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WMO OZONE AND UV BULLETIN

Foreword

Prof. Petteri Taalas, Secretary-General, WMO

Until 2016, WMO, in collaboration with the European Ozone Research Coordinating Unit, published periodic Arctic and Antarctic Ozone Bulletins. They contained information and updates on the development of the ozone layer over the course of the year and were targeted at WMO Members who operate atmospheric monitoring stations and satellites to observe ozone and related parameters globally.

After seven years of interruption, I am happy to launch the WMO/Global Atmosphere Watch (GAW) Ozone and UV Bulletin 2023! It promotes the long-standing efforts of the GAW community in coordinating the global ozone observing network. The ozone layer protects life on Earth from harmful solar ultraviolet (UV) radiation, thus ozone observations are critical to protect human and environmental health. I would like to highlight the work that has been done over the past decades to continuously deliver long-term stratospheric ozone observations and track the current levels and trends of ozone depleting substances (ODSs). The Montreal Protocol, signed in 1987 and which came into force in 1989, has curbed the amount of ODSs in the atmosphere, resulting in a slow recovery of the ozone layer. These efforts have enabled strong collaboration between the Parties to the Montreal Protocol and produced observations critical to tracking the Antarctic ozone “hole”.

In the present Bulletin, you will find the latest news on the Antarctic ozone hole, global stratospheric ozone levels, the policy-relevant ozone assessment, the monitoring networks operating Brewer and Dobson spectrophotometers, and more.

Introduction

Matthew Tully, Chair, WMO Scientific Advisory Group on Ozone and Solar UV Radiation

In 1985, the governments of the world agreed to the Vienna Convention for the Protection of the Ozone Layer, quickly followed in 1987 by the Montreal Protocol on Substances that Deplete the Ozone Layer.

Due to actions taken under the Montreal Protocol and its subsequent amendments and adjustments, the rapid accumulation of ODSs in the global atmosphere taking place at that time was halted. In 2023, observations show that the total atmospheric abundance of chlorine and bromine from long-lived ODSs has now been in decline for more than 20 years. Early indications of the recovery of stratospheric ozone can now be seen, with a full recovery in most parts of the atmosphere projected to occur in the coming decades.

The current period is therefore sometimes referred to as the "accountability phase" of the Montreal Protocol. Continued high-quality measurements of stratospheric ozone and its drivers remain essential to ensure that the long-term changes in the ozone layer are well measured and their causes understood. Even with the expected continued full compliance to the Montreal Protocol by all nations of the world, a wide range of other human activities and natural events will continue to influence stratospheric ozone and surface UV radiation to a significant extent over the remainder of the twenty-first century.

WMO has played a critical role in the world's response to ozone depletion. From the late 1950s, through the Global Ozone Observing System (GO3OS), and since 1989, through the WMO GAW, WMO has supported and co-ordinated the high-quality measurement of stratospheric ozone and UV radiation around the world and the systematic storage and distribution of observational data. GAW has made a major contribution to the scientific study of stratospheric ozone and informed assessments of the state of the ozone layer, which have then been used by policymakers to make decisions based on the best available science.

This issue of the WMO Ozone and UV Bulletin presents news and information about the state of the ozone layer in 2022 and its influences, the state of ozone monitoring networks, and the latest assessments from the Scientific Assessment Panel and Environmental Affects Assessment Panel under the Montreal Protocol. As the protection of human health is the fundamental motivation of all such work, the Bulletin also provides information about a new smartphone app, launched in July 2022 with support from WMO in cooperation with the World Health Organization (WHO), the United Nations Environment Programme (UNEP) and the International Labour Organization (ILO). The SunSmart app was designed primarily to positively influence sun protection behaviour by letting individual users know the times of the day when sun protection is required.

The ozone layer in 2022

Wolfgang Steinbrecht, Antje Inness

The Montreal Protocol and its amendments have successfully phased out up to 99% of the production and consumption of controlled ODSs. The concentration of ozone depleting chlorine in the stratosphere reached its peak in the late 1990s. Since then, chlorine loading has been decreasing and stratospheric ozone is on a slow path to recovery which is expected to continue into the second half of this century. This slow recovery is masked by substantial ozone variations from year to year, which are largely driven by variations in atmospheric transport.

Figure 1 shows how the annual mean total ozone columns in 2022 have changed relative to the 2003 to 2021 climatology. The map in Figure 1 displays higher than normal ozone columns at the tropics and subtropics (latitudes lower than about 30°), and lower than normal ozone columns at higher latitudes, particularly in the southern hemisphere. It is quite typical to see such large differences in the total ozone between the higher and lower latitudes. It is related to the intensity of the mean meridional Brewer-Dobson Circulation (BDC), which redistributes ozone from low to high latitudes. In 2022, the BDC was relatively weak, resulting in high ozone at low latitudes and low ozone at higher latitudes. Three atmospheric conditions contributed to a weak BDC in 2022:

(1) A pronounced La Niña, with a cold tropical troposphere and reduced ascent in the tropical part of the BDC (Benito-Barca et al., 2022);

(2) The mostly westerly shear phase of the Quasi-Biennial-Oscillation (above 30 hPa), which caused a weakening in tropical upwelling of the BDC (Baldwin et al., 2001);

(3) The unprecedented amount of water vapour and additional aerosol injected into the stratosphere by the Hunga Tonga-Hunga Ha'apai underwater volcanic eruption in January 2022. Radiative cooling due to the enhanced water vapour resulted in an unusually cold southern hemisphere stratosphere, which also slowed the BDC in the southern hemisphere (Coy et al., 2022; Wang et al., 2022).

