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WMO OZONE AND UV BULLETIN

Introduction

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

The year 2025 marks the fortieth anniversary of the signing of the Vienna Convention in 1985 and the fiftieth anniversary of the 1975 WMO statement "Modification of the ozone layer due to human activities and some possible geophysical consequences". Prepared by a group of international experts, this declaration recognized the potential danger of damage to the ozone layer and called for an intensive programme of research and observations to be carried out under the leadership of WMO. Despite the great success of the Montreal Protocol in the intervening decades, this work is not yet finished, and there remains an essential need for the world to continue careful systematic monitoring of both stratospheric ozone and of ozone-depleting substances and their replacements. For over 70 years, WMO has coordinated global ozone monitoring and research, and the present Bulletin provides the latest information on many aspects of this work. Protecting the ozone layer and thereby human, environmental and agricultural health has enabled significant progress towards achieving many of the United Nations Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-Being), SDG 13 (Climate Action), SDG 2 (Zero Hunger) and SDG 15 (Life on Land).

State of the ozone layer in 2024

Wolfgang Steinbrecht, Mark Weber, Antje Inness

In 2024, high values were observed for mean total ozone columns compared to the 2003 to 2022 long-term average geographic distribution, as seen in Figure 1. Over the Canadian Arctic, large positive anomalies with values

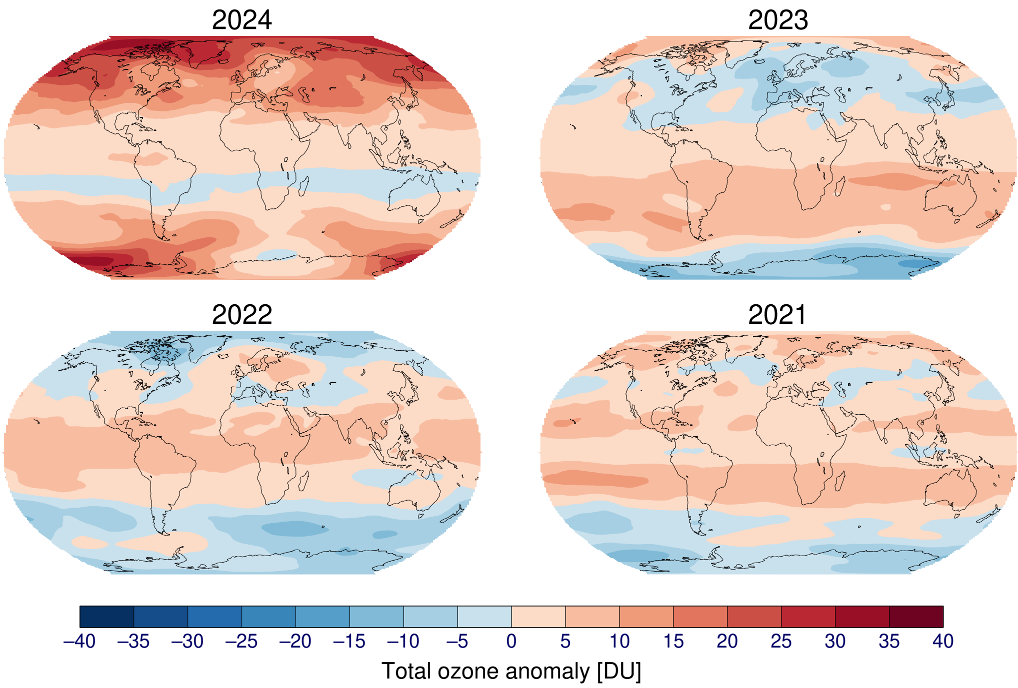

Figure 1. Deviation of recent annual mean total ozone columns from the geographic long-term average distribution. A Dobson unit (DU) represents the integrated amount of ozone in the atmospheric column; 300 DU is a typical level for mid-latitudes, but this value can be higher or lower in the polar and tropical regions, respectively.

Source: Third-party map. This map was provided by Wolfgang Steinbrecht and Antje Inness on 11 July 2025 and may not fully align with United Nations and WMO map guidance. Results are from the Copernicus Atmospheric Monitoring Service Reanalysis (Inness et al., 2019).

