-based FTIR spectroscopy, and studies of chlorine trends, polar intrusions, and tropospheric transport of pollutants, including those from wildfires, over Toronto.

TAO is also part of the validation program for TROPOMI. Among other studies, since 2020, TAO data have been used to investigate the impact of the COVID-19 pandemic on ozone (Steinbrecht et al., GRL 2021; Ortega et al., Elementa 2023), and ozone time series and trends over Toronto (Yamanouchi et al., ERC 2021; Yamanouchi et al., ESSD 2023).

3. THEORY, MODELLING, AND OTHER OZONE RELATED RESEARCH

3.1 Stratospheric ozone related modelling

Simulations with the Canadian Middle Atmosphere Model (CMAM) have been contributed to an international multi-model effort to provide updated ozone projections for the 2026 Scientific Assessment of Ozone Depletion. These simulations were originally intended to be contributed for the 2022 assessment, but time was not sufficient to allow for a large number of models to participate and for a thorough analysis of the results. In addition to updated long-term projections of ozone recovery, this set of simulations includes a specific set of experiments to investigate the effects of geoengineering through stratospheric aerosol injection. Additional simulations with CMAM are being conducted to support a special report on the effects of the Hunga Tonga-Hunga Ha'apai eruption, also expected to provide important information for the 2026 Scientific Assessment of Ozone Depletion. Development work is focused on integrating the chemistry components of CMAM into the most recent version of the Canadian Earth System Model, to take advantage of improvements in various components of the underlying climate model and allow for a more complete description of the interaction of important components of the Earth System.

3.2 Chemical data assimilation and forecasting

A priority activity has been incorporating the capability for chemical data assimilation (CDA) into ECCC's integrated global-regional forecasting and EnVar-based (ensemble-variational) assimilation systems. The related forecasting models are the GEM weather forecasting model with incorporated prognostic ozone relying on linearized ozone chemistry (LINOZ) and the GEM-MACH air quality forecast model. The latter consists of a largely tropospheric chemistry module embedded into the GEM model. The assimilation components are part of what is called the Modular and Integrated Data Assimilation System (MIDAS) applicable to both weather and constituent data.

Operational ozone assimilation and forecasting was activated as part of the global weather forecasting system with GEM in November 2021. Here, prognostic ozone is provided to the model radiation package affecting weather. The assimilated ozone data include data from the following instruments: TROPOMI from Sentinel 5P, OMI-Aura, OMPS-NM from Suomi-NPP and NOAA-20 and OMPS-NP from NPP, and MLS-Aura. The possible addition of OMPS-LP from Suomi-NPP is being evaluated. Ozone forecast products consist of hourly three-dimensional and total column fields generated at intervals of six hours with ten-day forecasts provided twice a day. The model also provides hourly UV Index forecasts as further described in the following section. Work is underway for making gridded ozone and related UV Index products publicly available. A study on improvements from adding heterogeneous ozone chemistry to the linearized model was also completed and submitted for journal publication.

Regional ozone assimilation experiments with the GEM-MACH air quality forecast model are underway using the same satellite observation sources as above. The current experiments serve to investigate the regional ozone forecast impact from ozone assimilation, from including ozone lateral boundary conditions provided by the operational global weather forecast system, and from differing ozone background error covariances. In a later phase, both surface and satellite ozone observations will be applied in assimilation.

3.3 New UV index prediction project

The previous UV Index prediction system relies on the total column ozone derived from statistical regression based on ECCC GEM weather forecast conditions with scaling to ground-based total column ozone values from the Canadian Brewer measurements. The current system relies instead on the surface irradiances provided by the same weather forecast model with added radiatively active prognostic ozone. The model ozone field is improved through assimilation (previous section). It provides diurnally varying clear-sky and all-sky UV Index forecasts of up to ten days. As indicated in the previous section, the current UV Index system was made operational as of November 2021. The global UV Index products are operationally interpolated to regional and high-resolution grids accounting for the differing topography, snow cover, and cloud impact on surface irradiances from the weather forecasts at the different resolutions.

As the initial phase in making new UV Index products publicly available, the one-day to two-day daily maximum clear-sky UV Index forecast fields of the new system have replaced the previously operational estimates used by the current delivery system as of 25 April 2023. Here, the final daily maximum UV index forecasts provided for various Canadian locations consist of the corresponding clear-sky UV Index attenuated by the forecaster predicted sky opacity. conditions. The next phase is to extend this to hourly UV Index forecasts.

An initial examination of forest fire and aerosol impact on UV Index forecasts was undertaken and is to be continued as part of experiments of the GEM-MACH aerosol feedback on weather forecasts through the radiation package.

3.4 Results from usage of space-based data

Researchers developed a predictive model relating stratospheric gas anomalies with tropospheric changes of surface trace gas abundances. SCISAT's CFC and N_2O datasets were used to compare and improve the model, explaining up to 70% variability in the troposphere. SCISAT observations are critical to acquire knowledge on how the layers of the Earth's atmosphere interact with each other (Lickley et al., 2021).

4. DISSEMINATION OF RESULTS

4.1 Data reporting

Brewer ozone and UV data are available in near real-time and used for various applications. They are produced as hourly bulletins for UV index forecasts and used for satellite data validation. Brewer data also are used in the Bulletin American Meteorological (BAMS) State of the Climate reports and other publications.

Total column ozone and ozonesonde data from the Canadian Brewer Spectrophotometer Network, and the Canadian Ozonesonde Network, respectively, are submitted to the WMO WOUDC.

Real-time profile data from the Canadian Ozonesonde Network are disseminated to forecast centres around the world via the WMO Global Telecommunications System (GTS). In addition, the data are provided to NDACC.

Total column ozone and other atmospheric composition data from the Canadian Pandora measurement program can be accessed the Pandonia Global Network (https://data.pandonia-global-network.org/).

SCISAT data is available in near real-time and remains open on the SCISAT mission data portal (ace.uwaterloo.ca) for Canadian and international data users. The dataset is also reported through the NASA Aura Validation Data Center and the ESA Third Party Mission data portal.

OSIRIS data is available within one month of data reception and remain open on the OSIRIS mission data portal (odin-osiris.usask.ca) for Canadian and international data users. The dataset is also reported through the ESA Third Party Mission data portal.