Overall, these variations contributed, to a large part, to the ozone anomalies shown in Figure 1. More details about the 2022 Antarctic ozone hole, and about the Hunga Tonga eruption can be found in later sections of this Bulletin.

The Antarctic ozone hole in 2022: Later and longer in duration

Jos de Laat

The two key characteristics of the 2022 Antarctic ozone hole were its relatively late onset in September and its relatively large extent and depth in October and November (Figure 2).

The late onset of ozone depletion in September is consistent with previous years and is in line with the post-2000 decreasing trend in the early September Ozone Mass Deficit (OMD) (Figure 3). Compared with the 1990–2010 daily Antarctic ozone hole statistics, depletion is delayed between three to five days (Figure 2). As described in Chapters 4 of both the *Scientific Assessment of Ozone Depletion: 2022* (Chipperfield et al., *GAW Report No. 278*)

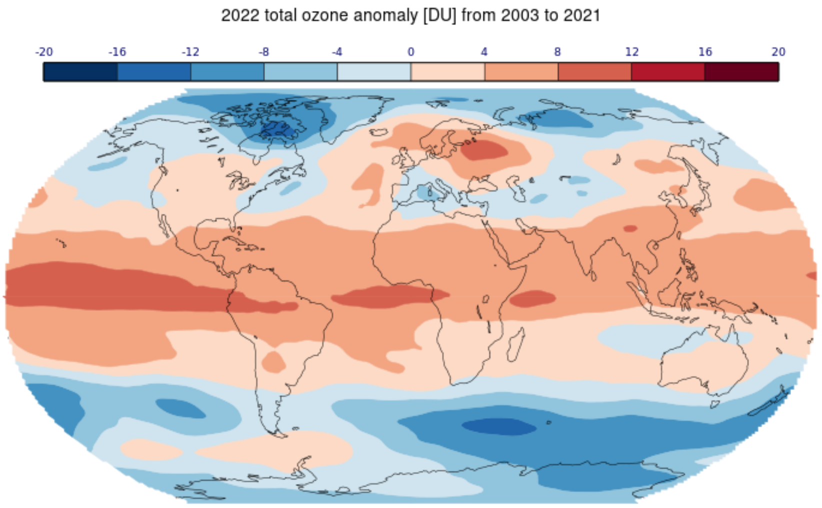


Figure 1. Deviation of the 2022 annual mean total ozone column from the 2003 to 2021 climatology
Source: Results are from the Copernicus Atmosphere Monitoring Service Reanalysis (Inness et al., 2019).

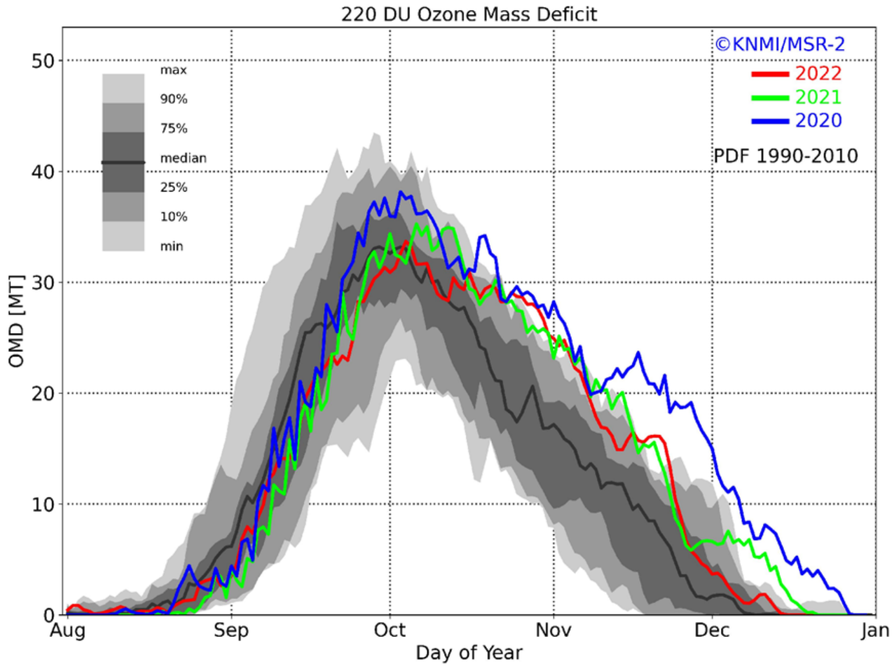


Figure 2. Probability distribution of daily Antarctic 220 Dobson Unit (DU) Ozone Mass Deficit (OMD, in megaton (Mt.)). The grey envelope denotes the 1990–2010 daily probability distribution, with the median value in black. The recent years of 2020, 2021 and 2022 are indicated by the coloured lines (red, green and blue).

