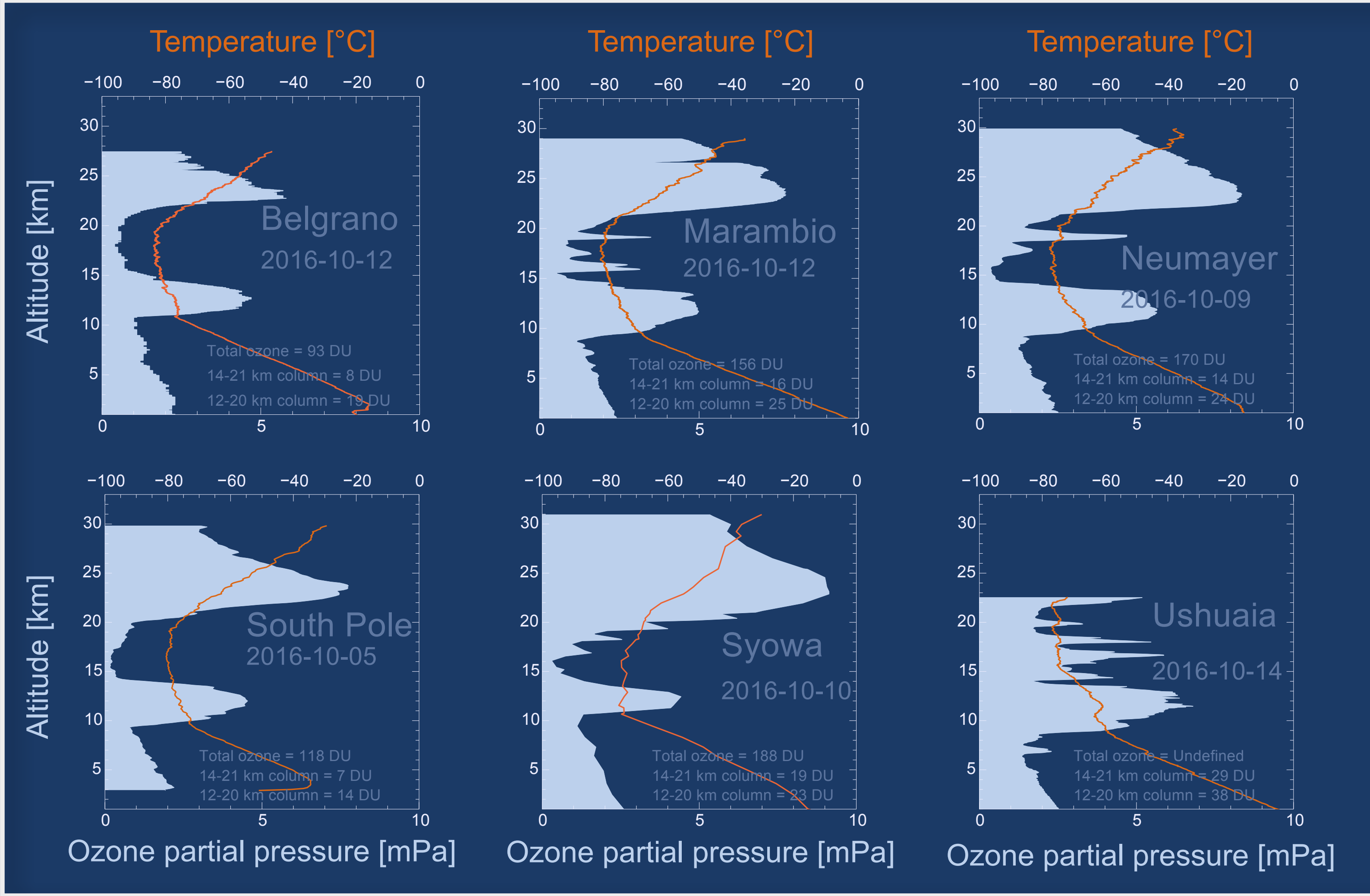
Antarctic Ozone Bulletin

No 2/2016



Selected ozone profiles from some ozonesonde stations. These profiles are the ones with the smallest 14-21 km partial column at each station so far this year. At Belgrano and the South Pole, the 14-21 km partial columns on these dates (8 and 7 DU, respectively) are similar to the most depleted profiles of 2015 (7 and 5 DU, respectively). At Marambio, the lowest 14-21 km column measured last year was 29 DU compared to this year's 16 DU. At Neumayer, the lowest 14-21 km partial column observed last year was 9 DU, compared to 14 DU so far this year. At Syowa, the lowest 14-21 km partial column observed last year was 15 DU, compared to 19 DU so far this year. At Ushuaia, the lowest 14-21 km partial column observed last year was 47 DU, compared to 29 DU so far this year. See executive summary for further discussion.

WMO OMM

16 October 2016

Global Atmosphere Watch

GAW

Executive Summary

Stratospheric temperatures over Antarctica have been below the PSC type I threshold of 194.6 K since 17 May and below the PSC type II threshold of 187.8 K since 12 June. The daily minimum temperatures at the 50 hPa level were close to the 1979-2015 average from April to mid July. From mid July until the end of August the minimum temperature was somewhat lower than the long term mean. From late August until present it has been close to or slightly below the long term mean. From mid October the minimum temperature is forecast to increase rapidly.

The average temperature at 50 hPa over the 60-90°S region the was oscillating around the long term mean from April until mid August, after which it has been above the long term mean.

At 10 hPa, the 60-90°S mean temperature was oscillating around the long term mean during the early April to the late July time period. In August, September and so far in October the mean temperature has been oscillating around the long term mean.

Since the onset of NAT temperatures in mid May, the NAT area was oscillating around the long term mean from May through August. In early September the NAT area decreased somewhat more rapidly than the long term mean but near the end of the month a cold spell led to a rapid increase in the NAT area before it went down again. In October the NAT area has been near the average. On 30th July the NAT area reached a maximum for the season with 27.7 million km^2, which is a bit lower than the 28.2 million km^2 reached in 2015, but higher than the maximum reached in other recent years.