TAO and PEARL FTIR, UV-VIS, and DIAL ozone data are contributed to NDACC and CAMS as noted in Section 2 and are publicly available.

4.2 Information to the public

Canada publishes daily UV index forecasts bulletins through ECCC's daily UV Index forecast bulletins (https://weather.gc.ca/forecast/public_bulletins_e.html?Bulletin=fpcn49.cwao). If the maximum UV Index value for the day is expected to reach 1 or greater, it is also included in Environment and Canada's daily weather forecast (https://weather.gc.ca/canada_e.html). Typical summer values for the UV index across North America are summarized at Canada.ca (https://www.canada.ca/en/environment-climate-change/services/weather-health/uv-index-sun-safety/how-to-find.html#X-201701131109103).

UV Index are also provided by organizations such as the Weather Network: http://www.theweathernetwork.com/uvreport/canuv_en/?ref=topnav_homepage_uvrepo.

Canada publishes a variety of daily ozone and ozone depletion substance profiles on its SCISAT mission data portal. These include profiles for O_3, N_20, CFC-11, CFC-12, HCl, HCN, SO_2, and extinction profiles at 1mm.

4.3 Relevant scientific papers

Canada contributed to the following ozone and UV-related reports:
- 2022 WMO/UNEP Scientific Assessment of Ozone Depletion
- BAMS State of Climate reports

Scientific publications (February 2020 – January 2024) are as follows (alphabetical order):

Bernath P., Boone C., Crouse J., Wildfire smoke destroys stratospheric ozone, Science v375, p1292, 2022.

Bernath P., C. Boone, A. Pastorek, D. Cameron, M. Lecours, Satellite characterization of global stratospheric sulfate aerosols released by Tonga volcano, J. Quant. Spectrosc. Rad. Transfer v299, 108520, 2023.

Bernhard, G.H., Fioletov, V.E., GrooB, J.-U., Ialongo, I., Johnsen, B., Manney, G.L., Muller, R. and T. Svendby (2020). Record-breaking increases in Arctic solar ultraviolet radiation caused by exceptionally large ozone depletion in 2020. Geophysical Research Letters, 47, e2020GL090844. https://doi.org/10.1029/2020GL090844.

Blumenstock, T., F. Hase, A. Keens, D. Czurlok, O. Colebatch, O. Garcia, D.W.T. Griffith, M. Grutter, J.W. Hannigan, P. Heikkinen, P. Jeseck, N. Jones, R. Kivi, E. Lutsch, M. Makarova, H.K. Imhasin, J. Mellqvist, I. Morino, T. Nagahama, J. Notholt, I. Ortega, M. Palm, U. Raffalski, M. Rettinger, J. Robinson, M. Schneider, C. Servais, D. Smale, W. Stremme, K. Strong, R. Sussmann, Y. Té, and V.A. Velazco. Characterization and potential for reducing optical resonances in Fourier transform infrared spectrometers of the Network for the Detection of Atmospheric Composition Change (NDACC). *Atmos. Meas. Tech.*, **14**, 1239-1252, 2021. https://doi.org/10.5194/amt-14-1239-2021

Bognar, K., R. Alwarda, K. Strong, M.P. Chipperfield, S.S. Dhomse, J.R. Drummond, W. Feng, V. Fioletov, F. Goutail, B. Herrera, G.L. Manney, E.M. McCullough, L.F. Millan, A. Pazmino, K.A. Walker, T. Wizenberg, and X. Zhao. Unprecedented spring 2020 ozone depletion in the context of 20 years of measurements at Eureka, Canada. *J. Geophys. Res. Atmos.*, 126, e2020JD034365, 2021. https://doi.org/10.1029/2020JD034365

Bognar, K., X. Zhao, K. Strong, R.Y.-W. Chang, U. Frieß, P.L. Hayes, A. McClure-Begley, S. Morris, S. Tremblay, and A. Vicente-Luis. Measurements of tropospheric bromine monoxide over four halogen activation seasons in the Canadian high Arctic. J. Geophys. Res. Atmos., 125, e2020JD033015, 2020. https://doi.org/10.1029/2020JD033015

Boone C.D., P. Bernath, A. Pastorek, M. Lecours, Sulfate Aerosol Properties Derived from Combining Coincident ACE-FTS and SAGE III/ISS Measurements, J. Quant. Spectrosc. Rad. Transfer v312, 108815, 2024.

Chipperfield M.P., Hossaini R., Montzka S.A., Reimann S., Sherry D., Tegtmeier S., Renewed and emerging concerns over the production and emission of ozone-depleting substances, Nature Rev. Earth Env. V1, p251, 2020.

Donner, S., J. Kuhn, M. Van Roozendael, A. Bais, S. Beirle, T. Bösch, K. Bognar, I. Bruchkousky, K.L. Chan, T. Drosoglou, C. Fayt, U. Frieß, F. Hendrick, C. Hermans, J. Jin, A. Li, J. Ma, E. Peters, G. Pinardi, A. Richter, S.F. Schreier, A. Seyler, K. Strong, J.-L. Tirpitz, Y. Wang, P. Xie, J. Xu, X. Zhao, and T. Wagner. Evaluating different methods for elevation calibration of MAX-DOAS (Multi AXis Differential Optical Absorption Spectroscopy) instruments during the CINDI-2 campaign. *Atmos. Meas. Tech.*, **13**, 685-712, 2020. https://doi.org/10.5194/amt-13-685-2020

Fioletov, V., Zhao, X., Abboud, I., Brohart, M., Ogyu, A., Sit, R., Lee, S. C., Petropavlovskikh, I., Miyagawa, K., Johnson, B. J., Cullis, P., Booth, J., McConville, G., and McElroy, C. T.: Total ozone variability and trends over the South Pole during the wintertime, Atmos. Chem. Phys., 23, 12731–12751, https://doi.org/10.5194/acp-23-12731-2023, 2023.

