Australia's National Science Agency

The 2024 Antarctic Ozone Hole Summary

Paul B. Krummel, Cathy M. Trudinger and Paul J. Fraser
CSIRO Environment – Climate, Atmosphere & Oceans Interactions

June 2025

Report prepared for the Australian Government Department of Climate Change, Energy, the Environment and Water, Refrigerant Reclaim Australia, and the Australian Refrigeration Council.

Australian Government
Department of Climate Change, Energy, the Environment and Water

Refrigerant Reclaim Australia

Australian Refrigeration Council

CSIRO Environment – Climate, Atmosphere & Oceans Interactions

Citation

Krummel, P. B., C. M. Trudinger ,and P. J. Fraser, The 2024 Antarctic Ozone Hole Summary: Final Report, Report prepared for the *Australian Government Department of Climate Change, Energy, the Environment and Water, Refrigerant Reclaim Australia, and the Australian Refrigeration Council*, CSIRO, Australia, vi, 31 pp., 2025.

Acknowledgments

The TOMS and OMI data used in this report are provided by the TOMS ozone processing team, NASA Goddard Space Flight Center, Atmospheric Chemistry & Dynamics Branch, Code 613.3. The OMI instrument was developed and built by the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) and NASA. The OMI science team is lead by the Royal Netherlands Meteorological Institute (KNMI) and NASA. The MERRA-2 heat flux and temperature figures and data are courtesy of NASA GSFC Ozone Watch webpages.

The OMPS total column ozone data used in this report are provided by NASA's NPP Ozone Science Team at the Goddard Space Flight Center, Atmospheric Chemistry & Dynamics Branch, Code 613.3 (see OMPS website for more details). NPP is the National Polar-orbiting Partnership satellite (NPP) and is a partnership is between NASA, NOAA and DoD (Department of Defense), see NPP website for more details.

The Equivalent Effective Stratospheric Chlorine (EESC) data used in this report are calculated using observations of ozone depleting substances (ODS) from the Advanced Global Atmospheric Gases Experiment (AGAGE). AGAGE is supported by MIT/NASA (all sites); Australian Bureau of Meteorology and CSIRO (Cape Grim, Australia); UK Department of Energy and Climate Change (DECC) (Mace Head, Ireland); National Oceanic and Atmospheric Administration (NOAA) (Ragged Point, Barbados); Scripps Institution of Oceanography and NOAA (Trinidad Head, USA; Cape Matatula, American Samoa). The authors would like to thank all the staff at the AGAGE global stations for their diligent work in collecting AGAGE ODS data.

This research is carried out under contract from the Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW), Refrigerant Reclaim Australia (RRA) and the Australian Refrigeration Council (ARC) to CSIRO.

Contents

Figures

Tables

Executive summary

The salient points on the 2024 Antarctic ozone hole are listed below in bullet point format

- The ozone hole metrics indicate that ozone recovery has commenced, with a general trend following the decline in the levels of ozone depleting substances in the stratosphere. However, due to the recent 4 years (2020-2023) which saw large/deep ozone holes, this has given rise to larger uncertainties on the average of the metrics from the last 6 years, compared with those from 1996-2001, resulting in the error bars from the simple statistics used overlapping.
- In this report, we have implemented a different formulation for Equivalent Effective Stratospheric Chlorine (EESC) based on Engel *et al*. (2018), which improves on the method of Newman *et al.* (2007) reported previously. This new formulation results in a delay in the return of mid-latitude EESC to 1980 levels of more than a decade (approximately 2066) when compared with the Newman formulation. For the Antarctic stratosphere, EESC is predicted to occur around 2088.
- However, as summarised in the 'Executive Summary: Scientific Assessment of Ozone Depletion: 2022' (WMO, 2022), the changes in the ozone layer in the latter part of this century will be complex to predict and vary considerably depending on which future greenhouse gas scenarios are used, with the current best estimates for ozone layer recovery to 1980 levels being 2045 for the Southern Hemisphere mid-latitudes. For the Antarctic ozone hole, a return to 1980 levels for the spring-time total ozone column is not expected until the around 2065.
- The Ozone Depleting Gases Index (ODGI) values based on the Engel et al. (2018) EESC formulation suggest that the atmosphere, by 2024, is about 26% along the path to Antarctic ozone recovery and 40% along the path to ozone recovery at mid-latitudes.
- The 2024 Antarctic ozone hole began in earnest in the last week of August and first week of September, which was 2-3 weeks later than the recent ozone holes. The ozone hole peaked in size in the last week of September and in depth in early October. The ozone hole metrics then slowly recovered for the remainder of October and November, before dropping/increasing rapidly in the first week of December to be fully recovered. However, during 17-21 December, the ozone hole briefly reformed in a small pocket, but this was short-lived.
- The lower to mid-stratospheric meteorological conditions for the 2024 ozone hole season were dominated by some large-scale wave activity that resulted in very high to record high level of heat transport towards the pole during June, July and the beginning of August and moderate (higher than average) heat transport towards the pole for the remainder of August and into September. In mid-September there was a cooling event, but this was short lived and from the end of September through to mid-November the heat flux was predominately close to the long-term average. From mid-November through to the end of December, there was once again low to very low heat transport towards the pole.
- This resulted in close to average lower to mid-stratospheric temperatures for June and part of July, after which the temperatures were well above average and at times at record high

levels during July, August and into September. From mid-September until the beginning of November the temperatures were close to the long-term average with some higher than average excursions. Finally, for most of November through to the end of December the low- to mid-stratospheric temperatures were below average.

- Compared to historical ozone hole metrics, the 2024 ozone hole would be considered middle of the pack for some metrics, and lower than average for others. The 2024 ozone hole daily area and 15-day average area metrics ranked 28th and 29th largest out of 45 years of satellite data, well down the rankings. The daily minima, 15-day average minima, daily deficit and integrated deficit metrics ranked 23rd or 24th, close to the middle of the rankings. The colder temperatures and lower heat transport in November and December resulted in a somewhat persistent ozone hole in 2024, with and initial recovery on 8 December but then briefly reformed during 17-21 December, giving it a recovery date that is equal sixth latest on record.
- Overall, the 2024 Antarctic ozone hole was of average depth and lower than average area, with its size and depth close to expected levels following the relatively large ozone holes in the four years prior (2020 to 2023).
- The 2000 and 2006 ozone holes remain the largest ozone holes ever, depending on the metric that is used.

Animations of the daily images from the 2024 ozone hole (along with previous years' holes) in various video formats can be downloaded from:

DropBox

Animations of the historical October 1-15 averages for all available years in the period 1979-2024 are also available, along with the ozone hole metrics presented in this report.

1 The 2024 Antarctic ozone hole

The ozone hole forms in the stratosphere above Antarctica each Southern Hemisphere spring and usually recovers by mid-December. There are several factors that are important in determining the size and duration of the ozone hole. These are meteorological conditions such as the size and strength of the polar vortex, polar stratospheric wave activity, very cold polar stratospheric temperatures and the presence of polar stratospheric clouds (PSCs) (which form at temperatures below 195 K); stratospheric aerosol loading (for example from major volcanic eruptions or unprecedented wildfires); the amount of ozone depleting substances (ODS) in the stratosphere; and the presence of sunlight. Since the levels of ODS in the stratosphere change relatively slowly year to year, and major volcanic eruptions are sporadic, the variability in the size and depth of the Antarctic ozone hole each year is largely determined by the meteorological conditions.

The first excursions below 220 DU of the ozone minima in 2024 occurred briefly on 9-11 July, and again on 14 July, before rising above 220 DU again. The next excursions below 220 DU occurred during 30-31 July and 2-4 August, and from 12 August, the ozone minima remained below 220 DU until it recovered in December. The last week of August and first week of September saw rapid declines in the ozone minima and a sharp rise in the ozone hole area, which was 2-3 weeks later than the recent ozone holes. During the second week of September, the ozone hole became fully formed with the 220 DU contour encircling Antarctica, and remaining closed for the rest of the ozone hole season (see images in Appendix A). During the remainder of September, the daily ozone minima steadily decreased, following the long-term 1979-2023 average until the last week of September where it diverged to much lower values. Likewise, the daily estimated ozone hole area rose during the second half of September, and reached its peak value for the year on 28 September (along with the estimated daily ozone deficit). The images for September and October (Appendix A) show how the ozone hole deepened and grew in size as the polar night receded. The daily ozone minima reached a minimum in the first week of October. The ozone hole metrics then slowly recovered for the remainder of October and November, before dropping/increasing rapidly in the first week of December to be fully recovered. However, during 17-21 December, the ozone hole briefly reformed in a small pocket, but this was short-lived. Another prominent feature during the 2024 ozone hole season was that the ridge of high ozone in a band approximately between 40-60°S was present again, similar to the 2023 season, but was considerably diminished during the 2020-2022 ozone hole seasons when very large/deep ozone holes formed.

The lower to mid-stratospheric meteorological conditions for the 2024 ozone hole season were dominated by some large-scale wave activity that resulted in very high to record high level of heat transport towards the pole during June, July and the beginning of August. This then gave way to moderate (higher than average) heat transport towards the pole for the remainder of August and into September. By mid-September there was a cooling event with low heat transport towards the pole, but this was short lived and from the end of September through to mid-November the heat flux was predominately close to the long-term average. From mid-November through to the end of December, there was once again low to very low heat transport towards the pole. All of this resulted in close to average lower to mid-stratospheric temperatures for June and part of July, after which the temperatures were well above average and at times at record high levels during July, August and into September. From mid-September until the beginning of November the temperatures were close to the long-term average with some higher than average excursions. Finally, for most of November through to the end of December the low- to mid-stratospheric temperatures were below average. The impact of this on the 2024 ozone hole was that the hole was smaller than the average size and with an average amount of ozone depletion within it during September and October. The colder temperatures and lower heat transport in November and December resulted in a somewhat persistent ozone hole in 2024, with and initial recovery on 8 December but then briefly reformed during 17-21 December, giving it a recovery date that is equal sixth latest on record.

Compared to historical ozone hole metrics (Section 2/Table 1), the 2024 ozone hole would be considered middle of the pack for some metrics, and lower than average for others. Table 1 shows that the 2024 ozone hole daily area and 15-day average area metrics ranked 28th and 29th largest out of 45 years of satellite data, well down the rankings. The daily minima, 15-day average minima, daily deficit and integrated deficit metrics ranked 23rd or 24th, close to the middle of the rankings.

Overall, the 2024 Antarctic ozone hole was of average depth and lower than average area, with its size and depth close to expected levels following the relatively large ozone holes in the four years prior (2020 to 2023).

1.1 Ozone hole metrics

1.1.1 Daily ozone minima

Figure 1 shows the Antarctic ozone hole 'depth', which is the daily minimum ozone (in Dobson Units – DU) observed south of 35°S, throughout the ozone hole season (July to December each year).

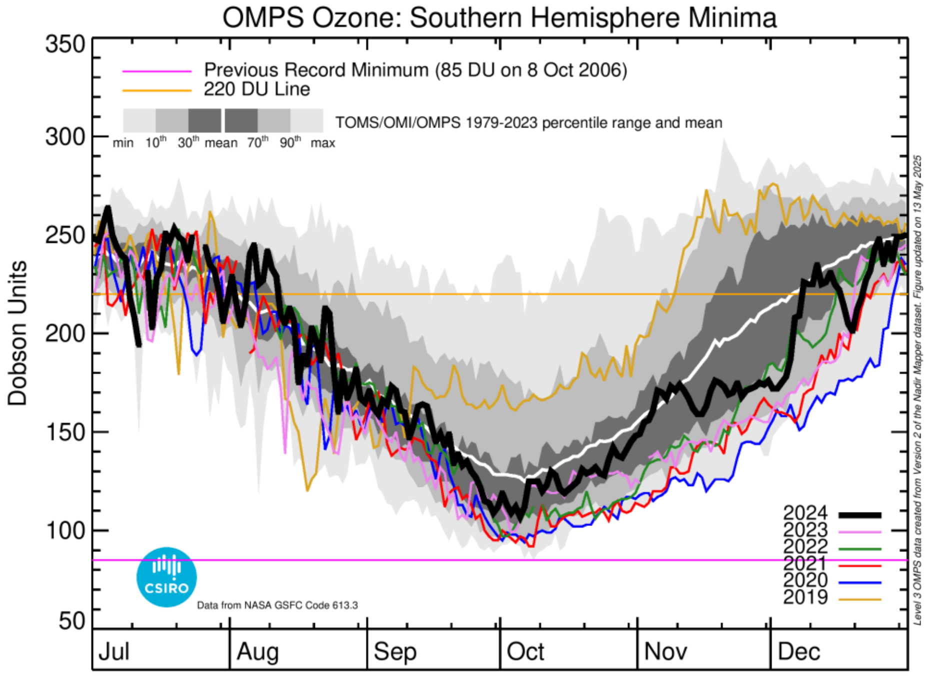
The first excursions below 220 DU of the ozone minima (220 DU is used as the threshold in defining the ozone hole) in 2024 occurred briefly on 9-11 July, and again on 14 July, before rising above 220 DU. The next excursions below 220 DU occurred during 30-31 July and 2-4 August, and from 12 August, the ozone minima remained below 220 DU until it recovered in December. This was followed by a sharp drop to 175 DU on 16 August before rising to 203 DU on 19 August. The minima metric typically shows a lot of variability in August due to the ozone hole still forming around the fringes of the polar night, and 2024 was no different. The variability was superimposed on an overall decline in the minima through August and into mid-September that predominantly followed the long-term (1979-2023) average.

