WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

No. 2 – SEPTEMBER 2024

WMO OZONE AND UV BULLETIN

Introduction

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

The recent meeting of the Ozone Research Managers (attendees pictured in Figure 1) noted that, due to the success of the Montreal Protocol on Substances that Deplete the Ozone Layer (hereinafter, the Montreal Protocol), atmospheric abundances of tropospheric chlorine and bromine from long-lived ozone-depleting substances have continued to decline, and that evidence has strengthened for ozone recovery in some parts of the atmosphere.

From its inception up to the present day, one of the pillars of the Montreal Protocol has been its foundation in very high-quality science.

The WMO Global Atmosphere Watch (GAW) Programme continues to play an essential role in supporting ozone science through observations, analysis, modelling, data stewardship and capacity-building. It is critical that observations of ozone, ozone-depleting substances and ultraviolet (UV) radiation are maintained with the quality, resolution and global coverage necessary to account for changes in ozone over the coming decades. Many factors will influence the expected recovery of ozone, which must be fully measured and understood.

This second edition of the *WMO Ozone and UV Bulletin* presents global news and information about the state of the ozone layer and the Antarctic ozone hole in 2023. It also outlines measures to protect human health and the environment from damaging UV radiation, as well a recent major activity to restore Brewer observations in South America, supported by the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention (hereinafter, the Trust Fund).

State of the ozone layer in 2023

Wolfgang Steinbrecht, Mark Weber, Antje Inness

Figure 2 shows the distribution of the annual mean total ozone column anomaly for 2023. In general, the distribution was similar to that seen in 2022 (WMO, 2023). The 2023 Antarctic and northern mid-latitude ozone values were below their 2003–2021 climatological average values, while ozone values were higher than their climatological average values in a broad latitude band from 30° N to 60° S and over the North Polar region.

Figure 1. Attendees at the Ozone Research Managers twelfth meeting, Geneva, April 2024
Photo credit: Fabian Rubiolo

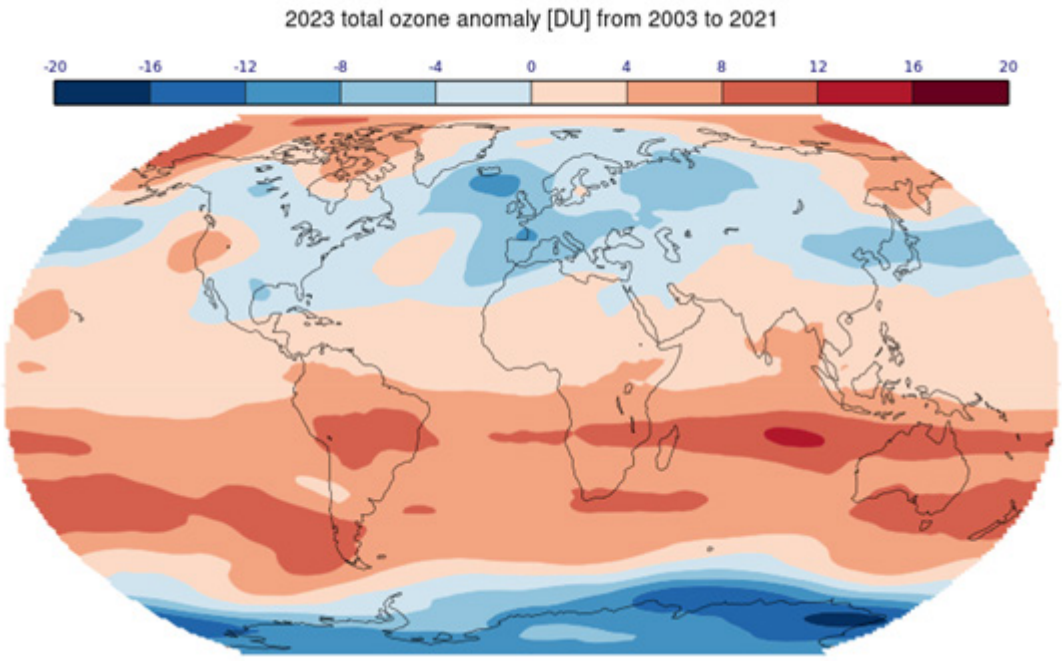

Figure 2. Deviation of the 2023 annual mean total ozone column, in Dobson units (DU), compared to the 2003–2021 climatology
Source: Results are from the Copernicus Atmosphere Monitoring Service Reanalysis (Inness et al., 2019).

