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NASA's role in monitoring stratospheric ozone. Are ozone layer protection measures effective?

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Review article

Abstract

The stratospheric ozone layer (10–50 km) absorbs biologically harmful ultraviolet radiation, enabling life to persist on Earth. Early NASA measurements from the 1960s–1970s showed that natural ozone levels are controlled by trace nitrogen oxides, hydrogen oxides, and halogens. Approximately 20 NASA missions, together with NOAA, ESA, and other international partners, have contributed to global ozone monitoring. Observations revealed a severe springtime ozone depletion over Antarctica in 1984–1985. NASA recorded the lowest ozone value ever measured over the South Pole—73 DU on September 30, 1994—and the largest single-day ozone hole extent of $29.9 \cdot 10^6$ km^2 on September 9, 2000. The Montreal Protocol (1987) led to a 99% phase-out of regulated ozone-depleting substances. According to the latest WMO/UNEP assessment, the ozone layer is projected to return to 1980 levels by approximately 2066 over Antarctica, 2045 over the Arctic, and 2040 globally, assuming current controls remain in place. Although episodic deep ozone depletion occurred in 2023, NASA's 2025 data show continued long-term recovery. In 2025, the minimum Antarctic ozone concentration was 147 DU on October 6, and the maximum ozone hole extent was $23 \cdot 10^6$ km^2 on September 9—the largest ever recorded hole was about 30% bigger. These observations confirm that Montreal Protocol regulations are driving the gradual restoration of the ozone layer.

Keywords

- ozone depletion
- ozone monitoring
- space missions
- international regulations

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Introduction

Ozone, although present in the atmosphere only in trace concentrations, is fundamental to atmospheric radiative transfer and photochemistry. Its strong absorption in the ultraviolet (UV) spectral range allows the stratospheric ozone layer (10–50 km altitude) to attenuate biologically harmful UV radiation. Nearly the entire UV-C range and most UV-B radiation are absorbed by ozone, while UV-A is only partially attenuated. Insufficient ozone shielding leads to enhanced UV exposure, increasing the risk of skin cancer, ocular damage, and negative impacts on ecosystems [1]. Early NASA measurements from the 1960s–1970s showed that natural ozone levels are controlled by trace nitrogen oxides, hydrogen oxides, and halogens. Without NASA missions, together with NOAA, ESA, and other international partners the global ozone monitoring would not be possible.

Stratospheric ozone monitoring

Systematic monitoring by NASA revealed a pronounced decline in austral spring stratospheric ozone over Antarctica during 1984–1985. NASA's Goddard Space Flight Center maintains a continuous observational record of global ozone dating back to 1979. The NASA Ozone Watch platform [2–3] provides open-access ozone datasets (daily, monthly, annual), false-colour ozone maps expressed in Dobson Units, meteorological analyses, multimedia resources, and educational materials. Links to ozone-related research, environmental regulations, and atmospheric missions are also provided (Figure 1).

About 20 NASA, NOAA, ESA, and associated international missions have contributed to global ozone monitoring. Their contribution to ozone research started in early 1970s when the first satellite-based measurements of ozone column using the UV Backscatter Ultraviolet method occurred. Later more developed methods were used, and highly accurate ozone profiles were achieved. Also comprehensive studies of atmospheric chemistry: ozone, chlorine, CFCs, and ozone-depleting reactions were done. Various Balloon Ozone Experiments (NASA Balloon Program) since the 1970s give validation measurements of ozone profiles over the Arctic and Antarctic which are key for satellite calibration. Most of NASA missions are satellites and orbiting probes rather than crewed astronaut missions. Global ozone measurements and ozone profile data are best obtained from space. Some missions—for example, the Space Shuttle Columbia with the Shuttle Ozone Limb Sounding Experiment-2 (SOLSE-2)—were crewed. Although their operational time was limited, they provided an important demonstration of the limb-sounding technique (side-view atmospheric profiling) for ozone measurements. Long-term and continuous ozone monitoring is possible thanks to a sequence of instruments and satellites (such as TOMS → OMI → OMPS), which enables scientists to track global trends, seasonal variations, and the effects of regulations that reduce emissions of ozone-depleting substances. Most important missions, instruments or programs as well as time of operation and contribution to ozone research are presented in Table 1. [2–26]