The second half of September saw the daily ozone minima decrease more rapidly reaching 109 DU on 29 September. The beginning of October saw the daily ozone minima drop to its lowest point for the 2024 season, reaching 107 DU on 5 October. Following this, the daily ozone minima increased sharply to 130 DU by 12 October. From 13 to 24 October, the daily ozone minima remained relatively stable in the range of 119-132 DU. By the end of October the daily minima was increasing, reaching 148 DU on 31 October.

The daily ozone minima continued to increase during the beginning of November, reaching 174 DU by 10 November. The week of 11-18 November saw the daily ozone minima decrease down again to 159 DU on 14/15 November, before increasing again to 176 DU by 18 November. The daily ozone minima stayed relatively constant in the range of 168-176 DU during the remainder of November.

The beginning of December saw the daily minima increase rapidly to 226 DU on 8 December which is above the 220 DU threshold used here to define the ozone hole. However, during 17-21 December, the ozone hole briefly reformed in a small pocket, dropping down to 201 DU on 19 December, after which it increased rapidly 20 248 DU by 25 December.

Figure 1. Antarctic ozone hole 'depth' (minimum ozone, DU) based on OMPS satellite data. The 2024 ozone hole based on OMPS data is indicated by the thick black line. The ozone holes for the last five years 2019-2023 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded areas show the 1979-2023 TOMS/OMI/OMPS percentile ranges and the white line shows the 1979-2023 mean.



Overall, this resulted in the 2024 ozone hole being of moderate depth; the minimum ozone level recorded in 2024 (107 DU) was ranked equal 23rd lowest on record out of 45 years of TOMS/OMI/OMPS satellite data, see Table 1. The lowest minimum ozone ever recorded, and hence the deepest hole ever, was in 2006 (85 DU), the second deepest in 1998 (86 DU) and the 3rd deepest in 2000 (89 DU).

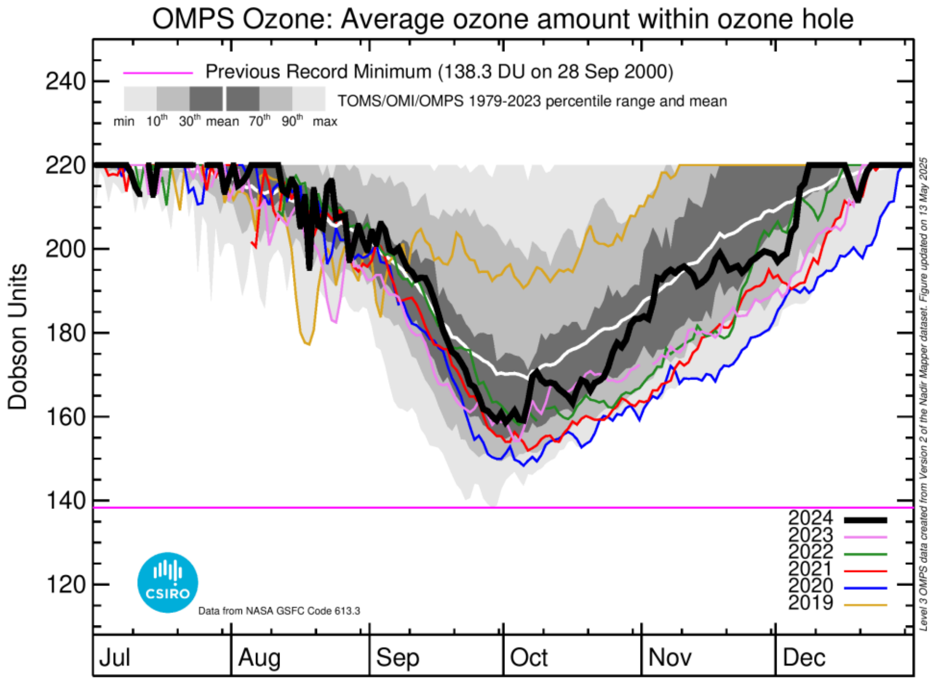
1.1.2 Average amount of ozone within the Antarctic ozone hole

Figure 2 shows the average amount of ozone (DU) within the Antarctic ozone hole throughout the 2024 season. This metric is the averaged column ozone amount in the hole weighted by area.

The minimum average ozone within the hole in 2024 was 159 DU on 1 October, the 22nd deepest recorded, indicating an average ozone hole based on this metric. The lowest reading was in 2000 (138 DU), the second lowest in 2006 (144 DU) and the 3rd lowest in 1998 (147 DU).

Figure 2. Average amount (DU) of ozone within the Antarctic ozone hole throughout the season based on OMPS satellite data. The 2024 ozone hole based on OMPS data is indicated by the thick black line. The ozone holes for the last five years 2019-2023 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded

areas show the 1979-2023 TOMS/OMI/OMPS percentile ranges and the white line shows the 1979-2023 mean.



1.1.3 Daily Antarctic ozone hole area

Figure 3 shows the Antarctic ozone hole area (defined as the area within the 220 DU contour) throughout the 2024 season.

During July and the first week of August there were only very minor ozone depletion events. It was not until 12 August that the ozone hole began to grow and only reached modest to well below average sizes (for this time of year) for the next 12 days of 0.6 to 3.5 million km^2. The last week of August saw the ozone hole area begin to grow in earnest, from 6.6 million km^2 to around 8 million km^2 by the end of the month. This growth was approximately 2-3 weeks later than recent ozone holes, and well below the average for most of August.

The first week of September saw the daily ozone hole area increase rapidly reaching 18.4 million km^2 on 7 September, just above average for this time of year. During the second week of September the daily ozone hole area remained relatively constant in the range of 17.7 to 19.3 million km^2, which is close to the long-term 1979-2023 average, but well below the ozone hole areas seen in the last 4 years for this time of year. From mid-September the daily ozone hole area increased steadily, reaching the peak value for 2024 of 22.4 million km^2 on 28 September.

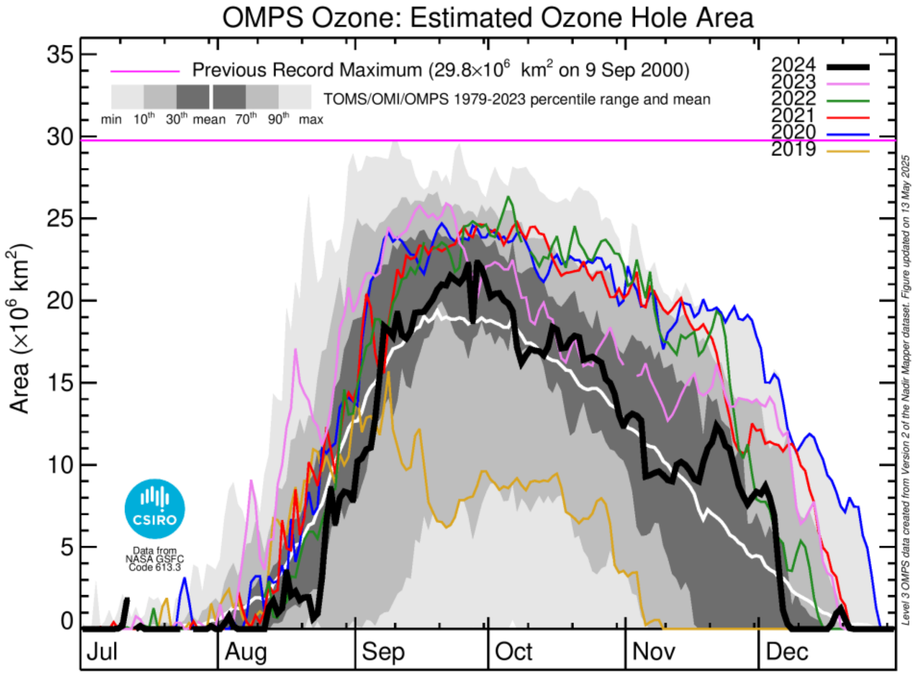
The end of September and first week of October saw the daily ozone hole area decline down to 19.4 million km^2 by 6 October. The second week of October saw the daily ozone hole area drop rapidly, down to 16.2 million km^2 on 8 October and ending the period at 17.2 million km^2 on 14 October. During the third week of October, the estimated daily ozone hole area stayed relatively constant in the range 17.1-18.4 million km^2. The end of October saw the daily ozone hole area decline again, down to 12.3 million km^2 by 31 October.

The beginning of November saw the daily ozone hole area decline rapidly, down to 9.3 million km^2 on 5 November. This is close to the long-term 1979-2023 mean for this time of year. From 6 to 17 November, the daily ozone hole area remained in the range of 9 to 10.2 million km^2.

Following this, the daily ozone hole area increased again, peaking at 12.4 million km² on 21 November before declining to 8.1 million km² on 27 November.

The period of 28 November through to 4 December saw the daily ozone hole area remain in the range of 7.6-8.6 million km², before then plummeting to zero in the space of a few days, being fully recovered by 8 December 2024. However, there was a small reforming of the ozone hole during a 5-day period from 17-21 December, with a small peak in the daily area of 1.2 million km² reached on 19 December.

Figure 3. Antarctic ozone hole area based on OMPS satellite data. The 2024 ozone hole based on OMPS data is indicated by the thick black line. The ozone holes for the last 5 years 2019-2023 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded areas show the 1979-2023 TOMS/OMI/OMPS percentile ranges and the white line shows the 1979-2023 mean.



The maximum daily area of the 2024 ozone hole (22.4 million km² on 28 September) was only the 28th largest hole on record, with the largest in 2000 (29.8 million km²), the 2nd largest in 2006 (29.6 million km²) and the 3rd largest in 2003 (28.4 million km²). The maximum in the 15-day average ozone hole area for 2024 of 21.0 million km² was the 29th largest area ever recorded, with the largest being in 2000 (28.7 million km²) and second largest in 2006 (27.6 million km²). These statistics indicate that while the 2024 ozone hole was relatively large (just under 3 times the area of Australia), in terms of rankings it fell below the average compared with the ozone holes from the 45 years of satellite records, see Table 1.

1.1.4 Daily estimated ozone deficit

Figure 4 shows the daily (24 hour) maximum ozone deficit in the Antarctic ozone hole, which is a function of both ozone hole depth and area. This metric is not the amount of ozone lost within the hole each day, but rather is a measure of the accumulated loss summed over the lifetime of ozone within the hole as measured each day.

During most of August there were only minor levels of ozone depletion, with the estimated daily ozone deficit reaching only 1.2 million tonnes on 18 August and 1.7 million tonnes on 25 August, well below previous years. The daily estimated ozone deficit only increased marginally during the last week of August and reached 3.4 million tonnes by 31 August, well below the long-term 1979-2023 range.

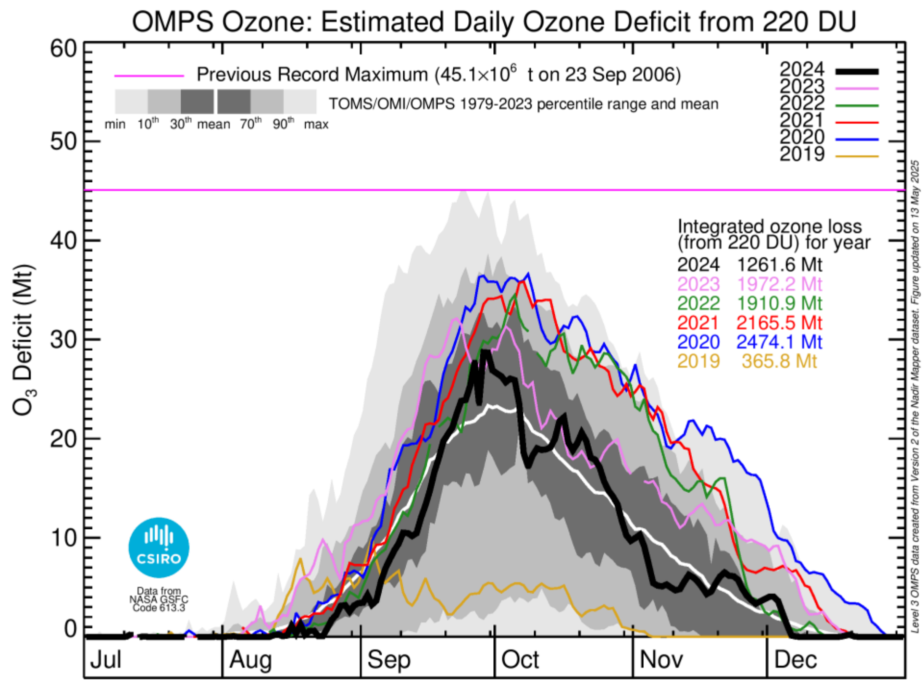
During the first two weeks of September the estimated daily ozone deficit increased to 12 million tonnes, but was still below average for that time of year. The daily estimated ozone deficit increased rapidly during the second half of September, reaching a peak value for 2024 of 28.7 million tonnes on 28 September. This had reduced to 26.9 million tonnes by 30 September.

The first week of October saw the estimated daily ozone deficit drop sharply, dipping to 17.2 million tonnes on 8 October, before rising to 22.1 million tonnes on 16 October. The remainder of October saw a relatively sharp decline in the daily ozone deficit, reaching 9.7 million tonnes on 31 October.

During the beginning of November the estimated daily ozone deficit continued to drop rapidly, reaching 4.7 million tonnes on 10 November. During 11-25 November the daily ozone deficit fluctuated in the range of 4.3 to 6.5 million tonnes.

From 25 November through to 3 December the estimated daily ozone deficit remained in a range of 3.4-4.8 million tonnes before dropping rapidly to zero on 8 December. The brief reforming of the ozone hole during 17-21 December only resulted in a small peak in the daily ozone deficit of 0.2 million tonnes.

