

# The 2018 Antarctic Ozone Hole Summary: Final Report

Final Report

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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 <http://ozoneaq.gsfc.nasa.gov/omps/> for more details). NPP is the National Polar-orbiting Partnership satellite (NPP) and is a partnership between NASA, NOAA and DoD (Department of Defense), see <http://npp.gsfc.nasa.gov/> 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

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# 1 Satellite data used in this report

Full information on the satellite instruments mentioned below can be found on the following NASA website:

<https://ozoneaq.gsfc.nasa.gov/missions>

Below is a summary of the instruments, satellite platforms and resultant data that are used in this report.

## 1.1 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.

## 1.2 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 2015 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 ( $\leq 1\%$ ) 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.

## 1.3 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 (<http://ozoneaq.gsfc.nasa.gov/omps/>). The partnership is between NASA, NOAA and DoD (Department of Defense), see <http://npp.gsfc.nasa.gov/> 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. For the 2017 ozone hole season, we also used the OMPS total column ozone data as the primary source of data for the metrics, but also produced metrics from OMI Level 3 global gridded daily total ozone column product for comparison.

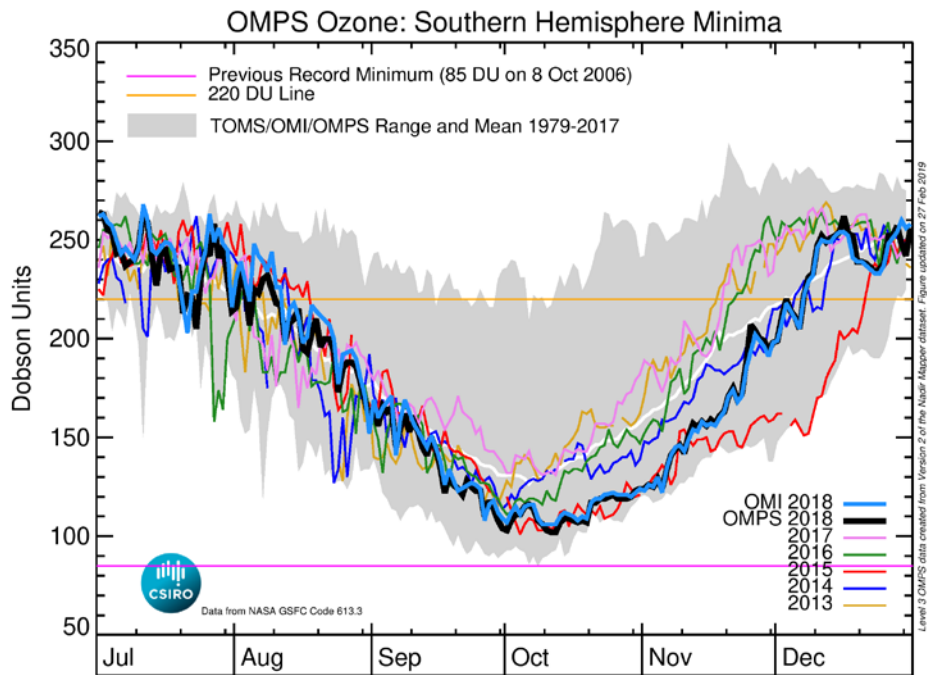
In May 2017, Version 2 of the Nadir Mapper dataset from Suomi-NPP's Ozone Mapping and Profiler Suite (OMPS) was released. The Level 3 global gridded daily total ozone column data generated from these have been used in this report.



## 2 The 2018 Antarctic ozone hole

### 2.1 Ozone hole metrics

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 season. In 2018, the first excursions below 220 DU of the ozone minima occurred sporadically in the second half of July and again in early August around the fringes of the polar night. From 10 August the ozone minima remained below 220 DU until the ozone hole closed in the first week of December. The daily minimum ozone metric is highly variable during August due to the extent of the polar night, which is seen as large fluctuations. The variability in this metric reduces as the polar night shrinks and the ozone hole fully forms. During the second half of August the ozone minima dropped to 173 DU on 24 August before rising again to 188 DU by 26 August, and dropping again to 159 DU by 31 August.



**Figure 1. Ozone hole 'depth' (minimum ozone, DU) based on OMPS & OMI satellite data. The 2018 hole based on OMPS data is indicated by the thick black line while the light blue line indicates the 2018 hole based on OMI data. The holes for selected previous years 2013-2017 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded area shows the 1979-2017 TOMS/OMI/OMPS range and the white line shows the 1979-2017 mean.**

The first week of September saw the ozone hole minima drop to 145 DU on 6 September before rising again to 162 DU by 8 September, indicating that there is still moderate variability in this metric. From the second week of September onwards, the variability in this metric reduced significantly as the polar night reduced and the ozone hole fully formed. The ozone hole minima steadily dropped during the second and third weeks of September, reaching 121 DU on 21 September. The fourth week of September saw the ozone minima continue to fall, reaching 104 DU by 30 September, lower than the minimums reached during the previous 5 years (2013-2017) for that time of year.

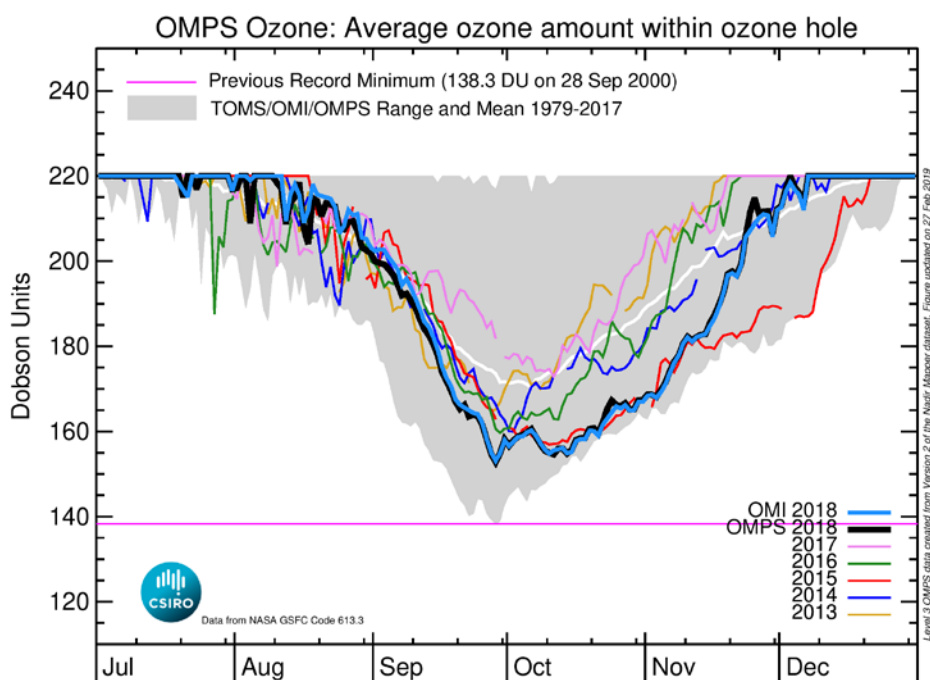
The first week of October saw the ozone minima drop to 103 DU on 1 October before increasing to 116 DU on 6 October and dropping again to reach 102 DU on 11 & 12 October, which was the lowest value for 2018 and very close to the minima reached in 2015 of 101 DU. For the period 14-19 October the daily ozone minima remained between 107-109 DU, before rising to 117 DU on 20 & 21 October.

The daily ozone minima increased slowly during late October and early November, reaching 129 DU by 4 November, which was very low for that time of year and was lower than the minimum daily values from the previous five years. The daily ozone minima showed a considerable recovery during the second week of

November, increasing from 129 DU on 4 November to 157 DU by 12 November. The recovery of the daily ozone minima during the third week of November was not as pronounced as that of the area or deficit metrics, going from 157 DU on 12 November to 161 DU on 18 November. The fourth week of November saw a large recovery in the daily ozone minima, going from 161 DU on 18 November to 207 DU by 25 November. During 26 November to 2 December, the ozone hole minima oscillated between 194 and 211 DU, briefly reaching 220 DU on 3 December, the dropping marginally below 220 DU for three days until full recovery on 7 December.

Overall, this resulted in the 2018 ozone hole being relatively large and in the top third ‘deepest’ ozone holes since 1979; the minimum ozone level recorded in 2018 (102 DU) was ranked 13<sup>th</sup> deepest hole, although it is ranked equal with the 2004 (12<sup>th</sup>) and 2008 holes (14<sup>th</sup>), out of 39 years of TOMS/OMI/OMPS satellite data, see Table 1. The deepest hole ever was in 2006 (85 DU), the second deepest in 1998 (86 DU) and the 3<sup>rd</sup> deepest in 2000 (89 DU).