Source: Data from Multi-Sensor Reanalysis version 2 (MSR-2) data set, Royal Netherlands Meteorological Institute (KNMI), accessible via https://www.temis.nl/protocols/O3global.php; see also van der A et al., 2015

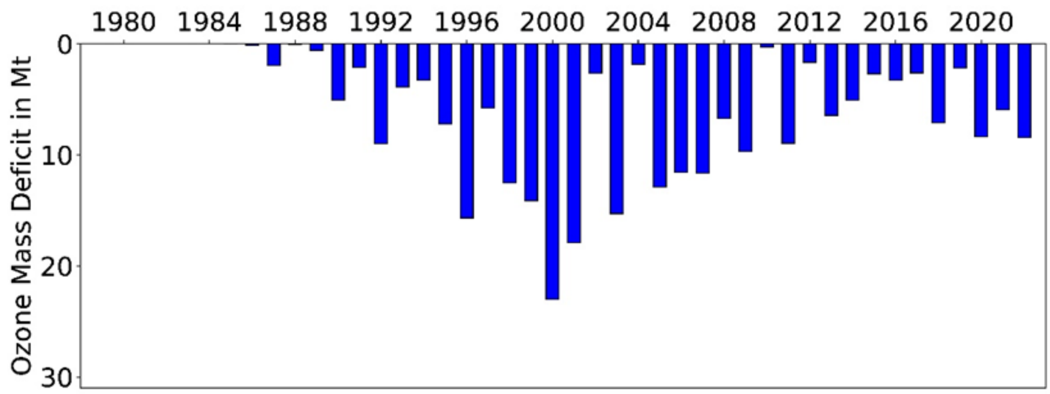


Figure 3. Average OMD (megaton O_3), 1–14 September, relative to the 220 DU threshold based on KNMI MSR-2 data. Post-2000 ordinary linear regression gives a slope of –0.44 ± 0.32 Mt/year (2σ). Excluding years with anomalously weak southern hemisphere planetary wave activity (2002, 2004, 2010, 2012, 2017, 2019) yields a slope of –0.68 ± 0.24 Mt/year.

and the *Scientific Assessment of Ozone Depletion: 2018* (Langematz et al., *GORMP Report No 58*) (and references therein), the delay and decreasing early September OMDs are considered key pieces of evidence that the ozone layer is beginning to recover.

Longevity and a late breakup of the Antarctic stratospheric vortex as in 2022 have been observed in four out of the last five years (2018, 2020, 2021, 2022). These years are characterized by anomalously weak southern hemisphere planetary wave activity (Kramarova et al., 2019, 2020, 2021, 2022 (2023 in preparation)). Planetary waves propagating upwards from the troposphere decelerate the polar stratospheric vortex, and transport ozone-rich air from the outer into the upper vortex while warming it. The lack of wave activity allows the inner stratospheric vortex air to remain colder than average for longer, favouring smaller than typical ozone column amounts. This phenomenon has kept the ozone mass deficit during recent years well above the 1990–2010 average (Figure 2).

In addition, this recent recurrence of years with late breakup dates has resulted in a statistically significant trend in later breakup dates of approximately five days per decade (Kramarova et al., 2023, in preparation). However, causes of the recent weak southern hemisphere planetary wave activity and the delayed breakup dates are currently unknown. Whether this trend is the result of random annual variations of below-average southern hemisphere planetary wave activity or of a yet unknown physical mechanism, is not yet fully understood.

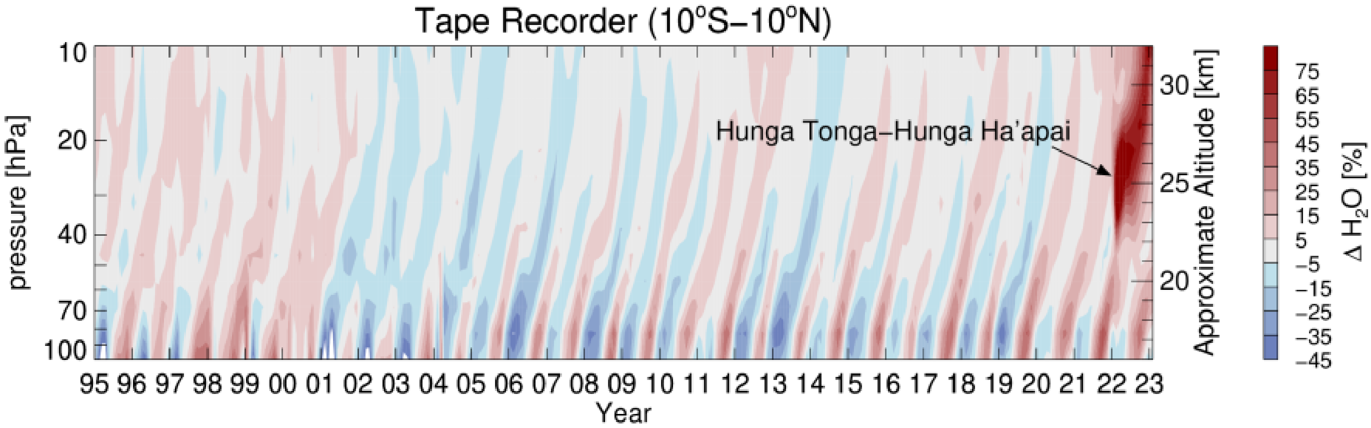


Figure 4. Deviation of water vapour content in the tropical stratosphere from the long-term mean

Source: Underlying data are from the global ozone chemistry and related trace gas data records for the stratosphere (GOZCARDS) satellite-composite, with recent MLS data appended. Updated from Millán et al. (2022).