This pattern of higher ozone at low latitudes and lower ozone at high latitudes is related to the intensity of the mean meridional Brewer-Dobson circulation (BDC) (which redistributes ozone from low to high latitudes). Particularly in winter months, a weak BDC will transport less ozone-rich air from low to high latitudes, resulting in high total ozone columns in the tropics and low columns at higher latitudes. In the first half of 2023, the weak BDC was due to the westerly phase of the Quasi-biennial Oscillation (QBO), the periodic variation of equatorial winds. This westerly QBO prevailed during the northern hemisphere winter and spring of 2022/2023 and induced a residual circulation, weakening the BDC in the northern hemisphere (Baldwin et al., 2001).

In contrast, in the southern hemisphere, more widespread higher positive anomalies were due to the combination of an easterly QBO after June 2023 and an emerging strong El Niño from the middle of 2023. Both strengthened the BDC in the southern hemisphere winter (Baldwin et al., 2001; Benito-Barca et al., 2022), resulting in enhanced ozone columns at southern mid-latitudes, particularly after August 2023, and larger positive anomalies, as seen in Figure 2, over much of the southern hemisphere (except for Antarctica: see the section *State of the Antarctic ozone hole in 2023* in the present Bulletin).

Total column ozone values in 2023 were within the range observed in previous years and in line with expectations, owing to the beginning of the decline of ozone-depleting chlorine and bromine in the stratosphere (WMO, 2022). In the southern hemisphere, the higher mid-latitude values of 2023 ended several years of low total ozone columns, caused in part by the large Australian wildfires in 2020/2021 and by ozone transport changes induced by excess water vapour from the Hunga Tonga-Hunga Ha'apai volcanic eruption in 2022. The 2023 Antarctic ozone hole started earlier than in previous years and lasted until mid-December, leading to the negative annual anomaly over Antarctica seen in Figure 2.

State of the Antarctic ozone hole in 2023

Jos de Laat

The 2023 Antarctic ozone hole was marked by two unusual characteristics: an early onset in late August, and persistence well into December. Although a long duration was also observed in 2022 (WMO, 2022), the 2023 early onset deviates from the trend of recent years. The consistent later onset of the development of the ozone hole prior to 2023 has been identified as a robust early indication that the ozone hole is recovering (WMO, 2022).

When compared to 2022, October and November of 2023 saw significantly less ozone loss (see Figure 3). The important eruption of the Hunga Tonga-Hunga Ha'apai volcano on 15 January 2022 increased the amount of water vapour in the stratosphere. While recent research indicates that in the lower Antarctic stratosphere this excess water vapour has had a limited effect on the rate of ozone destruction that is triggered by sunlight and the addition of certain chemical substances, such excess water vapour did enhance depletion in the middle and upper layers, particularly near the edge of the Antarctic stratospheric vortex (Zhang et al., 2024; Wohltmann et al., 2024). The cooling effect of water vapour further supported such ozone destruction, contributing to the early onset observed in 2023, although these losses remained smaller than those in the late Antarctic spring (Zhang et al., 2024; Wohltmann et al., 2024).