Figure 4. OMPS estimated daily ozone deficit (in millions of tonnes, Mt) within the Antarctic ozone hole. The 2024 ozone hole based on OMPS data is indicated by the thick black line. The ozone holes for the last five years 2019-2023 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded areas show the 1979-2023 TOMS/OMI/OMPS percentile ranges and the white line shows the 1979-2023 mean. The estimated total (integrated) ozone loss for each year is shown in the legend.



The maximum daily ozone deficit in 2024 of 28.7 Mt was the 24th largest daily deficit on record, indicating that the 2024 ozone hole was large but 'middle of the pack' compared with the other ozone holes from 45 years of satellite records; the largest was in 2006 (45.1 Mt).

Integrated over the whole ozone-hole season, the total ozone deficit (the sum of the daily ozone deficits) was about 1262 Mt of ozone in 2024 based on OMPS data, again middle of the pack ranking 24th largest cumulative ozone deficit recorded, the largest was in 2006 (2560 Mt) and the 2nd largest was in 2020 (2472 Mt).

1.2 Total column ozone images

The daily total column ozone data over Australia and Antarctica for August through to December 2023 from OMPS are shown in Appendix A Figures A.1 to A.5 respectively.

In Figure A.1, only small patches of ozone depletion can be seen forming in the fringes of the Antarctic polar night (which still covers most of Antarctica at this time of year) during 12-24 August. The strong ridge of high ozone in the band between about 40-60°S is stronger than recent years and appears to be 'patchy' with areas of lower ozone interspersed with areas of very high ozone, suggesting stratospheric wave activity and a weaker polar vortex. The week of 25-31 August saw the ozone hole developing more around the fringes of the polar night but was still a long way from being fully developed and enclosing around the polar night terminator. All 3 of the Australian Antarctic stations were outside of the ozone hole during all of August, while Arrival Heights may have been within the hole on 28/29 August.

The images in Figure A.2 show during the period of 1-8 September that the ozone hole finally completely formed on 7-8 September with the 220 DU contour encapsulating the whole of Antarctica. The polar vortex appeared to be relatively stable for most of September resulting in a relatively symmetrical ozone hole for the month, except for 30 September when the ozone hole started to show some distortion. The ozone hole can be seen to increase considerably in size and depth during September, with the peak area on 28 September. From 5 September until the end of September, Mawson, Davis and Arrival Heights stations were predominantly within the ozone hole or on the edge of it, while Casey station spent time inside, on the edge and outside of the ozone hole during this period. The ridge of high ozone to the south of Australia remained prominent during September in a band approximately between 40-60°S.

The total column ozone images (Figures A.2 & A.3) for the period of 28 September to 13 October show the ozone hole go from relatively stable and symmetrical (28 September & 4-5 October) to elongated (29 September-3 October & 6-13 October). This indicates stratospheric wave activity that strongly impacted the polar vortex, and hence ozone hole symmetry. The impact of the elongation can also be seen in the metrics whereby the area and deficit metrics dropped suddenly, and the minima metric increased in early October. The tip of South America was under the ozone hole on 1-2 October and again from 10-12 October. During 14-24 October, the total column ozone images show that the ozone hole/polar vortex was very stable and symmetrical, but remained offset of the pole towards the Atlantic Ocean. For the 25-31 October period the polar vortex/ozone hole became distorted again during and continued to be offset of the pole towards the Atlantic Ocean. The size and depth of the ozone hole can also be seen to reduce during this period. Mawson and Davis stations spent the majority of October within the ozone hole with only a few days outside of the hole. Conversely, Casey and Arrival Heights spent most of October outside of the ozone hole due to the displacement of the ozone hole towards the Atlantic Ocean.

During 1-11 November (Figure A.4), the total column ozone images show that the ozone hole/polar vortex became unstable and very elongated. The elongation/distortion was particularly pronounced during 2-5 November. From 12-17 November, the ozone hole reduced in size, became less distorted and was offset of the pole towards the Indian Ocean. During 18-21 November, the ozone hole/polar vortex became quite stable, and recentred over the pole. However, from 22-30 November the ozone hole reduced in size and was offset from the pole, initially towards the Atlantic Ocean and then towards the Indian Ocean. Mawson and Davis stations spent about half of November within the ozone hole, and the other half one the edge of or outside of the ozone hole. Similar to October, Casey and Arrival Heights spent more time in November outside of the ozone hole than inside of it. Late October and through November saw the ridge of high ozone in the band between 40-60°S dissipate considerably.

The total column ozone images for December (Figure A.5) show the ozone hole was offset from the pole towards the Indian ocean and relatively stable from 1-2 December before becoming very elongated and nearly splitting in two during 3 to 7 December and recovering by 8 December. The images from 17-21 December show the small pocket where the ozone hole briefly reformed.

1.3 Antarctic meteorology/dynamics

The 2024 MERRA2 45-day mean 45-75°S heat fluxes at 50 & 100 hPa are shown in the left-hand panels of Figure 5. A less negative heat flux usually results in a colder polar vortex, while a more negative heat flux indicates heat transported towards the pole (via some meteorological disturbance/wave activity) and results in a warming of the polar vortex. The corresponding 60-90°S zonal mean temperatures at 50 & 100 hPa for 2024 are shown in the right-hand panels of Figure 5, these usually show an anti-correlation to the heat flux.

For most of May, June, and the first half of July, the 45-day mean 45-75°S heat flux at 50 & 100 hPa were predominantly in the lowest 10th percentile band of the 1979-2024 range or at record lows, indicating strong heat transport towards the pole in the low to mid stratosphere. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa were close to, or above, average for this two-and-a-half-month period.

The second half of July into early August saw a stratospheric warming event with the 45-75°S heat flux at 50 & 100 hPa reaching record low values for a two-week period, before moving back into the lowest 10th percentile during the third week of August. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa reached record high values during this period, especially at the 50 hPa level, before returning to close to average and then increasing rapidly again during the second and third weeks of August. This level of temperature fluctuation was very unusual, and indicates strong polar stratospheric wave activity and a weaker or unstable polar vortex. The warmer polar stratospheric conditions impacted the overall level of ozone depletion in 2024.

During the last week of August and continuing into the first week of September, the 45-75°S heat flux at 50 & 100 hPa moved into the 10-30th percentile band of the long-term 1979-2024 range, indicating above average heat transport towards the pole. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa moved into the 70-90th percentile band of the 1979-

2024 range, continuing the much warmer than average low to mid-stratospheric temperatures for this time of year.

The remainder of September saw the 45-75°S heat fluxes at 50 & 100 hPa move first into the 50-70th percentile band of the 1979-2024 range and then into the 70-90th percentile band, before returning to the 50-70th percentile band, indicating less heat transport towards the pole than average. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa first moved into the 50-70th percentile band of the 1979-2024 range and then tracked very close to the long-term average or slightly below.

During October, the 45-75°S heat flux at 50 hPa predominantly followed the long-term 1979-2024 average, while at 100 hPa the heat flux was in the 50-70th percentile band. The 60-90°S zonal mean temperatures at both 50 & 100 hPa fluctuated during October, from close to the long-term 1979-2024 mean up to the 70-90th percentile band, continuing the warmer conditions in the low to mid-stratosphere.

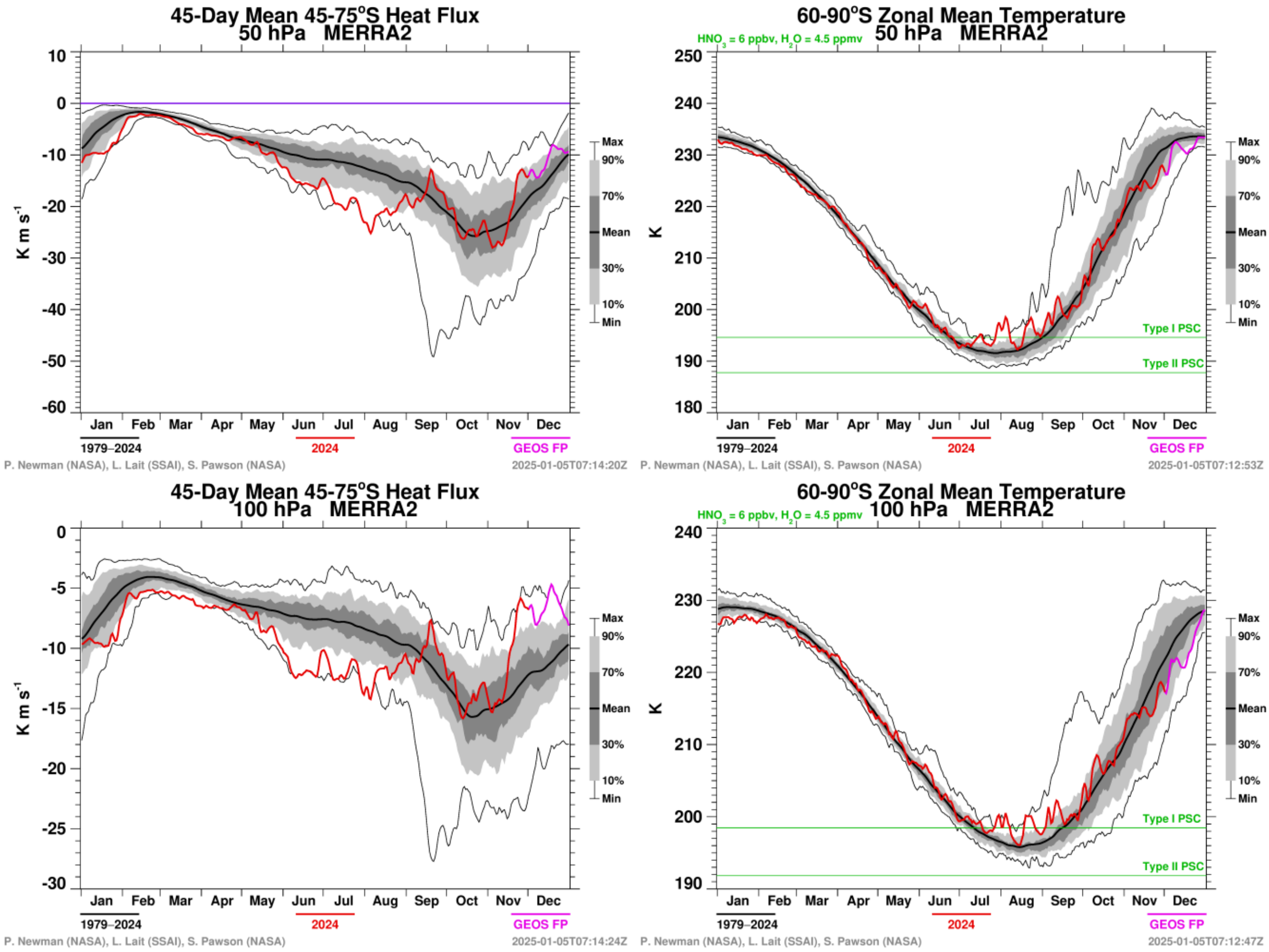
The during the first half of November, the 45-day mean 45-75°S heat flux at 50 hPa move into the 30-50th percentile band of the 1979-2024 range while the 100 hPa trace followed the long-term mean, indicating average to more heat transport towards the pole. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa were above average being in the 50-70th percentile band of the 1979-2024 range.

In mid-November the 45-day mean 45-75°S heat flux at 50 & 100 hPa increased sharply, and by the last week of November the 50 hPa trace moving into the 70-90th percentile band of the 1979-2024 range, while the 100 hPa trace moved into the upper 10th percentile band and at times at record high levels, indicating less heat transport towards the pole. These conditions remained through to the end of December. The corresponding 60-90°S zonal mean temperatures at both 50 & 100 hPa moved first into the 30-50th percentile band, and then into the 10-30th percentile band, indicating much colder than average temperatures at the end of the ozone hole season.

The 2024 stratospheric meteorological conditions were dominated by an initial period of high heat transport towards the pole and well above average low to mid-stratospheric temperatures. This was followed by a period of average to lower than average heat transport towards the pole and predominantly average temperatures. During November and December there was low heat transport towards the pole and resulted in below average temperatures of this period. This likely resulted prolonging the recovery of the ozone hole.

At 50 hPa, the type 1 PSC ($HNO_3.3H_2O$) formation threshold temperature (195 K) was reached towards the end of June, but oscillated above and below the threshold until the end of August, after which the 50 hPa temperature remined above the threshold. It was a similar pattern at 100 hPa.

Figure 5. NASA MERRA2 heat flux and temperature for 2024. The 45-day mean 45°S-75°S eddy heat flux at 50 and 100 hPa are shown in the two left hand panels. The 60°S-90°S zonal mean temperature at 50 & 100 hPa are shown in the right two panels. Images courtesy of NASA GSFC.



2 Comparison to historical metrics

Table 1 contains the ranking for all 45 ozone holes recorded since 1979 for the various metrics that measure the 'size' of the Antarctic ozone hole: 1 = lowest ozone minimum, greatest area, greatest ozone loss etc.; 2 = second lowest or largest….