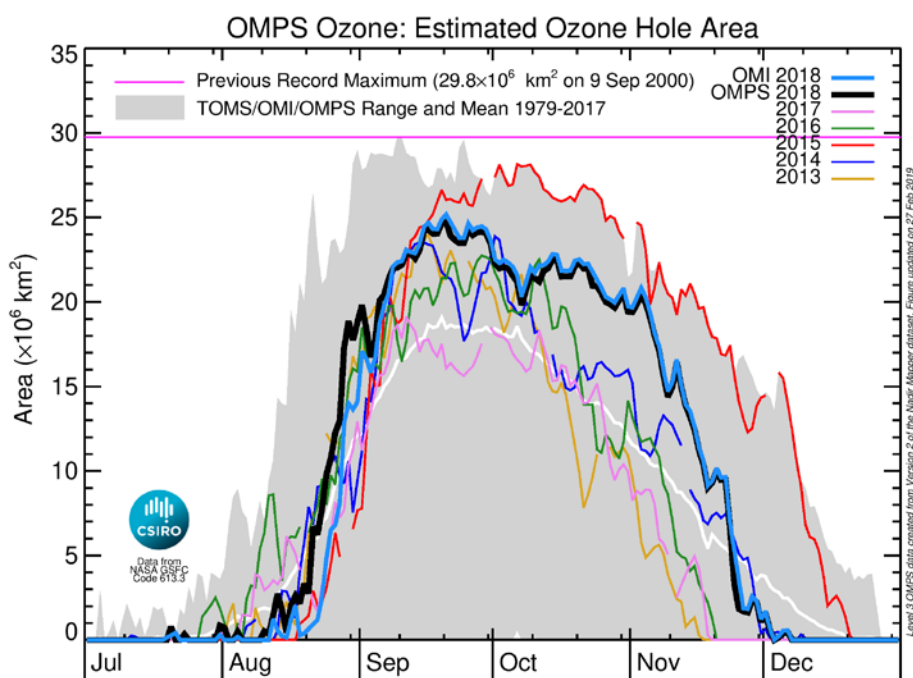
Figure 2 shows the average amount of ozone (DU) within the Antarctic ozone hole throughout the 2018 season. The minimum average ozone within the hole in 2018 was 153 DU on 28 September, the 13<sup>th</sup> deepest recorded, again indicating a relatively large ozone hole based on this metric. The lowest reading was in 2000 (138 DU), the second lowest in 2006 (144 DU) and the 3<sup>rd</sup> lowest in 1998 (147 DU).



**Figure 2. Average amount (DU) of ozone within the Antarctic ozone hole throughout the season based on OMPS & OMI satellite data. The 2018 hole based on OMPS data is indicated by the thick black line; the light blue line indicates the 2018 hole based on OMI data. The holes for selected previous years 2013-2017 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded area shows the 1979-2017 TOMS/OMI/OMPS range and the white line shows the 1979-2017 mean.**

Figure 3 shows the Antarctic ozone hole area (defined as the area within the 220 DU contour) throughout the 2018 season. The maximum daily area of the hole (24.7 million km<sup>2</sup> on the 20<sup>th</sup> of September) was the 17<sup>th</sup> largest hole on record, with the largest in 2000 (29.8 million km<sup>2</sup>), the 2<sup>nd</sup> largest in 2006 (29.6 million km<sup>2</sup>) and the 3<sup>rd</sup> largest in 2003 (28.4 million km<sup>2</sup>). The maximum in the 15-day average ozone hole area for 2018 of 24.1 million km<sup>2</sup> was the 14<sup>th</sup> largest area ever recorded, with the largest being in 2000 (28.7 million km<sup>2</sup>) and second largest in 2006 (27.6 million km<sup>2</sup>). These statistics indicate that the 2018 ozone hole was on the larger side of ‘middle of the pack’ and larger in area compared to the ozone holes from the last 5 years except for 2015 (see Table 1). As a comparison, the area of Australia is ~7.7 million km<sup>2</sup>.

The 2018 Antarctic ozone hole area as shown in Figure 3 is characterised by several events. The ozone hole grew rapidly in size from mid-August and peaked in area on 20<sup>th</sup> September. Late September and early October saw two small warming events which reduced the ozone hole area from around 24 million km<sup>2</sup> to around 22 million km<sup>2</sup>, and a further dip briefly to 20 million km<sup>2</sup> before the area increased again to around 22 million km<sup>2</sup> again. The ozone hole area remained in the 20-22 million km<sup>2</sup> range for the remainder of October and first week of November. The second week of November saw the first signs of major recovery of the 2018 Antarctic ozone hole with the daily ozone hole area dropping from around 20 million km<sup>2</sup> on 4 November to be at about 15 million km<sup>2</sup> on 12 November. This continued during the third week of November with the daily ozone hole area dropping from 15 million km<sup>2</sup> on 12 November to 8.9 million km<sup>2</sup> on 18 November, an even larger drop than the week before. The fourth week of November saw the Antarctic ozone hole continue to recover at a rapid rate, with the daily ozone hole area dropping to 1.8 million km<sup>2</sup> by 25 November, before fully recovering by 7 December. The recovery was driven by a series of warming events in the lower to mid-stratosphere as indicated in the heat flux and temperature traces shown in Figure 5.



**Figure 3. Ozone hole area based on OMPS & OMI satellite data. The 2018 hole based on OMPS data is indicated by the thick black line while the light blue line indicates the 2018 hole based on OMI data. The holes for selected previous years 2013-2017 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded area shows the 1979-2017 TOMS/OMI/OMPS range and the white line shows the 1979-2017 mean.**

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 is a measure of the accumulated loss summed over the lifetime of ozone within the hole as measured each day. The maximum daily ozone deficit in 2018 was 34.8 million tonnes (Mt) in late September, the 12<sup>th</sup> largest deficit on record, again indicating large ozone hole compared with the other 39 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 1810 Mt of ozone in 2018 based on OMPS data, the 13<sup>th</sup> largest cumulative ozone deficit recorded, the largest was in 2006 (2560 Mt).

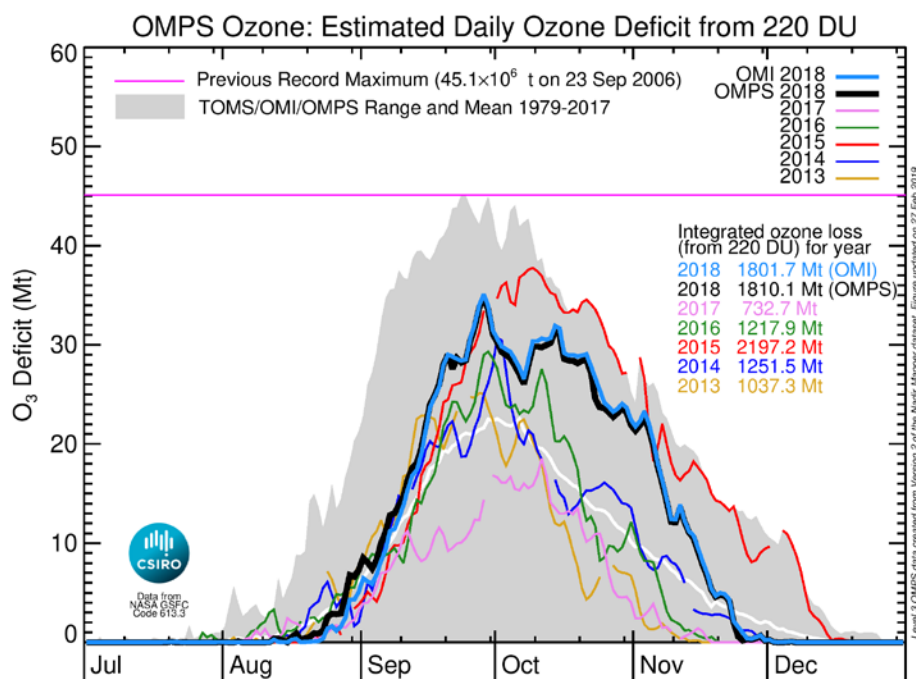


Figure 4. OMI & OMPS estimated daily ozone deficit (in millions of tonnes, Mt) within the ozone hole. The 2018 hole based on OMPS data is indicated by the thick black line while the light blue line indicates the 2018 hole based on OMI data. The holes for selected previous years 2013-2017 are indicated by the thin orange, blue, red, green and pink lines respectively; the grey shaded area shows the 1979-2017 TOMS/OMI/OMPS range and the white line shows the 1979-2017 mean. The estimated total (integrated) ozone loss for each year is shown in the legend.

## 2.2 Total column ozone images

The daily total column ozone data over Australia and Antarctica for August through to December 2018 from OMPS are shown in Appendix A Figures A.1 to A.5 respectively.

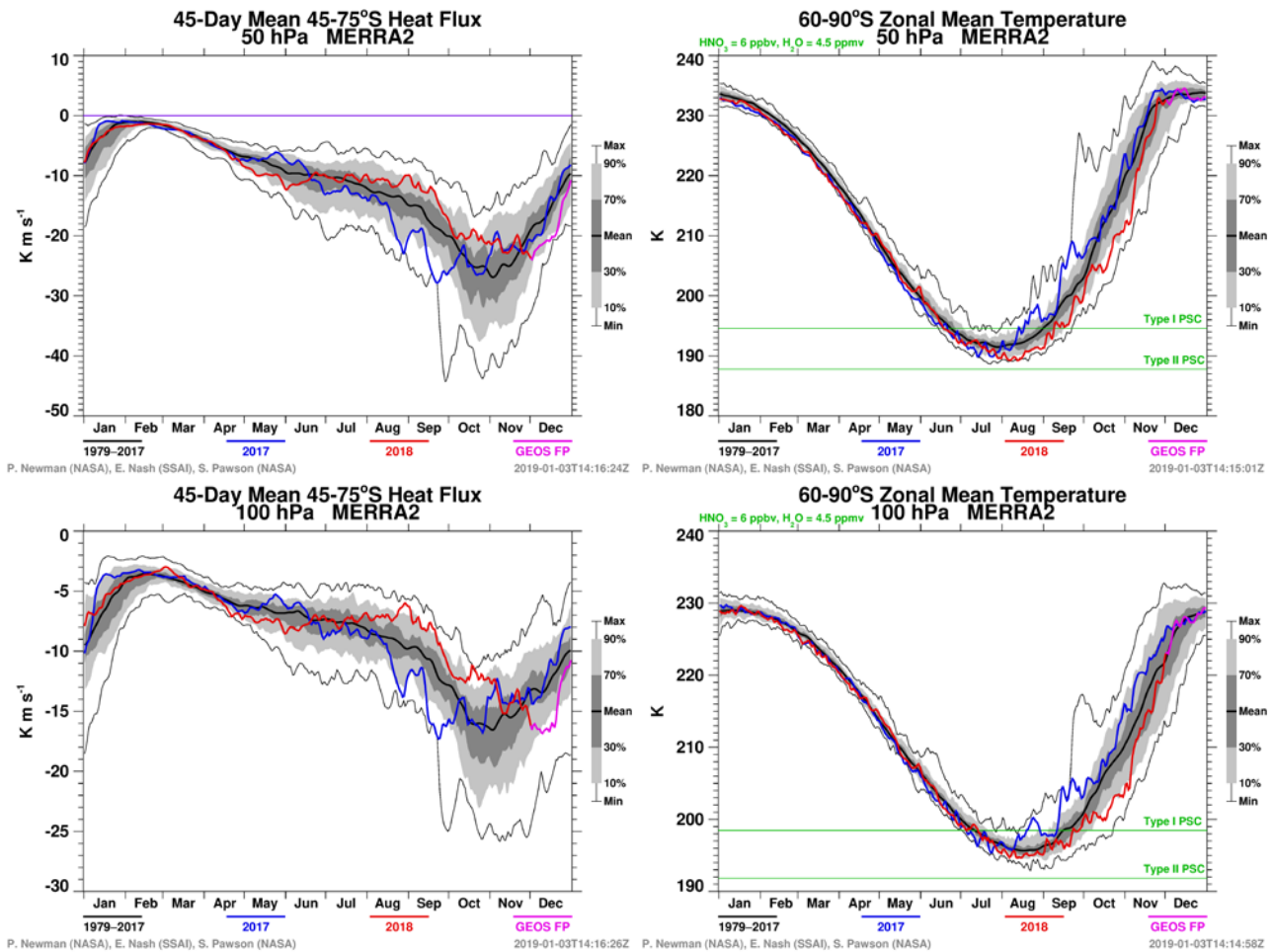
Around 10 August onwards, the ozone hole can be seen forming in an area south of South America along the edge of the polar night. From 21 August onwards, the ozone hole began to form in earnest, with the 220 DU contour that defines the ozone hole completely closing (briefly) on 29 August and then again on 5 September, after which it remained fully closed until the ozone hole recovered on 7 December 2018.