Record-high Arctic total column ozone during springtime 2024

Jos de Laat

Observations of average March 2024 Arctic (63°N–90°N) total ozone columns were high relative to the 1960–2023 period. Values were 55 to 60 Dobson units higher than average, making the ozone layer approximately 14% thicker (Newman et al., 2024). This is mainly attributable to consistent and enhanced planetary wave events that caused significant stratospheric warmings. These wave events lead to poleward and downward advection of ozone-rich air from the middle and upper stratosphere into the polar lower stratosphere. Model simulations suggest that decreased concentrations of ozone-depleting substances and increasing greenhouse gas concentrations may both have contributed to the high stratospheric ozone levels observed over the Arctic. Lower concentrations of ozone-depleting substances reduce ozone destruction, while higher concentrations of greenhouse gases enhance the poleward transport of ozone-rich tropical stratospheric air towards polar regions. The contribution of these processes is difficult to quantify as there are large uncertainties. These high ozone levels persisted well into the summer and fall, resulting in a decrease of northern hemisphere middle- and high-latitude summertime ultraviolet radiation at the surface in the range of –5%.

above 40 Dobson units (DU) were observed (red regions in Figure 1). Two regions show negative anomalies in 2024 (shown in blue): a limited region near Antarctica, and a zonal belt around 15°S. Compared to previous years, total ozone was higher over much of the globe with hardly any negative anomalies.

With respect to the historical long-term data (Weber et al., 2022), the 2024 near-global (60°S to 60°N) mean, the northern hemisphere mean (35°N to 60°N) and the tropical belt mean (20°S to 20°N) all reached the highest values observed in decades (see also Newman et al., 2024). The high values of the 2024 southern hemisphere zonal mean (35°S to 60°S) brought an end to the series of low values recorded since 2020. Several factors contributed to the high values observed in 2024:

- The Quasi-biennial Oscillation of equatorial winds was in its easterly shear phase from January to April, with winds blowing from the east at 27 km altitude, and no wind or wind from the west at 17 km altitude. This shear favours larger total ozone columns in the extra-tropics and reduced ozone columns in the tropics (Baldwin et al., 2001).
- Strong El Niño conditions prevailed in the first months of 2024. El Niño favours enhanced total ozone columns in the extra-tropics and reduced ozone columns in the tropical Pacific (Benito-Barca et al., 2022).
- Planetary wave activity was unusually high in boreal winter and spring, resulting in a very active Brewer–Dobson circulation and enhanced transport of ozone to higher latitudes (Newman et al., 2024).
- Solar activity remained near its maximum in 2024, producing more ozone in the upper stratosphere and favouring larger total ozone columns (Dhomse et al., 2022).

In general, most year-to-year fluctuations of total ozone columns are driven by changes in atmospheric transport, which can mask the long-term recovery of the ozone layer. This recovery – towards 1980s levels – is expected to continue over the coming decades thanks to the successful ban of ozone-depleting substances under the universally ratified Montreal Protocol (see also *WMO Ozone and UV Bulletin, No. 1*).

State of the Antarctic ozone hole

Jos de Laat

The depth of 2024 Antarctic ozone hole was below the 1990–2020 average, with a maximum ozone mass deficit (OMD) of 46.1 million tonnes on 29 September (Figure 2). Its onset was relatively slow, and delayed ozone depletion was observed through the month of September, followed by a relatively rapid recovery after the maximum deficit was reached. The below-average level of ozone loss persisted through mid-November. The Antarctic stratospheric vortex remained unusually persistent, with the final breakup not occurring until December 2024.

This late onset of ozone depletion and below-average maximum depth deviates from the patterns observed between 2020 and 2023 and more closely resembles the persistent later onsets seen between 2015 and 2019. This persistent later onset has been identified as a robust indication of initial recovery of the Antarctic ozone hole. The late onset in 2024 is also related to sudden stratospheric warming (SSW) events that affected the southern hemisphere (Zi et al., 2025). July and August saw the earliest SSWs over Antarctica since 1979. These events are characterized by rapid increases in stratospheric temperatures during winter months and are accompanied by a weakening of stratospheric winds around the poles and increases in stratospheric ozone.