The NAT volume has been below the long term mean during most of the winter and spring, except for a period from early July to mid August, when it was close to the long term mean. In September the NAT volume was below the long term mean, but the towards the end of the month it increased for a few days before going down again. The maximum NAT volume for the season was reached on 29 July with 310 million km^3. This is the highest daily maximum since 2008, when 325 million km^3 was recorded.

During the whole period from May until present, the 45-day mean of the heat flux at 100 hPa has been larger than or close to the 1979-2015 average. In early-mid September it was, on a couple of days, close to the long term maximum for those dates. This is an indication of a disturbed vortex.

At the 45.4 hPa level (altitude of ~18.5-19.5 km) the vortex was almost entirely depleted of hydrochloric acid (HCl), one of the reservoir gases that can be transformed to active chlorine, during August and early September. By 5 October HCl has recovered and is more abundant inside than outside the vortex.

Certain parts of the vortex contained more than 3.8 ppb of active chlorine ($ClO + 2Cl_2O_2$) in August and into early September. By early October there is almost no active chlorine left.

Satellite observations show that the area where total ozone is less than 220 DU ("ozone hole area") has been significantly above zero since 7 August. This is a relatively early onset of ozone depletion and about ten days earlier than in 2015. The ozone hole area reached it maximum for 2016 on 28 September with 23.1 million km^2, whereas it reached 28.2 million km^2 on 2 October 2015. The date of the onset of ozone depletion varies considerably from one year to the next, depending on the position of the polar vortex and availability of sunshine after the polar night. In 2016, the vortex has been relatively perturbed and shifted somewhat away from the South Pole. This can explain the relatively early onset of ozone depletion in 2016.

Measurements with ground based instruments and with balloon sondes show clear signs of ozone depletion at all sites. In this issue data are reported from the following stations: Arrival Heights, Belgrano, Davis, Dôme Concordia, Dumont d'Urville, Halley, Kerguelen, Macquarie Island, Marambio, Mirny, Neumayer, Novolazarevskaya, Río Gallegos, Rothera, San Martín, South Pole, Syowa, Ushuaia, Vernadsky, Vostok and Zhongshan.

Balloon soundings show that stations deep inside the vortex, such as Belgrano, Neumayer and the South Pole have experienced somewhat less ozone depletion in the 14-21 km altitude range this year as compared to 2015. Stations on the vortex edge or mostly outside the vortex, such as Marambio and Ushuaia, have experienced more ozone depletion in this altitude range this year as compared to 2015. This can be explained by the fact that, despite somewhat less ozone depletion deep inside the polar vortex, the vortex has been more perturbed and made more frequent excursions into regions that are usually outside of the vortex.

WMO and the scientific community will use ozone observations from the ground, from balloons and from satellites together with meteorological data and modelling results to keep a close eye on the development during the coming weeks and months.

Introduction

The meteorological conditions in the Antarctic stratosphere found during the austral winter (June-August) set the stage for the annually recurring ozone hole. Low temperatures lead to the formation of clouds in the stratosphere, so-called polar stratospheric clouds (PSCs).

The amount of water vapour in the stratosphere is very low, only 5 out of one million air molecules are water molecules. This means that under normal conditions there are no clouds in the stratosphere. However, when the temperature drops below -78°C, clouds that consist of a mixture of water and nitric acid start to form. These clouds are called PSCs of type I. On the surface of particles in the cloud, chemical reactions occur that transform passive and innocuous halogen compounds (e.g. HCl and HBr) into so-called active chlorine and bromine species (e.g. ClO and BrO). These active forms of chlorine and bromine cause rapid ozone loss in sun-lit conditions through catalytic cycles where one molecule of ClO can destroy thousands of ozone molecules before it is passivated through the reaction with nitrogen dioxide (NO_2).

When temperatures drop below -85°C, clouds that consist of pure water ice will form. These ice clouds are called PSCs of type II. Particles in both cloud types can grow so large that they no longer float in the air but fall out of the stratosphere. In doing so they bring nitric acid with them. Nitric acid is a reservoir that liberates NO_2 under sunlit conditions. If NO_2 is physically removed from the stratosphere (a process called denitrification), active chlorine and bromine can destroy many more ozone molecules before they are passivated. The formation of ice clouds will lead to more severe ozone loss than that caused by PSC type I alone since halogen species are more effectively activated on the surfaces of the larger ice particles.

The Antarctic polar vortex is a large low-pressure system where high velocity winds (polar jet) in the stratosphere circle the Antarctic continent. The region poleward of the polar jet includes the lowest temperatures and the largest ozone losses that occur anywhere in the world. During early August, information on meteorological parameters and measurements from ground stations, balloon sondes and satellites of ozone and other constituents can provide some insight into the development of the polar vortex and hence the ozone hole later in the season.

The situation with annually recurring Antarctic ozone holes is expected to continue as long as the stratosphere contains an excess of ozone depleting substances. As stated in the Executive Summary of the 2010 edition of the WMO/UNEP Scientific Assessment of Ozone Depletion, severe Antarctic ozone holes are expected to form during the next couple of decades.

For more information on the Antarctic ozone hole and ozone loss in general the reader is referred to the WMO ozone web page: http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html.

Meteorological conditions

The meteorological data used here originate from NASA's Global Modelling and Assimilation Office (GMAO, http://gmao.gsfc.nasa.gov/research/merra/) and from the European Centre for Medium Range Weather Forecasts (ECMWF). Reanalyses from GMAO, the so-called MERRA data, have been downloaded from the NASA Ozonewatch web site (http://ozonewatch.gsfc.nasa.gov/). The ECMWF data have been extracted at and downloaded from the Norwegian Institute for Air Research (NILU) who make these data available through a project funded by the European Space Agency (ESA).

Temperatures

MERRA data from GMAO show that stratospheric temperatures over Antarctica have been below the PSC type I threshold of 194.6 K since 17 May and below the PSC type II threshold of 187.8 K since 12 June, as shown in Figure 1. This figure also shows that the daily minimum temperatures at the 50 hPa level were close to the 1979-2015 average from April to mid July. From mid July until the end of August the minimum temperature was somewhat lower than the long term mean.