Flood, V.A., K. Strong, C.H. Whaley, K.A. Walker, T. Blumenstock, J.W. Hannigan, J. Mellqvist, J. Notholt, M. Palm, A.N. Röhling, S. Arnold, S. Beagley, R.-Y. Chien, J. Christensen, M. Deushi, S. Dobricic, X. Dong, J.S. Fu, M. Gauss, W. Gong, J. Langner, K.S. Law, L. Marelle, T. Onishi, N. Oshima, D.A. Plummer, L. Pozzoli, J.-C. Raut, M.A. Thomas, S. Tsyro, and S. Turnock. Evaluating modelled tropospheric columns of CH_4, CO, and O_3 in the Arctic using ground-based Fourier transform infrared (FTIR) measurements, Atmos. Chem. Phys., 24, 1079–1118, 2024. https://doi.org/10.5194/acp-24-1079-2024

Hannigan, J.W., I. Ortega, S.B. Shams, T. Blumenstock, J.E. Campbell, S. Conway, V. Flood, O. Garcia, D. Griffith, M. Grutter, F. Hase, P. Jeseck, N. Jones, E. Mahieu, M. Makarova, M. De Mazière, I. Morino, I. Murata, T. Nagahama, H. Nakijima, J. Notholt, M. Palm, A. Poberovskii, M. Rettinger, J. Robinson, A.N. Röhling, M. Schneider, C. Servais, D. Smale, W. Stremme, K. Strong, R. Sussmann, Y. Te, C. Vigouroux, and T. Wizenberg. Global atmospheric OCS trend analysis from 22 NDACC stations. *J. Geophys. Res. Atmos.*, **127**, e2021JD035764, 2022. https://doi.org/10.1029/2021JD035764

Jalali, A., K.A. Walker, K. Strong, R.R. Buchholz, M.N. Deeter, D. Wunch, S. Roche, T. Wizenberg, E. Lutsch, E. McGee, H.M. Worden, P.F. Fogal, and J.R. Drummond. A comparison of carbon monoxide retrievals between the MOPITT satellite and Canadian High-Arctic ground-based NDACC and TCCON FTIR measurements, *Atmos. Meas. Tech.*, **15**, 6837–6863, 2022. https://doi.org/10.5194/amt-15-6837-2022

Jeffery, P., K.A. Walker, C.E. Sioris, C.D. Boone, D. Degenstein, G.L. Manney, C.T. McElroy, L. Millan, D.A. Plummer, N.J. Ryan, P.E. Sheese, J. Zou, Water vapour and ozone in the upper troposphere-lower stratosphere: Global climatologies from three Canadian limb-viewing instruments, Atmos. Chem. Phys. V22, 14709-14734, 2022.

Khaykin S., Podglajen A., Ploeger F., Grooß J.-U., Tence F., Bekki S., Khlopenkov K., Bedka K., Rieger L., Baron A., Godin-Beekmann S., Legras B., Sellitto P., Sakai T., Barnes J., Uchino O., Morino I., Nagai T., Wing R., Baumgarten G., Gerding M., Duflot V., Payen G., Jumelet J., Querel R., Liley B., Bourassa A., Clouser B., Feofilov A., Hauchecorne A., Ravetta F., Global perturbation of stratospheric water and aerosol burden by Hunga eruption, Nature Comm. v3, p316, 2022.

Kreher, K., M. Van Roozendael, F. Hendrick, A. Apituley, E. Dimitropoulou, U. Frieß, A. Richter, T. Wagner, J. Lampel, N. Abuhassan, L. Ang, M. Anguas, A. Bais, N. Benavent, T. Bösch, K. Bognar, A. Borovski, I. Bruchkouski, A. Cede, K.L. Chan, S. Donner, T. Drosoglou, C. Fayt, H. Finkenzeller, D. Garcia-Nieto, C. Gielen, L. Gómez-Martín, N. Hao, B. Henzing, J. Herman, C. Hermans, S. Hoque, H. Irie, J. Jin, P.

Johnston, J. Khayyam Butt, F. Khokhar, T. Koenig, J. Kuhn, V. Kumar, C. Liu, J. Ma, A. Merlaud, A. Mishra, M. Müller, M. Navarro-Comas, M. Ostendorf, A. Pazmino, E. Peters, G. Pinardi, M. Pinharanda, A. Piters, U. Platt, O. Postylyakov, C. Prados-Roman, O. Puentedura, R. Querel, A. Saiz-Lopez, A. Schönhardt, S. Schreier, A. Seyler, V. Sinha, E. Spinei, K. Strong, F. Tack, X. Tian, M. Tiefengraber, J.-L. Tirpitz, J. van Gent, R. Volkamer, M. Vrekoussis, S. Wang, Z. Wang, M. Wenig, F. Wittrock, P. Xie, J. Xu, M. Yela, C. Zhang, and X. Zhao. Intercomparison of NO_2, O_4, O_3 and HCHO slant column measurements by MAX-DOAS and zenith-sky UV-Visible spectrometers during the CINDI-2 campaign. *Atmos. Meas. Tech.,* **13**, 2169-2208, 2020. https://doi.org/10.5194/amt-13-2169-2020

Kwon, H.-A., G. González Abad, C. R. Nowlan, H. Chong, A. H. Souri, C. Vigouroux, A. Röhling, R. Kivi, M. Makarova, J. Notholt, M. Palm, H. Winkler, Y. Té, R. Sussmann, M. Rettinger, E. Mahieu, K. Strong, E. Lutsch, S. Yamanouchi, T. Nagahama, J. W. Hannigan, M. Zhou, I. Murata, M. Grutter, W. Stremme, M. De Mazière, N. Jones, D. Smale, and I. Morino. Validation of OMPS Suomi NPP and OMPS NOAA-20 formaldehyde total columns with NDACC FTIR observations. *Earth and Space Science*, **10**, e2022EA002778, 2023. https://doi.org/10.1029/2022EA002778

Law, K.S., J. Liengaard Hjorth, J. B. Pernov, C.H. Whaley, H. Skov, M. Collaud Coen, J. Langner, S.R. Arnold, D. Tarasick, J. Christensen, M. Deushi, P. Effertz, G. Faluvegi, M. Gauss U. Im, N. Oshima, I. Petropavlovskikh, D. Plummer, K. Tsigaridis, S. Tsyro, S. Solberg and S.T. Turnock (2023), Arctic Tropospheric Ozone Trends, *GRL,* 50, e2023GL103096. https://doi.org/10.1029/2023GL103096.

Lecours M., P. Bernath, C. Boone, J. Crouse, Infrared Transmittance Spectra of Polar Stratospheric Clouds, J. Quant. Spectrosc. Rad. Transfer v294, 108406, 2023.