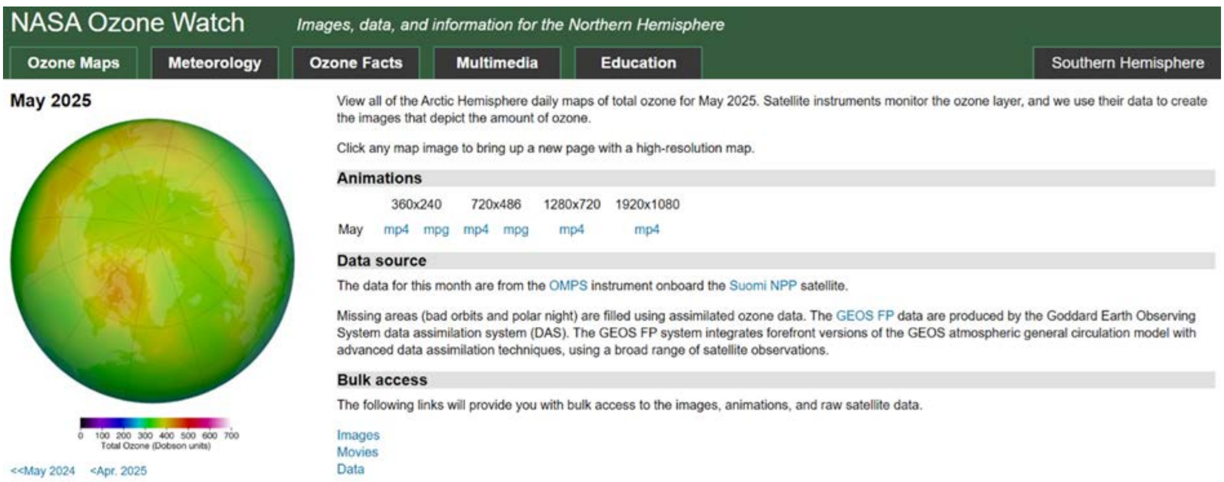

Figure 1. NASA Ozone Watch web page provides open-access ozone datasets [2]

Table 1. NASA and associated international missions, instruments and programs, time of operation and contribution to ozone research [2–26]