The dominant feature of the daily images for 2018 (which was also seen in 2016/2017 but was largely absent from the 2015 ozone hole season) was once again the ridge of high ozone immediately south of Australia, which was persistently present for most of September, October and the first half of November. At times there were extended areas in the ridge (between 30-60°S latitude) with total column ozone concentrations greater than 400 DU. The other stand out feature in the daily images was the persistent symmetry of the ozone hole during the 2018 season, indicating a very stable polar vortex. Apart from a few minor elongations (for example 9-14 September), the 2018 ozone hole was remarkably stable and symmetrical from the beginning of September through to 4 November, after which the impact of a series of warming events/disturbances can be seen in the daily images represented by large elongations of the ozone hole/polar vortex and a sharp reduction in the size/depth of the ozone hole. This ultimately led to a full recovery of the ozone hole on 8 December, and in the process the ozone hole briefly split in two during 23-25 November.

As a result of the persistent ridge of high ozone between 30-60°S, and a very stable and symmetrical polar vortex/ozone hole, the Australian Antarctic stations of Mawson, Davis and to a lesser extent Casey, were often completely inside the ozone hole, while the Australian sub-Antarctic station at Macquarie Island spent most of the 2018 ozone hole season under the high ridge of ozone.

## 2.3 Antarctic meteorology/dynamics

The 2018 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 2018 are shown in the right-hand panels of Figure 5, these usually show an anti-correlation to the heat flux.



**Figure 5. NASA MERRA2 heat flux and temperature. 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 – <https://ozonewatch.gsfc.nasa.gov/meteorology/SH.html>.**

During mid-June to end of July the 45-75°S heat flux at 50 & 100 hPa was around the average of the 1979-2017 range. The corresponding 60-90°S zonal mean temperatures at 50 hPa were, however, lower than average during this period, generally being in the lower 10-30<sup>th</sup> percentile of the 1979-2017 range, while at 100 hPa the temperature was close to the long-term 1979-2017 mean.

From August until mid- to late-September, the 45-75°S heat flux at 50 hPa & 100 hPa was predominantly in the 70-90 percentile mark of the 1979-2017 range, indicating less heat transport towards the pole and a period of cooling. The 60-90°S zonal mean temperatures at 50 hPa for this period dropped into the lowest 10 percentile range for the whole of August, and at times was close to near record low levels, before moving into the lower 10-30<sup>th</sup> percentile of the 1979-2017 range for September. At 100 hPa the temperature dropped into the 10-30<sup>th</sup> percentile of the 1979-2017 range during August, while September saw some variability in the temperature at this level with it residing in the 50-70<sup>th</sup> percentile for the first half, while during the second half of September it moved predominantly into the lower 10-30<sup>th</sup> percentile of the 1979-2017 range. These relatively cold temperatures and less heat flux towards the pole contributed significantly to a stable polar vortex and ozone hole.

A small warming event occurred in late September/early October and again in mid-October, which is characterised by relatively small changes in the 60-90°S zonal mean temperatures at 50 & 100 hPa, and the 45-75°S heat flux at 50 & 100 hPa becoming more negative. However, these were relatively minor and for much of October the 45-75°S heat flux at 50 & 100 hPa was considerably higher than the mean (either in the 70-90<sup>th</sup> percentile or the highest 10<sup>th</sup> percentile) with the corresponding temperatures being much lower than the average (in the 10-30<sup>th</sup> percentile or the lowest 10<sup>th</sup> percentile). Again, this contributed to the very stable ozone hole in 2018.

The first week of November saw the first major warming event with the 60-90°S zonal mean temperatures at 50 & 100 hPa increasing quite rapidly from being in the lowest 10<sup>th</sup> percentile at the beginning of November to being close to the long-term 1979-2017 mean by the end of November. This ultimately was the period when the 2018 ozone hole recovered quite rapidly as can be seen in the daily images in Appendix Figure A.4. Interestingly, the 45-75°S heat flux at 50 hPa didn't show a rapid jump in November, but rather a steady decline, while at 100 hPa a rapid step is seen in this metric in the first week of November.

At 50 hPa, the type 1 PSC ( $\text{HNO}_3 \cdot 3\text{H}_2\text{O}$ ) formation threshold temperature (195 K) was reached around mid-June, staying below the threshold until the end of the first week of September. At 100 hPa, the threshold temperature was reached during the first week of July and remained below the threshold until the third week of September.

### 3 Comparison to historical metrics

Table 1 contains the ranking for all 39 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 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 daily maximum area (metric 2) falls below 0.5 million km<sup>2</sup> (sorted by decreasing day-of-year number)

From Table 1 it can be seen that the 2018 ozone hole was relatively large, generally being in the top-third largest in the metrics in Table 1, except for the area metrics where it ranked just outside the top-third. The 2018 hole ranked 14<sup>th</sup> & 17<sup>th</sup> in the area metrics, and for the other metrics it ranked either 12<sup>th</sup> or 13<sup>th</sup>. These are comparisons from 39 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 <sup>6</sup> KM <sup>2</sup>	YEAR	10 <sup>6</sup> KM <sup>2</sup>	YEAR	DU	YEAR	DU	YEAR	DU	YEAR	MT	YEAR	MT	YEAR	DATE (DAY)
1	2000	28.7	2000	29.8	2000	93.5	2006	85	2000	138.3	2006	45.1	2006	2560	2008	26-Dec (361)
2	2006	27.6	2006	29.6	2006	93.7	1998	86	2006	143.6	2000	44.9	1998	2420	1999	27-Dec (361)
3	2015	27.6	2003	28.4	1998	96.8	2000	89	1998	146.7	2003	43.4	2001	2298	2010	21-Dec (355)
4	2003	26.9	2015	28.1	2001	98.9	2001	91	2003	147.5	1998	41.1	1999	2250	2015	20-Dec (354)
5	1998	26.8	1998	27.9	1999	99.9	2003	91	2001	148.8	2008	39.4	2015	2197	2011	19-Dec (353)
6	2008	26.1	2005	27.2	2011	100.9	1991	94	1999	149.3	2001	38.5	1996	2176	2001	19-Dec (353)
7	2001	25.7	2008	26.9	2003	101.9	2011	95	2005	149.4	2015	37.7	2000	2164	2006	16-Dec (350)
8	2005	25.6	1996	26.8	2009	103.1	2009	96	2009	150.4	2011	37.5	2011	2124	1990	15-Dec (349)
9	2011	25.1	2001	26.4	1993	104.0	1999	97	1996	150.6	2005	37.1	2008	1983	2007	15-Dec (349)
10	1996	25.0	2011	25.9	1996	106.0	1997	99	2008	150.8	2009	35.7	2003	1894	1998	13-Dec (347)
11	1993	24.8	1993	25.8	2015	107.1	2015	101	2011	151.2	1999	35.3	2005	1871	2005	11-Dec (345)
12	1994	24.3	1999	25.7	1997	107.2	2004	102	1997	151.3	<b>2018</b>	<b>34.8</b>	1993	1833	1996	08-Dec (343)
13	2007	24.1	1994	25.2	<b>2018</b>	<b>107.9</b>	<b>2018</b>	<b>102</b>	<b>2018</b>	<b>152.8</b>	1997	34.5	<b>2018</b>	<b>1810</b>	1992	08-Dec (343)
14	<b>2018</b>	<b>24.1</b>	2007	25.2	2008	108.9	2008	102	2007	155.1	1996	33.9	2009	1806	1987	08-Dec (342)
15	2009	24.0	1997	25.1	2005	108.9	1996	103	1993	155.2	1992	33.5	2007	1772	2004	05-Dec (340)
16	1992	24.0	1992	24.9	1992	111.5	2005	103	1992	156.3	2007	32.9	1997	1759	2003	05-Dec (339)
17	1999	24.0	<b>2018</b>	<b>24.7</b>	2007	112.7	1993	104	2015	156.9	1993	32.6	1992	1529	1993	04-Dec (338)
18	1997	23.3	2009	24.5	1991	113.4	1992	105	2016	159.7	2014	30.7	1987	1366	1997	03-Dec (337)
19	2013	22.7	2013	24.0	1987	115.7	1989	108	2014	160.0	2016	29.3	2010	1353	<b>2018</b>	<b>03-Dec (337)</b>
20	2014	22.5	2014	23.9	2004	116.0	2007	108	1991	162.5	1991	26.6	2014	1252	1985	03-Dec (337)
21	2016	21.6	2016	22.7	2016	117.5	1987	109	1987	162.6	2010	26.2	2016	1218	2014	02-Dec (336)
22	2010	21.6	2004	22.7	1990	117.8	2016	111	1990	164.4	1987	26.2	1990	1181	1989	01-Dec (335)
23	1987	21.4	1987	22.4	1989	120.4	1990	111	2010	164.5	2013	25.1	2013	1037	1984	28-Nov (333)
24	2004	21.1	1991	22.3	2014	124.3	2014	114	2013	164.7	1990	24.3	1991	998	2009	29-Nov (333)
25	1991	21.0	2010	22.3	2010	124.3	2013	116	1989	166.2	1989	23.6	2004	975	1994	25-Nov (329)
26	1989	20.7	2002	21.8	2013	127.8	2010	119	2004	166.7	2002	23.2	1989	917	2016	20-Nov (325)
27	1990	19.5	1989	21.6	1985	131.8	2012	124	2002	169.8	2004	22.8	2017	733	2000	19-Nov (324)
28	2012	19.3	2012	21.2	2012	131.9	1985	124	2012	170.2	2012	22.5	2012	720	1991	18-Nov (322)
29	2002	17.7	1990	21.0	2017	135.9	2017	131	2017	172.9	2017	18.5	1985	630	2017	18-Nov (322)
30	2017	17.6	2017	19.1	2002	136.0	2002	131	1985	177.1	1985	14.5	2002	575	2013	16-Nov (320)
31	1985	16.6	1985	18.6	1986	150.3	1986	140	1986	184.7	1986	10.5	1986	346	1986	14-Nov (318)
32	1986	13.4	1984	14.4	1984	156.1	1984	144	1984	190.2	1984	9.2	1984	256	1982	12-Nov (316)
33	1984	13.0	1986	14.2	1983	160.3	1983	154	1983	192.3	1983	7.0	1988	198	2012	07-Nov (312)
34	1988	11.3	1988	13.5	1988	169.4	1988	162	1988	195.0	1988	6.0	1983	184	1980	06-Nov (311)
35	1983	10.1	1983	12.1	1982	183.3	1982	170	1982	199.7	1982	3.7	1982	73	2002	06-Nov (310)
36	1982	7.5	1982	10.6	1980	200.0	1980	192	1980	210.0	1980	0.6	1980	13	1983	05-Nov (309)