Lickley M., Solomon S., Kinnison D., Krummel P., Mühle J., O'Doherty S., Prinn R., Rigby M., Stone K.A., Wang P., Weiss R., Young D., Quantifying the Imprints of Stratospheric Contributions to Interhemispheric Differences in Tropospheric CFC-11, CFC-12, and N2O Abundances, Geophys. Res. Let. v48, e2021GL093700, 2021.

Lutsch, E., K. Strong, D.B.A. Jones, T. Blumenstock, S. Conway, J.A. Fisher, J.W. Hannigan, F. Hase, Y. Kasai, E. Mahieu, M. Makarova, I. Morino, T. Nagahama, J. Notholt, I. Ortega, M. Palm, A.V. Poberovskii, R. Sussmann, and T. Warneke. Detection and attribution of wildfire pollution in the Arctic and northern mid-latitudes using a network of FTIR spectrometers and GEOS-Chem. *Atmos. Chem. Phys.*, **20**, 12813-12851, 2020. https://doi.org/10.5194/acp-20-12813-2020

Mahieu, E., E.V. Fischer, B. Franco, M. Palm, T. Wizenberg, D. Smale, L. Clarisse, C. Clerbaux, P.-F. Coheur, J.W. Hannigan, E. Lutsch, J. Notholt, I. Pardo Cantos, M. Prignon, C. Servais, and K. Strong. First retrievals of peroxyacetyl nitrate (PAN) from ground-based FTIR solar spectra recorded at remote sites, comparison with model and satellite data. Elementa: Science of the Anthropocene, 9(1): 00027, 2021. https://doi.org/10.1525/elementa.2021.00027

Millán L., Santee M.L., Lambert A., Livesey N.J., Werner F., Schwartz M.J., Pumphrey H.C., Manney G.L., Wang Y., Su H., Wu L., Read W.G., Froidevaux L., The Hunga Tonga-Hunga Ha'apai Hydration of the Stratosphere, Geophys. Res. Let. v49, e2022GL099381, 2022.

Morgenstern, O., Frith, S. M., Bodeker, G. E., Fioletov, V., & van der A, R. J. (2021). Reevaluation of total-column ozone trends and of the effective radiative forcing of ozone-depleting substances. Geophysical Research Letters, 48, e2021GL095376. https://doi.org/10.1029/2021GL095376.

Nilsen, K., R. Kivi, M. Laine, R. Van Malderen, D. Poyraz, L. Thölix, P. von der Gathen, D. Tarasick, and N. Jepsen (2023), Time-varying decadal trends from Arctic ozonesonde time series in the years 1994 to 2022, Nature *Scientific Reports,* in review.

Ortega, I., B. Gaubert, J.W. Hannigan, G. Brasseur, H.M. Worden, T. Blumenstock, H. Fu, F. Hase, P. Jeseck, N. Jones, C. Liu, E. Mahieu, I. Morino, I. Murata, J. Notholt, M. Palm, A. Röhling, Y. Té, K. Strong, Y. Sun, and S. Yamanouchi. Anomalies of O_3, CO, C_2H_2, H_2CO, and C_2H_6 detected with multiple ground-based Fourier-transform infrared spectrometers and assessed with model simulation in 2020: COVID-19 lockdowns versus natural variability. *Elementa: Science of the Anthropocene*, **11(1)**, 00015, 2023. https://doi.org/10.1525/elementa.2023.00015

Pak, N.M., J.K. Hedelius, S. Roche, L. Cunningham, B. Baier, C. Sweeney, C. Roehl, J. Laughner, G. Toon, P. Wennberg, H. Parker, C. Arrowsmith, J. Mendonca, P. Fogal, T. Wizenberg, B. Herrera, K. Strong, K.A. Walker, F. Vogel, and D. Wunch. Using portable low-resolution spectrometers to evaluate Total Carbon Column Observing Network (TCCON) biases in North America. *Atmos. Meas. Tech.*, **16**, 1239-1261, 2023. https://doi.org/10.5194/amt-16-1239-2023

Pazmino, A., F. Goutail, S. Godin-Beekmann, A. Hauchecorne, J.-P. Pommereau, M.P. Chipperfield, W. Feng, F. Lefèvre, A. Lecouffe, M. Van Roozendael, N. Jepsen, G. Hansen, R. Kivi, K. Strong, K.A. Walker, and S. Colwell. Trends in polar ozone loss since 1989: potential sign of recovery in the Arctic ozone column. *Atmos. Chem. Phys.*, **23**, 15655–15670, 2023. https://doi.org/10.5194/acp-23-15655-2023

Pinardi, G., M. Van Roozendael, F. Hendrick, A. Richter, P. Valks, R. Alwarda, K. Bognar, U. Frieß, J. Granville, M. Gu, P. Johnston, C. Prados-Roman, R. Querel, K. Strong, T. Wagner, F. Wittrock, and M. Yela Gonzalez. Ground-based validation of the MetOp-A and MetOp-B GOME-2 OClO measurements. *Atmos. Meas. Tech.*, **15**, 3439-3463, 2022. https://doi.org/10.5194/amt-15-3439-2022

Salawitch R.J., McBride L.A., Australian wildfires depleted the ozone layer, Science v378, p829, 2022.

Santee M.L., Lambert A., Manney G.L., Livesey N.J., Froidevaux L., Neu J.L., Schwartz M.J., Millán L.F., Werner F., Read W.G., Park M., Fuller R.A., Ward B.M., Prolonged and Pervasive Perturbations in the Composition of the Southern Hemisphere Midlatitude Lower Stratosphere From the Australian New Year's Fires, Geophys. Res. Let. v49, e2021GL096270, 2022.

Smit, H. G. J., Poyraz, D., Van Malderen, R., Thompson, A. M., Tarasick, D. W., Stauffer, R. M., Johnson, B. J., and Kollonige, D. E.: New insights from the Jülich Ozone Sonde Intercomparison Experiment: calibration functions traceable to one ozone reference instrument, Atmos. Meas. Tech., 17, 73–112, https://doi.org/10.5194/amt-17-73-2024, 2024.

Solomon S., Dube K., Stone K., Yu P., Kinnison D., Toon O.B., Strahan S.E., Rosenlof K.H., Portmann R., Davis S., Randel W., Bernath P., Boone C., Bardeen C.G., Bourassa A., Zawada D., Degenstein D., On the stratospheric chemistry of midlatitude wildfire smoke, PNAS v119, e2117325119, 2022.