Hunga Tonga-Hunga Ha'apai volcanic eruption changes the stratosphere

Wolfgang Steinbrecht

In January 2022, the Hunga Tonga-Hunga Ha'apai volcano ("Hunga Tonga"), located under the ocean surface in the western Pacific, erupted. This eruption was the largest in the last 100 years, and was comparable to the immense Krakatoa eruption of 1883. The eruption itself occurred under the ocean's surface and injected ice and water vapour high into the stratosphere. Figure 4 shows the enhanced water vapour "hot spot" due to Hunga Tonga in 2022 (greater than +70% shown in dark red). Overall, the eruption increased the water vapour content of the stratosphere by 5% to 10%, but some local enhancements reached several hundred ppmV (Vömel et al., 2022; Millán et al., 2022). Compared to previous eruptions, such as Pinatubo in 1991, the increase in stratospheric aerosol was relatively small (Khaykin et al., 2022).

Figure 5 shows the detailed distribution of the Hunga Tonga water vapour cloud spread from the tropics to higher latitudes. In 2022, the greatest spread of water vapour reached further into the southern hemisphere than into the northern hemisphere. The additional water vapour has resulted in substantial cooling of the stratosphere above the southern hemisphere, by several kelvin (Coy et al., 2022; Wang et al., 2022). This slowed the meridional BDC and resulted in less ozone in the lower stratosphere of the southern hemisphere in 2022. In the mid- to upper stratosphere, the net effect on ozone appears to be small so far.

As seen in Figure 5, the enhanced water vapour did not reach the 2022 Antarctic and 2022/2023 Arctic polar vortices. For the next several winters, however, enhanced water vapour and aerosol in the polar vortices is expected. This could result in more polar stratospheric clouds (PSCs), enhanced ozone depletion (Wang et al., 2022), and larger and longer-lasting "ozone holes".

The eruption of Hunga Tonga is likely to trigger significant and unprecedented effects over the next several years. Their explanation will require continued precise and regular measurements, from ground- and space-based systems, such as the National Aeronautics and Space Administration (NASA) Microwave Limb Sounder (MLS) satellite instrument.

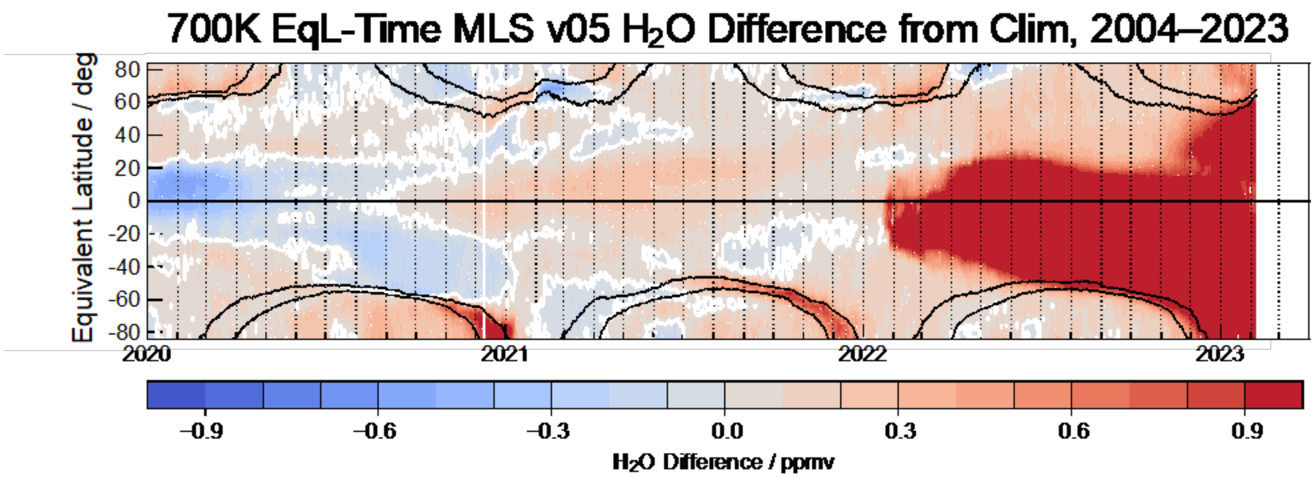


Figure 5. As for Figure 4, but showing the evolution of water vapour anomalies (zonal means) on the 700 K isentropic surface (~18 hPa or 27 km altitude), as a function of time (since 2020) and equivalent latitude. The black isolines indicate the edges of the stratospheric polar winter vortices.

Source: Updated from Millán et al. (2022)

The SunSmart Global UV app: Increasing UV awareness and sun protection habits across the globe using the Global Solar UV Index

Craig Sinclair

Up to 95% of melanoma and 99% of non-melanoma skin cancers are a result of over exposure to UV radiation. Despite being largely preventable, skin cancer remains a global problem, with an estimated 1.5 million people diagnosed in 2020 worldwide.