The data used in Table 1 are from a series of different satellite platforms and sensors. A quick summary of the satellite/sensor data used is:

1979-1992: Nimbus 7 TOMS

1993-1994: Meteor 3 TOMS

1996-2004: Earth Probe TOMS

2005-2015: Aura OMI

2016-onwards: NPP OMPS

The definitions of the eight metrics used here are (note that the metrics use 220 DU as the threshold in total column ozone to define the boundary of the ozone hole):

- 15-day average ozone hole area is the maximum of the 15-day moving average of the daily ozone hole area.
- Daily ozone hole area is the maximum daily ozone hole area on any day during the ozone hole season.
- The 15-day average ozone hole depth (or minima) is the minimum of the 15-day moving average of the daily ozone hole depth.
- Ozone hole depth (or daily minima) is based on the minimum column ozone amount south of 35°S on any day during ozone hole season.
- Minimum average ozone is the minimum daily average ozone amount (within the hole) on any day during the ozone hole season.
- Daily maximum ozone deficit is the maximum ozone deficit on any day during the ozone hole season.
- Ozone deficit is the integrated (total) ozone deficit for the entire ozone hole season.
- Breakdown date is the final date at which the 5-day smoothed daily area (metric 2) falls below 0.5 million km^2 (sorted by decreasing day-of-year number)

Table 1 shows that while the 2024 ozone hole was relatively large, it overall ranked middle of the pack or less. The daily area and 15-day average area metrics ranked 28th and 29th largest out of 45 years of satellite data. The daily minima ranked 23rd, while the 15-day average minima, daily deficit and integrated ozone deficit metrics all ranked 24th. The ozone hole recovery date in 2024 was ranked 6th latest, but this was due to the brief reforming of the hole from 17-21 December, following the initial closing on 8 December, otherwise is would have been ranked much lower. These are comparisons from 45 years of TOMS/OMI/OMPS satellite records.

Table 1. Antarctic ozone hole metrics based on TOMS/OMI/OMPS satellite data - ranked by size or minima.

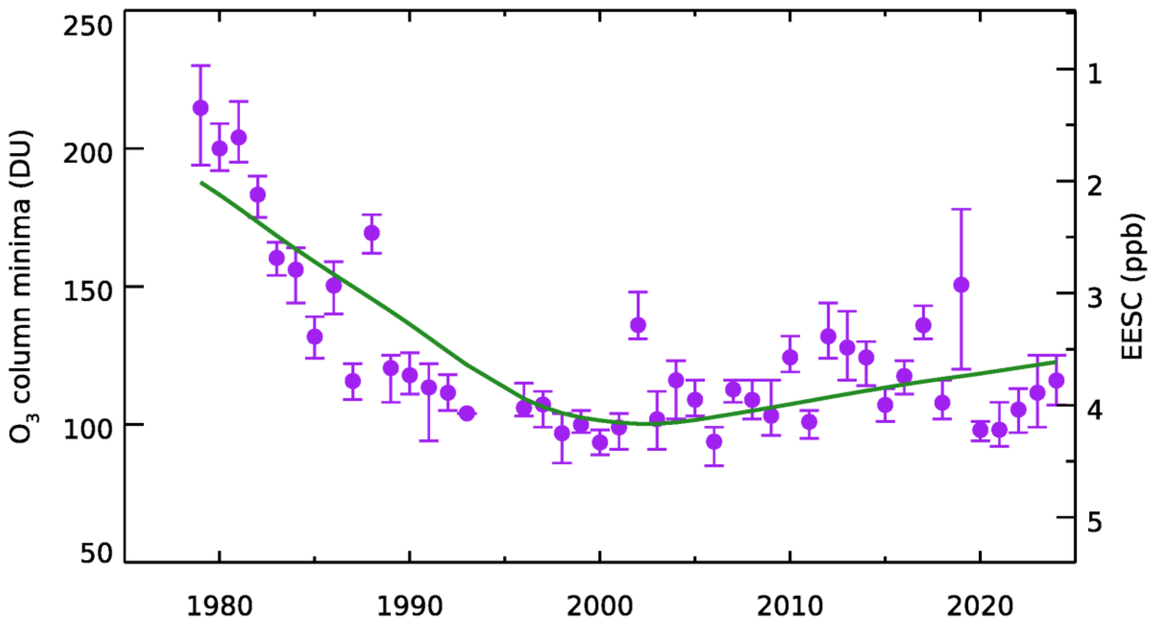
Rank	15-day average ozone hole area		Daily ozone hole area maxima		15-day average ozone hole minima		Ozone hole daily minima		Daily minimum average ozone		Daily maximum ozone deficit		Integrated ozone deficit		Breakdown date	
	Year	10^6 km^2	Year	10^6 km^2	Year	DU	Year	DU	Year	DU	Year	Mt	Year	Mt	Year	Date (day)
1	2000	28.706	2000	29.751	2000	93.5	2006	85	2000	138.3	2006	45.1	2006	2560.0	2020	29-Dec (364)
2	2006	27.555	2006	29.574	2006	93.7	1998	86	2006	143.6	2000	44.9	2020	2474.1	1999	28-Dec (362)
3	2015	27.550	2003	28.408	1998	96.8	2000	89	1998	146.7	2003	43.4	1998	2419.9	2008	26-Dec (361)
4	2003	26.912	2015	28.146	2020	98.0	2001	91	2003	147.5	1998	41.1	2001	2298.2	2010	22-Dec (356)
5	1998	26.793	1998	27.882	2021	98.1	2003	91	2020	148.3	2008	39.4	1999	2249.6	2021	22-Dec (356)
6	2008	26.111	2005	27.249	2001	98.9	2021	92	2001	148.8	2001	38.5	2015	2197.2	**2024**	**21-Dec (356)**
7	2001	25.720	2008	26.896	1999	99.9	2020	94	1999	149.3	2015	37.7	1996	2175.7	2015	21-Dec (355)
8	2005	25.572	1996	26.751	2011	100.9	1991	94	2005	149.4	2011	37.5	2021	2165.5	2001	20-Dec (354)
9	2011	25.084	2001	26.411	2003	101.9	2011	95	2009	150.4	2005	37.1	2000	2164.0	2011	20-Dec (354)
10	1996	25.025	2022	26.345	2009	103.1	2009	96	1996	150.6	2020	36.6	2011	2123.6	2023	20-Dec (354)
11	2023	24.977	2023	25.917	1993	104.0	1999	97	2008	150.8	2021	35.8	2008	1982.7	2006	17-Dec (351)
12	1993	24.786	2011	25.870	2022	105.4	2022	97	2011	151.2	2009	35.7	2023	1972.2	1990	16-Dec (350)
13	2022	24.688	1993	25.777	1996	106.0	2023	99	1997	151.3	1999	35.3	2022	1910.9	2022	16-Dec (350)
14	1994	24.328	1999	25.680	2015	107.1	1997	99	2021	151.9	2018	34.8	2003	1893.6	1998	15-Dec (349)
15	2021	24.256	1994	25.229	1997	107.2	2015	101	2018	152.8	2022	34.5	2005	1870.9	2007	14-Dec (348)
16	2007	24.125	2007	25.163	2018	107.9	2004	102	2023	154.2	1997	34.5	1993	1832.9	1996	10-Dec (345)
17	2018	24.075	1997	25.066	2008	108.9	2008	102	2007	155.1	1996	33.9	2018	1810.1	1992	09-Dec (344)
18	2020	24.053	1992	24.896	2005	108.9	2018	102	1993	155.2	1992	33.5	2009	1806.3	1987	08-Dec (342)
19	2009	24.013	2021	24.773	2023	111.5	2005	103	1992	156.3	2007	32.9	2007	1772.0	2005	07-Dec (341)
20	1992	23.983	2018	24.728	1992	111.5	1996	103	2015	156.9	1993	32.6	1997	1758.6	1993	06-Dec (340)
21	1999	23.974	2020	24.702	2007	112.7	1993	104	2022	158.0	2023	32.1	1992	1528.6	1997	04-Dec (338)
22	1997	23.320	2009	24.462	1991	113.4	1992	105	**2024**	**158.7**	2014	30.7	1987	1365.6	2018	04-Dec (338)
23	2013	22.674	2013	23.970	1987	115.7	**2024**	**107**	2016	159.7	2016	29.3	2010	1352.6	2003	03-Dec (337)

Rank	15-day average ozone hole area		Daily ozone hole area maxima		15-day average ozone hole minima		Ozone hole daily minima		Daily minimum average ozone		Daily maximum ozone deficit		Integrated ozone deficit		Breakdown date	
24	2014	22.472	2014	23.879	**2024**	**115.9**	1989	108	2014	160.0	**2024**	**28.7**	**2024**	**1261.6**	1985	03-Dec (337)
25	2016	21.646	2016	22.745	2004	116.0	2007	108	1991	162.5	1991	26.6	2014	1251.5	2014	02-Dec (336)
26	2010	21.606	2004	22.741	2016	117.5	1987	109	1987	162.6	2010	26.2	2016	1217.9	1989	02-Dec (336)
27	1987	21.356	1987	22.386	1990	117.8	1990	111	1990	164.4	1987	26.2	1990	1180.7	2004	29-Nov (334)
28	2004	21.104	**2024**	**22.355**	1989	120.4	2016	111	2010	164.5	2013	25.1	2013	1037.3	2009	30-Nov (334)
29	**2024**	**21.025**	1991	22.324	2014	124.3	2014	114	2013	164.7	1990	24.3	1991	998.3	1994	27-Nov (331)
30	1991	20.958	2010	22.278	2010	124.3	2013	116	1989	166.2	1989	23.6	2004	974.7	2016	21-Nov (326)
31	1989	20.692	2002	21.817	2013	127.8	2010	119	2004	166.7	2002	23.2	1989	916.7	2000	20-Nov (325)
32	1990	19.535	1989	21.617	1985	131.8	2019	120	2002	169.8	2004	22.8	2017	732.7	2017	20-Nov (324)
33	2012	19.341	2012	21.151	2012	131.9	2012	124	2012	170.2	2012	22.5	2012	719.7	1991	19-Nov (323)
34	2002	17.666	1990	21.045	2017	135.9	1985	124	2017	172.9	2017	18.5	1985	629.6	2013	17-Nov (321)
35	2017	17.580	2017	19.128	2002	136.0	2002	131	1985	177.1	1985	14.5	2002	574.8	1986	15-Nov (320)
36	1985	16.563	1985	18.596	1986	150.3	2017	131	2019	177.2	1986	10.5	2019	365.8	1984	16-Nov (320)
37	1986	13.399	2019	15.686	2019	150.6	1986	140	1986	184.7	2019	10.0	1986	346.2	1982	13-Nov (317)
38	1984	12.959	1984	14.413	1984	156.1	1984	144	1984	190.2	1984	9.2	1984	255.5	2012	09-Nov (314)
39	2019	12.208	1986	14.235	1983	160.3	1983	154	1983	192.2	1983	7.0	1988	197.6	2002	07-Nov (311)
40	1988	11.327	1988	13.542	1988	169.4	1988	162	1988	195.0	1988	6.0	1983	184.0	2019	07-Nov (311)
41	1983	10.136	1983	12.121	1982	183.3	1982	170	1982	199.7	1982	3.7	1982	73.1	1980	05-Nov (310)
42	1982	7.465	1982	10.601	1980	200.0	1980	192	1980	210.0	1980	0.6	1980	12.8	1983	06-Nov (310)
43	1980	1.988	1980	3.197	1981	204.0	1979	194	1979	210.2	1981	0.6	1981	3.5	1981	30-Oct (303)
44	1981	1.303	1981	2.888	1979	214.7	1981	195	1981	210.2	1979	0.3	1979	1.0	1988	28-Oct (302)
45	1979	0.229	1979	1.234	1994	NaN	1994	NaN	1994	NaN	1994	NaN	1994	NaN	1979	19-Sep (262)

Figure 6 shows the 15-day moving average of the minimum daily column ozone levels recorded in the hole since 1979 from TOMS, OMI and OMPS satellite data. This metric shows a consistent downward trend in ozone minima from the late 1970s until the mid-to-late-1990s, with signs of ozone recovery by 2023. The 1996-2001 mean was 100±5 DU, while the 2018-2023 mean was 113±20 DU. Using simple statistics, there is a suggestion that ozone is recovering but it may not yet be significant with the uncertainties still overlapping (at 1 σ level). Applying the Student's t-test for differences of mean with unequal variances for the 1996-2001 versus 2019-2024 periods indicates that this increase is statistically significant only at the 83% confidence limit. This is not surprising given the relatively deep ozone holes during 2020 to 2023.

The green line in Figure 6 (and in Figures 7, 8, 9 and 10) is a simple linear regression of Antarctic Equivalent Effective Stratospheric Chlorine (EESC-A; see Section 3 for more details) against the 15-day smoothed column minima (and the other metrics in Figures 7, 8, 9 and 10), plotted against time. EESC is calculated from Cape Grim data – both *in situ* and from the Cape Grim Air Archive – and AGAGE global measurements of Ozone Depleting Substances (ODSs: chlorofluorocarbons, hydrochlorofluorocarbons, halons, methyl bromide, carbon tetrachloride, methyl chloroform and methyl chloride (Fraser *et al*. 2014)). The regressed EESC broadly matches the decadal variations in the ozone minima indicating a slow recovery since early to mid-2000s. It also gives a guide to the relative importance of the meteorological variability, especially in recent years.

Figure 6. Minimum ozone levels observed in the Antarctic ozone hole using a 15-day moving average of the minimum daily column ozone levels during the entire ozone season for all available years of TOMS (1979-2004), OMI (2005-2015) and OMPS (2016 onwards) data. The green line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text. The error bars represent the range of the daily ozone minima in the 15-day average window.



Using an outlier-resistant two-variable linear regression technique, a linear fit was applied to the complete 1996-2024 data shown in Figure 6 to give an estimate of yearly recovery rate. This yielded an ozone growth of 0.5±0.3 (1σ) DU/yr, indicating signs of slow recovery. This suggests that over the 29-year period (1996-2024) a total increase in ozone of 14.5 DU has occurred, which is consistent with the difference between the 1996-2001 and 2019-2024 means stated above. It should be noted that the ozone holes during 2020 to 2023 were deep (intense ozone loss) and large when compared to the holes from the last 10-15 years, which is notable in Figures 6-9, and this impacts the simple statistic calculations used here.