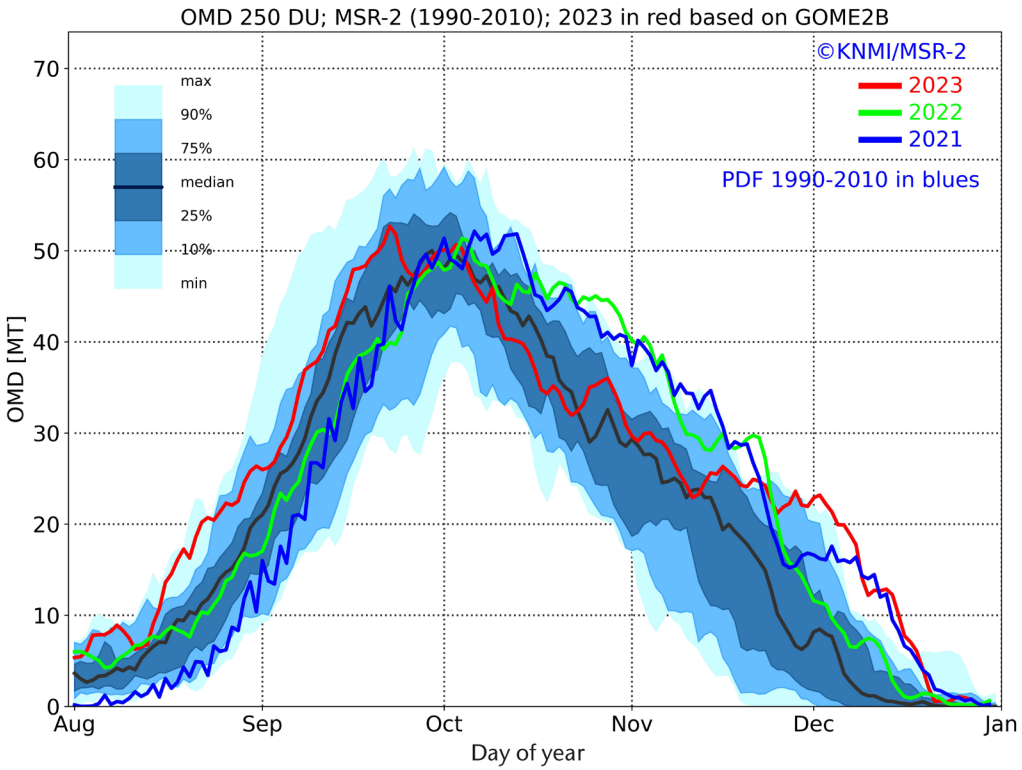

Figure 3. Daily Antarctic ozone mass deficit (OMD in megatonnes (MT)) relative to the 250 Dobson units (DU) total ozone column level (Strahan et al., 2019) based on multi-sensor reanalysis (MSR-2) total ozone reanalysis data (van der A et al., 2015). The red, green and blue lines show data for 2023, 2022 and 2021, respectively. The blue envelope represents the historical envelope and probability distribution of daily OMD data for the period 1990–2020 (PDF = probability density function).

Source: Modified from https://temis.nl/protocols/o3hole/index.php, Royal Netherlands Meteorological Institute (KNMI)

It is interesting to note that no accelerated ozone destruction was detected in September 2023, with model simulations indicating that ozone loss due to additional water vapour has been minor (4 DU) (Wohltmann et al., 2024; Santee et al., 2023). October and November 2023 saw a reduction in the ozone mass deficit (OMD) (Zhang et al., 2024; see also Figure 3), a sign that springtime ozone depletion was milder than earlier in the century. This is likely a reflection of the decline of ozone-depleting substances in the atmosphere and another indication that halogen-driven ozone depletion has decreased.

However, total ozone levels over the Antarctic were lower than average between January and July 2023 (Zhou et al., 2024), which led to an earlier detection of the ozone hole, based on normal detection thresholds of either 220 DU or 250 DU for OMD (Strahan et al., 2019). Total ozone column levels were impacted into the Antarctic spring due to these low starting levels. This could be related to enhanced mid-latitude stratospheric ozone depletion from the Hunga Tonga-Hunga Ha'apai eruption.

The last six Antarctic ozone holes, excluding 2019, have shared one or both of these two unusual characteristics, namely the early onset and the persistence of the Antarctic ozone hole. These findings reflect the influence of a weaker Brewer-Dobson circulation and planetary wave activity, which result in less mixing of ozone-rich air from the outer Antarctic stratospheric vortex, and could delay the final warming and breakup of the vortex (Kessenich et al, 2023; Kramarova et al., 2024). These persistent features are not fully understood but are the focus of ongoing research.