Evidence shows that personal habits in relation to ongoing sun exposure, including sunscreen use, clothing choice and time spent outdoors, are the most important individual risk factors for UV-related skin and eye damage. While great gains have been made in relation to the implementation of the Montreal Protocol which have reduced the impact of UV on human health, it is still vitally important for the public to garner a better understanding of the dangers of prolonged UV radiation exposure.

A new app for smartphones has been recently launched globally, providing localized information on UV radiation levels through a five-day forecast. The app seeks to bring worldwide consistency to UV reporting and public health messaging, in order to tackle the worldwide burden of skin cancer and UV-related eye damage. It does this by bringing sun protection advice to anyone with the app on their mobile phone based on their selected location.

Developed in Australia by the Cancer Council Victoria, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) and the Bureau of Meteorology, the app was launched in July 2022 with the support of the WHO, WMO, the United Nations Environment Programme (UNEP) and the ILO. The SunSmart app was designed primarily to influence sun protection behaviour by letting individual users know the times of the day when sun protection is required, no matter their location.

Features

- Supported by world leading health and meteorological organizations;
- UV and sun protection alerts each day: live UV data is updated by the minute and is available to anyone within a 100 km radius of a fixed UV monitoring site;
- Option to create unique alerts that suit user's schedule and location;
- Access to worldwide UV levels for up to five locations that can be specifically tailored, providing clear guidance on when sun protection is and is not required;
- Five-day UV forecast of sun protection times and weather information;
- Available in eight languages: English, French, Spanish, Dutch, Chinese, German, Italian and Russian.

The SunSmart Global UV app is available free of charge at both the Apple App and Google Play stores.

If you would like the app to include a link to a live UV data feed for your country or if you would like any further information about the SunSmart Global UV App, please contact sunsmart.enquiries@cancervic.org.au.

The General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention for the Protection of the Ozone Layer

Sophia Mylona

The General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention for the Protection of the Ozone Layer (the Trust Fund) was established in February 2003 pursuant to Decision VI/2 of the sixth meeting of the Conference of the Parties to the Vienna Convention. It is an extrabudgetary fund based on voluntary contributions from parties and international organizations.

The primary aim of the Trust Fund is to provide complementary support for the continued maintenance and calibration of the existing WMO/GAW ground-based stations for monitoring column ozone, ozone profiles and UV radiation in developing countries and in countries with economies in transition, to promote balanced global coverage. Consideration of support is also given to other activities for the improvement of the observation network, identified by the Ozone Research Managers and in consultation with the co-chairs of the Montreal Protocol's Assessment Panels.

Since 2015, the activities of the Trust Fund have been overseen by an Advisory Committee which also implements the long-term strategy and short-term plan of action it has developed, taking into consideration the recommendations of the Ozone Research Managers.

From the inception of the Trust Fund in 2003 to date, 22 activities have been endorsed, out of which 16 have been completed, 2 are ongoing, and 4 are planned. The geographical distribution and type of approved activities are presented in Figure 6. Further information on activities supported by the Trust Fund can be found on the Ozone Secretariat website.

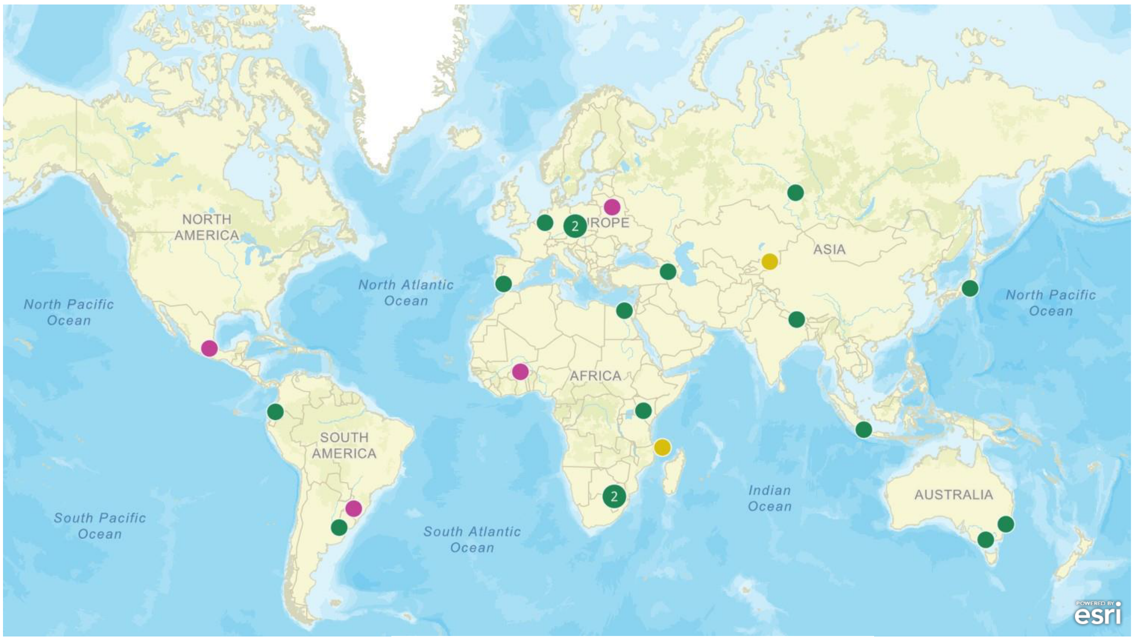
European Brewer Network: Five years on

John Rimmer

The European Brewer Network, EUBREWNET, was developed and implemented through COST Action ES1207 with the aim of harmonizing the Brewer spectrophotometer measurements of ozone, UV, and aerosol optical depth (AOD) in the UV (AODUV). The Action ended in 2017 with the successful implementation of the network and reporting and archiving of the total column ozone product (Rimmer et al., 2018). The network employs central data processing and quality assurance systems to ensure that the data collected from different instruments is equivalent and spatially consistent.

