JAPAN

1. OBSERVATIONAL ACTIVITIES

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

Total column ozone and Umkehr measurements were conducted by the Japan Meteorological Agency (JMA) at three sites in Japan (Sapporo, Tsukuba, and Naha) and the Syowa Station in Antarctica. The measurements at Sapporo and Naha were ended in January 2022. Brewer spectrophotometers have been in operation replacing from Dobson spectrophotometers at Tsukuba and Syowa Station since February 2018 and February 2022, respectively. Locations for column ozone and Umkehr measurement sites by JMA are summarized in Table 1.

Table 1. Locations of column ozone and Umkehr measurement sites operated by JMA

Observation site	Latitude	Longitude	Altitude (m)	WMO station number
Tsukuba	36° 03′ N	140° 08′ E	31	47646
Syowa	69° 00′ S	39° 35’ E	29	89532

The Center for Global Environmental Research (CGER) of the National Institute for Environmental Studies (NIES) and JMA monitored the concentrations of ozone-depleting substances and other atmospheric constituents. The monitoring sites are listed in Table 2. CGER/NIES monitors ozone-depleting substances (CFCs, CCl_4, CH_3CCl_3, and HCFCs), HFCs, surface ozone, CO_2, CH_4, CO, N_2O, SF_6, NO_x, H_2, O_2/N_2 ratio, and aerosols at remote sites (Hateruma and Ochiishi). JMA reconstructed the monitoring network for atmospheric constituents in April 2024, focusing monitoring efforts on the background concentration of atmospheric constituents. JMA started to measure CFCs, CCl_4, CH_3CCl_3, and N_2O (in addition to CO_2, CH_4, HFCs, surface ozone, and CO which have been already measured) at Minamitorishima (GAW Global Station). On the other hand, the station Yonagunijima (GAW Regional Station) was closed and measurements other than CO_2 and CH_4 at Ryori (GAW Regional Station) were ended.

The Japanese Ministry of the Environment (MOE) monitors the concentrations of halocarbons (CFCs, CCl_4, CH_3CCl_3, halons, HCFCs, and CH_3Br) and HFCs at remote sites around Wakkanai and Nemuro, which are far from their emission sources, and at an urban site in Kawasaki.

JMA also monitors CFCs, CO_2, N_2O, and CH_4 concentrations in both the atmosphere and seawater of the western Pacific on board the research vessels *Ryofu Maru* and *Keifu Maru*.

The Pandora spectrometer measures NO_2 and O_3 columnar amounts (total and tropospheric column amounts) at nine locations across a wide range of Japan, including Sapporo, Tsukuba, Tokyo, Yokosuka, Nagoya, Kobe, and Fukuoka. The observations began in 2021 and 2022 at most of these locations. In addition, CH_2O, SO_2, and H_2O amounts were measured. These data are available on the Pandonia Global Network website (https://www.pandonia-global-network.org/).

A Brewer spectrophotometer has been operated in a different location in Sapporo since July 2022 through a collaboration between Hokkaido University and JMA. The instrument is co-located with a Pandora instrument for long-term intercomparison, facilitating for total column ozone measurements between the two instruments.

Table 2. Locations of monitoring sites for ozone-depleting substances and other minor atmospheric constituents

Monitoring site	Latitude	Longitude	Altitude (m)	Year	Organization
Ochiishi	43° 10′ N	145° 30′ E	4242	Oct 1995 -	CGER/NIES
Hateruma	24° 0404′ N	123° 49′ E	10	Oct 1993 -	CGER/NIES
Ryori	39° 02′ N	141° 49′ E	260	Jan 1987 - Mar 2024	JMA
Minamitorishima	24° 17′ N	153° 59′ E	7	Mar 1993 -	JMA
Yonagunijima	24° 28′ N	123° 01′ E	30	Jan 1997 — Mar 2024	JMA
Syowa	69° 00′ S	39° 35′ E	29	Jan 1997 -	JMA

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

1.2.1 Ground-based and sonde measurements

From October 1990 to March 2011, CGER/NIES conducted measurements of vertical profiles of stratospheric ozone at Tsukuba using ozone laser radar (ozone lidar), which were recorded in the Network for the Detection of Atmospheric Composition Change (NDACC) database. Additionally, CGER/NIES measured ozone vertical profiles using millimeter-wave radiometers from September 1995 to March 2011. The measurements with millimeter-wave radiometers were also carried out at Rikubetsu from March 1999 to March 2011, and since April 2011 these measurements have been conducted by Nagoya University (Ohyama et al., 2016).

The JMA conducts weekly monitoring of vertical ozone profiles using an ozonesonde at Tsukuba in Japan and the Syowa Station in Antarctica. Ozonesonde monitoring by JMA ended in Sapporo and Naha in January 2018.