Solomon S., Stone K., Yu P., Murphy D.M., Kinnison D., Ravishankara A.R., Wang P., Chlorine activation and enhanced ozone depletion induced by wildfire aerosol, Nature v615, p259, 2023.

Stauffer, R. M., Thompson, A. M., Kollonige, D. E., Witte, J. C., Tarasick, D. W., Davies, J., H. Vömel, G.A. Morris, R. Van Malderen, B.J. Johnson, R.R. Querel, H.B. Selkirk, R. Stübi, H.G.J. Smit (2020), A post-2013 dropoff in total ozone at a third of global ozonesonde stations: Electrochemical concentration cell instrument artifacts? Geophys. Res. Lett., 47, e2019GL086791. https://doi.org/10.1029/2019GL086791.

Steinbrecht, W., D. Kubistin, C. Plass-Dülmer, J. Davies, D. W. Tarasick, P. von der Gathen, H. Deckelmann, N. Jepsen, R. Kivi, N. Lyall, M. Palm, . Notholt, B. Kois, P. Oelsner, M. Allaart, A. Piters, M. Gill, R. Van Malderen, A.W. Delcloo, R. Sussmann, E. Mahieu, C. Servais, G. Romanens, R. Stübi, G. Ancellet, S. Godin-Beekmann, S. Yamanouchi, K. Strong, B. Johnson, P. Cullis, I. Petropavlovskikh, J.W. Hannigan, J.-L. Hernandez, A. Diaz Rodriguez, T. Nakano, F. Chouza, T. Leblanc, C. Torres, O. Garcia, A.N. Röhling, M. Schneider, T. Blumenstock, M. Tully, C. Paton-Walsh, N. Jones, R. Querel, S. Strahan, R.M. Stauffer, A.M. Thompson, A. Inness, R. Engelen, K.-L. Chang, and O.R. Cooper. COVID-19 crisis reduces free tropospheric ozone across the Northern Hemisphere. *Geophys. Res. Lett.*, **48**, e2020GL091987, 2021. https://doi.org/10.1029/2020GL091987

Tarasick**,** D.W., H.G.J. Smit, A.M. Thompson G.A. Morris, J.C. Witte, J. Davies, T. Nakano, R. van Malderen, R.M. Stauffer, T. Deshler, B.J. Johnson, R. Stübi, S.J. Oltmans and H. Vömel (2021), Improving ECC ozonesonde data quality: Assessment of current methods and outstanding issues. *Earth and Space Science*, 8, e2019EA000914. https://doi.org/10.1029/2019EA000914.

Tarasick, D., R.M. Stauffer, H.G.J. Smit, A.M. Thompson, J. Davies, R. Van Malderen, B. Johnson, H. Vömel (2023), Improving data quality in long-term Canadian ozone sounding records, IUGG23-4503, 28th

IUGG (International Union of Geodesy and Geophysics) General Assembly, July 11-20, 2023, Berlin, Germany.

Tirpitz, J.-L., U. Frieß, F. Hendrick, C. Alberti, M. Allaart, A. Apituley, A. Bais, S. Beirle, S. Berkhout, K. Bognar, T. Bösch, I. Bruchkouski, A. Cede, K.L. Chan, M. den Hoed, S. Donner, T. Drosoglou, C. Fayt, M.M. Friedrich, A. Frumau, L. Gast, C. Gielen, L. Gomez-Martín, N. Hao, A. Hensen, B. Henzing, C. Hermans, J. Jin, K. Kreher, J. Kuhn, J. Lampel, A. Li, C. Liu, H. Liu, J. Ma, A. Merlaud, E. Peters, G. Pinardi, A. Piters, U. Platt, O. Puentedura, A. Richter, S. Schmitt, E. Spinei, D. Stein Zweers, K. Strong, D. Swart, F. Tack, M. Tiefengraber, R. van der Hoff, M. van Roozendael, T. Vlemmix, J. Vonk, T. Wagner, Y. Wang, Z. Wang, M. Wenig, M. Wiegner, F. Wittrock, P. Xie, C. Xing, J. Xu, M. Yela, C. Zhang, and X. Zhao. Intercomparison of MAX-DOAS vertical profile retrieval algorithms: studies on field data from the CINDI-2 campaign, *Atmos. Meas. Tech.*, **14**, 1-35, 2021. https://doi.org/10.5194/amt-14-1-2021

Vandenbussche, S., B. Langerock, C. Vigouroux, M. Buschmann, N.M. Deutscher, D.G. Feist, O. García, J.W. Hannigan, F. Hase, R. Kivi, N. Kumps, M. Makarova, D.B. Millet, I. Morino, T. Nagahama, J. Notholt, H. Ohyama, I. Ortega, C. Petri, M. Rettinger, M. Schneider, C.P. Servais, M.K. Sha, K. Shiomi, D. Smale, K. Strong, R. Sussmann, Y. Té, V.A. Velazco, M. Vrekoussis, T. Warneke, K.C. Wells, D. Wunch, M. Zhou, and M. De Mazière. Nitrous Oxide Profiling from Infrared Radiances (NOPIR): Algorithm Description, Application to 10 Years of IASI Observations and Quality Assessment. *Remote Sensing*, **14**, 1810, 2022. https://doi.org/10.3390/rs14081810

Verhoelst, T., S. Compernolle, G. Pinardi, J.-C. Lambert, H.J. Eskes, K.-U. Eichmann, A.M. Fjæraa, J. Granville, S. Niemeijer, A. Cede, M. Tiefengraber, F. Hendrick, A. Pazmiño, A. Bais, A. Bazureau, K. F. Boersma, K. Bognar, A. Dehn, S. Donner, A. Elokhov, M. Gebetsberger, F. Goutail, M. Grutter de la Mora, A. Gruzdev, M. Gratsea, G.H. Hansen, H. Irie, N. Jepsen, Y. Kanaya, D. Karagkiozidis, R. Kivi, K. Kreher, P.F. Levelt, C. Liu, M. Müller, M. Navarro Comas, A.J.M. Piters, J.-P. Pommereau, T. Portafaix, C. Prados-Roman, O. Puentedura, R. Querel, J. Remmers, A. Richter, J. Rimmer, C. Rivera Cárdenas, L. Saavedra de Miguel, V. P. Sinyakov, W. Stremme, K. Strong, M. Van Roozendael, J.P. Veefkind, T. Wagner, F. Wittrock, M. Yela González, and C. Zehner. Ground-based validation of the Copernicus Sentinel-5P TROPOMI NO_2 measurements with the NDACC ZSL-DOAS, MAX-DOAS and Pandonia global networks, *Atmos. Meas. Tech.*, **14**, 481–510, 2021. https://doi.org/10.5194/amt-14-481-2021