Since its inauguration, EUBREWNET has been funded and operated by AEMET (the State Meteorological Agency, Spain) and in five years it has grown from a European to a global network, with 63 individual stations registered (Figure 7). Instrument characterizations and intercomparison campaigns have led to better data processing algorithms which account for error sources. The UV and AODUV products have also been made available as data that are collected and made available automatically in near real time. EUBREWNET is now a fiducial reference network for the Copernicus Climate Change Service (C3S) satellite validation programme. Data are available in various file formats and a version 2 algorithm is currently being tested that incorporates, inter alia, updated absorption cross-sections.

EUBREWNET has also been active in providing operator training and station assistance, often in cooperation with WMO and the UNEP Ozone Secretariat.



Project types	No of projects
Brewer calibrations	3
Brewer relocation	1
Dobson intercomparisons	7
Dobson relocations	3
Ozone observatory	1
Ozone sondes[1]	2
UV-B monitoring	1
Workshops[2]	4
Total	**22**

1 Ozone sondes include launch and training

2 Workshops on data quality, data management, training of Dobson and Brewer instrument operators, Dobson calibration

Activities ● Completed ● Ongoing ● Planned

Figure 6. Geographical distribution of completed, ongoing and planned activities approved under the Vienna Convention Trust Fund on Research and Systematic Observations since 2003. More than one activity at a location is indicated by a number in the corresponding circle.

Source: Environmental Systems Research Institute (ESRI), UNEP Ozone Secretariat

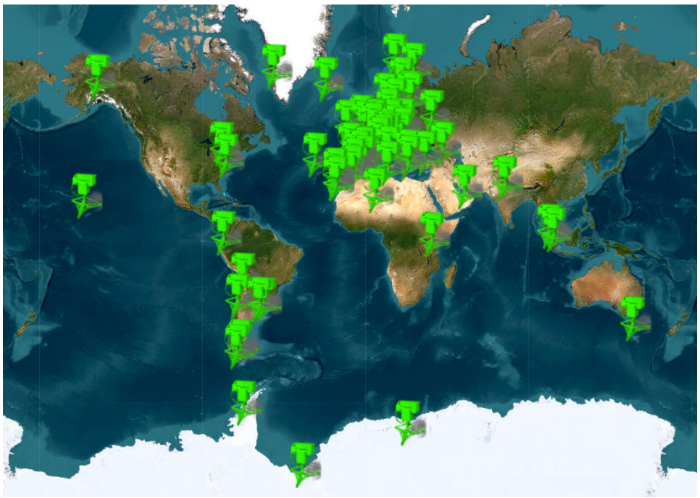


Figure 7. A recent snapshot of the EUBREWNET showing the growing global coverage

Dobson network and World Dobson Calibration Center news

Irina Petropavlovskikh

The WMO/GAW Dobson total ozone observing network consists of approximately 55 currently active stations operating the Dobson ozone spectrophotometer (Figure 8).

Data products are shared through the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) maintained by Environment and Climate Change Canada.

The WMO World Dobson Calibration Center is hosted by the National Oceanic and Atmospheric Administration (NOAA) in Boulder, United States of America, and maintains the World Standard Dobson D083, which is used for regular calibration of the Regional Dobson Standards.

Every two years, a series of measurements are made with D083 at the Mauna Loa Observatory to re-derive its calibration constant using the Langley method. The unique location of Mauna Loa Observatory makes it ideal for this function, being above the marine boundary layer and far from major pollution sources. The limited presence of aerosols and clouds allows for stable observing conditions over the large range of solar zenith angles needed for precise calibrations.

Regional Standard Dobsons are compared and calibrated to the World Standard every four years. Periodic calibrations ensure the comparability and traceability of global measurements of total column ozone and the stability of satellite-based ozone records.

The most recent calibration of D083 at Mauna Loa took place in July and August of 2021. In November 2022, an eruption of the volcano damaged the service road to the observatory and calibrations at the site have had to be suspended. The next calibration campaign is therefore being planned at the Izaña Atmospheric Observatory in Tenerife (Spain) for the northern hemisphere summer of 2023, with the assistance of the Spanish State Meteorological Agency (AEMET).