Surface ozone concentrations were measured in operational networks at more than 1000 sites by the MOE, Japan, and at a remote site, Minamitorishima by the JMA. Additionally, research-based observations and long-term monitoring were conducted by the NIES and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The NIES measures surface ozone and its ancillary species, such as NOx and SO_2 at Ochiishi and Hateruma. Over-ocean atmospheric trace species, including ozone, have been observed during more than 20 cruise legs on board the R/V Mirai of JAMSTEC from 67° S to 75° N. Ozone mixing ratios of <10 ppb were more frequently observed than those found in model simulations over the western Pacific equatorial region, suggesting a missing sink due to halogen chemistry (Kanaya et al., 2019).

1.2.2 Airborne measurements

Since 2011, the JMA started monthly airborne *in-situ* measurements (flask sampling) of CO_2, CH_4, CO, and N_2O concentrations at an altitude of approximately 6 km along the flight path from the main island of Japan to Minamitorishima. After achieving the intended purpose of identifying the concentration level and latitudinal distribution of these substances in the free troposphere through more than 10 years of observations, the airborne measurements were discontinued in April 2024.

Atmospheric greenhouse gases have been measured since 2005 using a commercial airliner with Continuous CO_2 Measuring Equipment (CME) and automatic air Sampling Equipment (ASE) as part of the CONTRAIL project managed by NIES and JMA's Meteorological Research Institute (MRI).

1.2.3 Satellite measurements

The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) was developed for deployment in the Japanese Experiment Module (JEM) on the International Space Station (ISS), in cooperation with the Japan Aerospace Exploration Agency (JAXA) and the Japanese National Institute of Information and Communications Technology (NICT). SMILES conducted atmospheric observations for approximately six months from October 2009 to April 2010 to measure the concentrations of minor species in the stratosphere and mesosphere. The processing of SMILES data provided global and vertical distributions of atmospheric constituents related to ozone chemistry (e.g., O_3, HCl, ClO, HO_2, HOCl, BrO, O_3 isotopes, HNO_3, and CH_3CN). These data were distributed by ISAS/JAXA from DARTS (Data Archives and Transmission System; https://darts.isas.jaxa.jp/stp/smiles/; DOI:10.17597/ISAS.DARTS/STP-00001) for use by the scientific community.

SMILES observations have been extensively compared with other satellite data because of their high sensitivity measurements (e.g., Frith et al., 2020; Nara et al., 2020). They are also used as valuable reference data for chemistry-climate models (e.g., Akiyoshi et al., 2016) and as fundamental validation data for the international modeling community, including initiatives like the Chemistry-Climate Model Initiative (CCMI), as well as for reanalysis data including chemical species (Schanz et al., 2021).

1.3 UV measurements

1.3.1 Broadband measurements

Since 2000, CGER/NIES has utilized broadband radiometers to monitor surface UV-A and UV-B radiation at four observation sites in Japan. CGER/NIES calculates the UV Index from observed data and makes it available to the public hourly via the Internet.

1.3.2 Spectroradiometers

The JMA monitors surface UV-B radiation using Brewer spectrophotometers at Tsukuba in Japan and Syowa Station in Antarctica.

1.4 Calibration activities

1.4.1 International Center Activities

The JMA operates the Quality Assurance/Science Activity Center (QA/SAC) and the Regional Dobson Calibration Centre (RDCC) under the GAW program of the World Meteorological Organization (WMO) to ensure the quality of ozone observations in the WMO Regional Associations (RA) II (Asia) and V (Southwest Pacific). The Regional Standard Dobson (D116) was calibrated against the global standard instrument (D083) in February 2022 in Melbourne, Australia.

The JMA has finished to use Dobson instruments for its operational observations. Accordingly, the JMA intends to close those centers (QA/SAC and RDCC) after conducting the next Regional Intercomparison of Dobson Spectrophotometers for Asia, tentatively scheduled for September 2025.

1.4.2 National standard

The National Standard Brewer instrument was calibrated against the World Standard Triad, maintained by the Environment and Climate Change Canada (ECCC). The most recent calibrations were conducted in September 2023, in Toronto, Canada.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

Trend analyses of total ozone concentrations at the three sites (Sapporo, Tsukuba, and Naha), after accounting for solar activity, QBO, ENSO, and stratospheric aerosol variations, revealed an overall decrease in total ozone from 1979 to 1996 at Sapporo and Tsukuba; however, no marked changes have been observed since 2000. Vertical ozone profiles from Umkehr and sonde measurements from 1979 to 1996 showed decreasing trends in ozone levels at altitudes of 15-35 km at Sapporo, 20-42 km at Tsukuba, and 20–25 km and 35–38 km at Naha. In contrast, increasing trends in ozone levels since 2000 have been identified at altitudes between 30 and 35 km in Sapporo, and between 30 and 42 km in Tsukuba.