Overall, the two key unusual characteristics do not challenge the recent findings (as set out in WMO, 2022) that recovery of ozone in the Antarctic ozone hole has started. They do, however, highlight that there are relatively rare atmospheric events that can have a significant impact on the Antarctic ozone hole; that there is much variability at timescales from days to years in the development of the Antarctic ozone hole; that there are still gaps in the scientific understanding of that variability; and that it remains crucial to maintain an observational infrastructure that enables us to attribute unusual or unexpected variations to particular geophysical processes and events.

Benefits of the Montreal Protocol on pollution from plastics

Anu Heikkilä, Alkis Bais

Global production of plastics has grown 200-fold since the 1950s and doubled over the last two decades without signs of deceleration. In terms of malleability and durability, plastics often outperform alternative materials. It is no wonder that plastics are nowadays being used everywhere in everyday commodities ranging from food packaging to 3D printed housing.

Unfortunately, along with plastic production, the amount of mismanaged plastic waste has also rapidly increased. Once migrated into the environment, the macro-sized debris undergo a weathering process that leads to fragmentation into smaller pieces (see Figure 4). Solar UV radiation is the main factor initiating the superficial photodegradation (the process of degradation of a material by light) of plastics in the environment. Further deterioration, which is caused by solar UV radiation together with other stress agents like heat, moisture and mechanical forces, results in fragments of various sizes: microplastics with dimensions less than 5 mm, and nanoplastics smaller than 0.1 μm. Therefore, changes in UV radiation are expected to influence the abundance of these compounds (plastic debris) in the environment.

The Montreal Protocol has been recognized as the most effective global environmental treaty of all time. Indeed, it has successfully prevented global-scale increase of medium-wave ("UV-B") solar radiation reaching the Earth's surface. In the context of plastic degradation, the Montreal Protocol has helped in curbing the uncontrolled formation of micro and nanoplastics. As a fortunate side effect, the Montreal Protocol has partly mitigated global warming by reducing ozone-depleting substances that also function as greenhouse gases. This side effect has slowed plastic fragment production by reducing the effectiveness of relevant outdoor weathering processes.

Today, micro and nanoplastics are found everywhere on the planet: in water bodies, from the bottom of the oceans to the sea ice of the Arctic, as well as in soil and air. Unfortunately, they have also been detected in organisms of all sizes, including humans (Amereh et al., 2022; Blackburn and Green, 2022; Liu et al., 2023). In ecosystems, micro and nanoplastics have numerous direct and indirect consequences, most of which are difficult to quantify. The situation is further complicated by the leaching of various potentially toxic substances used as additives to improve durability and/or performance of plastics.

In its Update Assessment 2023, the Environmental Effects Assessment Panel of the United Nations Environment Programme has assessed the current understanding on the interactive effects of solar UV radiation and climate change on the production of plastic pollution (UNEP, 2023; see also Jansen et al., 2024). Despite gaps in knowledge, the Panel concludes that micro and nanoplastics represent one of the most alarming environmental concerns today. When striving towards a healthy sustainable planet, solar UV radiation and climate-mediated impacts on fragmentation of plastics are key considerations.

Effective planning tool for local UV protection measures

Cornelia Baldermann, Matthias Sühring, Helge Knoop, Katrin Gehrke, Sebastian Lorenz

UV radiation is carcinogenic (El Ghissassi et al., 2009), and the main cause of skin cancer. It can also lead to serious diseases of the eyes and skin that occur both immediately and later in life (German Commission on Radiological Protection, 2016). Skin cancer is the most common cancer in fair-skinned people worldwide (Apalla et al., 2017) and its incidence is steadily increasing across all populations worldwide. As this situation threatens to worsen regionally with climate change (Baldermann et al., 2023), more effective preventive measures are urgently needed. These measures include designing people's surroundings in such a way that high UV exposure can be avoided. Here, changes in urban planning, infrastructure and building design, as well as landscape architecture, among others, are called upon. A tool is needed to identify possible UV exposure during the construction planning phase, and to incorporate structural-technical measures, including vegetation, in the plan to reduce UV exposure as effectively as possible.