Figure 7 shows the average ozone amount in the ozone hole (averaged column ozone amount in the hole weighted by area) from 1979 to 2024 from TOMS, OMI and OMPS satellite data. This metric shows a consistent downward trend in average ozone from the late-1970s until the late-1990s, with some sign of ozone recovery by 2024. The 1996-2001 mean was 148±5 DU while the 2019-2024 mean was 158±10 DU. Again, simple statistics suggest that there are signs that ozone is recovering but with the uncertainties still overlapping (at 1 σ level) for this metric. The Student's t-test was applied to these data and this indicated that this increase is statistically significant at the 95% confidence limit.

Applying the afore mentioned robust linear regression to the 1996-2024 data in Figure 7 yields an ozone growth (recovery) of 0.4±0.2 (1 σ) DU/yr. Ozone recovery is also suggested by the regressed EESC-A line.

Figure 7. The average ozone amount in the ozone hole (averaged column ozone amount in the hole weighted by area) for all available years of TOMS (1979-2004), OMI (2005-2015) and OMPS (2016 onwards) data. The green line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text.

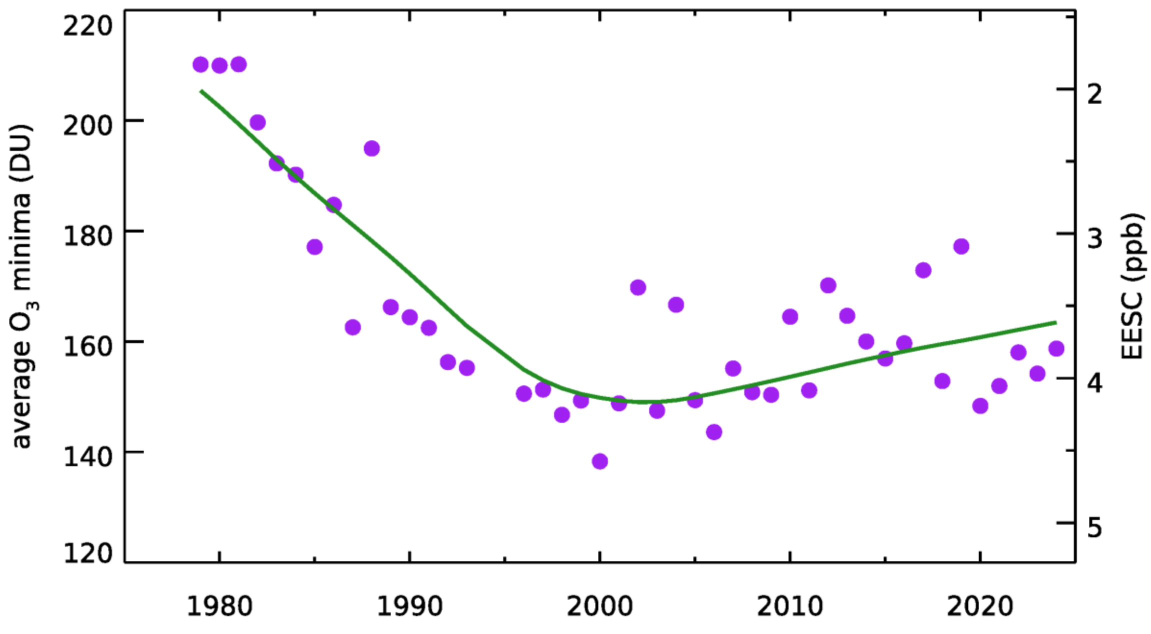


Figure 8 shows the maximum ozone hole area (15-day average) recorded since 1979 from TOMS, OMI and OMPS satellite data. Visually disregarding the unusual years (1988, 2002, 2019) when the polar vortex broke up early, this metric suggests that the ozone hole stopped growing around the year 2000 (date of maximum ozone hole area), and may now be showing overall signs of a decline in area, despite the recent 4 large ozone holes (2020, 2021, 2022, 2023). The 1996-2001 mean was (25.6±2.0) x10^6 km^2, while the 2019-2024 mean was (21.9±4.9) x10^6 km^2, indicative of the commencement of possible ozone recovery, but not statistically significant using the simple statistic that the 1 σ standard deviations considerably overlap. This is confirmed by applying the Student's t-test which showed these means only being just significant at the 87% confidence limit.

Applying the robust linear regression to the 1996-2024 data in Figure 8 yields an ozone hole area decline of (0.12±0.07) x10^6 km^2/yr over this period.

Figure 8. Maximum ozone hole area (area within the 220 DU contour) using a 15-day moving average during the ozone hole season, based on TOMS (1979-2004), OMI (2005-2015) and OMPS (2016 onwards) data. The green line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text. The error bars represent the range of the ozone hole size in the 15-day average window.

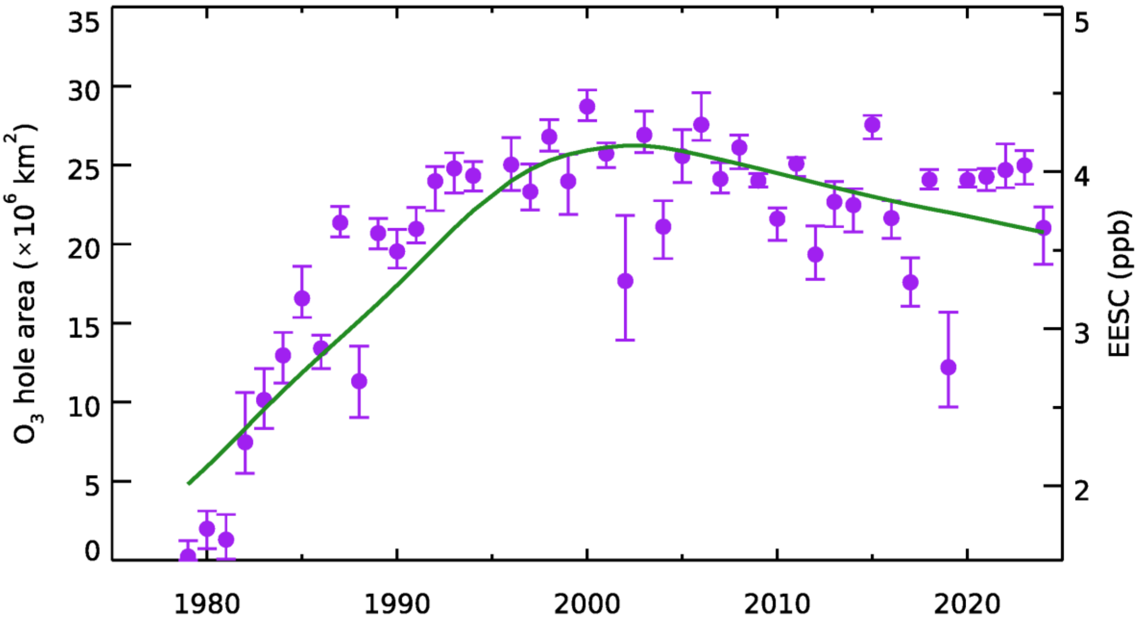
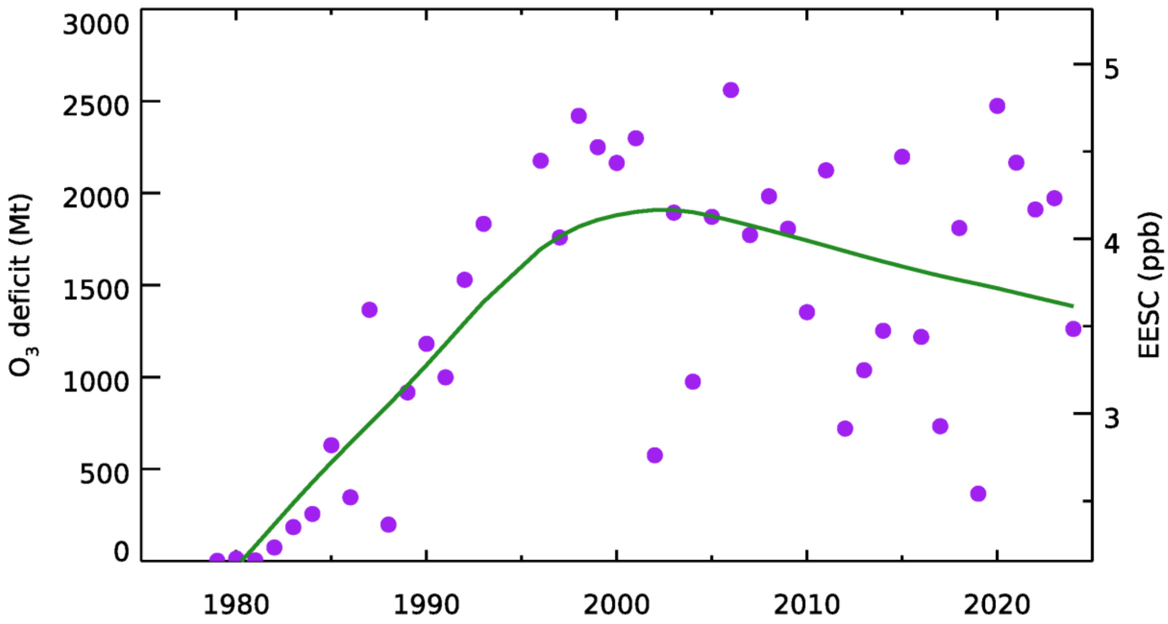


Figure 9 shows the integrated ozone deficit (Mt) from 1979 to 2024. The ozone deficit rose steadily from the late-1970s until the late-1990s/early 2000s, where it peaked at approximately 2300 Mt, and then started to drop. This metric is very sensitive to meteorological variability resulting in large year to year fluctuations; however, there appears to be broad evidence of ozone recovery with a general reduction in ozone deficit since the early 2000s. The 1996-2001 mean was 2180±230 Mt while the 2019-2024 mean was 1690±760 Mt, indicative of the commencement of ozone recovery, but again with the uncertainties overlapping (at 1 σ level) for this metric. The Student's t-test applied to these data indicated that this decrease is only just significant at the at 81% confidence limit, partly because this metric has large variability.

Applying the robust linear regression to the 1996-2024 data in Figure 9 resulted in a decline in ozone deficit of 18±13 (1σ) Mt/yr over this period.

Figure 9. Estimated total ozone deficit for each year in millions of tonnes (Mt), based on TOMS (1979-2004), OMI (2005-2015) and OMPS (2016 onwards) satellite data. The green line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text.



3 Antarctic ozone recovery

Ozone recovery over Antarctica is complex to model. Apart from the future levels of ozone depleting chlorine and bromine in the stratosphere, temperature trends and variability in the stratosphere, the impact of major volcanic events and the future chemical composition (for example H_2O, CH_4 and N_2O) of the stratosphere are likely to be important factors in determining the rate of ozone recovery. Model results and observations show that the solar cycle changes have an influence on tropical ozone but do not significantly affect stratospheric ozone levels over Antarctica.

Equivalent Chlorine (ECl: chlorine plus weighted bromine) levels, derived from CSIRO Kennaook/Cape Grim and other AGAGE surface and CSIRO Antarctic firn observations of ODSs, are likely to decline steadily over the next few decades at about 1% per year, leading to reduced ozone destruction. Equivalent Effective Stratospheric Chlorine for mid- (EESC-ML) and Antarctic (EESC-A) latitudes, calculated with an improved formulation outlined in Engel *et al*. (2018) is now being used here. The Engel method is similar to that by Newman *et al*. (2007) used in previous reports but differs in two aspects. First, chemical loss is described by new time-independent fractional release factors; and second, a new method for calculating the air age distribution/spectrum is used where the transit times from the classical age spectrum are weighted with the chemical loss during transit time (termed "release time distribution").

Figure 10 shows the differences between the Engel and Newman formulations of EESC. For the EESC-A (Antarctic) case, there are only minor differences with a small increase in the estimated 1980 recovery date using the Engel method. The biggest change, which is described in detail in Engel *et al.* (2018), is with the mid-latitudes case where the Engel formulation yields a recovery date which is more than 10 years later than that using the Newman formulation. The shift in recovery date is mainly caused by a lower EESC level calculated for the 1980 reference value (which is the period of rapidly increasing ODSs).

Using the Engel formulation, EESC-A peaked at 4.166 ppb in 2002 and EESC-ML at 1.889 ppb in 2001 respectively, falling to 3.614 and 1.556 ppb respectively by 2024, declines of 13.2% and 17.6% respectively.

Table 2 shows the species contributing to the declines in EESC-A (~0.55 ppb) and in EESC-ML (~0.33 ppb) since their peak values in 2002 and 2001 respectively. The decline since 2002/2001 to 2024 is dominated by methyl chloroform, followed by the CFCs & methyl bromide, then carbon tetrachloride. The halons and HCFCs have made an overall growth, albeit smaller, contribution to EESC-A and EESC-ML since 2002/2001.

The initial (1-2 decades) decline in EESC-ML and EESC-A have been and will be dominated by the shorter-lived ODSs, such as methyl chloroform and methyl bromide, whereas the long-term decline will be dominated by CFCs and carbon tetrachloride because of their longer atmospheric life-times. The atmospheric concentration of methyl chloroform at the end of 2024 had dropped below 1 ppt (parts-per-trillion) indicating that most of the rapid decline in this shorter lived ODS has already occurred.

Table 2. ODS contributions to the decline in EESC at Antarctic and mid-latitudes (EESC-A, EESC-ML) observed in the atmosphere in 2024 since their peak values in 2002 and 2001 respectively. These are based on the Engel *et al.* (2018) EESC formulations. Note values have been rounded to three decimal places.