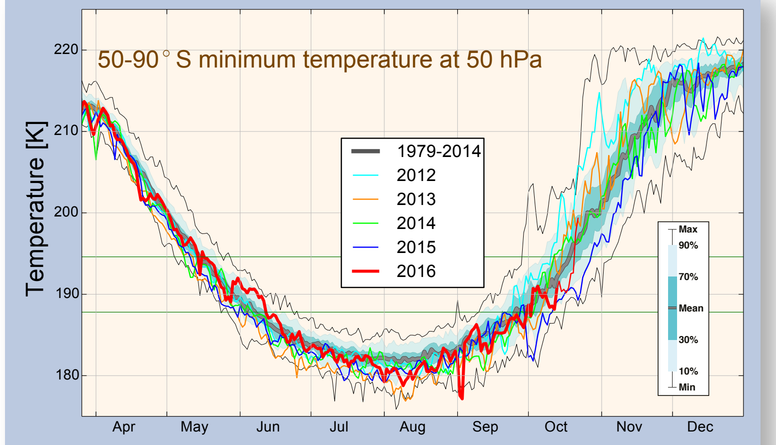


Figure 1. Time series of daily minimum temperatures at the 50 hPa isobaric level south of 50°S. The thick red curve shows 2016. The thinner extension of the red curve is a 10-day forecast. The blue line shows 2015, the green line 2014 and the orange line 2013. The average of the 1979-2015 period is shown for comparison in grey. The thin black lines represent the highest and lowest daily minimum temperatures in the 1979-2015 time period. The light blue-green shaded area represents the 10th and 90th percentile values and the dark blue-green shaded area the 30th and 70th percentiles. The two horizontal green lines at 195 and 188 K show the thresholds for formation of PSCs of type I and type II, respectively. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA, which are based on data from NOAA/NCEP.

From late August until present it has been close to or slightly below the long term mean. From mid October the minimum temperature is forecast to increase rapidly.

Figure 2 (upper panel) shows temperatures averaged over the 60-90°S region at 50 hPa. It can be seen from the figure that the average temperature was oscillating around the long term mean from April until mid August, after which it has been above or near the long term mean.

At 10 hPa (Figure 2, lower panel), the 60-90°S mean temperature was oscillating around the long term mean during the early April to the late July time period. In August, September and so far in October the mean temperature has been oscillating around the long term mean.

The mean temperature over the 55-75°S region has behaved quite similarly to the temperature averaged over the 60-90°S region at all levels from 30 to 150 hPa.

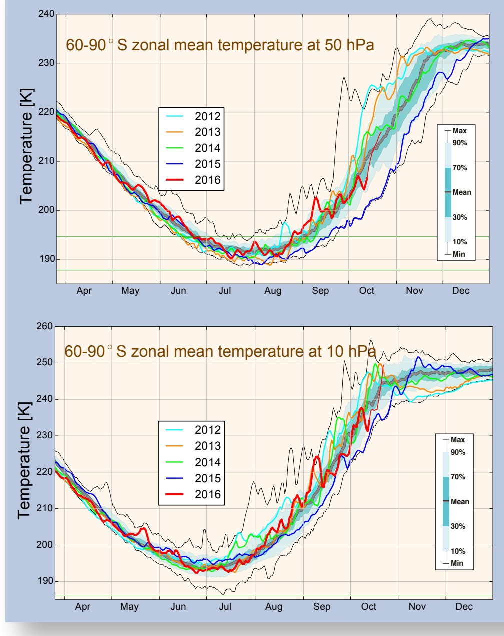


Figure 2. Time series of temperature averaged over the region south of 60°S at the 50 hPa level (left) and at 10 hPa (right). The red curve shows 2016. The blue, green and orange curves represent 2015, 2014 and 2013, respectively. The average of the 1979-2015 period is shown for comparison in grey. The two thin black lines show the maximum and minimum average temperature for during the 1979-2015 time period for each date. The light blue-green shaded area represents the 10th and 90th percentile values and the dark blue-green shaded area the 30th and 70th percentiles. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA, which are based on data from NOAA/NCEP.

PSC Area and Volume

Since 28 June, temperatures low enough for nitric acid trihydrate (NAT or PSC type I) formation have covered an area of more than 20 million square kilometres at the 460 K isentropic level (Figure 3, upper panel). Since the onset of NAT temperatures in mid May, the NAT area was oscillating around the long term mean from May through August. In early September the NAT area decreased somewhat more rapidly than the long term mean. In early September the NAT area was lower than the long term mean but near the end of the month a cold spell led to a rapid increase in the NAT area before it went down again. In October the NAT area has been near the average. On 30th July the NAT area reached a maximum for the season with 27.7 million km^2, which is a bit lower than the 28.2 million km^2 reached in 2015, but higher than the maximum reached in other recent years. With the exception of 2015, one has to go back to 2008 to find a higher PSC area maximum (28.3 million km^2).

Rather than looking at the NAT area at one discrete level of the atmosphere it makes more sense to look at the volume of air with temperatures low enough for NAT formation. The so-called NAT volume is derived by integrating the NAT areas over a range of input levels. The daily progression of the NAT volume in 2015 is shown in Figure 3 (lower panel) in comparison to recent winters and long-term statistics. The NAT volume has been below the long term mean during most of the winter and spring, except for a period from early July to mid August,