Viatte, C., R. Abeed, S. Yamanouchi, W. Porter, S. Safieddine, M. Van Damme, L. Clarisse, B. Herrera, M. Grutter, P.-F. Coheur, K. Strong, and C. Clerbaux. NH_3 spatio-temporal variability over Paris, Mexico and Toronto and its link to PM2.5 during pollution events. *Atmos. Chem. Phys.*, **22**, 12907–12922, 2022. https://doi.org/10.5194/acp-22-12907-2022

Vigouroux, C., B. Langerock, C.A. Bauer Aquino, T. Blumenstock, Z. Cheng, M. De Mazière, I. De Smedt, M. Grutter, J. W. Hannigan, N. Jones, R. Kivi, Lutsch, E. Loyola, D., E. Mahieu, M. Makarova, J.-M. Metzger, I. Morino, I. Murata, T. Nagahama, J. Notholt, I. Ortega, M. Palm, G. Pinardi, A. Röhling, D. Smale, W. Stremme, K. Strong, R. Sussmann, Y. Té, M. van Roozendael, P. Wang, and H. Winkler. TROPOMI–Sentinel-5 Precursor formaldehyde validation using an extensive network of ground-based Fourier-transform infrared stations, *Atmos. Meas. Tech.*, **13**, 3751-3767, 2020. https://doi.org/10.5194/amt-13-3751-2020

Wang, H., D.W. Tarasick, J.J. Liu, H.G.J. Smit, R. van Malderan and T. Zhao (2024), Quantitative consistency of tropospheric ozone from ozonesonde (WOUDC) and aircraft (IAGOS) observations: vertical distribution, ozonesonde types and station-pair distance, to be submitted to *ACP,* TOAR-II Special Issue.

Weber, M., Arosio, C., Coldewey-Egbers, M., Fioletov, V. E., Frith, S. M., Wild, J. D., Tourpali, K., Burrows, J. P., and Loyola, D.: Global total ozone recovery trends attributed to ozone-depleting substance (ODS) changes derived from five merged ozone datasets, Atmos. Chem. Phys., 22, 6843–6859, https://doi.org/10.5194/acp-22-6843-2022, 2022.

Wilka, C., S. Solomon, D. Kinnison and D. Tarasick (2021), An Arctic Ozone Hole in 2020 If Not For the Montreal Protocol, *Atmos. Chem. Phys., 21*, 15771–15781, https://doi.org/10.5194/acp-21-15771-2021.

Wizenberg, T., K. Strong, D.B.A. Jones, E. Lutsch, E. Mahieu, B. Franco, and L. Clarisse. Exceptional wildfire enhancements of PAN, C_2H_4, CH_3OH, and HCOOH over the Canadian high Arctic during August

2017. *Journal of Geophysical Research: Atmospheres*, **128**, e2022JD038052, 2023. https://doi.org/10.1029/2022JD038052

Wizenberg, T., K. Strong, K. Walker, E. Lutsch, T. Borsdorff, and J. Landgraf. Intercomparison of CO measurements from TROPOMI, ACE-FTS, and a high-Arctic ground-based Fourier transform spectrometer. Atmos. Meas. Tech., 14, 7707-7728, 2021. https://doi.org/10.5194/amt-14-7707-2021

Wohltmann, I., von der Gathen, P., Lehmann, R., Maturilli, M., Deckelmann, H., Manney, G. L., et al. (2020). Near-complete local reduction of Arctic stratospheric ozone by severe chemical loss in spring 2020. Geophysical Research Letters, 47, e2020GL089547. https://doi.org/10.1029/2020GL089547.

Yamanouchi, S., S. Conway, K. Strong, O. Colebatch, E. Lutsch, S. Roche, J. Taylor, C.H. Whaley, and A. Wiacek. Network for the Detection of Atmospheric Composition Change (NDACC) Fourier transform infrared (FTIR) trace gas measurements at the University of Toronto Atmospheric Observatory from 2002 to 2020. *Earth Syst. Sci. Data*, **15**, 3387–3418, 2023. https://doi.org/10.5194/essd-15-3387-2023

Yamanouchi, S., K. Strong, O. Colebatch, S. Conway, D.B.A. Jones, E. Lutsch, and S. Roche. Atmospheric trace gas trends obtained from FTIR column measurements in Toronto, Canada from 2002-2019. Environmental Research Communications, 3, 051002, 2021. https://iopscience.iop.org/article/10.1088/2515-7620/abfa65

Yamanouchi, S., K. Strong, E. Lutsch, and D.B.A. Jones. Detection of HCOOH, CH_3OH, CO, HCN, and C_2H_6 in wildfire plumes transported over Toronto using ground-based FTIR measurements from 2002-2018. *J. Geophys. Res. Atmos.*, **125**, e2019JD031924, 2020. https://doi.org/10.1029/2019JD031924

Yamanouchi, S., C. Viatte, K. Strong, E. Lutsch, D.B.A. Jones, C. Clerbaux, M. Van Damme, L. Clarisse, and P.-F. Coheur. Multiscale observations of NH_3 around Toronto, Canada, *Atmos. Meas. Tech.*, **14**, 905-921, 2021. https://doi.org/10.5194/amt-14-905-2021

Yang, X., A.-M. Blechschmidt, K. Bognar, A. McClure–Begley, S. Morris, I. Petropavlovskikh, A. Richter, H. Skov, K. Strong, D. Tarasick, T. Uttal, M. Vestenius, and X. Zhao. Pan-Arctic surface ozone: modelling vs measurements. *Atmos. Chem. Phys.*, **20**, 15937-15967, 2020. https://doi.org/10.5194/acp-20-15937-2020

You, Y., B. Byrne, O. Colebatch, R.L. Mittermeier, F. Vogel, and K. Strong. Quantifying the impact of the COVID-19 pandemic restrictions on CO, CO_2, and CH_4 in downtown Toronto using open-path Fourier transform spectroscopy. *Atmosphere*, 12(7), 848, 2021. https://doi.org/10.3390/atmos12070848

Zang, Z., J.J. Liu, D.W. Tarasick, O. Moeini*, B. Jianchun, J. Zhang, R. Van Malderen, A.M. Thompson, H.G.J. Smit, R.M. Stauffer and B.J. Johnson (2024), An updated and improved Trajectory-mapped Ozonesonde dataset for the Stratosphere and Troposphere (TOST) from 1970-2021, to be submitted to *ACP,* TOAR-II Special Issue.