The UV radiation levels at three sites in Japan (Tsukuba, Naha, and Sapporo) have increased since the early 1990s. In Sapporo and Tsukuba, the annual cumulative daily erythemal UV radiation levels have significantly increased since the early 1990s. However, no statistically significant increase was observed for Naha. The increase rates were 3.3% (18.1 kJ/m^2) per decade at Sapporo and 4.1% (29.7 kJ/m^2) per decade at Tsukuba. These increases in UV radiation are considered to be related to the decrease in aerosol amounts and air pollution during this period. However, weather may also have contributed, and the cause of the increase in UV radiation has not been quantitatively determined.

The duration of solar exposure required for vitamin D_3 synthesis in the human body was estimated using radiative transfer calculations and UV-B and UV-A data recorded at four locations in Japan: Ochiishi, Rikubetsu, Tsukuba, and Hateruma (Miyauchi and Nakajima, 2016). The quasi-real-time data were acquired from the website of the Center for Global Environmental Research, National Institute for Environmental Studies, under the title "Information on Vitamin D Synthesis / Erythemal UV" at: http://db.cger.nies.go.jp/dataset/uv_vitaminD/en/index.html. The exposure time for the erythemal UV dose to reach 1 Minimal Erythema Dose (MED) is also provided on this website.

Atmospheric halocarbon measurements at Hateruma were utilized to estimate the emissions of the banned ozone-depleting substance CFC-11 in East Asia (Park et al., 2021). The study revealed that the unexpected increase in Chinese CFC-11 emissions starting in 2013 (Rigby et al., 2019) returned to pre-2013 levels in 2019.

3. THEORY, MODELLING, AND OTHER OZONE-RELATED RESEARCH

NIES, MRI, JAMSTEC, and Nagoya University have been developing chemistry-climate models. These institutes in Japan have provided simulation results of the recent past and future evolution of chemical species and climate to an international project, the Chemistry Climate Model Initiative (CCMI) (Morgenstern et al., 2017). NIES primarily developed simulations of stratospheric processes, JAMSTEC focused on tropospheric processes, and MRI addressed both stratospheric and tropospheric processes.

The latest version of the NIES CCM is CCSRNIES-MIROC5, developed based on the MIROC5 GCM by incorporating a stratospheric chemical process. The total ozone distribution has shown improvement compared to MIROC3.2, particularly in Northern Hemisphere high-latitude winters and springs. An ocean-coupled version of the MIROC5 CCM has also been developed. In addition to the chemistry-climate interaction simulation recommended by the CCMI, these models are used as chemical transport models (CTM). In the past, meteorological data were assimilated using a method of nudging for ozone simulation. Large multi-ensemble experiments using NIES CCMs, have investigated the effects of HFCs on the ozone layer (Dupuy et al., 2021), changes in the Arctic ozone layer (Yamashita et al., 2021; Akiyoshi et al., 2023; Hasebe et al., 2023), and the relationship between southern hemisphere sea surface temperature and the winter/spring Antarctic vortex strength/ozone ratio (Yamashita et al., 2023), among other topics. Some of these studies explored cases with extremely low and high ozone levels in large internal variations.

MRI has developed both the CTM and CCM to study stratospheric and tropospheric ozone. The current version of the model, MRI-CCM Version 2.1 (MRI-CCM2.1; Deushi and Shibata, 2011; Yukimoto et al., 2019), includes detailed tropospheric and stratospheric ozone chemistry. The model, used at the JMA, simulates ozone distributions by incorporating total ozone data from the Ozone Mapping & Profiler Suite (OMPS) instruments onboard the NOAA-20(JPSS-1) since 2023 and has produced several-day ozone forecasts. These calculated ozone distributions can be utilized to monitor variations in stratospheric ozone and total column ozone, and provide UV forecast services. The ozone distributions used in the JRA-3Q reanalysis (JRA-3Q Ozone) were calculated using MRI-CCM2.1 (Kosaka et al., 2024). For the JRA-3Q Ozone, bias-corrected multi-sensor total column ozone satellite data (Naoe et al., 2020) were assimilated into the model. MRI-CCM2.11 is also an important component model of the MRI earth-system model version 2.0 (MRI-ESM2.0; Yukimoto et al., 2019), which participated in the sixth phase of the Coupled Model Intercomparison Project (CMIP6).