Mission / Instrument / Program	Start year / Period of operation	Contribution to ozone research
Nimbus 4 (BUV)	1970–1977	The first satellite-based measurements of ozone column using the UV Backscatter Ultraviolet method
Nimbus 7 (TOMS)	1978–1994	Daily global monitoring of total-column ozone; enabled the identification of the ozone hole
Solar Mesosphere Explorer (SME)	1981–1989	Measurements of ozone in the mesosphere; study of upper-atmosphere photochemistry
SAGE I (Stratospheric Aerosol and Gas Experiment)	1979–1981	Profile measurements of ozone in the stratosphere using the transmission (limb occultation) method
SAGE II	1984–2005	Highly accurate ozone profiles; key data during the era of discovery and analysis of the ozone hole
SAGE III (on the ISS)	2017–present	High-quality ozone profiles from the International Space Station
UARS (Upper Atmosphere Research Satellite)	1991–2005	Comprehensive studies of atmospheric chemistry: ozone, chlorine, CFCs, and ozone-depleting reactions
TOMS-EP (Earth Probe)	1996–2006	Continuity of global ozone column measurements; daily data collection
METEOR-3 (TOMS on a Russian satellite)	1991–1994	International mission—continuation of global ozone monitoring
Aura (OMI)	2004–present	High-resolution global ozone mapping; measurements of aerosols and ozone-depleting gases
Suomi NPP (OMPS)	2011–present	Ozone profiles and total-column ozone; next-generation measurements under the NPOESS/NPP program
NOAA-20 (OMPS)	2017–present	Continuation of OMPS measurements; current international maps of the ozone layer status
LIMB Ozone Sounding Experiment (SOLSE 1/2—on Space Shuttle Columbia)	1997, 2003	Crewed missions—demonstration of limb ozone-profile measurements from the Space Shuttle
MLS (Microwave Limb Sounder)—on Aura	2004–present	Precise profiles of ozone, HCl, and ClO—crucial for analysing ozone-depletion processes
HIRDLS (on Aura)	2004–2008	Profile data on temperature and trace gases, including ozone (limited operation due to malfunction)
TES (Tropospheric Emission Spectrometer—Aura)	2004–active until 2018	Profiling of tropospheric ozone and photochemical precursors
ATLAS Shuttle Missions (ATLAS-1 / 2 / 3)	1992–1994	Spectroscopic experiments (including MAPS) analysing ozone variability and atmospheric chemistry
ISS / HICO + other auxiliary instruments	2009–2014	Although not designed for ozone studies, they supported validation of atmospheric models
Balloon Ozone Experiments (NASA Balloon Program)	various since the 1970s	Validation measurements of ozone profiles over the Arctic and Antarctic; key for satellite calibration

International regulatory framework

The sharp decline in Antarctic ozone prompted the adoption of the Montreal Protocol in 1987 [27], a landmark international treaty mandating the phased elimination of ozone-depleting substances (ODS). It can be add that The Vienna Convention [28] is a framework treaty—it does not itself ban specific chemicals but establishes broad cooperation to protect the ozone layer. The Montreal Protocol (and its amendments [29–33]) are the core legally binding instruments that restrict and phase out ozone-depleting substances (ODS) such as CFCs, halons, HCFCs, methyl bromide, etc. The 2009 and 2014 EU Regulations translate the Protocol's requirements into binding law within the European Union — covering production, trade, and use of ODS (and later HFCs via F-gas regulations). [34–35] The Kigali Amendment (2016) extended regulation to HFCs—gases that replaced ODS but contribute heavily to climate change. Subsequent amendments and technical updates resulted in the global phase-out of approximately 99% of controlled ODS. The Scientific Assessment of Ozone Depletion: 2018 (WMO/UNEP, Report No. 58) synthesized recent advances in understanding ozone-layer dynamics, drawing upon extended observational records, updated chemistry–climate models, and refined diagnostic analyses. The assessment confirms early signs of ozone recovery in response to international regulatory measures. [36] The European Union has additionally implemented stringent controls on fluorinated gases. The European Union (EU) has announced a new set of regulations governing fluorinated gases, known as F-gases, with the approval of Regulation (EU) 2024/573 by both the European Parliament and the European Council. Regulations mandate a complete phase-out of hydrofluorocarbons (HFCs) by 2050 and impose strict restrictions on technologies where non-fluorinated alternatives are viable (e.g., refrigeration, air conditioning, heat pumps). The phase-out also includes other high-impact substances such as sulfur hexafluoride used in power-system insulation. [37] EU Regulations establishes a binding EU reduction target for net greenhouse gas emissions (emissions after deduction of removals) of at least 55% by 2030 compared to 1990 levels and the objective of achieving climate neutrality within the EU at the latest by 2050. [38] The EU has also enhanced its initial nationally determined contribution under the Paris Agreement of greenhouse gas emissions reductions from at least 40% by 2030, to at least 55%. However, the evaluation of Regulation (EU) No 517/2014 shows that the emission savings envisaged by 2030 in the context of the outdated Union climate objectives will not be fully achieved. [37, 38]