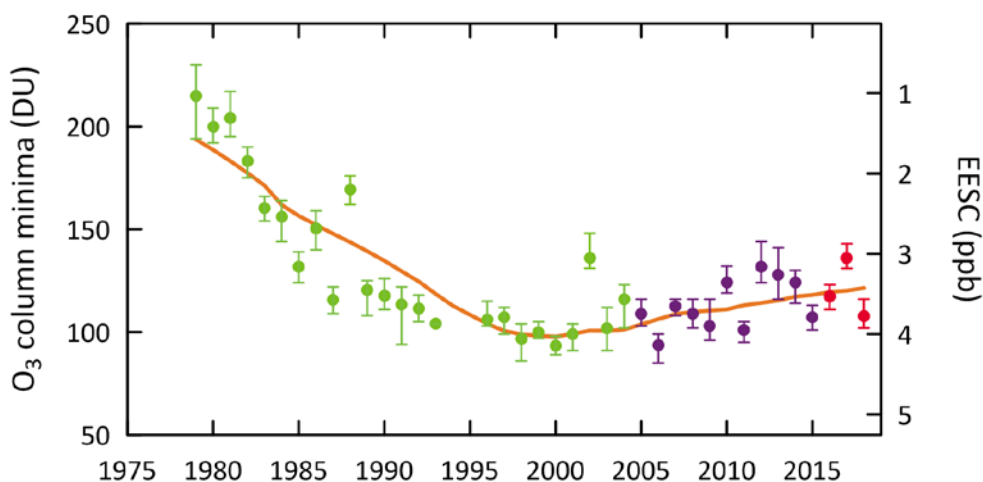


37	1980	2.0	1980	3.2	1981	204.0	1979	194	1979	210.2	1981	0.6	1981	4	1981	31-Oct (304)
38	1981	1.3	1981	2.9	1979	214.7	1981	195	1981	210.2	1979	0.3	1979	1	1988	26-Oct (300)
39	1979	0.2	1979	1.2	1994	NaN	1994	NaN	1994	NaN	1994	NaN	1994	NaN	1979	19-Sep (262)

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 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 2018. The 1996-2001 mean was  $100 \pm 5$  DU, while the 2013-2018 mean was  $120 \pm 11$  DU. Using simple statistics, there is a strong suggestion that ozone is recovering with the uncertainties no longer overlapping (at  $1 \sigma$  level). Applying the Student's t-test for differences of mean with unequal variances for the 1996-2001 versus 2013-2018 periods indicates that this increase is statistically significant at the 99% confidence limit. The 2018 ozone hole is ranked the thirteenth lowest for this metric.

The orange 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; 5.5 year lag) 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 (ODS: 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.

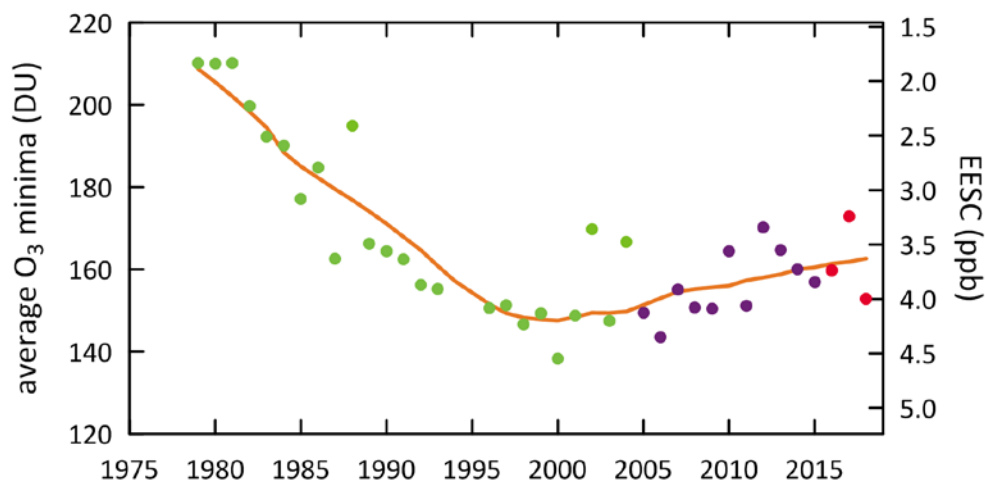
Using an outlier-resistant two-variable linear regression technique, a linear fit was applied to the complete 1996-2018 data shown in Figure 6 to give an estimate of yearly recovery rate. This yielded an ozone growth of  $1.0 \pm 0.4$  ( $1 \sigma$ ) DU/yr, indicating signs of slow recovery. This suggests that over the 23 year period (1996-2018) a total increase in ozone of 22 DU has occurred, which is very consistent with the difference between the 1996-2001 and 2013-2018 means stated above.



**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 (green), OMI (purple) and OMPS (red) data. The orange 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.**

Figure 7 shows the average ozone amount in the ozone hole (averaged column ozone amount in the hole weighted by area) from 1979 to 2018 from TOMS, OMI and OMPS 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 2018. The 1996-2001 mean was  $148 \pm 5$  DU while the 2013-2018 mean was  $161 \pm 7$  DU. Again, with these simple statistics, there is now a strong suggestion that ozone is recovering with the uncertainties no longer overlapping (at  $1 \sigma$  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 99% confidence limit.

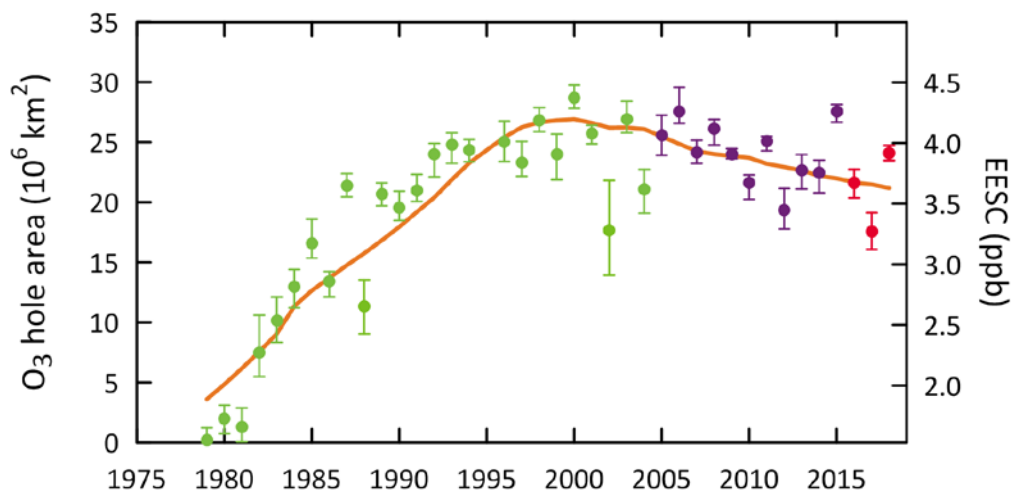
Applying the afore mentioned robust linear regression to the 1996-2018 data in Figure 7 yields an ozone growth (recovery) of  $0.7 \pm 0.3$  ( $1 \sigma$ ) DU/yr. Ozone recovery is also suggested by the regressed EESC-A line.