The 2024 ozone hole marks a break in the recent trend of deep and long-lasting holes observed from 2020 to 2023. Recent research suggests that various factors have contributed to these anomalies, including the initial state of stratospheric ozone at the start of the Antarctic winter, photochemical ozone loss processes and the transport of ozone-rich air from outside the polar vortex (Wargan et al., 2025). However, none of

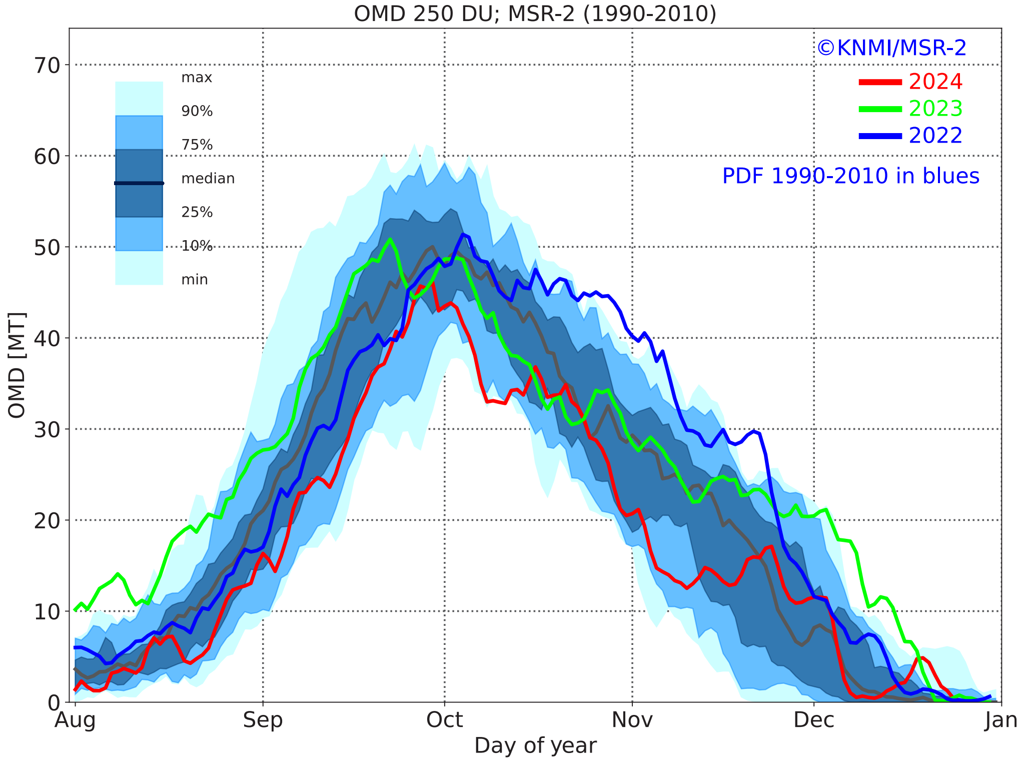

Figure 2. Daily Antarctic ozone mass deficit (OMD) in megatonnes (MT) relative to the 250 Dobson unit (DU) total ozone column (TOC) level (Strahan et al., 2019) based on multi-sensor reanalysis, version 2 (MSR-2) total ozone reanalysis data (van der A et al., 2015). The OMD is the mass of ozone that would need to be added to bring the TOC within the ozone hole up to the 250 DU level. The red, green and blue lines show data for 2024, 2023 and 2022, 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)

these short-term influences are linked to the gradual decline in atmospheric concentrations of ozone-depleting substances. Therefore, the anomalies of the past few years do not undermine confidence in the continuing recovery of Antarctic stratospheric ozone attributable to the success of the Montreal Protocol and its ongoing implementation.

Evaluating the BTS-solar instrument for the third generation of total column ozone ground-based network devices

Luca Egli and Voltaire Velazco

Next year marks 100 years of Dobson measurements in Switzerland. For many years scientists have depended on traditional Brewer and Dobson spectrometer instruments for long-term worldwide total ozone column (TOC) monitoring. However, operating at a global level is complex, and maintenance has become challenging, as instrument types are no longer manufactured and spare parts are becoming harder to obtain. This has created a need for modern alternatives that are simple to use, reliable and cost-effective – particularly for expanding ozone monitoring networks in regions such as Africa, South America and East Asia.