Zhao, X., Fioletov, V., Redondas, A., Gröbner, J., Egli, L., Zeilinger, F., López-Solano, J., Arroyo, A. B., Kerr, J., Maillard Barras, E., Smit, H., Brohart, M., Sit, R., Ogyu, A., Abboud, I., and Lee, S. C.: The site-specific primary calibration conditions for the Brewer spectrophotometer, Atmos. Meas. Tech., 16, 2273–2295, https://doi.org/10.5194/amt-16-2273-2023, 2023.

Zhao, X., Fioletov, V., Brohart, M., Savastiouk, V., Abboud, I., Ogyu, A., Davies, J., Sit, R., Lee, S. C., Cede, A., Tiefengraber, M., Müller, M., Griffin, D., and McLinden, C.: The world Brewer reference triad – updated performance assessment and new double triad, Atmos. Meas. Tech., 14, 2261–2283, https://doi.org/10.5194/amt-14-2261-2021, 2021.

Zhao, X., V. Fioletov, A. Cede, J. Davies, and K. Strong, Accuracy, precision, and temperature dependence of Pandora total ozone measurements estimated from a comparison with the Brewer triad in Toronto, Atmos. Meas. Tech., 9, 5747-5761, 2016.

5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

5.1 WMO/GAW common Brewer Central Calibration Laboratory

Since late 2020, as directed by WMO/GAW, AEMET and ECCC formed a working group on building the scientific base for a combined, common Brewer CCL with one CCL each hosted by ECCC in Toronto, Canada and AEMET in Tenerife, Spain. Efforts are being made to evaluate the agreement between the European Regional Brewer references (AEMET) and World Brewer references (ECCC) of the calibration transfer and absolute calibration, and the findings will be published in peer-reviewed science papers. The first main paper will be on primary calibration theory and technical details (e.g., the difference between the Canadian (ECCC) and Spanish (AEMET) primary calibrations of Brewer instruments. It will also introduce a new Brewer uncertainty budget model to provide detailed uncertainties of Brewer observations. The second paper will focus on how the primary calibration is transferred to field Brewer instruments worldwide. In the context of having two CCLs, instead of the current one CCL, this work will evaluate the transfer results from the Canadian and Spanish primary calibrations to see if the calibration qualities are equivalent. It will use real campaign data (XVII Intercomparison Campaign of the Regional Brewer Calibration Center-Europe in 2022) and historical observations to examine the equivalence of the two CCLs. In addition, in August 2023, ECCC performed absolute calibration of the World reference Brewer #187 at AEMET's IZO, which provided an excellent opportunity to compare the World and European Brewer references.

As part of the above papers, Zhao et al. (2023) evaluated the site-specific conditions (e.g., stability of ozone field, weather, and Aerosol Optical Depth) for Brewer absolute calibration at different Brewer sites globally. This work provides solid scientific results to support why such primary calibration work can only be conducted at certain sites.

5.2 Collaborations with Canadian universities

- PAHA (Probing the Atmosphere of the High Arctic) project with three themes, one of which was Composition Measurements (CM), which included a project on Ozone and Related Species (CM-O3). PAHA was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC); this project and funding ended in June 2021.
- The Canadian Arctic ACE/OSIRIS Validation Campaigns at PEARL and the CASSAVA (Canadian Anchor Sites for SATellite Validation) PEARL project, both supported by the Canadian Space Agency.
- Collaboration on Arctic Monitoring and Assessment Program model-measurement comparisons for short-lived climate forcers (including ozone) using ACE-FTS, NDACC, and TCCON data.

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 11th OZONE RESEARCH MANAGERS MEETING

6.1 Research needs

6.1.1 Hydrofluorocarbons (HFCs)

On the monitoring of HFCs, Canada has produced a 20-year space-based dataset for three HFCs. These high-quality atmospheric profile measurements are primarily taken over the Earth's poles. Geographical coverage is sparse and would be increased by a satellite constellation of FTS instruments.

6.1.2 Stratospheric ozone – Climate coupling

On stratospheric ozone-climate coupling, Canada has produced 20+ year space-based datasets of many ODSs and all major GHGs. These profile measurements are from well-characterized and calibrated instruments that continue Canada's legacy in atmospheric chemistry monitoring from space. Future evolution of the stratospheric ozone layer will need to be measured through ODS concentrations and stratospheric temperatures and circulation measured from the same space-based platforms.

6.2 Systematic observations

6.2.1 Ground-based observations

Systematic observations are ongoing, including ground-based sites with long records and in the Arctic and Antarctic regions. All Dobson/Brewer and ozonesondes sites open in the 1950s and 1960s are operational. ECCC, within its resources, continues to work on improving the measurements of ozone and UV radiation. All Brewer sites are equipped with at least two instruments to deliver high quality observations with no data gaps. The testing and evaluation of the Pandora spectrometer continues for remote sensing of atmospheric composition, including ozone. Comparison of total column ozone between the Pandora and Brewer measurements with satellite observations and reanalysis data is ongoing.

6.2.1 Satellite observations

The CSA continues to work with space science instrument teams to maximize new knowledge from operational assets by supporting data production algorithm development on a continual basis. New data requirements are added on a regular basis that respond to priorities and needs of the Parties to the Montreal Protocol. Canada's SCISAT atmospheric chemistry monitoring mission has been extended by two additional years out to March 2026. Canada's OSIRIS instrument is currently funded out to March 2025. This allows Canada to continue limb emission and IR solar occultation observations from space, monitor vertical profiles of N_2O, CH_4 and water vapour through the troposphere and stratosphere, and to observe profile concentrations and chemical composition of stratospheric aerosols. These mission datasets need to be extended for as long as they continue producing high-quality data.