Species	Antarctic EESC value in 2002 (ppb Cl)	Antarctic EESC value in 2024 (ppb Cl)	Antarctic EESC decline (ppb Cl)	mid-latitudes EESC value in 2001 (ppb Cl)	mid-latitudes EESC value in 2024 (ppb Cl)	mid-latitudes EESC decline (ppb Cl)
methyl chloroform	0.240	0.006	0.234	0.138	0.003	0.135
methyl bromide	0.584	0.424	0.160	0.330	0.235	0.095
CFCs	1.933	1.760	0.173	0.698	0.628	0.070
carbon tetrachloride	0.398	0.311	0.087	0.223	0.171	0.052
methyl chloride	0.509	0.495	0.014	0.246	0.239	0.007
halons	0.433	0.454	-0.021	0.231	0.223	0.008
HCFCs	0.068	0.163	-0.095	0.023	0.057	-0.034
Total decline			0.552			0.333

If we simply look at EESC-ML and EESC-A values based on the baseline scenarios of ODS decline (Daniel & Reimann 2022), recovery of EESC to 1980 levels at mid-latitudes will occur around 2066 and in the Antarctic stratosphere will occur about 2088 (see Figure 10). Note again that using the Engel *et al.* (2018) formulations results in a delay in the return of mid-latitude EESC to 1980 levels of more than a decade when compared with the formulation of Newman. However, as summarised in the 'Executive Summary: Scientific Assessment of Ozone Depletion: 2022' (WMO, 2022), the changes in the ozone layer in the latter part of this century will be complex to predict and vary considerably depending on which future greenhouse gas scenarios are used, with the current best estimates for ozone layer recovery to 1980 levels being 2045 for the Southern Hemisphere mid-latitudes. For the Antarctic ozone hole, a return to 1980 levels for the spring-time total ozone column is not expected until the around 2065.

In response to the need to easily convey information to the general public about the levels of ozone-destroying chemicals in the atmosphere, and when might the ozone hole recover, NOAA has developed the Ozone Depleting Gas Index (ODGI) (Hofmann & Montzka 2009; and recent updates see NOAA ODGI website). The index neatly describes the state of the atmosphere, in relation to stratospheric halogen (chlorine plus bromine) levels and is based on atmospheric measurements of ODSs and the above EESC calculations. The index has two components, one relevant for ozone-depleting chemicals and the ozone hole over Antarctica (the ODGI-A), and one relevant for mid-latitudes (the ODGI-ML).

Figure 11 shows the CSIRO version of the ODGI-ML and ODGI-A indices derived from global AGAGE data including data from Cape Grim, using the Engel *et al.* (2018) formulation and the previously used Newman formulations. Based on data up to 2024 and the Engel method, the ODGI-A and ODGI-ML indices have declined by 26% and 40% respectively since their peak values in 2002 and 2001 respectively, indicating that the atmosphere in 2024 is 26% and 40% along the way toward a halogen level that should allow an ozone-hole free Antarctic stratosphere and a 'normal' (pre-1980s) ozone layer at mid-latitudes.

Figure 10. Equivalent Effective Stratospheric Chlorine for mid-and Antarctic latitudes (EESC-ML, EESC-A) derived from global measurements of all the major ODSs at Cape Grim (CSIRO/BoM) and other AGAGE stations and in Antarctic firn air (CSIRO) from Law Dome. EESC formulations from the updated Engel *et al.* (2018) method and the Newman *et al*. (2007) method are shown to illustrate the changes. Arrows indicate dates when the mid-latitude and Antarctic stratospheres return to pre-1980s levels of EESC, and approximately pre-ozone hole levels of stratospheric ozone, based on the WMO 2022 Ozone Assessment Baseline ODS scenario.

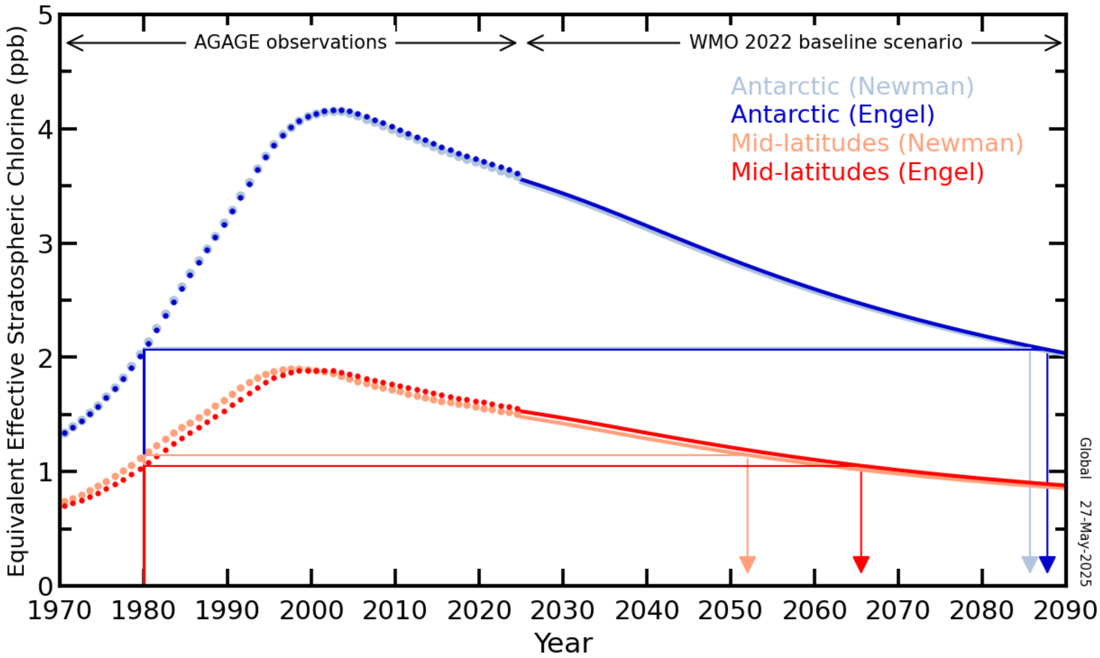
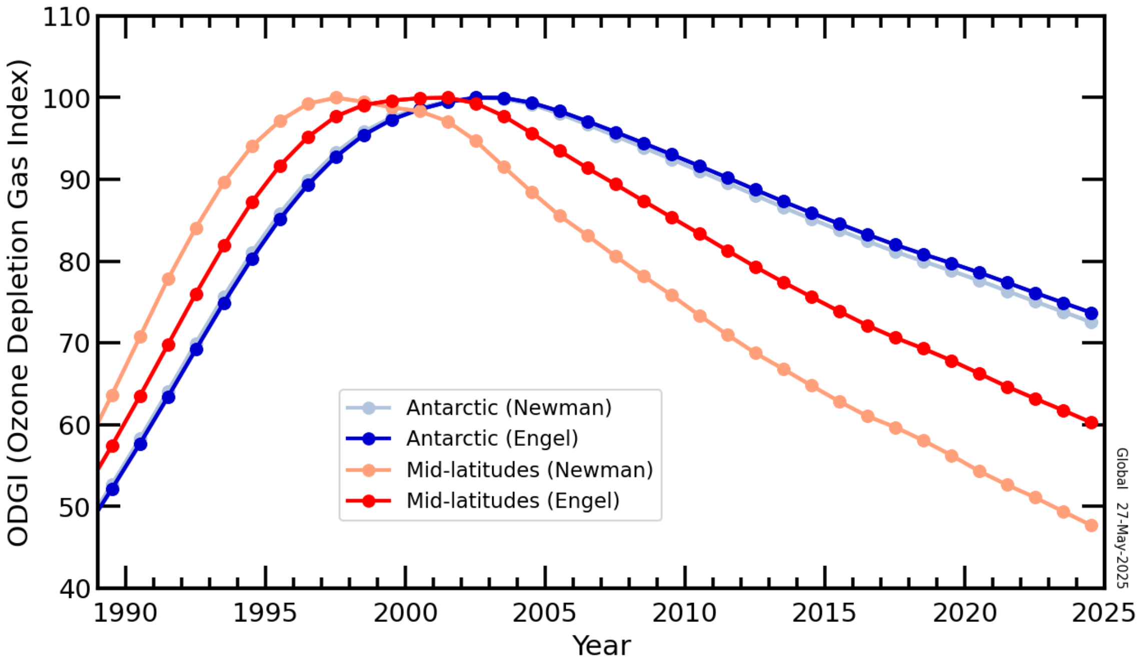


Figure 11. ODGI-A and ODGI-ML indices (Hofmann & Montzka 2009) derived from AGAGE ODS data using ODS fractional release factors from Engel *et al.* (2018) and Newman *et al*. (2007).



Appendix A: 2024 daily total column ozone images

Figure A1. OMPS ozone hole images for August 2024; the ozone hole boundary is indicated by the red 220 DU contour line. Green plus symbols indicate the location of the Australian Antarctic stations of Mawson (62.9°E, 67.6°S), Davis (78.0°E, 68.6°S) and Casey (110.5°E, 66.3°S), the New Zealand Antarctic station of Arrival Heights (166.7°E, 77.8°S) and Macquarie Island station (158.9°E, 54.5°S). The white area over Antarctica is missing data and indicates the approximate extent of the polar night. The OMPS instrument requires solar radiation to the earth's surface to measure the column ozone abundance.

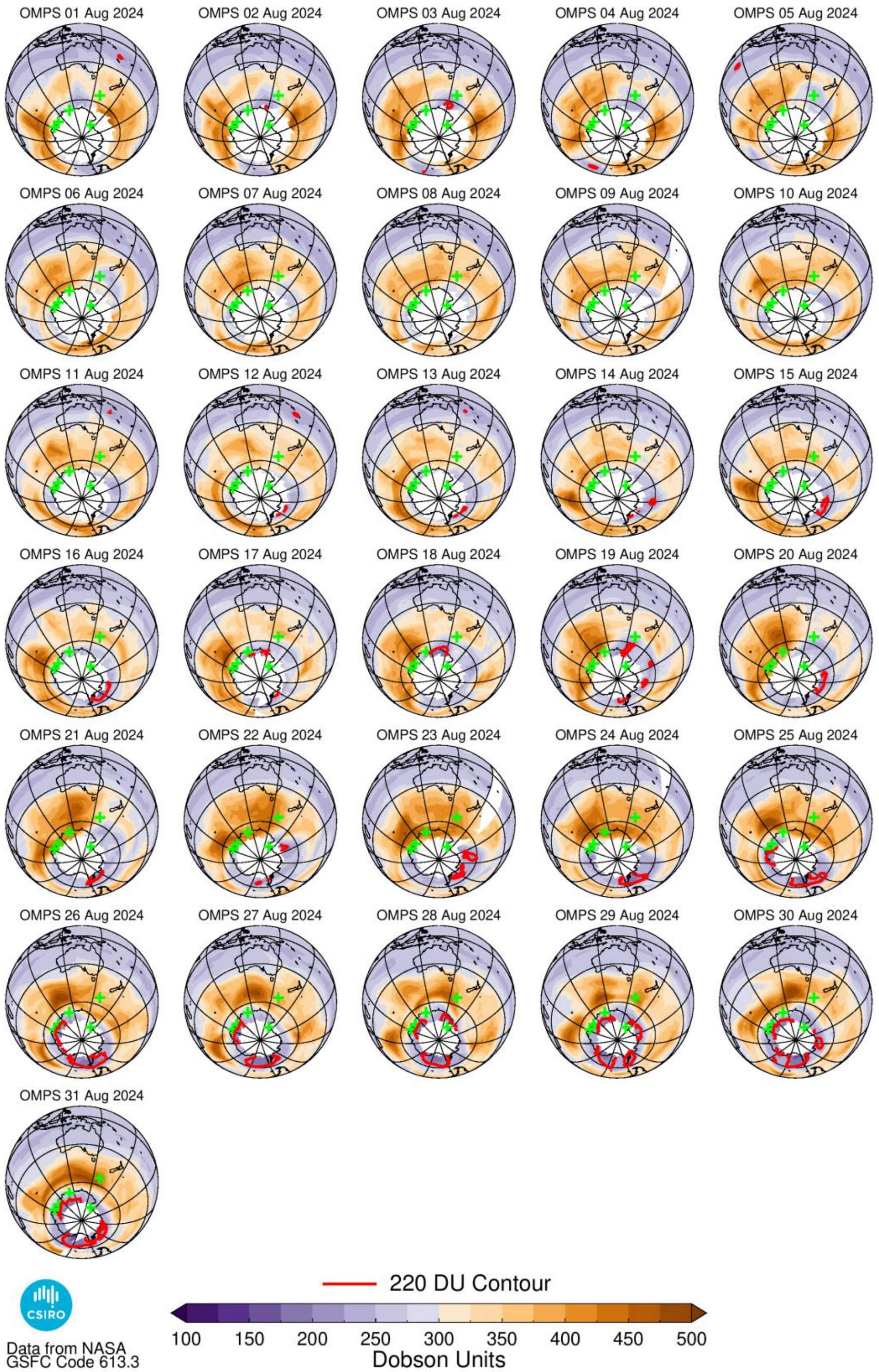


Figure A2. OMPS ozone hole images for September 2024; the ozone hole boundary is indicated by the red 220 DU contour line. Green plus symbols indicate the location of the Australian Antarctic stations of Mawson (62.9°E, 67.6°S), Davis (78.0°E, 68.6°S) and Casey (110.5°E, 66.3°S), the New Zealand Antarctic station of Arrival Heights (166.7°E, 77.8°S) and Macquarie Island station (158.9°E, 54.5°S). The white area over Antarctica is missing data and indicates the approximate extent of the polar night. The OMPS instrument requires solar radiation to the earth's surface in order to measure the column ozone abundance.