Over recent years, modern charge-coupled device (CCD) array-based spectrometers like the Pandora or BTS-Solar instruments have emerged as promising solutions to complement the established Brewer and Dobson spectrometers. Here we focus on the BTS-Solar spectrometer, which is compact, robust, automated and designed for operation in many environmental conditions.

Testing of the BTS-Solar instrument began in 2014 at the Izaña Observatory in Tenerife, Spain to address the traceability of TOC measurements. Following this, the Meteorological Observatory at Hohenpeissenberg in Germany introduced a BTS-Solar instrument alongside its Brewer spectrometer. At the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in Davos, Switzerland, researchers developed specialized software to retrieve TOC using a similar technique to that applied with traditional Dobson and Brewer instruments. Thanks to this approach, the TOC derived from a BTS-Solar instrument can be calibrated against measurements made with the Dobson or Brewer instruments, and a second retrieval method provides traceability to laboratory standards. This ensures reliability and continuity in long-term ozone records.

In June 2025 a BTS-Solar spectrometer (referred to as WMO-BTS) was deployed under hot conditions and high solar elevations at the WMO regional Brewer and Dobson intercomparison in El Arenosillo, Spain, also allowing calibration against these reference instruments. Deployments like these are necessary to demonstrate that

Figure 3. Three generations of total ozone column (TOC) instruments at Davos. The container on the left contains three automated Dobson spectrometers (first generation of TOC instruments). Three Brewer spectrometers (second generation) can be seen at the back. In the centre at the front: the new BTS-Solar instrument (third generation).

the BTS-Solar (or Pandora) spectrometers can become new tools for global ozone monitoring, providing accurate and long-term consistent measurements needed to track the expected recovery of the ozone layer.

A WMO task force will deploy the WMO-BTS at the high-latitude Sodankylä Arctic Space Centre in Finland (67.3°N) for at least one year starting in autumn 2025. Sodankylä presents particularly demanding conditions: harsh Arctic weather, low solar angles, and high ozone concentrations during spring. The WMO-BTS was tested at PMOD/WRC in Davos this past winter. Substantial improvements were implemented and cross-compared with the Arosa/Davos Brewer and Dobson triads (Figure 3). Thanks to these improvements, the instrument should be able to measure high ozone concentrations at low solar zenith angles – a key requirement for high-latitude stations like Sodankylä.

How do intercomparisons contribute to global ozone information

Voltaire Velazco and Irina Petropavlovskikh

In support of the Montreal Protocol, the WMO-led community developed and implemented guiding principles for ozone and ultraviolet (UV) monitoring networks. These principles aim to ensure broad observational coverage, define standards for operations, data processing and calibrations, and foster a network where scientists meet, exchange knowledge, receive training and explore opportunities for collaboration. This approach has proven invaluable for enabling effective and policy-relevant observations, and it is one of the keys to the success of the Montreal Protocol.

In the early years of ozone monitoring, it was recognized that neither Dobson nor Brewer ozone measuring instruments had a metrologically traceable standard. To address this issue, the WMO Global Atmosphere Watch (GAW) community designated special reference instruments which are calibrated "absolutely", using the Langley method under near-ideal environmental conditions.

A central calibration facility for Dobsons was established in Boulder, Colorado, USA in 1974, and five WMO Regional Calibration Centres were designated with regional reference instruments. The WMO World Primary Standard Spectrophotometer (Dobson #083) is calibrated every other year at Mauna Loa Observatory, Hawaii, USA. It is then brought to five WMO Regional Calibration Centres every four years to intercompare station instruments and transfer its calibration to the broader network. This Dobson intercomparison protocol has proven remarkably effective over several decades and remains a cornerstone of the global ozone monitoring network.

For the Brewer network, two centres currently provide calibration standards. Environment and Climate Change Canada maintains six instruments (two triads) in Toronto, Canada (Zhao et al., 2021). The Izaña Atmospheric Research Center maintains another triad on Tenerife Island (León-Luis et al., 2018).

A key requirement for the Dobson and Brewer networks is to maintain long-term stability of 1% or better, since ozone trends for the expected recovery period are of the order of 1% per decade or less. In the 1970s and 1980s, initial deviations among network Dobson instruments exceeding 10% were quite common, but such large discrepancies have not occurred since the early 1990s. Notably, in the four most recent intercomparisons (since 2020), over 80% of the instruments arriving for recalibration were already within the ±1% WMO-designated target. This improvement in baseline accuracy is illustrated in Figure 4.