Ozone layer recovery and recent anomalies

The WMO/UNEP projections indicate that, assuming full compliance with existing regulations, stratospheric ozone should return to pre-1980 values by approximately 2066 over Antarctica, by 2045 over the Arctic, and by 2040 at mid-latitudes. [36] Nevertheless, recent observations demonstrate that interannual variability remains substantial. Episodes of rapid ozone depletion occurred in austral late winter and spring of 2023 and 2024. Stratospheric ozone concentrations during August–October 2024 were significantly below climatological averages (Figure 2). Data from the analogous period in 2025, by contrast, show partial recovery. These fluctuations are likely related to specific dynamical and chemical conditions in the polar stratosphere, including variations in polar vortex strength, temperature anomalies, and volcanic or wildfire aerosol loading. [1, 36]

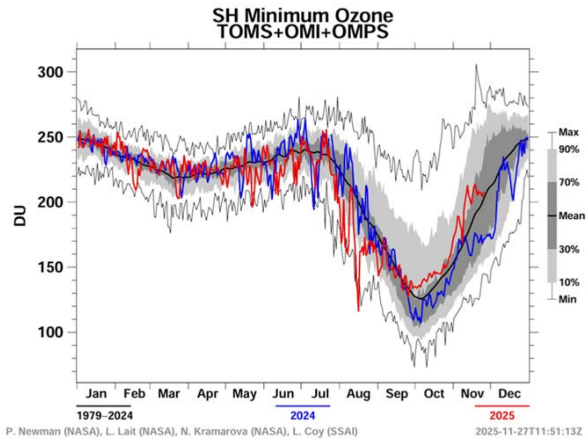

Figure 2. Minimum daily ozone level for southern hemisphere in 2024 (blue) and 2025 (red) as compared to data for 1979–2024 (grey) [2]

Continued long-term monitoring, including NASA satellite [3–25] and balloon-borne observations [26, 40], is essential for determining whether these anomalies represent deviations within natural variability or signals of emerging trends.

Ozone minimum and ozone hole maximum

Annual NASA datasets [2] were used to construct time series of minimum ozone values and the maximum aerial extent of the Antarctic ozone hole. As expected, the lowest ozone concentrations and largest ozone-hole areas consistently occur over the Antarctic region. At present researchers monitor the ozone layer around the world using instruments on NASA's Aura satellite, the NOAA-20 and NOAA-21 satellites and the Suomi National Polar-orbiting Partnership satellite that is jointly operated by NASA and NOAA. Observations from 2024 indicate anomalously low ozone levels, whereas 2025 measurements show relative improvement. NOAA scientists also use instruments carried on weather balloons and upward-looking surface-based instruments to measure stratospheric ozone directly above the South Pole Atmospheric Baseline Observatory. [26, 40] The latest status of the Antarctic ozone layer is presented at NASA's ozone watch webpage: https://ozonewatch. Weather balloon data showed that the 2025 ozone layer directly over the South Pole reached its lowest concentration of 147 Dobson Units on October 6, 2025. The lowest value ever recorded over the South Pole was in this mission 92 Dobson Units in October 2006. [40] Due to the other NASA data the lowest ozone value ever recorded over the South Pole was in 73 DU on September 30, 1994 (Figure 3). [3]

The ozone hole reached its greatest one-day extent for the 2025 year on September 9 at 23 · 10^6 km^2 (Figure 4). The largest ozone hole ever observed was about 30% bigger, with an average area of 29.9 · 10^6 km^2 on September 9, 2000. [3, 40]