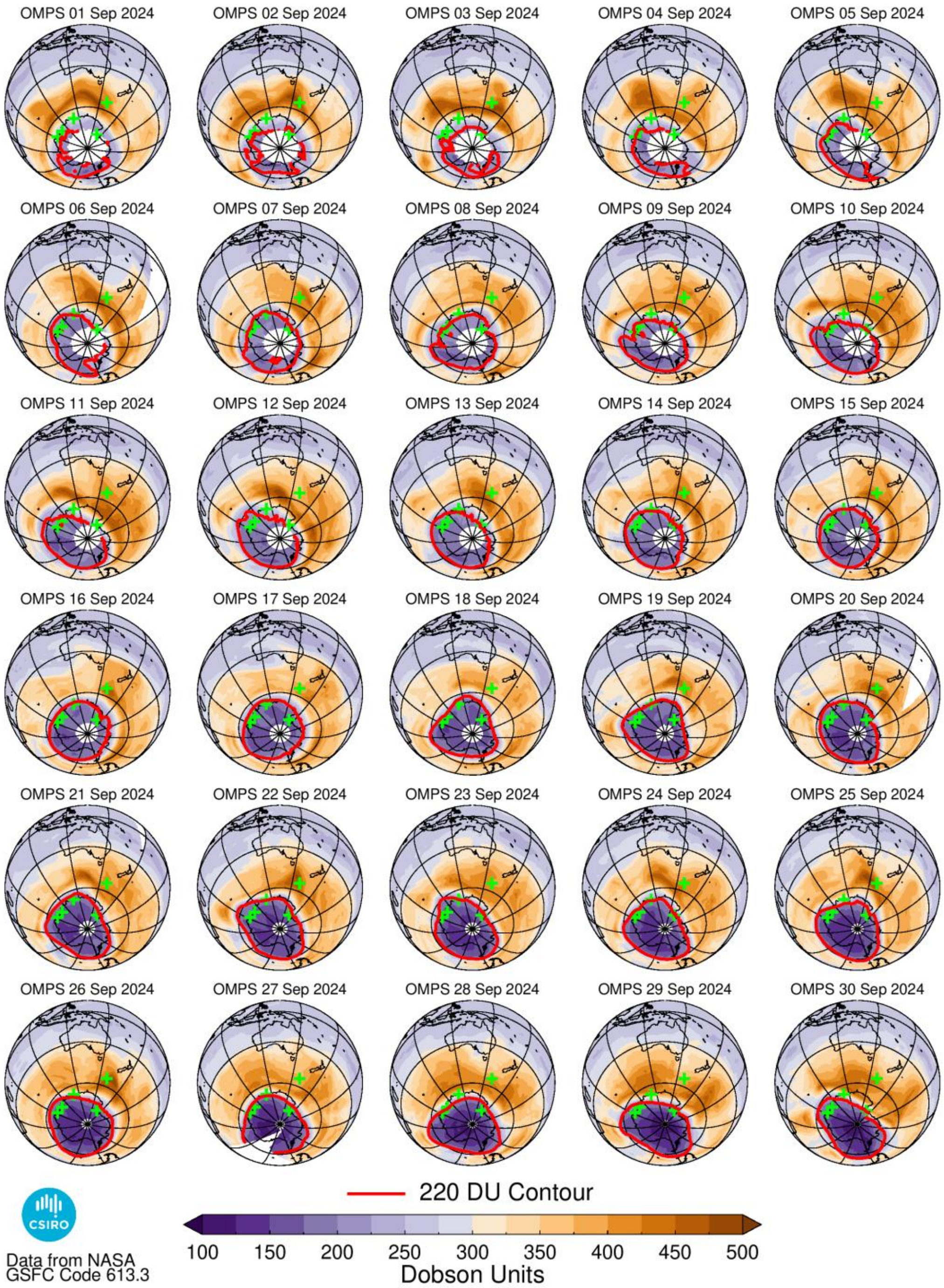


Figure A3. OMPS ozone hole images for October 2024; the ozone hole boundary is indicated by the red 220 DU contour line. Green plus symbols indicate the location of the Australian Antarctic stations of Mawson (62.9°E, 67.6°S), Davis (78.0°E, 68.6°S) and Casey (110.5°E, 66.3°S), the New Zealand Antarctic station of Arrival Heights (166.7°E, 77.8°S) and Macquarie Island station (158.9°E, 54.5°S).

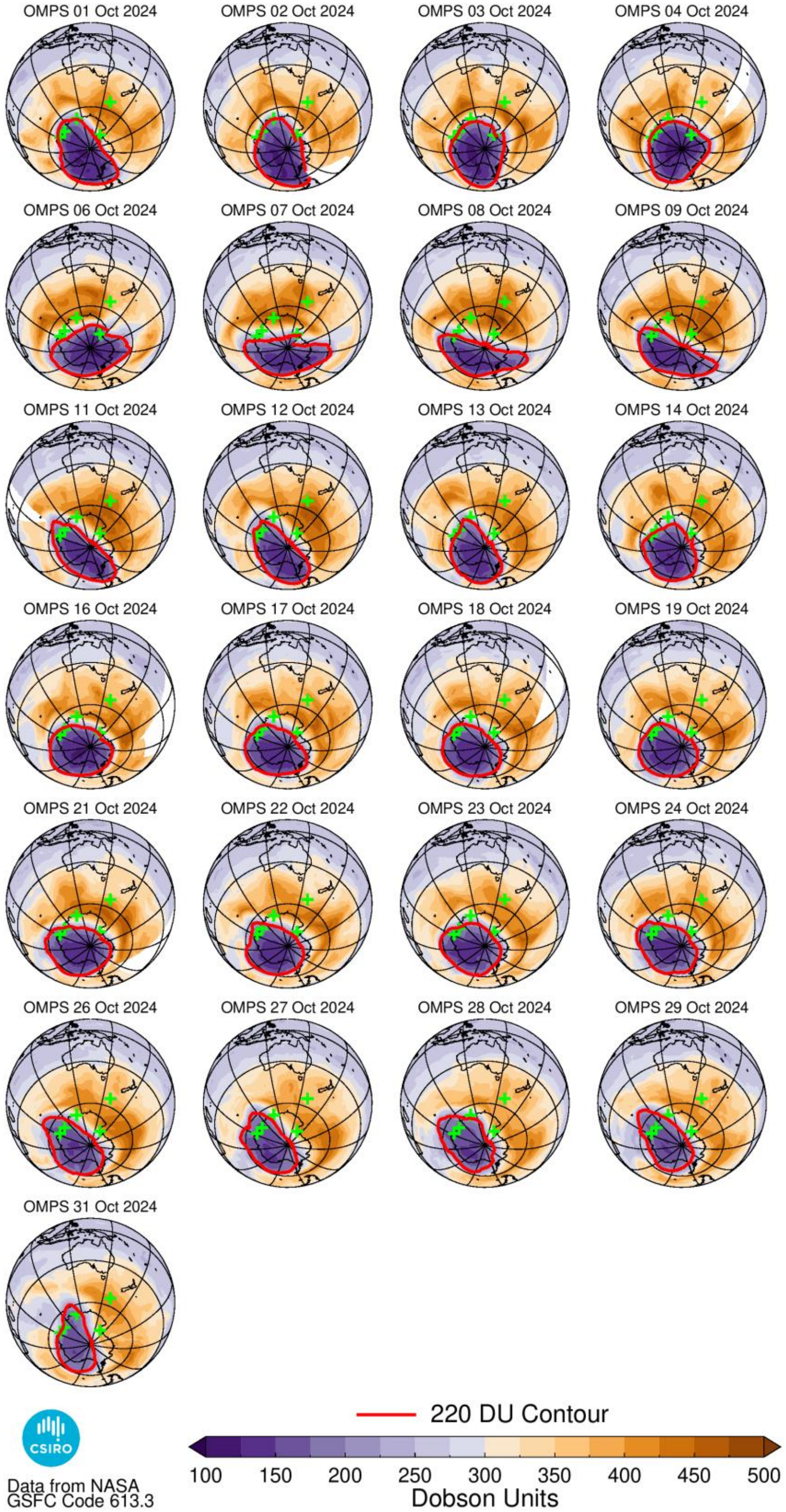


Figure A4. OMPS ozone hole images for November 2024; the ozone hole boundary is indicated by the red 220 DU contour line. Green plus symbols indicate the location of the Australian Antarctic stations of Mawson (62.9°E, 67.6°S), Davis (78.0°E, 68.6°S) and Casey (110.5°E, 66.3°S), the New Zealand Antarctic station of Arrival Heights (166.7°E, 77.8°S) and Macquarie Island station (158.9°E, 54.5°S).

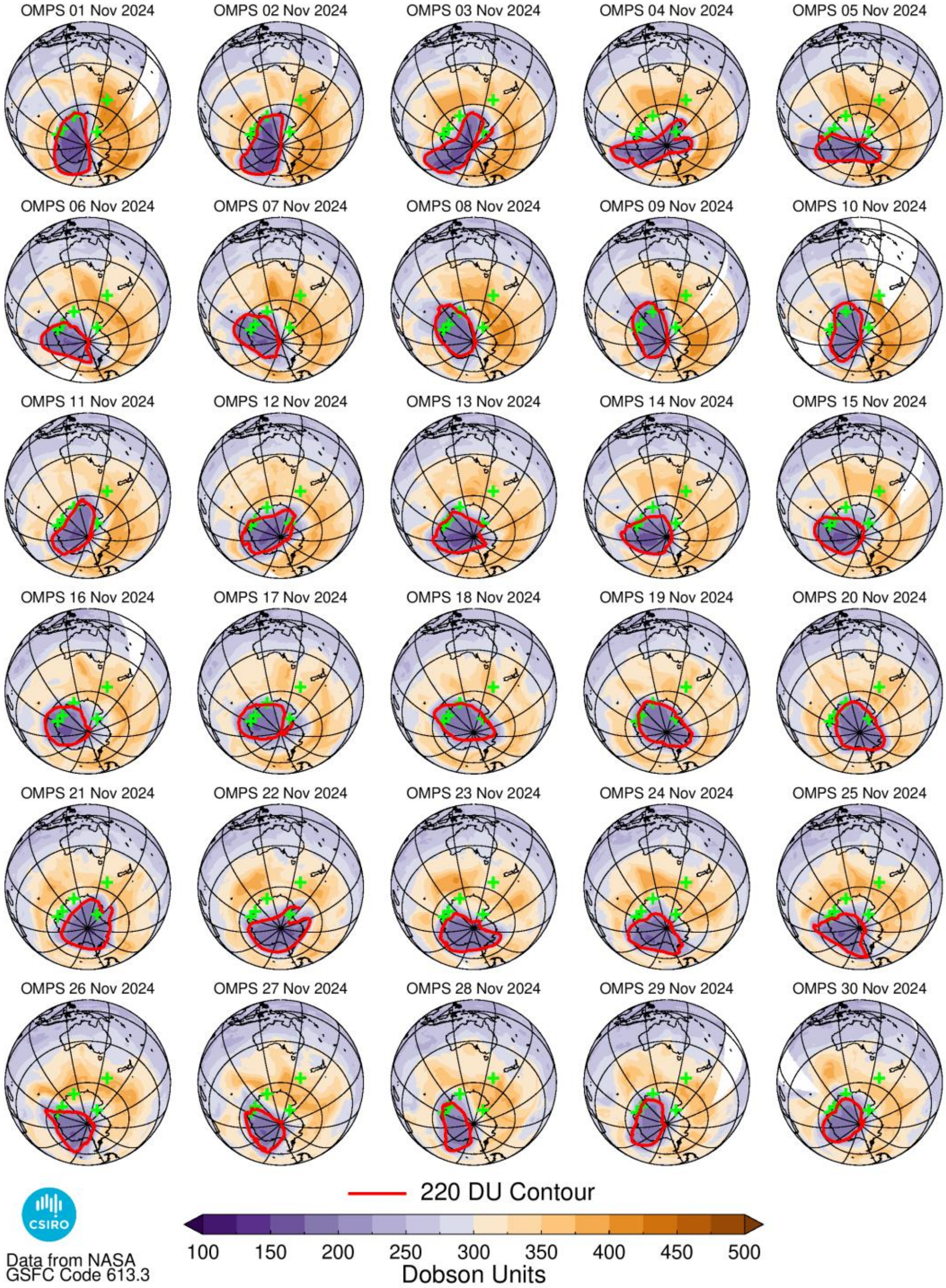
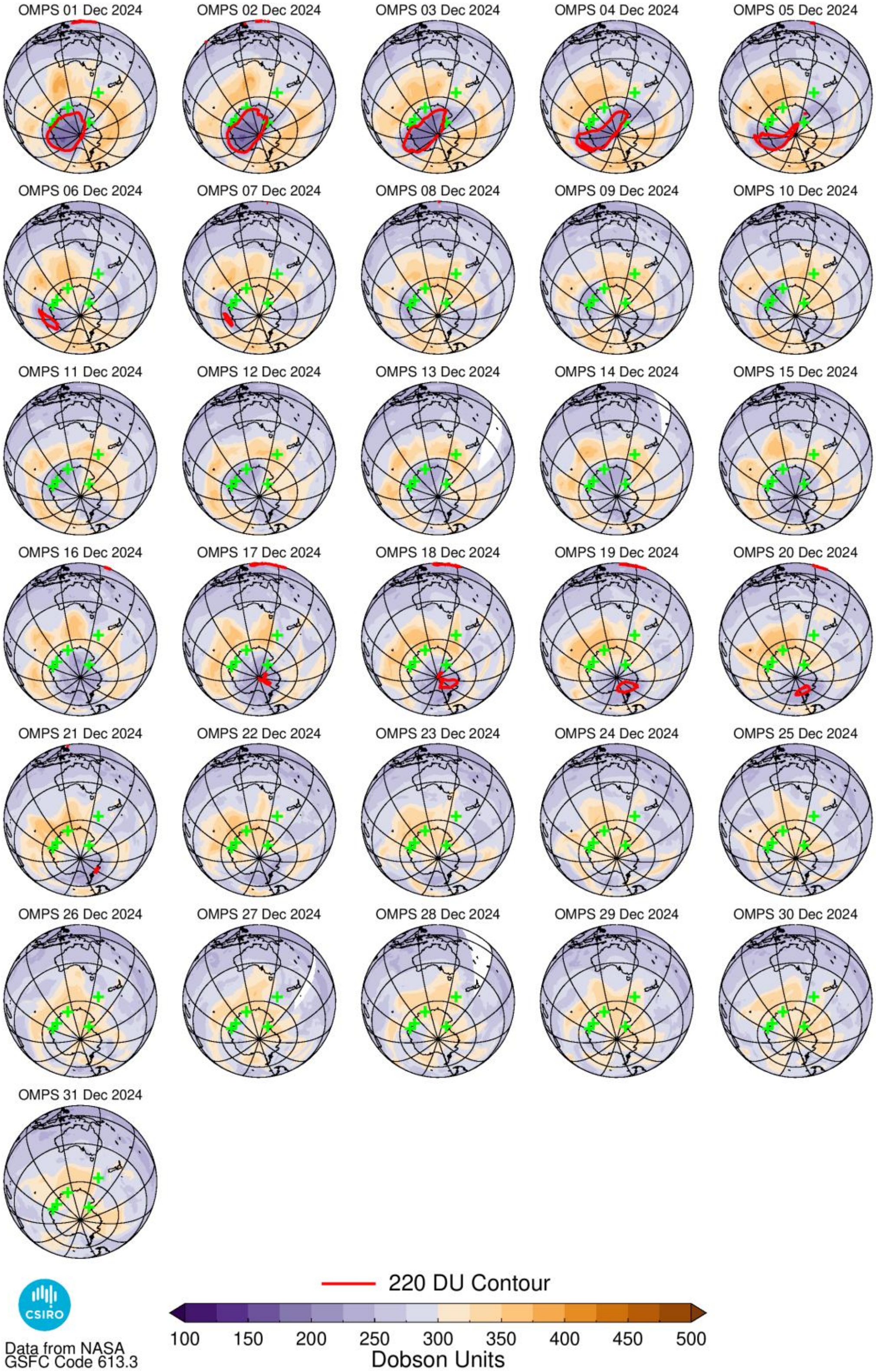