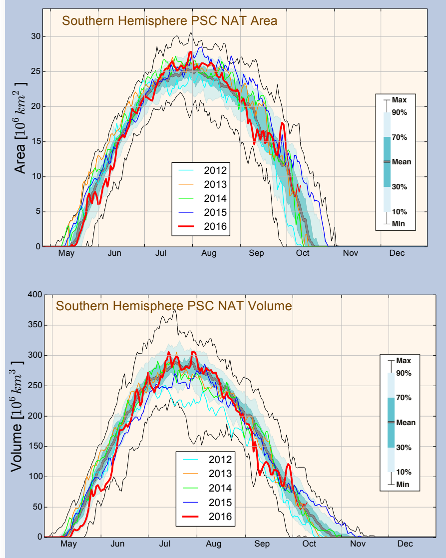


Figure 3. Upper panel: Time series of the area of the region where temperatures are low enough for the formation of nitric acid trihydrate (NAT or PSCs of type I) at the 460 K isentropic level. Lower panel: Time series of the volume of the region where temperatures are low enough for the formation of nitric acid trihydrate (NAT or PSCs of type I). The red curve shows 2016. The blue, green and orange curves represent 2014, 2013 and 2012, respectively. The average of the 1979-2014 period is shown for comparison in grey. The two thin black lines show the maximum and minimum PSC area during the 1979-2014 time period for each date. The light blue-green shaded area represents the 10th and 90th percentile values and the dark blue-green shaded area the 30th and 70th percentiles. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA, which are based on data from NOAA/NCEP.

when it was close to the long term mean. In September the NAT volume was below the long term mean, but the towards the end of the month it increased for a few days before going down again. The maximum NAT volume for the season was reached on 29 July with 310 million km^3. This is the highest daily maximum since 2008, when 325 million km^3 was recorded.

The area or volume with temperatures low enough for the existence of PSCs is directly linked to the amount of ozone loss that will occur later in the season, but the degree of ozone loss also depends on other factors, such as the amount of water vapour and HNO_3. In the previous issue of this Bulletin it was forecast that the 2016 ozone hole would be similar in size and depth to recent years but smaller than in 2015. This turns out to be the case and this is discussed in more detail under "Long term statistics" on page 48.

Vortex stability

The longitudinally averaged heat flux between 45°S and 75°S is an indication of to what degree the stratosphere is disturbed. The development of the heat flux is shown in Figure 4. See the figure caption for more details on how to interpret the graph.

During the whole period from May until early October, the 45-day mean of the heat flux at 100 hPa has been larger than or close to the 1979-2015 average. In early-mid September it was, on a couple of days, close to the long term maximum for those dates. This is an indication of a disturbed vortex. In mid October it is near the long term mean for this time of the year.

Figure 5 (next page) shows maps of potential vorticity (PV) at the isentropic level of 475 K for the date of 10 October for the years 2006 to 2016. This level corresponds to approximately 19 km altitude. One can see that the polar vortex in 2016 is relatively large compared to most of the other years. One can also see that the 2016 vortex on this date was less concentric around the South Pole than in 2015, and the PV values are less negative (less deep red and hence a weaker vortex) than in many of the recent years.

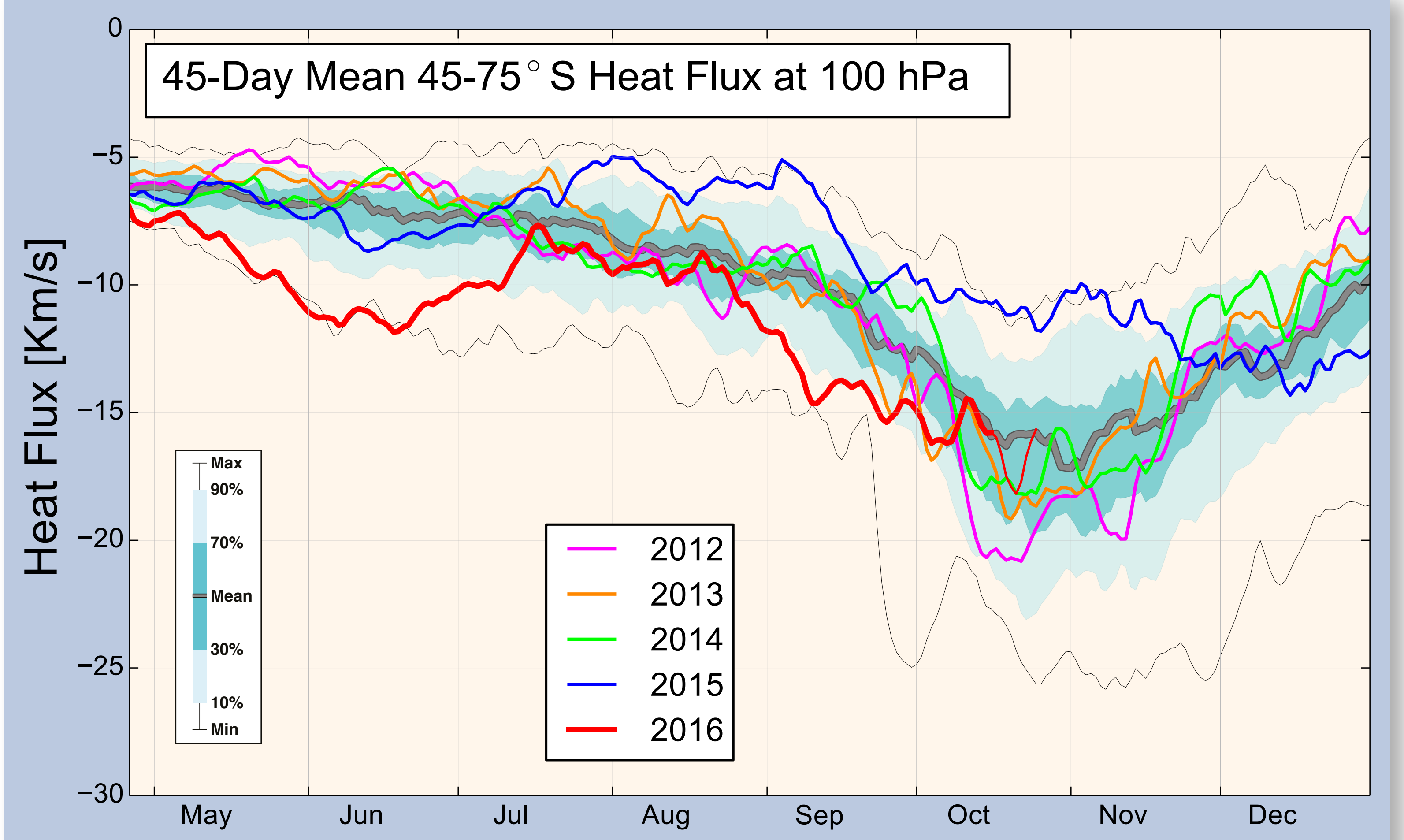


Figure 4. Time series of the meridional heat flux averaged over the 45-75 °S region. The red curve shows data for 2016 (updated until 19 September). Please note that a large negative number means a large heat flux. Values closer to zero means a small heat flux. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA, which are based on data from NOAA/NCEP.