6.3 Data archiving and stewardship

The World Ozone and Ultraviolet Radiation Data Centre (WOUDC) is operated by the Meteorological Service of Canada at ECCC. Updates for WOUDC are as follows:

- New contributors
    - Service National of Meteorology and Hidrology – Peru
    - University of Bern
    - Korea Polar Research Institute
    - National Agency of Civil Aviation and Meteorology of Cosmoros
- New stations
    - Copenhagen
    - Southern Space Observatory
    - St-Denis
    - Antananarivo
    - AnseQuitor
    - Barentsburg
    - Marcapomacocha
    - King Sejong
    - Oxford
    - Pengchiayu

    - Moroni
- New datasets
    - Add JOSIE and BESOS data to products page
        - Data available on https://woudc.org/archive/Summaries/josie-besos/
        - Web page to be created on WOUDC 2.0 (beta)
            - https://beta.woudc.org/archive/Summaries/josie-besos/
- WIS2 implementation
    - Add MQTT broker service
- Ozone maps search page 2.0
    - Development in progress
        - On WOUDC 2.0 (beta)
    - Migration of ozone map images from https://exp-studies.tor.ec.gc.ca to WOUDC 2.0 beta
    - Improve and modernize search page

In an ongoing study, ECCC is evaluating the data quality of total ozone records available from WOUDC.

6.4 Capacity building

Canada continues its commitment in supporting developing countries to carry out systematic observations of the ozone layer. Canada continues the sponsorship of the Brewer Trust Fund, a multi-year contribution agreement between ECCC and WMO. The Brewer Trust Fund is valid from April 1, 2021 to March 31, 2025, and provides 37,500 CAD per year. It is used for maintaining the high quality data collected by Brewer spectrophotometers in developing countries by supporting maintenance and calibration of Brewer instruments; participation of personnel at inter-comparison campaigns; and training on operations and data processing. Between fiscal years 2020-2024, the Brewer Trust Fund contributed to the following:

- Procurement of Brewer components for maintenance and repair of instruments.
- Repair of Brewer instrument stationed in Brazil.
- Service and calibration of two Brewer spectrophotometers from India.
- 2024 South American Brewer Intercomparison in Santa Maria, Brazil.

7. FUTURE PLANS

7.1 Climate change impact on long-term ozone monitoring

Since 2023, ECCC is working with PMOD-WRC to deploy a Brewer instrument in Davos, Switzerland to conduct climate change research. To understand the tropospheric column above Davos, and especially the lower boundary layer, an additional total column ozone monitoring station would be needed at a suitable location at a higher elevation than Davos, ideally, in special proximity to Davos. The plan is to deploy an ECCC-owned Brewer at Messfeld Weissfluhjoch (2540 m a.s.l), which is about 950 m above Davos, to perform long-term ozone monitoring. These measurements will be used to assess the diurnal, seasonal, and long-term variability of the boundary ozone layer over Davos, and thereby, allow the study of the impact of tropospheric ozone changes on the total column ozone measurements made at Davos. The separation of the tropospheric signal from the total column ozone measurements will be crucial to extracting the stratospheric ozone recovery signal from the total column ozone measurements over Davos to

deduce its long-term changes, and therefore, to quantify the stratospheric ozone recovery over Davos, which was shown to be a representative site at northern mid-latitudes[1].

7.2 Satellite validation with ground-based observations

One of the main applications of ECCC's ground-based remote sensing network, which includes ozone monitoring, is validation of satellite measurements of atmospheric composition related to air quality and stratospheric ozone. The satellite validation activities primarily relate to TROPOMI and NASA's TEMPO (Tropospheric Emissions: Monitoring Pollution) mission are as follows:

- Validation total columns of ozone, NO_2, SO_2, HCHO, and perhaps other species using Brewer and Pandora instruments, which assures the quality of satellite data over Canada.
- Validation of ECCC ozone and UV index forecasts using the Canadian Brewer Spectrophotometer Network.
- Validation of ozone profiles using ozonesonde measurements from Canadian stations to ensure satellite stratospheric and tropospheric ozone measurements are suitable for ECCC's UV Index and Air Quality Health Index (AQHI) applications (assimilation, validation, research, trend studies, etc.).
- Validation of trace gas profiles using MAX-DOAS measurements by Pandora and MAX-DOAS instruments.

7.3 Pandora instruments in the High Arctic

The University of Toronto will be installing two new Pandora instruments in Nunavut in mid-2024: one at the Canadian High Arctic Research Station in Cambridge Bay and the other at Iqaluit. This is part of the new Multidisciplinary Observatory for Arctic Climate Change and Extreme Events Monitoring (MOACC), funded by the Canada Foundation for Innovation.

7.4 Ozone and UV index forecasts

Continued updating of the ozone and UV index forecasts will be pursued along different avenues, including forecast model improvements, assimilation of additional ozone observation sources, and improvements of ozone assimilation approaches. This will be accompanied by a continued effort in making available the new ozone and UV index products for access to the public and to international studies. The operational implementation of regional ozone assimilation with GEM-MACH is to follow the already implemented global operational system with GEM. The assimilation of satellite measurements for other constituents will be progressively added, beginning with the assimilation of surface observations. While initially using static background error covariances with horizontally isotropic and homogeneous correlations, the background error covariances will gradually include spatially varying ensemble-based covariances.

8. NEEDS AND RECOMMENDATIONS

Space-based datasets from SCISAT and OSIRIS have contributed very well to the latest Scientific Assessment of Ozone Depletion, as well as supported important scientific discoveries that have advanced our knowledge of ozone and atmospheric chemistry. These instruments continue to operate after 20 years, continually producing high-quality datasets that are used by hundreds of scientists all over the world and have brought Canadian space data to the heart of international environmental policy. The international community has identified the cessation of space limb-viewing instruments as a major risk to monitoring the recovery of stratospheric ozone. It is recommended that follow-on missions be investigated with the aim to measure at the regional and sub-regional

[1] Rozanov, E., Egorova T., Egli L., Karagodin-Doyennel A., Sukhodolov T., Schill H., Stübi R.and J. Gröbner, Representativeness of the Arosa/Davos Measurements for the Analysis of the Global Total Column Ozone Behavior, Front. Earth Sci., 17 June 2021 | https://doi.org/10.3389/feart.2021.675084

level. Implementation of a possible mission constellation architecture would require important international collaboration.