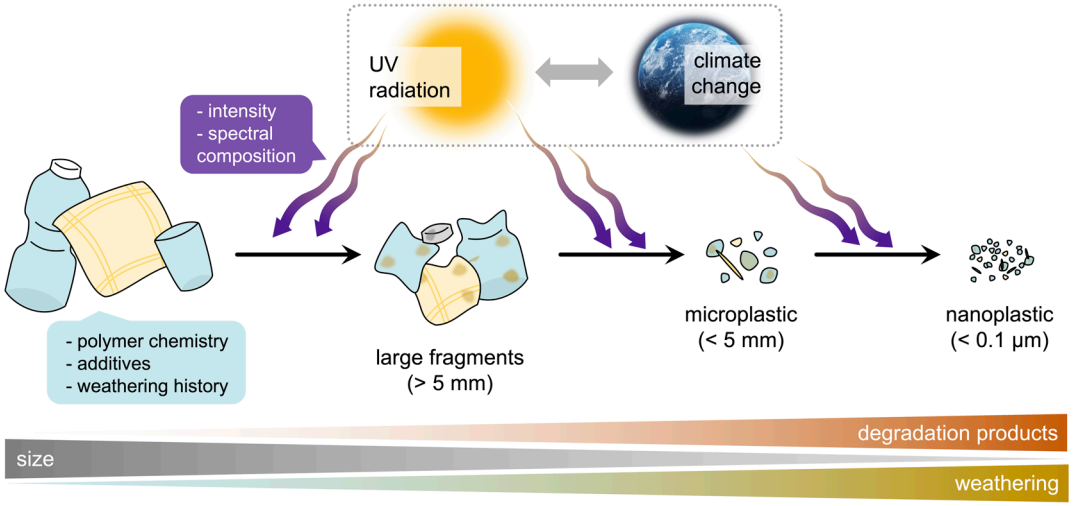

Figure 4. Schematic illustration of the process of solar UV radiation-initiated fragmentation of plastics and consequential release of micro and nanoplastics into the environment

Source: Jansen et al. (2024), originally published by Springer Nature

As part of a research project initiated and supervised by the German Federal Office for Radiation Protection (BfS), an urban UV radiation model was successfully implemented in the existing microscale building and plant-resolving atmospheric turbulence model, PALM (open-source software under the Gnu Public License (GPL)) (Maronga et al., 2020; Kadasch et al., 2021).

This UV model quantifies, based on the time of day, the erythemal UV irradiance in built-up areas with a grid resolution of less than 0.5 metres. 2D information about the local erythemal UV irradiance can be achieved (as seen in Figure 5). It considers shading of UV radiation by trees, buildings and sun protection devices, such as awnings or sun sails, as well as the transmission of UV radiation by vegetation and multiple reflections of UV radiation on urban surfaces.

The basic atmospheric UV scenario is modelled using an external radiative transfer model (the libRadtran software package, including uvspec; Mayer et al., 2005; Emde et al., 2016) for different solar zenith angles. The model was evaluated by comparing it to measured UV irradiance data. The comparisons showed good agreement at unshaded locations.

The UV model also reproduces the spatial and temporal variability of UV radiation caused by trees, buildings and awnings. It was found that a precise understanding of microscale environmental conditions, especially detailed information about trees, is essential for accurately modelling UV irradiance. The newly developed code was integrated into the PALM model system and released in July 2024 under the release number 24.04. The practical usability of the model requires a solid foundation of basic technical, numerical and physical knowledge, as it operates at both the user terminal and programming levels. A user-friendly, web-based interface still needs to be developed and implemented.