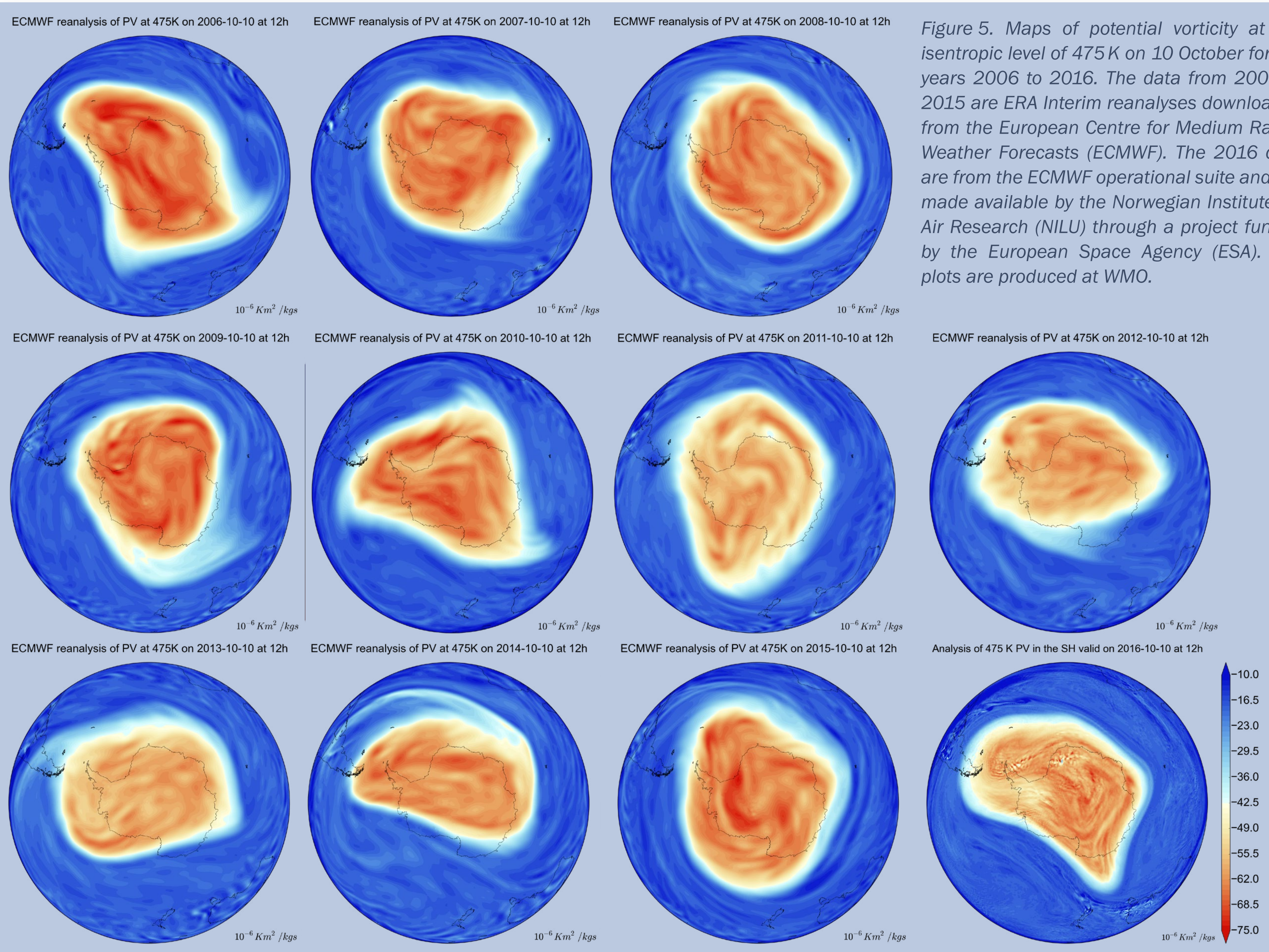


Figure 5. Maps of potential vorticity at the isentropic level of 475 K on 10 October for the years 2006 to 2016. The data from 2006 to 2015 are ERA Interim reanalyses downloaded from the European Centre for Medium Range Weather Forecasts (ECMWF). The 2016 data are from the ECMWF operational suite and are made available by the Norwegian Institute for Air Research (NILU) through a project funded by the European Space Agency (ESA). The plots are produced at WMO.

Ozone observations

Satellite observations

The sun has been back all over Antarctica after the polar night for several weeks. Both satellite data, ground based data and balloon soundings show that ozone depletion has gone through a maximum for this year and is now slowly recovering at most stations.

Figure 6 shows minimum ozone columns as measured by the GOME-2 instrument on board MetOp in comparison with data for years with substantial ozone loss. During most of August and September the minimum columns have been close to the long term (1979-2015) median for the time of the year. So far in October, minimum ozone has been somewhat larger than the long term median.

Figure 7 (next page) shows satellite maps from OMI for 7 October for the years 2006 - 2016. From these maps one can see that the vortex is less concentric in 2016 than in 2015 and it does not cover the entire Antarctic continent.