**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 (green), OMI (purple) and OMPS (red) data. The orange 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 data. Visually disregarding the unusual years (1988, 2002, 2004) 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. The 1996-2001 mean was  $(25.6 \pm 2.0) \times 10^6 \text{ km}^2$ , while the 2013-2018 mean was  $(22.7 \pm 3.3) \times 10^6 \text{ km}^2$ , indicative of the commencement of possible ozone recovery, but not statistically significant using the simple statistic that the  $1 \sigma$  standard deviations overlap. This is confirmed by applying the Student's t-test which resulted in these means only being just significant at the 90% confidence limit.

Applying the robust linear regression to the 1996-2018 data in Figure 8 yields an ozone hole area decline of  $(0.15 \pm 0.09) \times 10^6 \text{ km}^2/\text{yr}$  over this period.

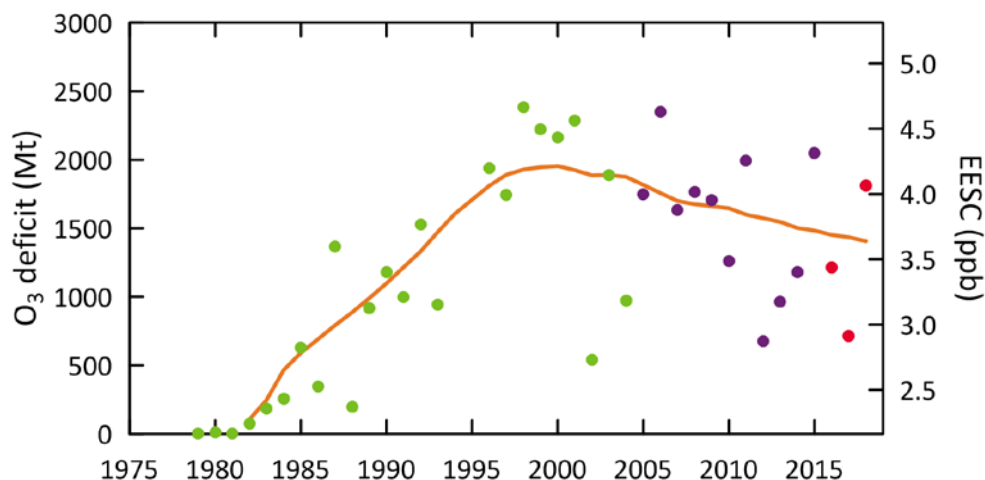


**Figure 8.** Maximum ozone hole area (area within the 220 DU contour) using a 15-day moving average during the ozone hole season, based on TOMS data (green), OMI data (purple) and OMPS (red). The orange line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text. The 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 2018. 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 back down. This metric is very sensitive to meteorological variability; 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  $2180 \pm 230 \text{ Mt}$  while the 2013-2018 mean was  $1375 \pm 535 \text{ Mt}$ , indicative of the commencement

of ozone recovery, with the uncertainties no longer overlapping (at  $1\sigma$  level) for this metric. The Student's t-test applied to these data indicated that this decrease is statistically significant at  $> 99\%$  confidence limit.

Applying the robust linear regression to the 1996-2018 data in Figure 9 resulted in a decline in ozone deficit of  $38\pm 16$  ( $1\sigma$ ) Mt/yr over this period.



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

The most quoted (though not necessarily the most reliable) metric in defining the severity of the ozone hole is the average minimum ozone levels observed over Halley Station (British Antarctic Survey - BAS), Antarctica, throughout October (Figure 10). NOTE that during the 2016/2017 Antarctic summer season, the BAS successfully relocated Halley Station to its new home on the Brunt Ice Shelf, 23 km from the original site, however, no data were collected in the 2017 ozone hole season. Due to subsequent logistical issues, there were no Halley total column ozone data in the Austral Spring of 2018 either. It is expected that automated measurements will resume during the Austral Spring of 2019 which should yield data again for 2019 (onwards). See <https://legacy.bas.ac.uk/met/jds/ozone/> for further information. The Halley total column ozone was the metric that was first reported in 1985 to identify the significant ozone loss over Antarctica. Based on this metric alone (up to 2016), it would appear that October mean ozone levels over Halley may have started to increase again. The minimum ozone level was observed in 1993, which has been attributed to residual volcanic effects (Mt Pinatubo, 1991). Ignoring the warm years of 2002 and 2004, the mean October ozone levels at Halley Station for 2011 to 2016 ( $157\pm 18$  DU) are higher than those observed from 1996 to 2001 ( $141\pm 4$  DU), indicative of the commencement of possible ozone recovery, but not statistically significant.

If we remove the significantly dynamically-influenced 2002 and 2004 ozone data from Figure 10, the remaining data (1996-2016) show significant ozone growth (recovery) of  $1.0\pm 0.5$  ( $1\sigma$ ) DU/yr. For the period 1993-2016 the ozone growth is  $1.4\pm 0.4$  ( $1\sigma$ ) DU/yr, although the early 1990s data may be low due to the impact of the Mt Pinatubo eruption. These results are in good agreement with those from the satellite records shown in Figure 6, and the estimated increase in column ozone of about 1.0 DU/yr.

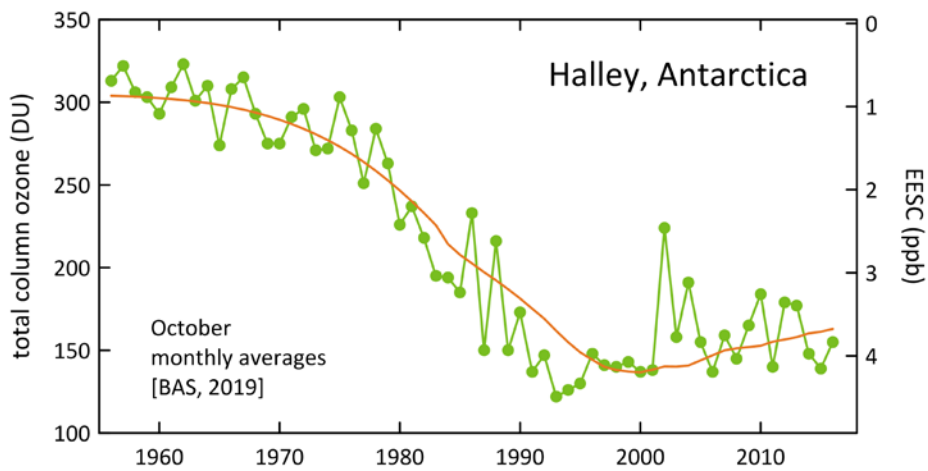


Figure 10. Total column ozone amounts (October mean) as measured at Halley Station, Antarctica, by the British Antarctic Survey from 1956 to 2016. The orange line is obtained from a linear regression to Antarctic EESC (EESC-A) as described in the text. Note that due to the Halley station being relocated and subsequent logistical issues, there are no Halley total column ozone data since 2016. It is expected that automated measurements will resume during the Spring of 2019 which should yield data again for 2019 (onwards). See <https://legacy.bas.ac.uk/met/jds/ozone/> for further information.

## 4 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<sub>2</sub>O, CH<sub>4</sub> and N<sub>2</sub>O) 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 maximum impact on tropical ozone and do not significantly impact on stratospheric ozone levels over Antarctica.

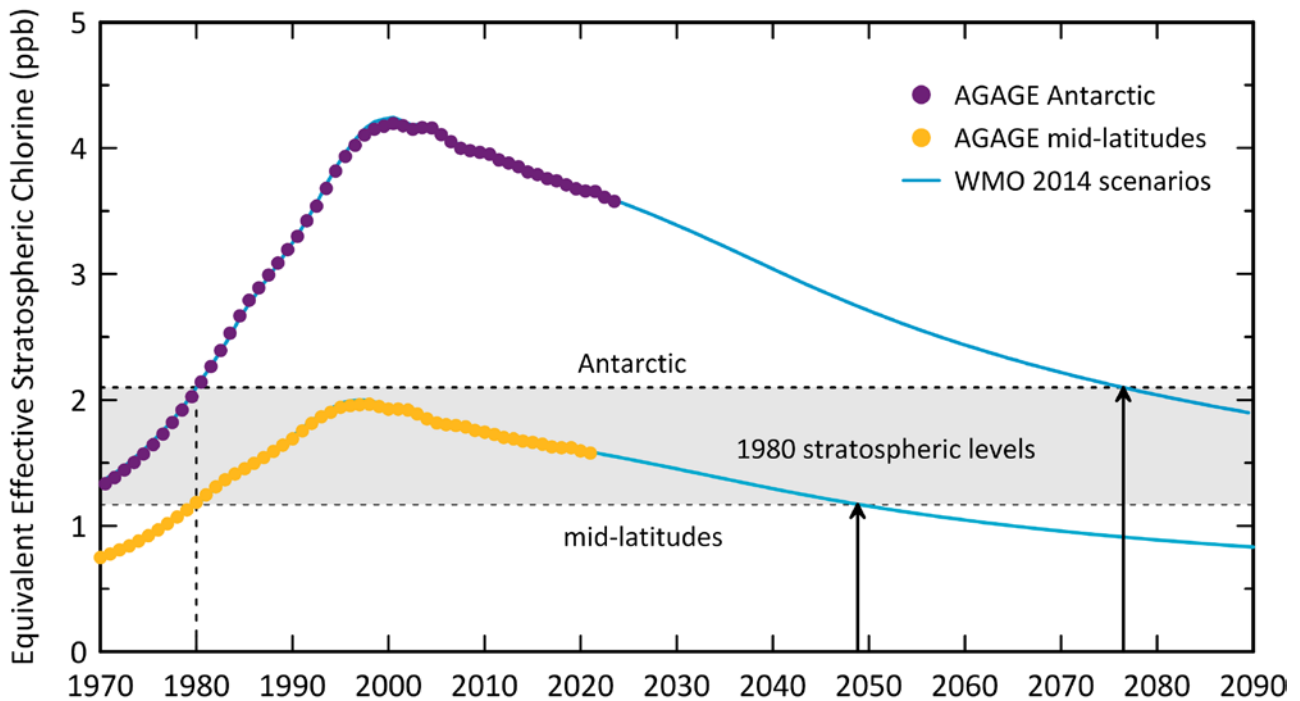
Equivalent Chlorine (ECl: chlorine plus weighted bromine) levels, derived from CSIRO Cape Grim and other AGAGE surface and CSIRO Antarctic firm observations of ODSs, are likely to decline steadily over the next few decades at about 1% per year, leading to reduced ozone destruction. Figure 11 shows Equivalent Effective Stratospheric Chlorine for mid- (EESC-ML) and Antarctic (EESC-A) latitudes, derived from ECl using fractional release factors from Newman *et al.* (2007), lagged 3 years (EESC-ML) and 5.5 years (EESC-A) to approximate the time taken to transport ECl to these regions of the stratosphere.