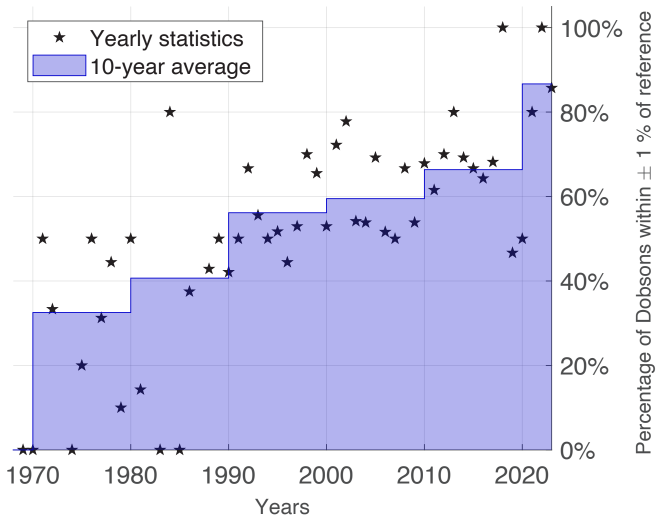

Figure 4. Stars: Percentage of Dobson instruments already within the ±1% WMO-designated target when compared to the standard Dobson upon arrival at intercomparison campaigns. Typically, the instruments had been in the field for four years since their last calibration. Data are grouped by decade. Blue shading: 10-year averages of the same data, grouped by decade.
Source: Steinbrecht et al., 2025, Figure 3

Figure 5. Top left: On-site, hands-on instruction during intercomparison campaigns is essential for teaching key techniques and refreshing operational procedures. Top right: Ten Dobsons, including the European standard. Bottom right: Brewers, a BTS-Solar spectrometer and other instruments measuring UV and ozone alongside the Dobsons. Bottom left: Dobson #073, one of the British Antarctic Survey (BAS) instruments that contributed to the discovery of the ozone hole (Farman et al., 1985), was flown in from Antarctica for maintenance in Germany and calibration in Spain, operated here by S. Kucieba (BAS). Centre: Instruments from Uganda (#056), Egypt (#069), and Algeria (#011) – one of the oldest Dobsons still operating, built around 1932 – also took part in the campaign.

Credit: A. Redondas and V. Velazco

During intercomparison campaigns (see Figure 5), calibration centres also train new operators and service network instruments. The campaigns thus provide an important platform for networking, discussing instrument developments, data reprocessing and many other important interactions. When other ozone measuring instruments (for example, Pandora, BTS-Solar, ultraviolet–visible (UV–Vis) spectrophotometer, ozonesondes, lidars, microwave (MW), Fourier transform infrared (FTIR)) take part, they offer valuable additional information and insight into cross-network consistency. Regional intercomparison campaigns, often supported by WMO and the United Nations Environment Programme (UNEP) under the Vienna Convention General Trust Fund for Research and Observations, have enabled Dobson or Brewer operators from across a WMO Region to come together. This has played an important role in building connections and contacts and fostering a scientific community.

Celebrating the 40th anniversary of the Vienna Convention for the Protection of the Ozone Layer

Sophia Mylona

The year 2025 marks the 40th anniversary of the adoption of the Vienna Convention for the Protection of the Ozone Layer. This landmark treaty, adopted in 1985, recognized stratospheric ozone depletion as a global problem and provided the framework for mobilizing international cooperation in ozone research, systematic observations and scientific assessments.

By encouraging nations to exchange information on human activities affecting the ozone layer and adopt measures to combat ozone depletion, the Vienna Convention paved the way for the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987. These ozone treaties were the first multilateral environmental agreements to be universally ratified, with 198 parties.

To date, the Montreal Protocol has led to the phase-out of over 99% of the production and consumption of controlled ozone-depleting substances. As a result, the ozone layer is now on track to recovery by the middle of the 21st century, significantly reducing risks of skin cancer, cataracts, and ecosystem damage due to excessive UV exposure.