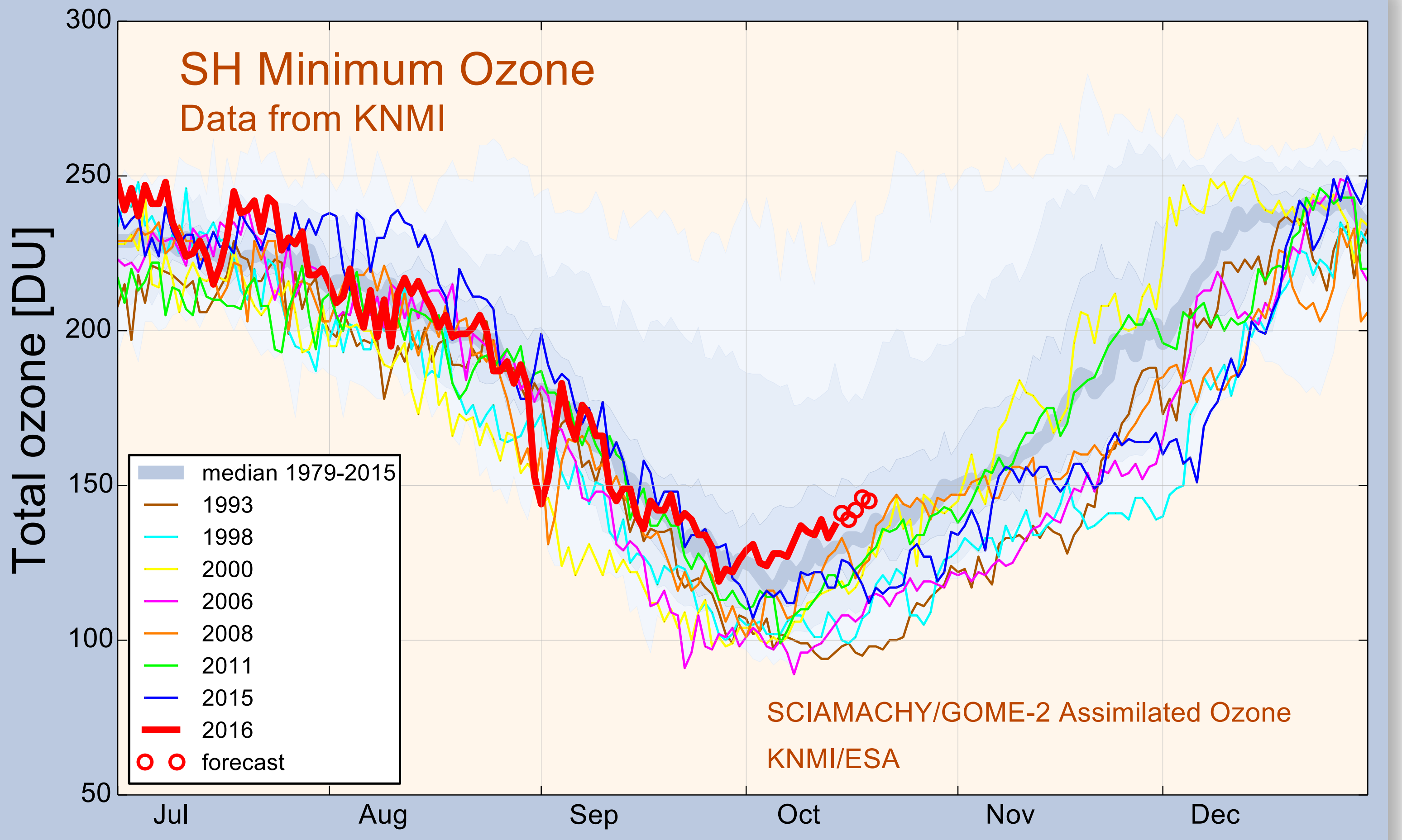


Figure 6. Daily minimum total ozone columns in the Southern Hemisphere as observed by GOME-2, and in the past by SCIAMACHY. The black dots show the GOME-2 observations for 2016 as of 21 September. The forecast for the next few days show that minimum ozone will continue to decrease. The figure is adapted from a plot provided by the Netherlands Meteorological Institute (KNMI).