EESC-A peaked at 4.20 ppb in 2000 and EESC-ML at 1.97 ppb in 1998 respectively, falling to 3.71 and 1.62 ppb respectively by 2018, declines of 11.7% and 17.8% respectively. Table 2 shows the species contributing to the declines in EESC-A (~0.49 ppb) and in EESC-ML (~0.35 ppb) since their peak values in 2000 and 1998 respectively. The decline since 2000/1998 to 2018 is dominated by methyl chloroform, followed by methyl bromide, the CFCs and carbon tetrachloride. The halons and HCFCs have made an overall growth contribution to EESC-A and EESC-ML since 2000/1998.

**Table 2. ODS contributions to the decline in EESC at Antarctic and mid-latitudes (EESC-A, EESC-ML) observed in the atmosphere in 2018 since their peak values in 2000 and 1998 respectively. Note values have been rounded to two decimal places.**

Species	EESC decline Antarctic ppb Cl	EESC decline mid-latitudes ppb Cl
<b>methyl chloroform</b>	0.29	0.20
<b>methyl bromide</b>	0.15	0.10
<b>CFCs</b>	0.13	0.06
<b>carbon tetrachloride</b>	0.07	0.05
<b>halons</b>	-0.07	-0.02
<b>HCFCs</b>	-0.08	-0.03
<b>Total decline</b>	<b>0.49</b>	<b>0.35</b>

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. The atmospheric concentration of methyl chloroform at the end of 2018 had dropped to about 1.8 ppt indicating that most of the rapid decline in this shorter lived ODS has already occurred. Based on EESC-ML and EESC-A values from scenarios of ODS decline (Harris and Wuebbles, 2014), ozone recovery at mid-latitudes will occur at about the mid- to late-2040s and ozone recovery in the Antarctic stratosphere will occur about the mid-2070s. This is now a few years later than reported in the previous ozone assessment due to the updated longer estimated lifetimes for CFC-11 and carbon tetrachloride (CCl<sub>4</sub>). These lead to slower atmospheric decay and thus an increased contribution to EESC in the future.



**Figure 11. 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) and other AGAGE stations and in Antarctic firn air (CSIRO) from Law Dome. EESC-A is lagged 5.5 years and EESC-ML 3 years to approximate the transport times for ODSs from the Earth’s surface (largely in the Northern Hemisphere) to the stratosphere at Southern Hemisphere mid- and Antarctic latitudes. 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.**

In response to the need to easily convey information to the general public about the levels of ozone-depleting chemicals in the atmosphere, and when might the ozone hole recover, NOAA has developed the Ozone Depleting Gas Index (ODGI) (Hofmann and Montzka, 2009; and recent updates see <http://www.esrl.noaa.gov/gmd/odgi/>). 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. 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 12 shows the CSIRO version of the ODGI-ML and ODGI-A indices derived from global AGAGE data including data from Cape Grim. Based on data up to 2018, the ODGI-A and ODGI-ML indices have declined by 22% and 44% respectively since their peak values in 2000 and 1998 respectively, indicating that the atmosphere in 2018 is 22% and 44% 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. The CSIRO version of the ODGI uses ODS fractional release factors from Newman *et al.* (2007).

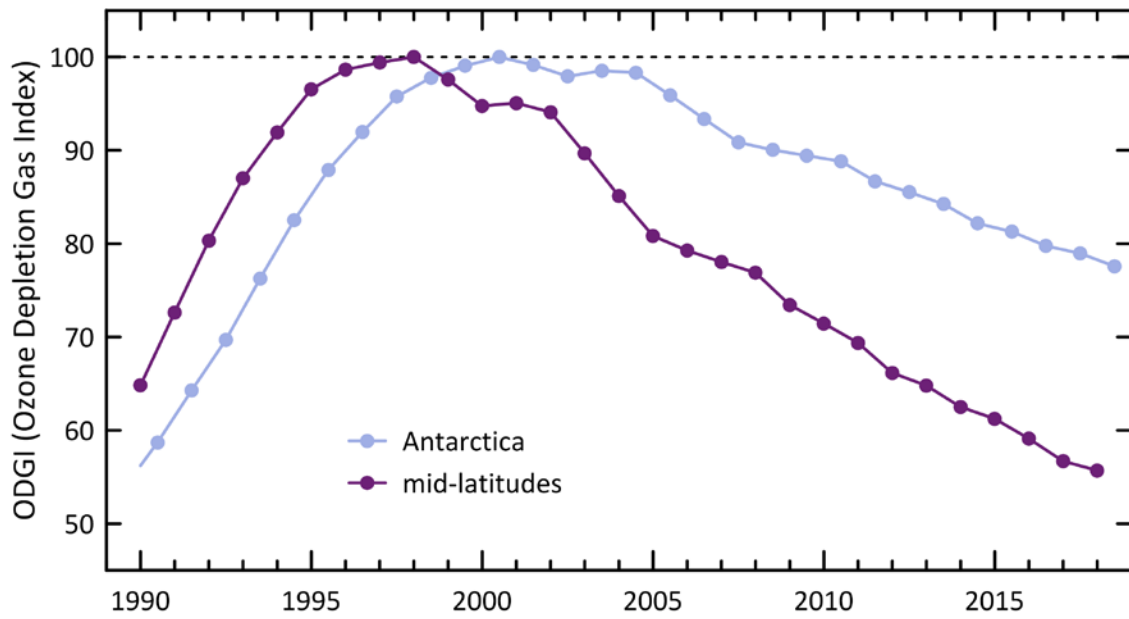


Figure 12. ODGI-A and ODGI-ML indices (Hofmann and Montzka, 2009) derived from AGAGE ODS data using ODS fractional release factors from Newman *et al.* (2007).