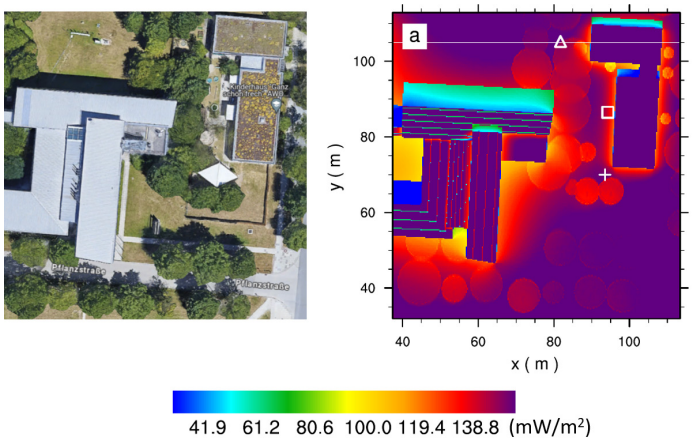

Figure 5. Result of the UV model in PALM: 2D information about the local erythemal UV irradiance. Left: aerial view of a kindergarten with outdoor area to the right of the structure; right: horizontal section of the erythemally weighted UV irradiance (mW/m^2) at 1100 Universal Time Coordinated (UTC) in the outdoor area of the kindergarten. The white markers show the position of the UV spectroradiometer measuring points.

SunSmart Global UV app

The free SunSmart Global UV app puts sun protection advice at your fingertips, so you know when UV levels can damage your skin, leading to skin cancer – wherever you are in the world. Supported by the World Health Organization and the World Meteorological Organization in conjunction with the United Nations Environment Programme and the International Labour Organization, the SunSmart Global UV app provides guidance when sun protection is recommended, no matter where you live. Recent updates to the app include the addition of Arabic along with eight other languages including French, English, Russian, Italian, Chinese, Dutch, Spanish and German. To download the app go to https://www.sunsmart.com.au/resources/sunsmart-app or scan the QR codes.

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A summary of the Quadrennial Ozone Symposium

Sophie Godin-Beekman, Irina Petropavlovskikh

The Quadrennial Ozone Symposium (QOS) is the quadrennial meeting of researchers and stakeholders interested in monitoring and understanding the processes that impact the ozone layer. In 2024, the QOS was held at the University of Colorado in Boulder from 15 to 19 July (see Figure 6). Information about the scientific programme can be found at https://qos2024.colorado.edu/home. The previous QOS was held virtually in 2021 and was very successfully organized by Yonsei University in Seoul, Republic of Korea.

Figure 6. Group photograph of the Quadrennial Ozone Symposium participants

QOS 2024 was collectively organized by the Cooperative Institute for Research in Environmental Sciences (CIRES), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the National Center for Atmospheric Research (NCAR), the University of Colorado and the International Ozone Commission (IO3C). IO3C set up the scientific committee of the symposium. Primary sponsors of the event were the International Union of Geodesy and Geophysics (IUGG), the International Association of Meteorology and Atmospheric Sciences (IAMAS), WMO GAW, CIRES, the University of Colorado in Boulder, NASA (HQ) in Greenbelt (United States of America), SciGlob, EN-SCI Environmental Science, BAE Systems and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

QOS 2024 brought together and facilitated scientific exchange between experts from around the world working on all aspects of ozone research. The sessions were available for online viewing and virtual presentations (including a 2-minute virtual poster presentation) to facilitate wider participation among countries in transition, at a minimal cost to researchers. The conference supported 22 early career scientists by waiving registration fees and 4 participants received additional travel grants. The QOS had more than 220 participants including 40 online participants, 7 keynote speakers, 6 invited speakers, 97 oral presentations (in 7 sessions) and 221 posters (34 posters online). Working group meetings for instrumental and research activities took place before and after the QOS, allowing combined travel for participants travelling to Boulder, to save carbon where possible.