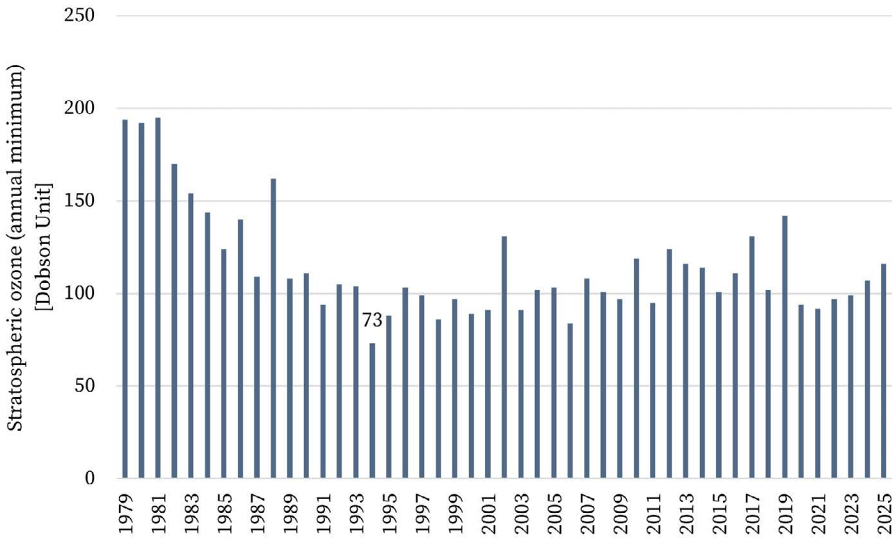

Figure 3. Stratospheric ozone changes, as minimum stratospheric ozone level in 1979–2025 (Author's own elaboration based on NASA data [3])

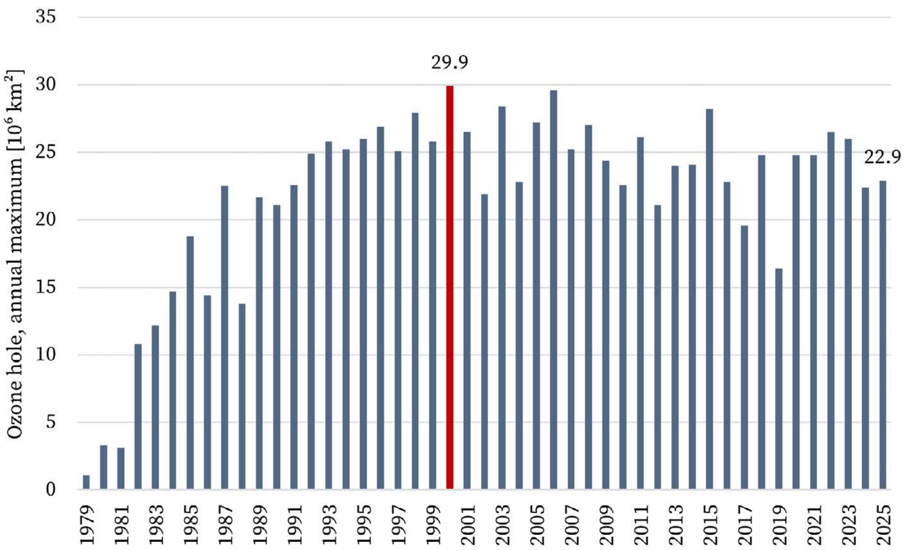

Figure 4. Ozone hole changes, as greatest one-day extent in 1979–2025 (Author's own elaboration based on NASA data [3])

NOAA and NASA scientists say this year's monitoring showed that controls on ozone-depleting chemical compounds established by the Montreal Protocol and subsequent amendments are driving the gradual recovery of the ozone layer, which remains on track to recover fully later this century as countries around the world replace ozone-depleting substances with less harmful alternatives. [40]

Conclusions

1. Approximately 20 NASA missions, together with NOAA, ESA, and other international partners, have contributed to global ozone monitoring.
2. Space missions have contributed to international action to protect the atmosphere and, as a result, to legal regulations on an international scale. The UN Montreal Protocol (1987) led to a 99% phase-out of regulated ozone-depleting substances.
3. Ongoing monitoring will clarify whether these variations reflect transient atmospheric phenomena or longer-term dynamical changes.

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