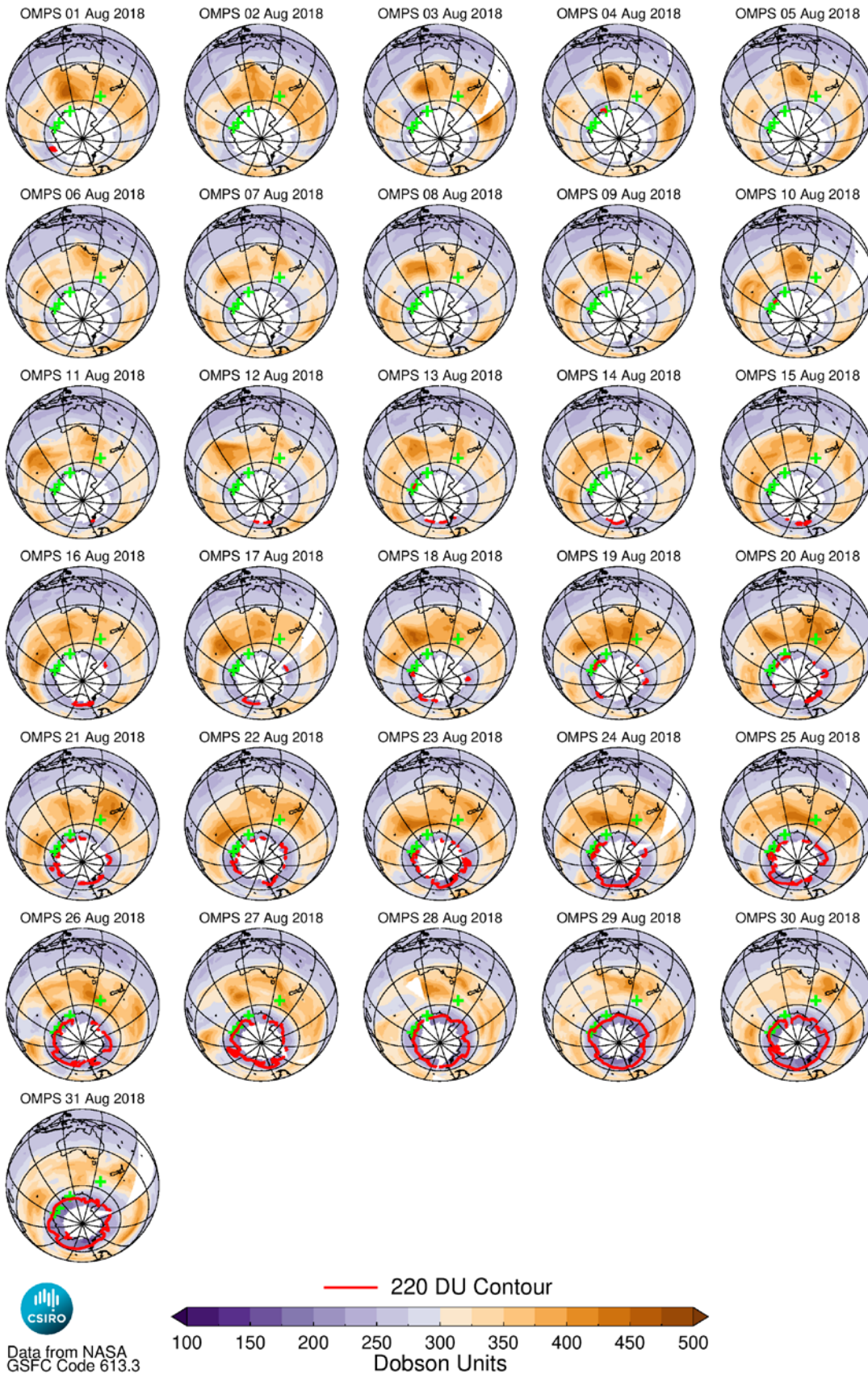
# Summary

- The 2018 Antarctic ozone hole was relatively large, generally being in the top-third largest across the metrics used in this report, except for the area metrics where it ranked just outside the top-third. The 2018 hole ranked 14<sup>th</sup> and 17<sup>th</sup> in the area metrics, and for the other metrics it ranked either 12<sup>th</sup> or 13<sup>th</sup>. These are comparisons from 39 years of TOMS/OMI/OMPS satellite records.
- The dominant features during the 2018 ozone hole season were the persistent ridge of high ozone immediately south of Australia, which was present for most of September, October and the first half of November, and that the ozone hole was remarkably stable and symmetrical from the beginning of September through to early November, indicating a very stable polar vortex. This is supported by the meteorological data that show that the low- to mid-stratospheric temperatures were considerably colder than average for much of the ozone hole season and the corresponding heat fluxes indicated lower than average heat transported towards the pole.
- From the first week on November the 2018 ozone hole was impacted by a series of warming events/disturbances which caused large elongations of the ozone hole/polar vortex and a sharp reduction in the size/depth of the ozone hole, with the ultimate recovery occurring by 7 December 2018.
- The 2000 and 2006 ozone holes were the largest ozone holes ever, depending on the metric that is used.
- Most ozone metrics discussed in this report show signs that ozone recovery has commenced.
- Comparison of trends in EESC and cumulative ozone deficit within the hole since the late 1970s suggest that ozone recovery has commenced.
- The EESC data from observations and future scenarios suggest that ozone recovery at mid-latitudes will occur at about the mid- to late-2040s and Antarctic ozone recovery at about the mid-2070s.
- The ODGI values suggest that the atmosphere, by 2018, is about 22% along the path to Antarctic ozone recovery and 44% along the path to ozone recovery at mid-latitudes.
- Changes in EESC-A and changes in ozone over Antarctica (satellite and Dobson) are highly correlated and the Dobson data at Halley Station suggest Antarctic ozone recovery has commenced. The correlation could be even more significant if temperature effects were removed from the ozone data.

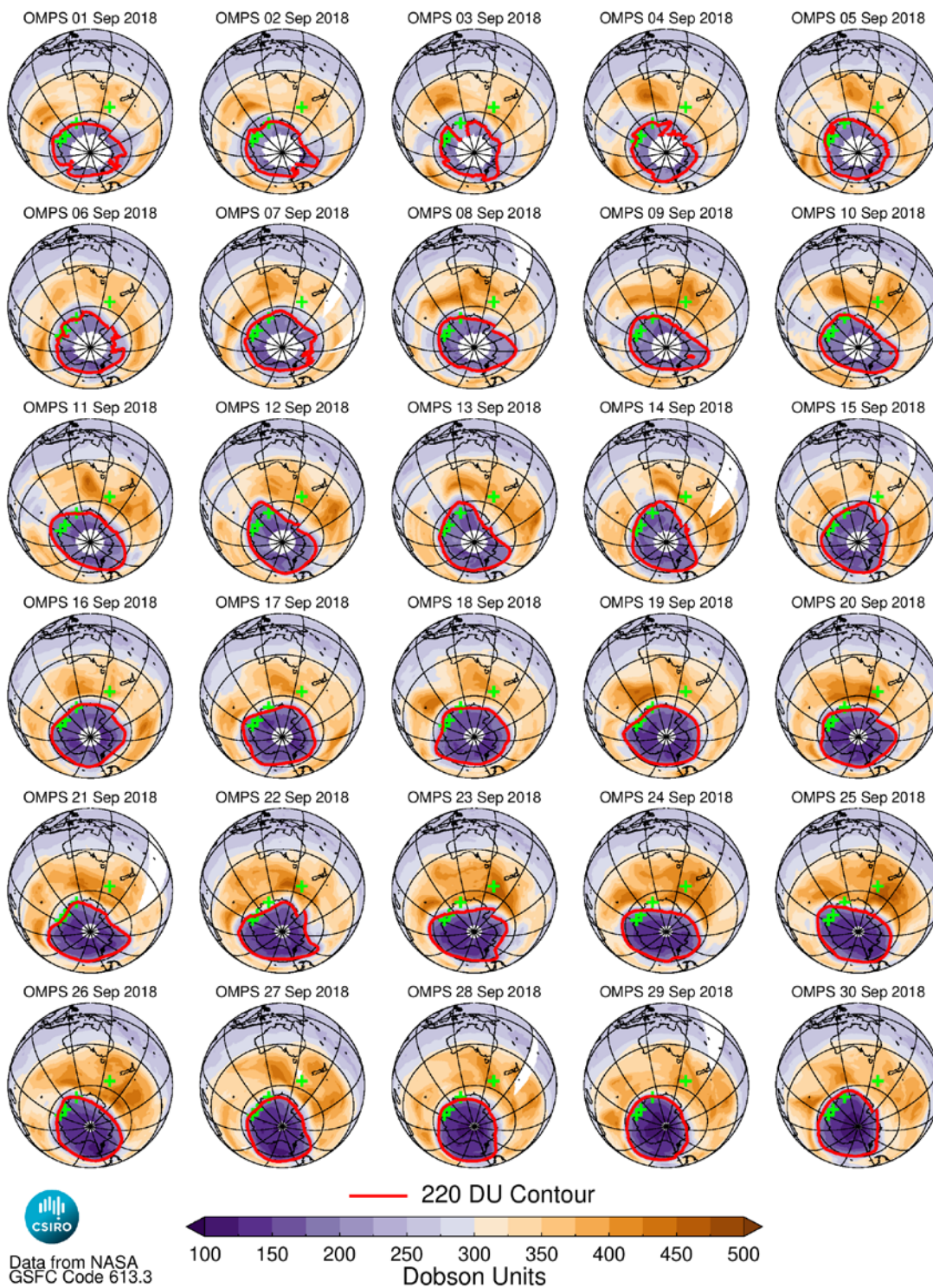
Animations of the daily images from the 2018 ozone hole (along with previous years' holes) in various video formats can be downloaded from [ftp://gaspublic:gaspublic@pftp.csiro.au/pub/ozone\\_hole/](ftp://gaspublic:gaspublic@pftp.csiro.au/pub/ozone_hole/).

Animations of the historical October 1-15 averages for all available years in the period 1979-2018 are also available from the above address, along with the ozone hole metrics presented in this report. To download, right click the file and select 'Copy to folder ...'.

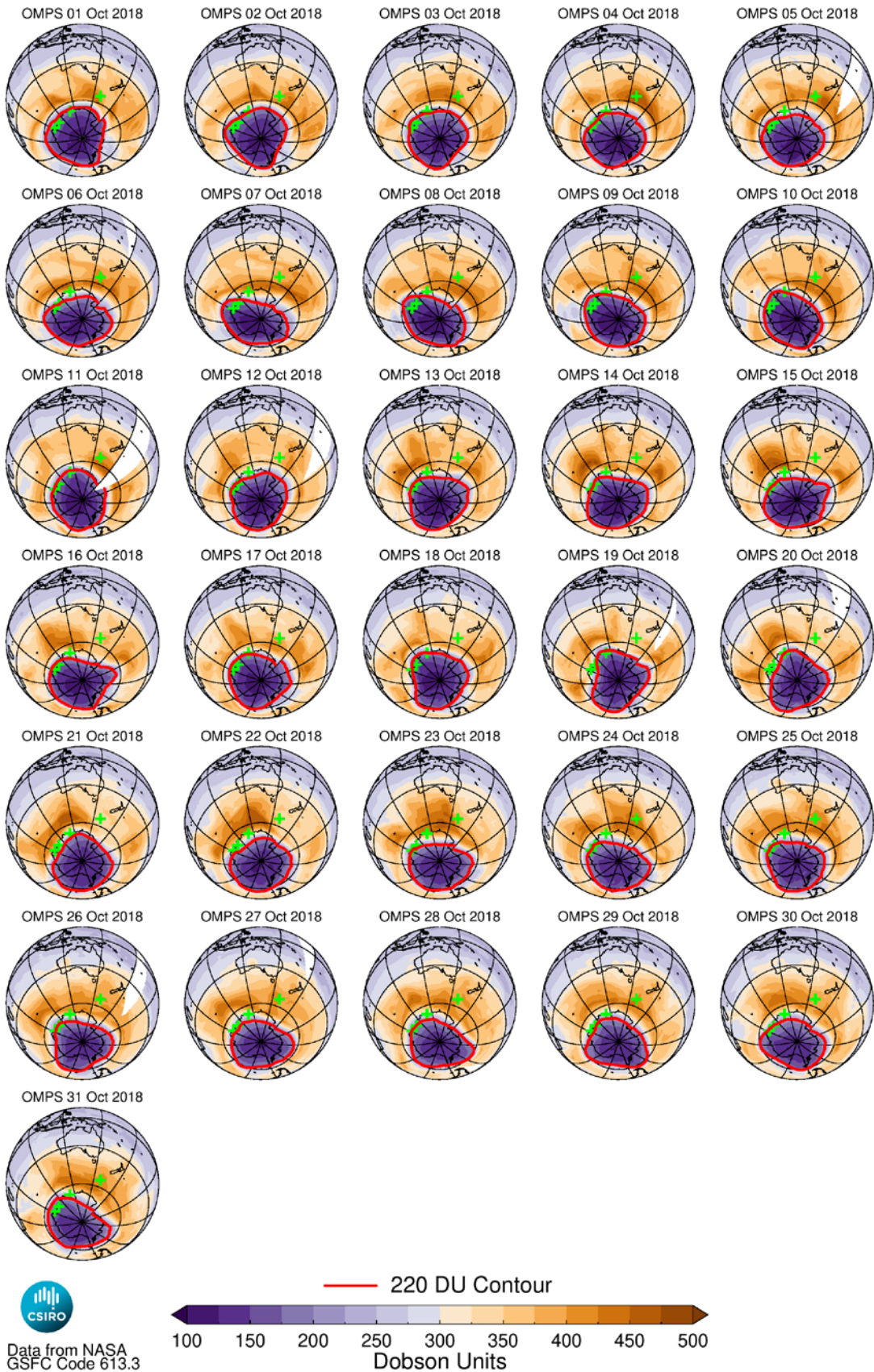
# Appendix A 2018 daily total column ozone images