With the adoption of the Protocol's Kigali Amendment in 2016, the phase-down of hydrofluorocarbons – powerful greenhouse gases used as substitutes for ozone-depleting substances – has commenced. With the Amendment ratified by 164 parties to date, the phase-down is progressing according to the agreed schedules and is expected to avoid up to 0.5 °C of global

FROM SCIENCE TO GLOBAL ACTION
40 Years of the Vienna Convention

warming by the end of the century. This could increase to 1 °C of avoided warming if transitions to energy efficient equipment are added to global climate warming mitigation efforts. These remarkable achievements, made possible by the Vienna Convention, are a testament to science-driven policies and global cooperation catalyzing and advancing transformative environmental action.

The work under the Vienna Convention is guided by the decisions of the Conference of the Parties (COP), which are informed by the recommendations of the Ozone Research Managers. Both bodies meet every three years. Activities relating to ozone observations are supported by the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention, established in 2002 and overseen by an Advisory Committee since 2015. Despite its limited resources, this fund, in close partnership with WMO, has been instrumental in facilitating such activities in developing countries and in countries with economies in transition, and has leveraged significant voluntary contributions.

With the adoption of two key decisions at the combined thirteenth meeting of the Conference of the Parties to the Vienna Convention (COP) and Thirty-Sixth Meeting of the Parties to the Montreal Protocol in 2024, the COP has recognized that the General Trust Fund is a viable mechanism for the monitoring of substances controlled under the Montreal Protocol. This development emerged in response to scientific findings that revealed major discrepancies between top-down and bottom-up emission estimates of controlled substances. This highlighted the need to strengthen emission monitoring at both global and regional levels, particularly in poorly sampled areas, to improve the detection and attribution of emissions and to ensure that the phase-out and phase-down of controlled substances achieved under the Montreal Protocol are sustained. Four decades later, the Vienna Convention continues to provide a dynamic platform for policy responses to emerging atmospheric challenges, reinforcing the importance of science–policy cooperation.

Road to the 2026 WMO/UNEP assessments of ozone depletion: History, insights and importance

Matt Tully and Alkis Bais

Among the key factors leading to the success of the Montreal Protocol has been the provision of authoritative scientific advice to the Parties. In 1988, the Parties to the Montreal Protocol agreed to establish four panels to provide accurate and authoritative information. Two panels were later merged, leaving the Scientific Assessment Panel (SAP), the Environmental Effects Assessment Panel (EEAP) and the Technology and Economic Assessment Panel (TEAP). WMO GAW plays an important role in SAP and EEAP, while TEAP provides technical information about technologies that use controlled substances and their alternatives.

The information provided by these panels has led to several adjustments and amendments to the Protocol, such as the 2007 Montreal Adjustment, which accelerated the phase-out of hydrochlorofluorocarbons (HCFCs), and the 2016 Kigali Amendment, in which Parties agreed to phase down the consumption and production of hydrofluorocarbons (HFCs).

SAP is tasked with providing advice on the current state of the ozone layer and the measures taken for its protection. SAP leads the quadrennial publication of the WMO/UNEP Scientific Assessment of Ozone Depletion, which assembles and assesses the best available scientific knowledge on these issues. The executive summary of the 2022 Assessment was published as a GAW Report (*Scientific Assessment of Ozone Depletion: 2022 – Executive Summary* (GAW Report No. 278)). The SAP co-chairs have convened a Scientific Steering Committee of experts from around the world to oversee the production of the 2026 Assessment, the tenth in the series.

The terms of reference for the 2026 Assessment were agreed at the 35th Meeting of the Parties to the Montreal Protocol held in Nairobi, Kenya, in October 2023. The timeline for the assessment is illustrated in Figure 6, and the chapter topics will follow the same structure as in 2022 (*Scientific Assessment of Ozone Depletion: 2022 – Executive Summary* (GAW Report No. 278)).

Some focus topics will be covered in multiple chapters, such as the impact of the projected growth of the space industry and the effects of the Hunga Tonga volcanic eruption on stratospheric ozone (see *WMO Ozone and UV Bulletin, No. 1*).