The topics of discussion included the monitoring of changes in global ozone levels, declining emissions of ozone-depleting substances regulated by the Montreal Protocol, climate processes impacting ozone, air quality effects on tropospheric ozone, environmental and health impacts, development of new instruments and techniques, and extreme events (volcanic and anthropogenic). Each topical session featured keynote and invited speakers, including oral and poster presentations, providing a platform for discussion and exchange in plenary sessions. The events featured an icebreaker, research group side meetings, an early career gathering and a conference dinner, during which several awards were presented. The Dobson award was given to the early career scientist Dr Luke Western for his article on the global increase of ozone-depleting chlorofluorocarbons from 2010 to 2020. The Farman award for life career achievement was given to both Dr Philippe Nedelec for the In-service Aircraft for a Global Observing System (IAGOS) MOZAIC long-term ozone records and to Dr Herman Smit for his unique contribution to the calibration and quality of the global ozone sonde record.

Summary of recommendations from the Ozone Research Managers twelfth meeting

Matt Tully

The Ozone Research Managers (ORM) meet every three years, six months prior to the Meeting of the Conference of the Parties to the Vienna Convention, to regularly review the status and needs of international ozone monitoring and research. The twelfth meeting took place from 24 to 26 April 2024 in Geneva, beginning with presentations by relevant organizations and invited experts. Regional summary reports were presented, reviewing activities and requirements from each part of the world. Recommendations were then made in five thematic areas: research needs, systematic observations, gaps in the global coverage of controlled substances, data archiving and stewardship, and capacity-building. WMO GAW has an important role to play in all five of these areas.

The ORM stressed that continued scientific work is needed to measure, understand and model the past and future distribution and trends of ozone and UV radiation. Essential for this are high-quality observations of ozone from both the ground and space, and enhanced

regional observations of ozone-depleting substances, including very short-lived substances (VSLS). Factors which are expected to influence the expected recovery of stratospheric ozone include changing climate, sporadic events, such as wildfires and volcanic eruptions, and human activities including the projected growth of supersonic aviation and space activity. The report notes the important role played by the Trust Fund and the need for full global coverage of measurements and participation of all countries in ozone science.

The third international solar UV radiometer calibration campaign

Julian Gröbner, Gregor Hülsen

The third international solar UV radiometer calibration campaign (UVC-III) was organized by the World Calibration Centre for UV (WCC-UV) at the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in Davos, Switzerland from 13 June to 26 August 2022. A total of 74 broadband filter radiometers from 42 institutes and 29 countries participated in the campaign. The long-awaited report from this event was published during 2023 in the WMO e-Library (GAW Report No. 284).

The purpose of the campaign was to provide responsivity calibrations traceable to the international system of units (SI), to support the harmonization of the worldwide solar UV measurements obtained with these radiometers. The calibration procedure consisted of measuring the normalized spectral and angular response functions of each radiometer in the optical radiometry laboratory of PMOD/WRC. This was followed by an outdoor comparison of solar UV measurements with the reference spectroradiometers QASUME and QASUMEII (as seen in Figure 7) to obtain the absolute spectral responsivity (Hülsen and Gröbner, 2007; Hülsen et al., 2016). The expanded uncertainties (k=2) of the calibrations varied between 3.1% to 12% for each radiometer.

The measurements of the solar UV radiometers were analysed both with the calibrations obtained during UVC-III and with the calibrations used by the home institutes. The average age of the user calibrations was three years prior to this campaign (that is, 2019) and 34 out of the 74 instruments were using only a single calibration factor, instead of the suggested calibration functions, depending on total column ozone and solar zenith angle. The relative differences between the measurements using the user calibration and the one derived from the UVC-III campaign varied between 0.8% to more than 50% for certain radiometers. Before applying the calibration of the UVC-III, 28 radiometers measured solar UV irradiances within 5% of the QASUME reference, 37 radiometers within 10% and 23 radiometers exceeded the 10% threshold. For 15 radiometers, no initial calibration was supplied. After the calibration, all radiometers measured within 5% of the reference.

Figure 7. Solar UV filter radiometers on the measurement platform of PMOD/WRC

Photo credit: G. Hülsen

The report of the campaign is published as WMO GAW Report No. 284 (Hülsen and Gröbner, 2023).