Ozone assessment: Scientific Assessment Panel, Environmental Effects Assessment Panel

Alkis Bais, David Plummer

The three Assessment Panels of the Montreal Protocol have now delivered their 2022 quadrennial assessment reports, produced following the Terms of Reference approved by the Parties at their thirty-first meeting in 2019 (Decision XXXI/2). The present update focuses on the activities of the Scientific Assessment Panel (SAP)

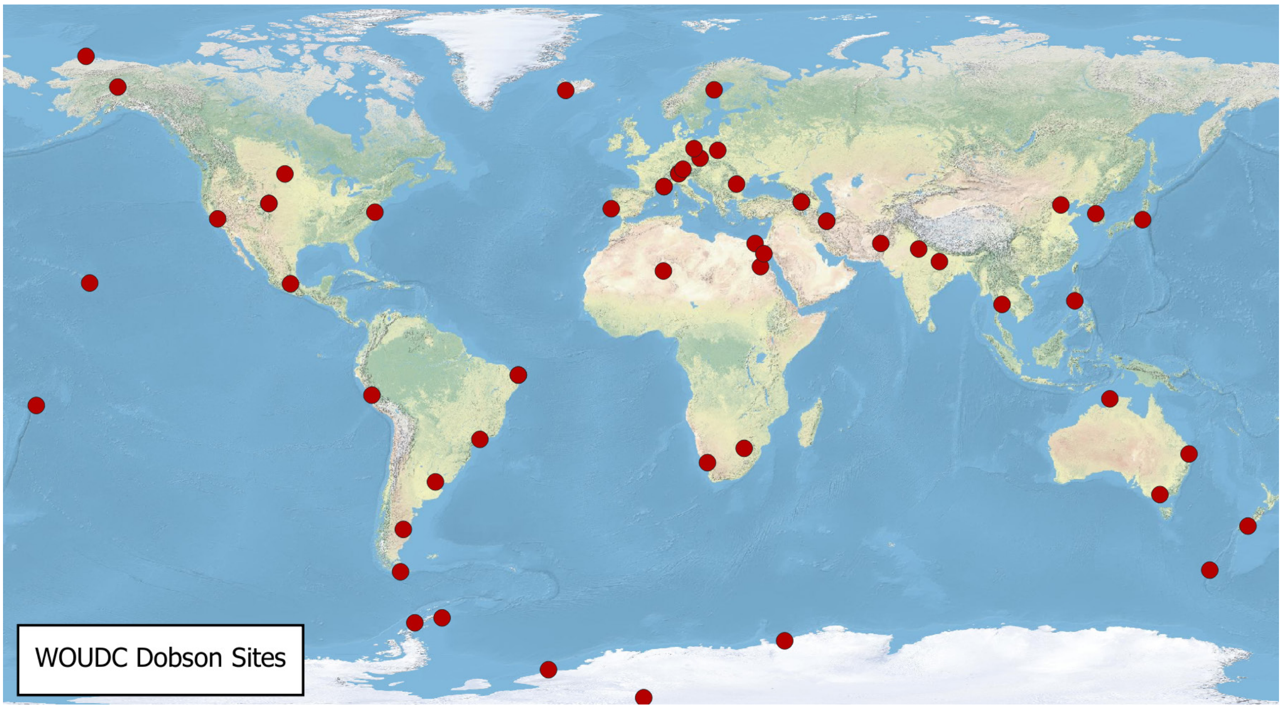


Figure 8. The GAW Dobson network (Dobson stations which have submitted ozone data to WOUDC within the 2018–2023 period are marked)

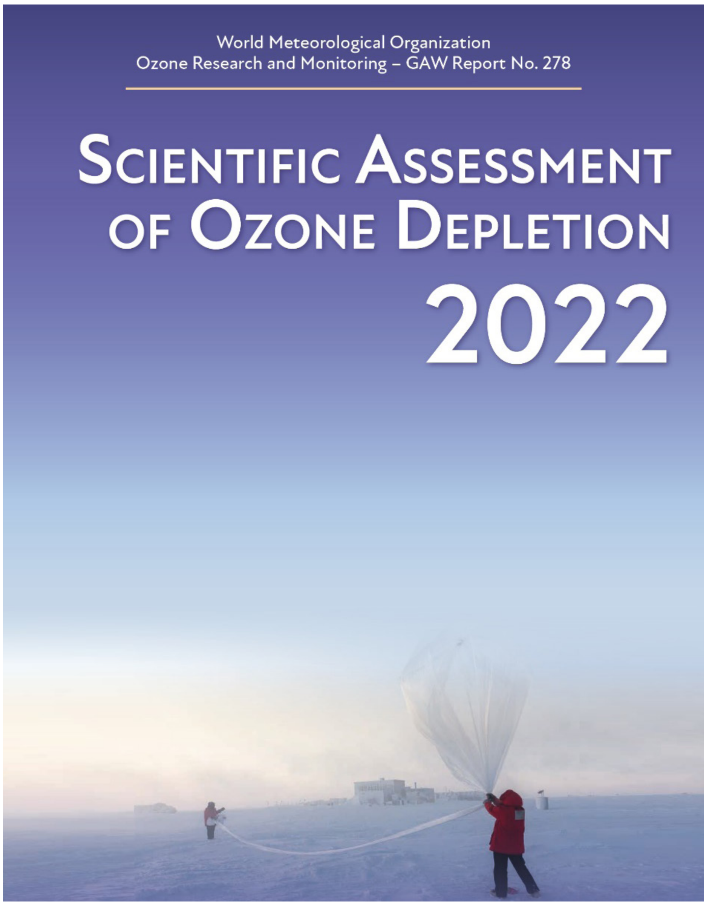


Figure 9. The cover of the Scientific Advisory Panel report for the 2022 ozone assessment