Similarly, EEAP is tasked with assessing the most recent scientific information on the environmental effects of ozone depletion and climate change and leads the quadrennial publication of the WMO/UNEP Assessment Report on the Environmental Effects of Ozone Depletion and Climate Change. For the 2026 Assessment, EEAP has been asked to include solar radiation modification scenarios (geoengineering) and forward-looking projections and scenarios, and to assess the effects of changes in the ozone layer and ultraviolet radiation, as well as their interactions with the climate system. The assessment will focus on: (a) human health; (b) the biosphere, biodiversity, and the health of flora, fauna and the ecosystem, including biogeochemical processes and global cycles; and (c) ecosystem services, agriculture, materials and microplastics. Additionally, EEAP will assess the accumulation and effects of breakdown products from controlled substances and their alternatives, in particular substances that are very persistent in the environment, such as perfluoro- and

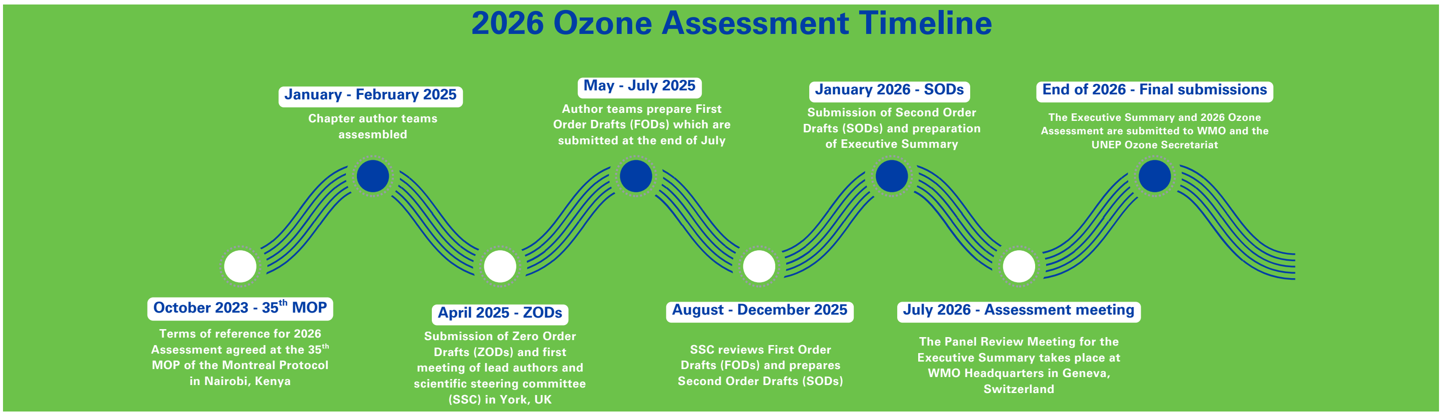

Figure 6. Schematic timeline of the process leading to the delivery of the 2026 Scientific Assessment of Ozone Depletion. MOP = Meeting of the Parties.

polyfluoroalkyl substances, including trifluoroacetic acid, in groundwater, surface waters and other relevant sinks. The 2026 EEAP Assessment will follow a similar timeline to the SAP Assessment, with a submission of the final version to WMO and the UNEP Ozone Secretariat by 31 December 2026.

Observed decadal changes in solar UV radiation in Central Europe

Sebastian Lorenz, Felix Heinzl, Marco Janßen, Daniela Weiskopf

Excessive UV exposure increases the risk of acute and long-term skin and eye diseases. Knowledge of the actual ground-level solar UV radiation is essential for assessing these risks. Precise measurements of UV radiation, conducted among others by the German solar UV monitoring network, provide valuable insights into intensity, spectral composition and temporal variations over both short and long periods.

In a comprehensive study, over one million UV data points from Dortmund, Germany and Uccle, Belgium were carefully processed and used to calculate temporal trends (Lorenz et al., 2024). For the trend analysis, researchers applied a novel model that accounts for autocorrelation (the correlation between consecutive measurements in a dataset) and heterogeneity of variance (when the variability in the data is inconsistent). To address data gaps, a validated imputation method was used (Heinzl et al., 2024), ensuring that the trend results remained robust. In addition to UV spectra, the study also examined ground-level measurements of global radiation and sunshine duration, as well as satellite-derived total ozone column. This approach enabled the identification of correlations with observed surface UV radiation data and potential drivers of the detected trends.