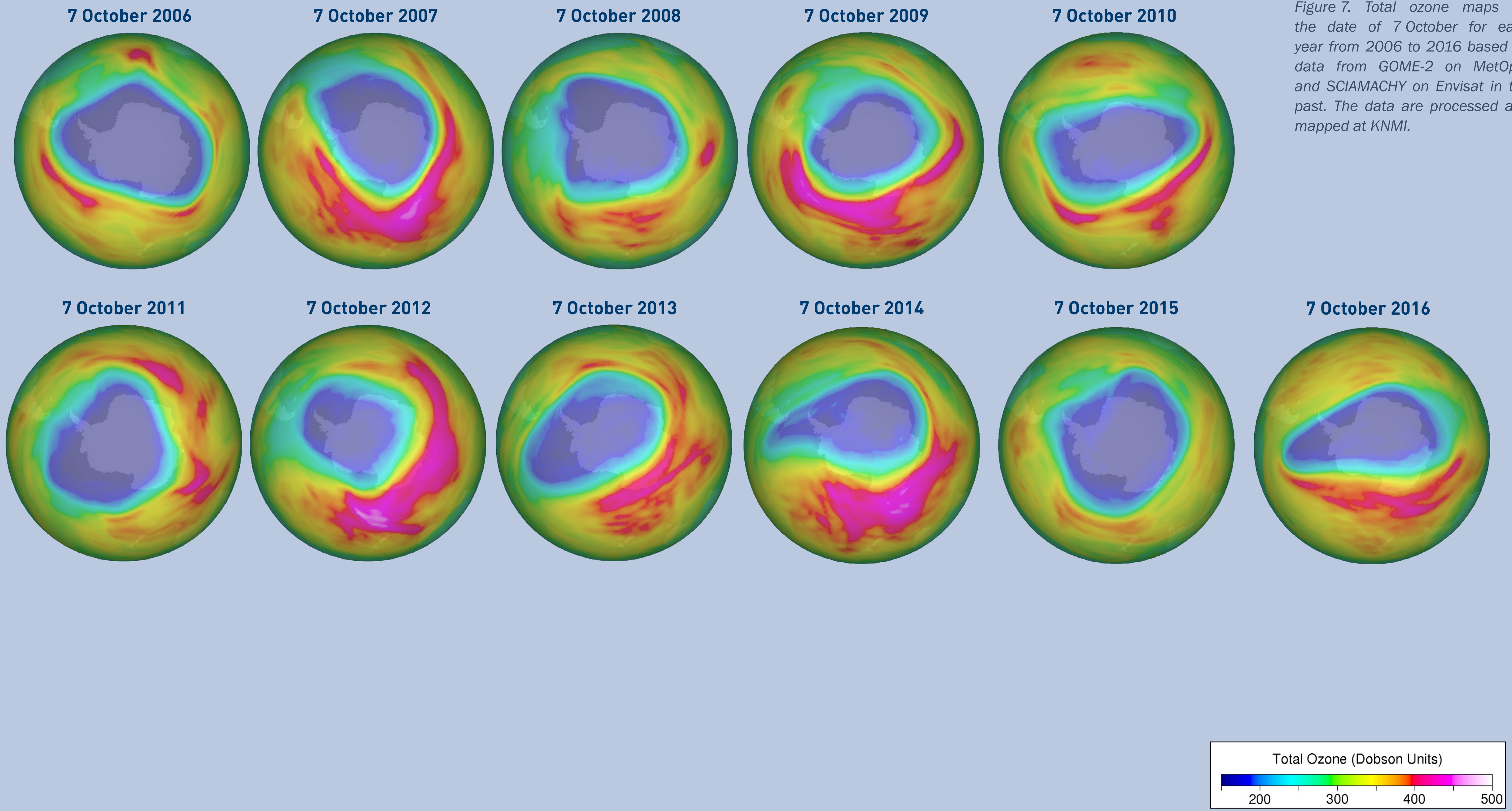
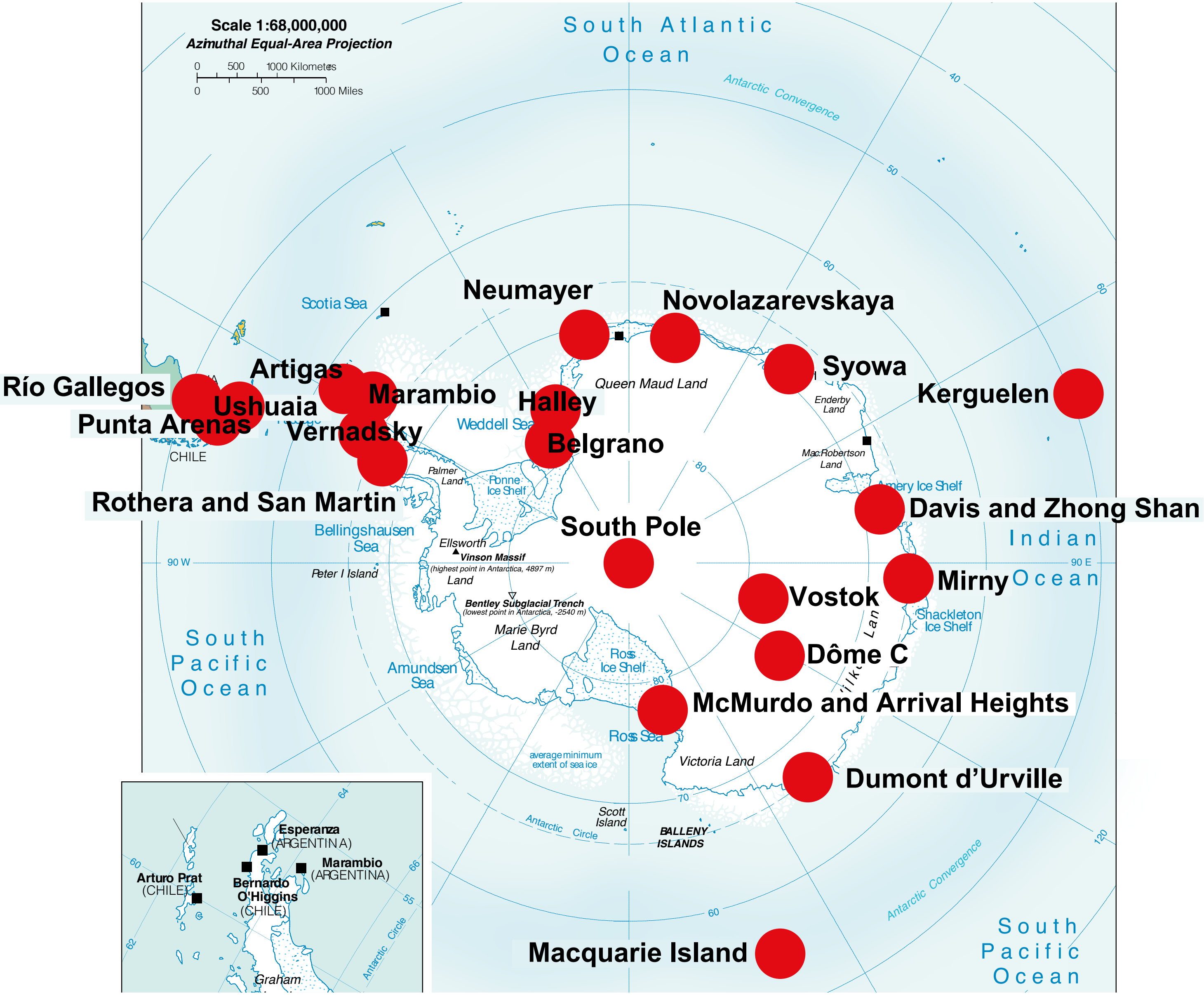


Figure 7. Total ozone maps for the date of 7 October for each year from 2006 to 2016 based on data from GOME-2 on MetOp-A and SCIAMACHY on Envisat in the past. The data are processed and mapped at KNMI.

Ground-based and balloon observations

Most of the stations are already reporting data and they are shown in this issue. The map to the right shows the location of the stations that provide data during the ozone hole season. In this issue there is ground-based and/or sounding data from Arrival Heights, Belgrano, Davis, Dôme Concordia, Dumont d'Urville, Halley, Kerguelen, Macquarie Island, Marambio, Mirny, Neumayer, Novolazarevskaya, Río Gallegos, Rothera, San Martín, South Pole, Syowa, Ushuaia, Vernadsky, Vostok and Zhongshan. Data from Artigas and Troll will be presented as soon as they become available. Ozone depletion has attained its maximum for this year and at most stations ozone is now slowly recovering. Some stations are located close to the vortex edge and might be influenced by both mid-latitude and by polar air masses, and hence showing large day-to-day variations in total ozone.