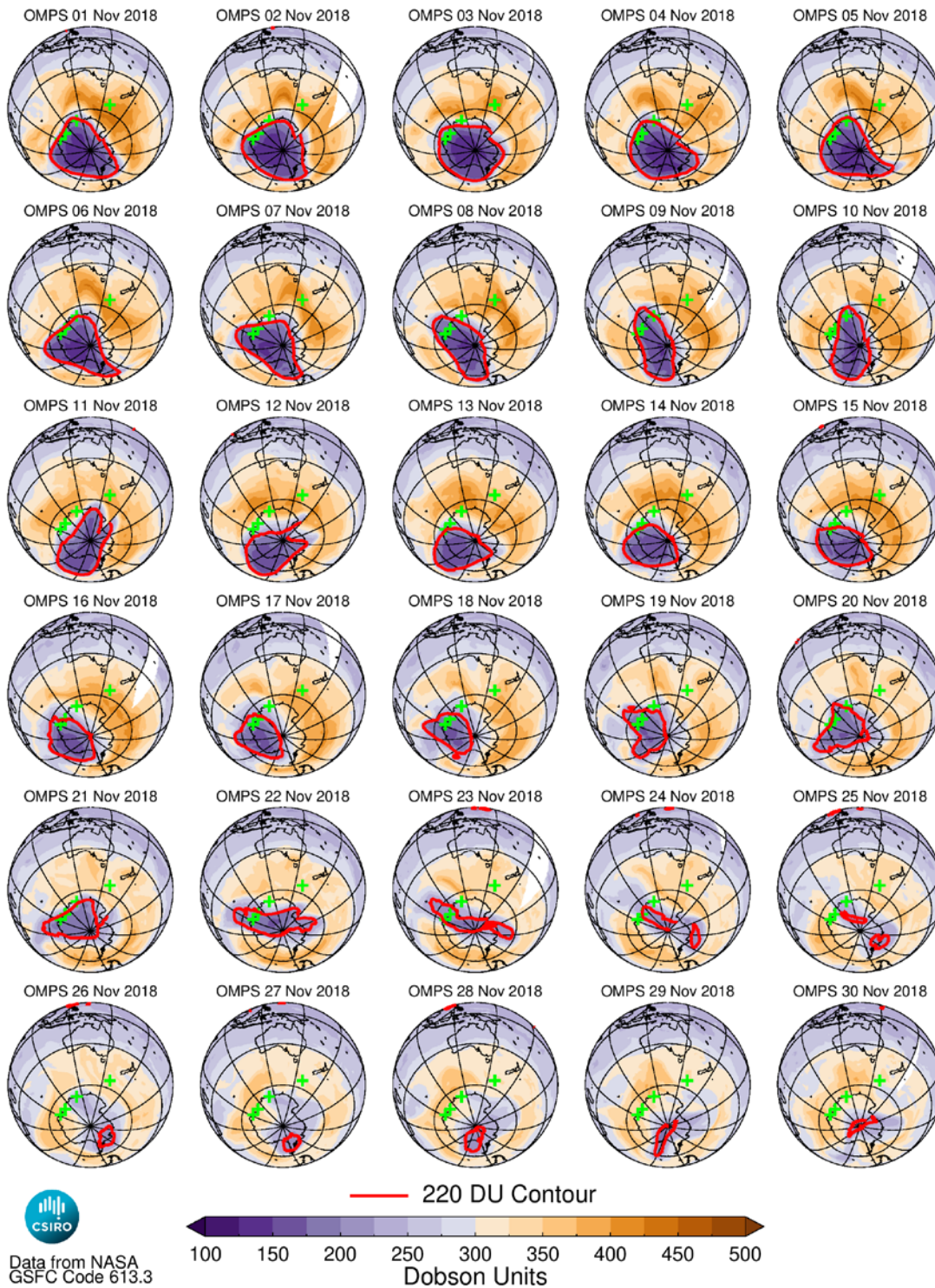
**Apx Figure A.1** OMPS ozone hole images for August 2018; the ozone hole boundary is indicated by the red 220 DU contour line. The Australian Antarctic (Mawson, Davis and Casey) and Macquarie Island stations are shown as green plus symbols. The white area over Antarctica is missing data and indicates the approximate extent of the polar night. The OMPS instrument requires solar radiation to the earth’s surface to measure the column ozone abundance.



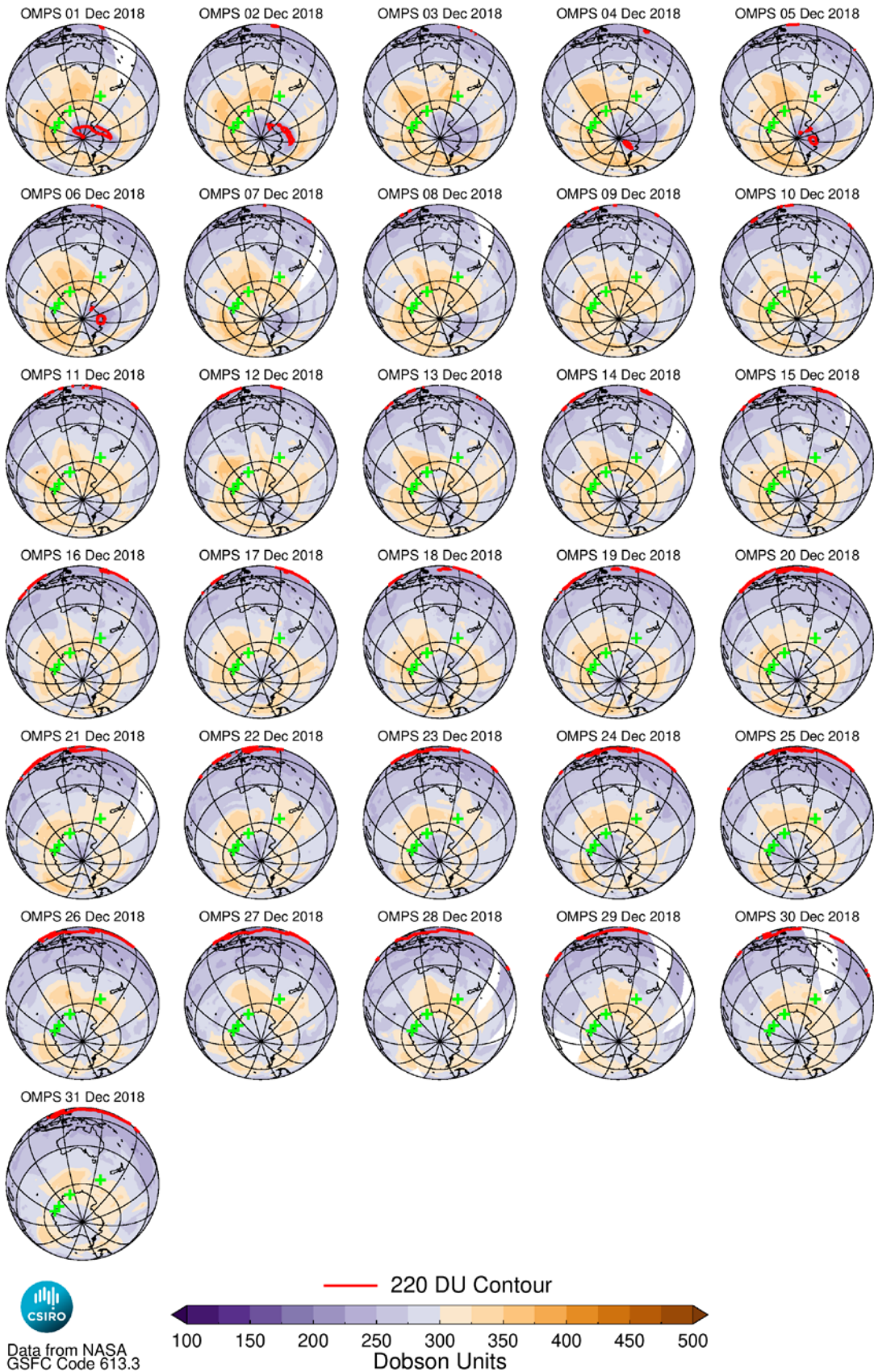
**Apx Figure A.2 OMPS ozone hole images for September 2018; the ozone hole boundary is indicated by the red 220 DU contour line. The Australian Antarctic (Mawson, Davis and Casey) and Macquarie Island stations are shown as green plus symbols. The white area over Antarctica is missing data and indicates 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.**



**Apx Figure A.3 OMPS ozone hole images for October 2018; the ozone hole boundary is indicated by the red 220 DU contour line. The Australian Antarctic (Mawson, Davis and Casey) and Macquarie Island stations are shown as green plus symbols.**



Apx Figure A.4 OMPS ozone hole images for November 2018; the ozone hole boundary is indicated by the red 220 DU contour line. The Australian Antarctic (Mawson, Davis and Casey) and Macquarie Island stations are shown as green plus symbols.



**Apx Figure A.5 OMPS ozone hole images for December 2018; the ozone hole boundary is indicated by the red 220 DU contour line. The Australian Antarctic (Mawson, Davis and Casey) and Macquarie Island stations are shown as green plus symbols.**

# Definitions

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<sub>2</sub> gases in the Kyoto Protocol (e.g. PFCs, HFCs, methane, and nitrous oxide). See <http://agage.eas.gatech.edu/index.htm> 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<sub>3</sub>; 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  $-78^{\circ}\text{C}$ , 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.

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.

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