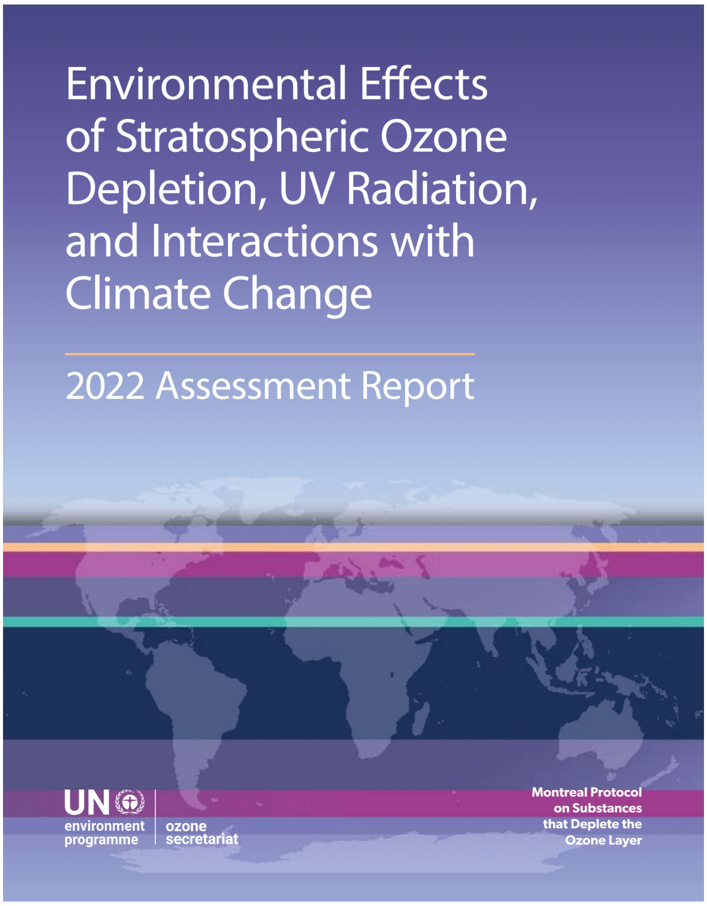


Figure 10. The cover of the Environmental Effects Assessment Panel report for the 2022 ozone assessment

and the Environmental Effects Assessment Panel (EEAP). The assessment of the third panel, the Technology and Economic Assessment Panel (TEAP), is not discussed here.

The SAP provides: policy-relevant information on the current state of the stratospheric ozone layer, including trends in ozone and the atmospheric abundance of ODSs; updates on our scientific understanding of processes that affect ozone; and projections of the future changes of ozone. Following the Terms of Reference for the 2022 assessment, the SAP report includes, for the first time, a chapter on the effects on the ozone layer of geoengineering by stratospheric aerosol injection. The 2022 report of the SAP shows a continued decrease in the atmospheric abundance of chlorine and bromine from the long-lived ODSs controlled under the Montreal Protocol. Evidence that the Antarctic ozone hole is recovering has strengthened since the 2018 Assessment. The recovery is most clearly seen in the early austral spring (September), with significant variability in the persistence of the ozone hole in the late spring due to year to year variability of meteorological conditions. Near global (60°S–60°N) total column ozone remains approximately 2% lower than the 1964–1980 average, while showing a small positive trend of 0.3% per decade over 1996–2020 that lies within the uncertainty range. Updated projections of the dates for recovery of total column ozone to 1980 values have the near-global (60°S–60°N) mean recovering around 2040, with the northern mid-latitude (35°N–60°N) columns recovering around 2035 and springtime (October) values over Antarctica (90°S–60°S) recovering around 2065. The full text of the report can be found at *Scientific Assessment of Ozone Depletion 2022*.

The EEAP evaluates the consequences of stratospheric ozone depletion in the context of a changing global climate within the framework of the United Nations Sustainable Development Goals (SDGs). As with the other assessment panels, the EEAP alerts the Parties to additional areas of potential importance to the Montreal Protocol. The 2022 quadrennial assessment focuses on the interactive effects of stratospheric ozone and climate change on solar UV radiation, human health including COVID-19, terrestrial and aquatic ecosystems, biogeochemical cycles, tropospheric compositions and air quality, natural and synthetic materials, and microplastics in the environment. Particular attention is given to the linkages between stratospheric ozone depletion and UV radiation, and climate change, with respect to their broad effects on the environment and human health. The variability of UV radiation in Antarctica was very large during the last four years, and despite initial signs of ozone recovery, increases in the UV Index of up to 80% relative to the historical mean were observed in the southern hemisphere spring of 2020 and 2021. In the Arctic, stratospheric ozone variations led to large variability in UV radiation at northern high latitudes during late northern hemisphere winter and spring. Outside the polar regions, the long-term changes in UV radiation are mainly controlled by changes in aerosols and clouds.

Benefits arising from the implementation of the Montreal Protocol on past, present, and future UV radiation and regional weather patterns are also discussed in this report, as well as the increased frequency and intensity of extreme climate events that are occurring together with the ongoing increase in emissions of greenhouse gases and consequent rising temperatures in many parts of the world. These changes also affect the amount of exposure to UV radiation of humans, other animals, and ecosystems, with implications for human well-being, food security, biodiversity and the overall sustainability of our Earth system. The full text of the report can be found at *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change: 2022 Assessment Report*.

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