Figure A5. OMPS ozone hole images for December 2024; the ozone hole boundary is indicated by the red 220 DU contour line. Green plus symbols indicate the location of the Australian Antarctic stations of Mawson (62.9°E, 67.6°S), Davis (78.0°E, 68.6°S) and Casey (110.5°E, 66.3°S), the New Zealand Antarctic station of Arrival Heights (166.7°E, 77.8°S) and Macquarie Island station (158.9°E, 54.5°S).



Appendix B: Satellite data used in this report

Full information on the satellite instruments used in this report can be found on the NASA website.

A brief summary of the instruments, satellite platforms and resultant data that are used in this report is given here.

B1. TOMS

The Total Ozone Mapping Spectrometers (TOMS) were a series of satellite borne instruments that measure the amount of back-scattered solar UV radiation absorbed by ozone in the atmosphere; the amount of UV absorbed is proportional to the amount of ozone present in the atmosphere. The TOMS instruments flew on a series of satellites: Nimbus 7 (24 Oct 1978 until 6 May 1993); Meteor 3 (22 Aug 1991 until 24 Nov 1994); and Earth Probe (2 July 1996 until 14 Dec 2005). The version of TOMS data used in this report have been processed with the NASA TOMS Version 8 algorithm.

B2. OMI

Data from the Ozone Monitoring Instrument (OMI) on board the Earth Observing Satellite (EOS) Aura, that have been processed with the NASA TOMS Version 8.5 algorithm, have been used in the weekly reports and in this summary report. For the yearly metrics used in this report, OMI data from 2005 until 2014 are used, after which data from the OMPS platform are used. OMI continued the NASA TOMS satellite record for total ozone and other atmospheric parameters related to ozone chemistry and climate.

On 19 April 2012 a reprocessed version of the complete (to date) OMI Level 3 gridded data was released. This is a result of a post-processing of the L1B data due to changed OMI row anomaly behaviour (see below) and consequently followed by a re-processing of all the L2 and higher data. These data were reprocessed by CSIRO, which at the time resulted in small changes in the ozone hole metrics we calculate.

In 2008, stripes of bad data began to appear in the OMI products apparently caused by a small physical obstruction in the OMI instrument field of view and is referred to as a row anomaly. NASA scientists guess that some of the reflective Mylar that wraps the instrument to provide thermal protection has torn and is intruding into the field of view. On 24 January 2009 the obstruction suddenly increased and now partially blocks an increased fraction of the field of view for certain Aura orbits and exhibits a more dynamic behaviour than before, which led to the larger stripes of bad data in the OMI images. Since 5 July 2011, the row anomaly that manifested itself on 24 January 2009 now affects all Aura orbits, which can be seen as thick white stripes of bad data in the OMI total column ozone images. It is now thought that the row anomaly problem may have started and developed gradually since as early as mid-2006. Despite various attempts, it turned out that due to the complex nature of the row anomaly it is not possible to correct the L1B data with sufficient accuracy (≤ 1%) for the errors caused by the row anomaly, which has ultimately resulted in the affected data being flagged and removed from higher level data products (such as the daily averaged global gridded level 3 data used here for the images and metrics calculations). However, once the polar night reduces enough then this should not be an issue for determining ozone hole metrics, as there is more overlap of the satellite passes at the polar regions which essentially 'fills-in' these missing data.

B3. OMPS

OMPS (Ozone Mapping and Profiler Suite) is a new set of ozone instruments on the Suomi National Polar-orbiting Partnership satellite (Suomi NPP), which was launched on 28 October 2011 and placed into a sun-synchronous orbit 824 km above the Earth. The partnership is between NASA, NOAA and DoD (Department of Defense), see Suomi NPP for more details. OMPS will continue the US program for monitoring the Earth's ozone layer using advanced hyperspectral instruments that measure sunlight in the ultraviolet and visible, backscattered from the Earth's atmosphere, and will contribute to observing the recovery of the ozone layer in coming years. From 2016 onwards, the OMPS total column ozone data is used as the primary source of data for the metrics used in this report.

In May 2017, Version 2 of the Nadir Mapper dataset from Suomi-NPP's Ozone Mapping and Profiler Suite (OMPS) was released. The Level 3 global gridded daily total ozone column data generated from these have been used in this report.

For the 2023 ozone hole season, there were some data delivery delays with the OMPS data products from 19 July until 11 August 2023 during which time no data were available. In addition, on 26 July 2023 the SNPP spacecraft entered a non-nominal state and all instruments went into a safe mode state. NOAA engineers successfully re-started the instruments with the data transmission resuming on 27 July, with only 1 day of lost data.

Glossary

Term	Definition
AGAGE	Advanced Global Atmospheric Gases Experiment; AGAGE, and its predecessors (the Atmospheric Lifetime Experiment, ALE, and the Global Atmospheric Gases Experiment, GAGE) have been measuring the composition of the global atmosphere continuously since 1978. AGAGE measures over the globe, at high frequency, almost all of the important trace gas species in the Montreal Protocol (e.g. CFCs and HCFCs) and almost all of the significant non-CO_2 gases in the Kyoto Protocol (e.g. PFCs, HFCs, methane, and nitrous oxide). See the AGAGE site for more details.
CFCs	chlorofluorocarbons, synthetic chemicals containing chlorine, once used as refrigerants, aerosol propellants and foam-blowing agents, that break down in the stratosphere (15-30 km above the earth's surface), releasing reactive chlorine radicals that catalytically destroy stratospheric ozone.
DU	Dobson Unit, a measure of the total ozone amount in a column of the atmosphere, from the earth's surface to the upper atmosphere, 90% of which resides in the stratosphere at 15 to 30 km.
Halons	synthetic chemicals containing bromine, once used as fire-fighting agents, that break down in the stratosphere releasing reactive bromine radicals that catalytically destroy stratospheric ozone. Bromine radicals are about 50 times more effective than chlorine radicals in catalytic ozone destruction.
MERRA	is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The project focuses on historical analyses of the hydrological cycle in a broad range of weather and climate time scales. It places modern observing systems (such as EOS suite of observations in a climate context. Since these data are from a reanalysis, they are not up-to-date. So, we supplement with the GEOS-5 FP data that are also produced by the GEOS-5 model in near real time. These products are produced by the NASA Global Modeling and Assimilation Office (GMAO).
MERRA2	MERRA2 was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA ozone observations after 2005. Additional advances in both the GEOS-5 model and the GSI assimilation system are included in MERRA-2.
ODS	Ozone Depleting Substances (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl bromide, carbon tetrachloride, methyl chloroform and methyl chloride).
Ozone	a reactive form of oxygen with the chemical formula O_3; ozone absorbs most of the UV radiation from the sun before it can reach the earth's surface.
Ozone Hole	ozone holes are examples of severe ozone loss brought about by the presence of ozone depleting chlorine and bromine radicals, whose levels are enhanced by the presence of PSCs (polar stratospheric clouds), usually within the Antarctic polar vortex. The chlorine and bromine radicals result from the breakdown of CFCs and halons in the stratosphere. Smaller ozone holes have been observed within the weaker Arctic polar vortex.
Polar night terminator	the delimiter between the polar night (continual darkness during winter over the Antarctic) and the encroaching sunlight. By the first week of October the polar night has ended at the South Pole.
Polar vortex	a region of the polar stratosphere isolated from the rest of the stratosphere by high west-east wind jets centred at about 60°S that develop during the polar night. The isolation from the rest of the atmosphere and the absence of solar radiation results in very low temperatures (less than -78°C) inside the vortex.
PSCs	polar stratospheric clouds are formed when the temperatures in the stratosphere drop below -78°C, usually inside the polar vortex. This causes the low levels of water vapour present to freeze, forming ice crystals and usually incorporates nitrate or sulphate anions.
Sudden stratospheric warming event	Normally during winter, very strong westerly winds develop in the stratosphere (called the polar vortex) due to large temperature differences between the polar region (no sunlight) and the Southern Ocean region (presence of sunlight). During spring, the polar region starts to warm as sunlight returns, and the westerly winds slowly weaken over a period of a few months. However, this weakening can happen faster in some years due to stratospheric wave activity causing a faster breakdown of the polar vortex and mixing of warmer air into the polar region. On very rare occasions, if the wave activity is strong enough, the polar vortex breaks down rapidly, and the polar stratospheric winds reverse direction (becoming easterly), with warmer air mixed rapidly into the polar region – this is known as a

	sudden stratospheric warming event. This severely affects the development of the Antarctic ozone hole as the chemical reactions require very cold temperatures to occur.
TOMS, OMI & OMPS	the Total Ozone Mapping Spectrometer, Ozone Monitoring Instrument, & Ozone Mapping and Profiler Suite, are satellite borne instruments that measure the amount of back-scattered solar UV radiation absorbed by ozone in the atmosphere; the amount of UV absorbed is proportional to the amount of ozone present in the atmosphere.
UV radiation	a component of the solar radiation spectrum with wavelengths shorter than those of visible light; most solar UV radiation is absorbed by ozone in the stratosphere; some UV radiation reaches the earth's surface, in particular UV-B which has been implicated in serious health effects for humans and animals; the wavelength range of UV-B is 280-315 nanometres.

References

Daniel, JS & Reimann, S (Lead Authors) 2022. 'Scenarios and Information for Policy Makers'. Chapter 7 in *Scientific Assessment of Ozone Depletion: 2022*, World Meteorological Organization (WMO) Global Ozone Research and Monitoring Project – GAW Report No. 278, pp. 385-434, WMO: Geneva, Switzerland.

Engel, A, Bonisch, H, Ostermoller, J, Chipperfield, MP, Dhomse, S & Jöckel, P 2018. 'A refined method for calculating equivalent effective stratospheric chlorine', *Atmos. Chem. Phys.*, 18, 601-619.

Fraser, PJ, Krummel, PB, Steele, LP, Trudinger, CM, Etheridge, DM, O'Doherty, S, Simmonds, PG, Miller, BR, Mühle, J, Weiss, RF, Oram, DE, Prinn, RG & Wang, RHJ 2014. 'Equivalent effective stratospheric chlorine from Cape Grim Air Archive, Antarctic firn and AGAGE global measurements of ozone depleting substances'. In *Baseline Atmospheric Program (Australia) 2009-2010*, N. Derek, PB, Krummel & Cleland, S (eds.), pp. 17-23. Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research, Melbourne, Australia.

Hofmann, D & Montzka, S 2009. 'Recovery of the ozone layer: the Ozone Depleting Gas Index', *Eos* 90(1), pp. 1-2.

Newman, P, Daniel, J, Waugh, & Nash, E 2007. 'A new formulation of equivalent effective stratospheric chlorine (EESC)'. *Atmos. Chem. Phys.* 7, pp. 4537-4552.

World Meteorological Organization (WMO), *Executive Summary: Scientific Assessment of Ozone Depletion: 2022*, World Meteorological Organization, Global Ozone Research and Monitoring Project – GAW Report No. 2788, 50 pp., Geneva, Switzerland, 2022.

As Australia’s national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
www.csiro.au

For further information
Oceans & Atmosphere – Climate Science Centre

Paul Krummel
+61 3 9239 4568
paul.krummel@csiro.au

https://www.csiro.au/en/Research/OandA

Oceans & Atmosphere – Climate Science Centre

Paul Fraser
+61 3 9239 4526
paul.fraser@csiro.au

https://www.csiro.au/en/Research/OandA