The results highlight how seasonal ozone patterns and periodic low-ozone events affect ground-level UV radiation. These low-ozone episodes can raise UV index values by 10%–20% in summer and up to 50% in winter. The analysis also shows that cloud clover plays an important role in modulating surface UV radiation, strongly influencing the relationship between the UV index and daily erythemal UV dose values. A comparison between Dortmund and Uccle provides valuable insight into the regional transferability of locally collected data.

The trend analysis reveals a significant increase in monthly UV radiation between 1997 and 2022. When considering all trends and influencing parameters, the increase can be attributed to changes in cloud cover. Satellite data confirm this conclusion, showing strong decreases in cloudiness over Central Europe over the study period (Goessling et al., 2024). The influence of clouds on surface UV levels also helps to explain why 2022 saw record-breaking UV radiation values (Figure 7), coinciding with severe and prolonged drought across Europe.

Figure 7 shows a time series of annual mean daily erythemal radiant exposure, annual mean of the daily global radiation and annual median of summer ozone values. Since cloudiness affects both UV radiation and global radiation, annual maxima in the time series are often observed in both parameters. However, the graph also shows that annual UV levels appear to be influenced by both clouds and summer ozone. This is evident for example when comparing the years 2018 and 2020; exceptionally low ozone values in 2020 resulted in higher UV radiation than would be expected based on global radiation.

When examining the ozone trend over the entire period from 1997 to 2022, differences occur depending on whether all months are considered or only the summer months (April–September) (Lorenz et al., 2024). These differences could be attributed to an increase in high-pressure systems, which are often accompanied by a rise in the altitude of the tropopause and lower total ozone column values. The occurrence of more phases with lower total ozone columns due to more frequent high-pressure systems would not contradict the successes of the Montreal Protocol but rather indicate the influence of a changing climate.

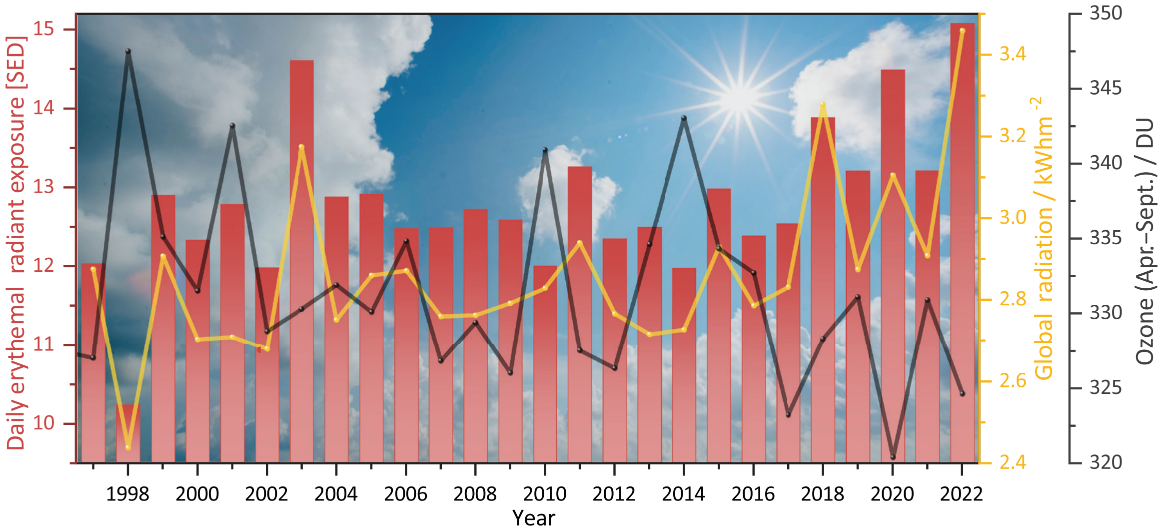

Figure 7. Time series of annual mean of daily erythemal radiant exposure in Dortmund, Germany (red bars), annual mean of the daily global radiation (yellow line) and annual median of summer ozone values (April–September, black line). For more information, see Lorenz et al. (2024). SED = standard erythemal dose.

The findings on changes in solar UV radiation and their influencing factors are crucial for the development of radiation protection concepts and preventive strategies aimed at minimizing health risks in the context of climate change.

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