Nagoya University, NIES, and JAMSTEC developed a CCM in 2011 (Watanabe et al., 2011), based on the MIROC climate model. This CCM was developed, by extending the upper boundary of the CHASER model from the lower stratosphere to the mesosphere, incorporating stratospheric chemistry and PSC processes. The CHASER model has been continuously utilized in CMIP-related model intercomparison projects (MIPs) such as CCMI and AerChemMIP, performing hindcast and future projections of global tropospheric and stratospheric ozone and aerosols (Morgenstern et al., 2017; Hakim et al., 2019). Additionally, a chemical data assimilation system based on the CHASER model (Miyazaki et al., 2012) was further developed by increasing spatial resolution (Sekiya et al., 2018).

4. DISSEMINATION OF RESULTS

4.1 Data reporting

The observational data recorded at the JMA stations were submitted monthly to the World Ozone and UV Data Centre (WOUDC) in Toronto, Canada. Additionally, provisional total ozone data were delivered daily in the Character Form for the Representation and Exchange of Data (CREX) through the WMO Global Telecommunication System (GTS) and utilized at the WMO Ozone Mapping Center in Thessaloniki, Greece, for mapping the total ozone distribution over the Northern Hemisphere.

The NIES and the Institute for Space-Earth Environmental Research (ISEE) of Nagoya University have established stations at Tsukuba and Rikubetsu equipped with NDACC instruments, including lidar systems, millimeter-wave radiometers, and FTIR spectrometers. These activities undertaken by these organizations have been integrated into NDACC measurements conducted in Japan.

4.2 Information to the public

JMA data summaries of total ozone, ozonesonde, and UV-B measurements are published monthly in Japanese (https://www.data.jma.go.jp/env/ozonehp/info_ozone.html). An annual report containing detailed trend analyses of ozone over Japan and globally is also published for both government and public use in Japan at https://www.data.jma.go.jp/env/ozonehp/annualreport_o3uv.html. Since 2005, the JMA has provided an Internet-based UV forecast service including hourly UV-index maps based on ozone forecast modeling techniques at https://www.data.jma.go.jp/env/uvindex/en/. The analytical UV maps and observations are also posted hourly on the same webpage. The MRI-CCM UV forecasts were replaced by MRI-CCM2 forecasts in 2014.

The Japanese MOE publishes an annual report on the state of the ozone layer, surface UV-B radiation, and atmospheric concentrations of ozone-depleting substances (in Japanese) at: http://www.env.go.jp/earth/ozone/o3_report/index.html.

The MOE supports research on environmental preservation in Japan and around the world, including ozone layer depletion, through the Environment Research and Technology Development Fund (ERTDF), and the results are published in Annual Summary Reports.

5. PROJECTS, COLLABORATION, TWINNING, AND CAPACITY BUILDING

N/A

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

Observational data acquired from all stations of JMA are submitted monthly to WOUDC.

CCMs have been developed and upgraded for reliable future predictions of ozone layer changes and a better understanding of chemistry-climate interactions.

7. FUTURE PLANS

The JMA is offering to host the Regional Intercomparison of Dobson Spectrophotometers for Asia in September 2025. Financial support is needed to cover transportation fees for Dobson instruments and trip expenses for their operators, especially for participants from developing countries.

Continued monitoring of ozone, water vapor, and other species at altitude levels near the tropical tropopause will further enhance our understanding of the role of the tropical transition layer in chemistry–climate interactions. Accurate measurements of trace gas concentrations in the stratosphere will continue to yield insights into its physical, chemical, and dynamical processes. For instance, precise monitoring of trace gases in the middle atmosphere allows for the determination of variability in the mean age of air variability and assessment of the capacity of current models to replicate changes in dynamical and transport processes.

The development and refinement of CCM and CTM numerical models will continue, leading to more predictions of future changes in the ozone layer and enhancing our understanding of mechanisms of chemistry–climate interactions.

Additionally, a satellite mission inspired by SMILES, known as SMILES-2, is being planned to observe temperature, wind fields, and distributions of atmospheric minor species across the full diurnal cycle from the middle atmosphere (stratosphere and mesosphere) to the upper atmosphere (thermosphere and ionosphere) over five years. SMILES-2 observations will provide unprecedented global information, including the upper mesosphere and lower thermosphere, areas that lacked observational data (Shiotani et al., 2019; Baron et al., 2020).

8. NEEDS AND RECOMMENDATIONS

Systematic observations to assess the evolving state of the ozone layer, including the detection of ozone layer recovery, should be sustained through cooperation with international monitoring networks such as NDACC and the WMO/GAW program.

A systematic calibration program and a well-coordinated monitoring network should be established to detect variations and long-term trends in ground-level UV radiation.

It is imperative to develop CCMs capable of accurately simulating the amount and distribution of water vapour in the stratosphere from the perspective of chemistry-climate interactions. These CCMs must be updated constantly based on the latest versions of climate models.

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