The campaign at PMOD/WRC was followed in the boreal autumn of 2022 by a national calibration campaign organized by the Servicio Meteorológico Nacional (SMN) of Argentina and in which Uruguay also participated. A total of 25 UV radiometers were calibrated, relative to two reference radiometers, which participated in the UVC-III, to link the calibrations to the WCC-UV. A report of the Argentinian campaign is in progress and will be published as a WMO GAW report.

Advisory Committee approves UV campaign in Central America and the Caribbean

John Rimmer

A proposed project led by Dr Mauro Valdés Barrón (Mexican Solarimetric Service, Institute of Geophysics, National Autonomous University of Mexico) on UV-B solar radiation monitoring in Central America and the Caribbean was accepted by the Advisory Committee to the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention (the Trust Fund). The monitoring is considered as an indirect way to gain knowledge on the condition and behaviour of the ozone layer.

The project is a collaboration between institutes in Mexico, Jamaica, Costa Rica, Cuba and the Dominican Republic. The Trust Fund contribution, intended as initial support for the monitoring network, will provide for the installation of UV radiation monitoring equipment at several sites in Central America and the Caribbean, as well as trainings for operating teams. Once in operation, the collected data will be regularly submitted to the World Ozone and Ultraviolet Radiation Data Centre (WOUDC).

The Observatorio de Radiación Solar (ORS) (part of the Mexican Solarimetric Service) is the regional centre for the measurement of solar radiation. The ORS has all the necessary infrastructure to perform the various calibration processes for solar radiation sensors, in addition to cavity radiometers. Every five years, the regional centres

participate in the International Pyrheliometer Comparison at the World Radiation Center in Davos, Switzerland.

South American Brewer intercomparison showcases collaborative work between countries and organizations

Alberto Redondas, John Rimmer

From 18 February to 8 March 2024, a campaign was conducted in Brazil, with the collaboration of several countries, to restore the Brewer network in South America, thereby reinstating stratospheric ozone measurements covering the whole continent.

The campaign for the calibration of South American Brewer instruments was organized by the State Meteorological Agency (AEMET) of Spain and the Federal University of Santa Maria (UFSM) of Brazil, with the support of WMO and the Trust Fund.

The event was attended by over 20 experts and operators of 10 instruments from Argentina (2), Plurinational State of Bolivia (1), Brazil (4), Chile (1), Ecuador (1) and Spain (1) (see Figure 8). The instruments were calibrated by intercomparison with the global reference provided by the Regional Brewer Calibration Center-Europe (RBCC-E), operated by AEMET's Izaña Atmospheric Research Centre (IARC).

The campaign took place over three weeks and was divided into three phases: the first week was dedicated to updating and repairing the instrumentation, the second included a training course for operators, conducted by AEMET and the Portuguese Institute for the Sea and Atmosphere (IPMA), and the final week was dedicated to the calibration itself. The update of the instruments was conducted by International Ozone Services (IOS). The main objective of the first phase was to restore the operational status of the Brazilian Brewers, some of which had not been operational for almost five years. In November 2023, a previous AEMET mission had been conducted to diagnose and collect information about the instrumental issues of three of these Brewers and restore to working order the instruments from Santa Maria and Santarem (Brazil).

The Brewer operators course took place in parallel with the campaign, organized by AEMET and WMO, with the participation of teachers from IPMA (Portugal), the Environmental Protection Agency of Aosta Valley (ARPA, Italy) and WMO.

Figure 8. Participants and their Brewers at the campaign for the calibration of South American Brewer instruments

Photo credit: Instituto Nacional de Pesquisas Espaciais (INPE)

During this first Ibero-American campaign, an EM27/SUN spectrometer from the Collaborative Carbon Column Observing Network (COCCON-Spain) at IARC-AEMET recorded greenhouse gas measurements on the same terrace as the Brewer instruments. The EM27/SUN, operating in the near infrared region, focuses on key greenhouse gases such as methane and carbon dioxide.

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JN 241037