The NIWA Observatory at Arrival Heights. Photo: NIWA.

At the GAW/NDACC station Arrival Heights (77.845°S, 166.67°E), operated by New Zealand, Dobson observations have been carried out since January 1988. In 2016, the regular observations of total ozone started after the polar night on 14 September, with a total ozone value of 195 DU. Moon observations were carried out in mid August. The Dobson data, together with OMI overpass data and long term (1992-2012) statistics can be seen in **Figure 8**. The OMI overpass data show that in late August and most of September, the total ozone values were above the 1992-2012 median. The most recent observations (mid October) are below the long term median.

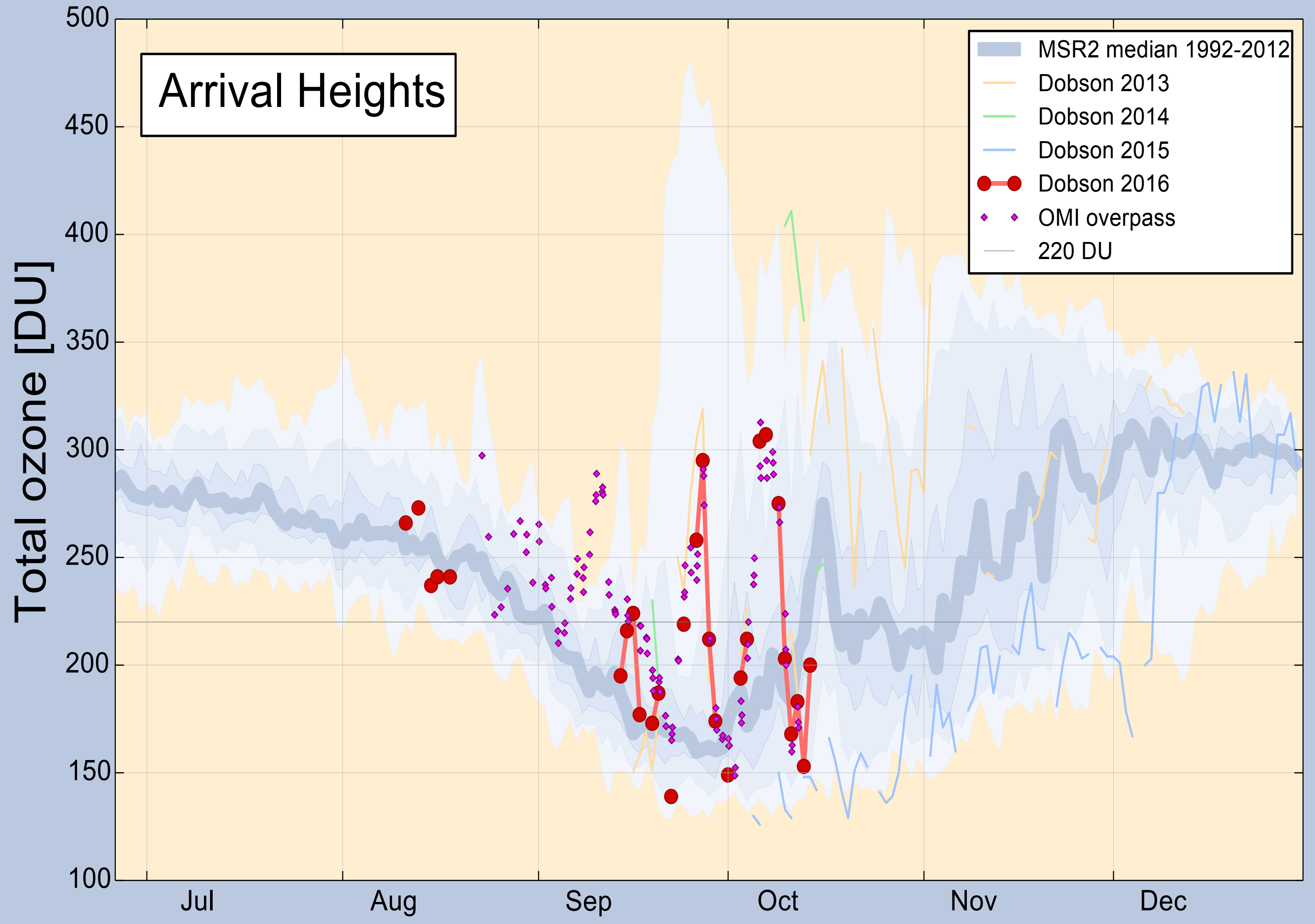


Figure 8. Time series of total ozone from the Arrival Heights Dobson spectrophotometer and satellite overpasses by OMI on board the AURA satellite. Dobson data have been provided by New Zealand's National Institute for Water and Air Research (NIWA). Satellite overpass data have been downloaded from the TEMIS web site. The plot is produced at WMO.

The Brewer instrument taking ozone measurements at Artigas.

The ozone station Artigas (62.1847°S and 58.9040°W) is located on King George Island, which is the largest of the South Shetland Islands, lying 120 kilometres off the coast of Antarctica. It is the northernmost ozone observatory in Antarctica. Total ozone is measured with a Brewer spectrophotometer. Ozone has been measured here since 1998. The measurements are carried out in collaboration between the *Instituto Antártico Uruguayo* and the *Servicio Meteorológico de la Fuerza Aérea Uruguaya.* Brewer data for 2016 will be shown as soon as they are reported. **Figure 9** shows Brewer data from 2014 together with OMI overpass data for 2016. In the figure one can see the large variations in total ozone as the polar vortex moves back and forth over the station.

The OMI overpass data show that total ozone was unusually high through most of July. Also in August, total ozone has been higher than the 1992-2012 median on most days. In September and early October, total ozone dropped to values around 150-180 DU on some days but values above 350 DU have also been observed.

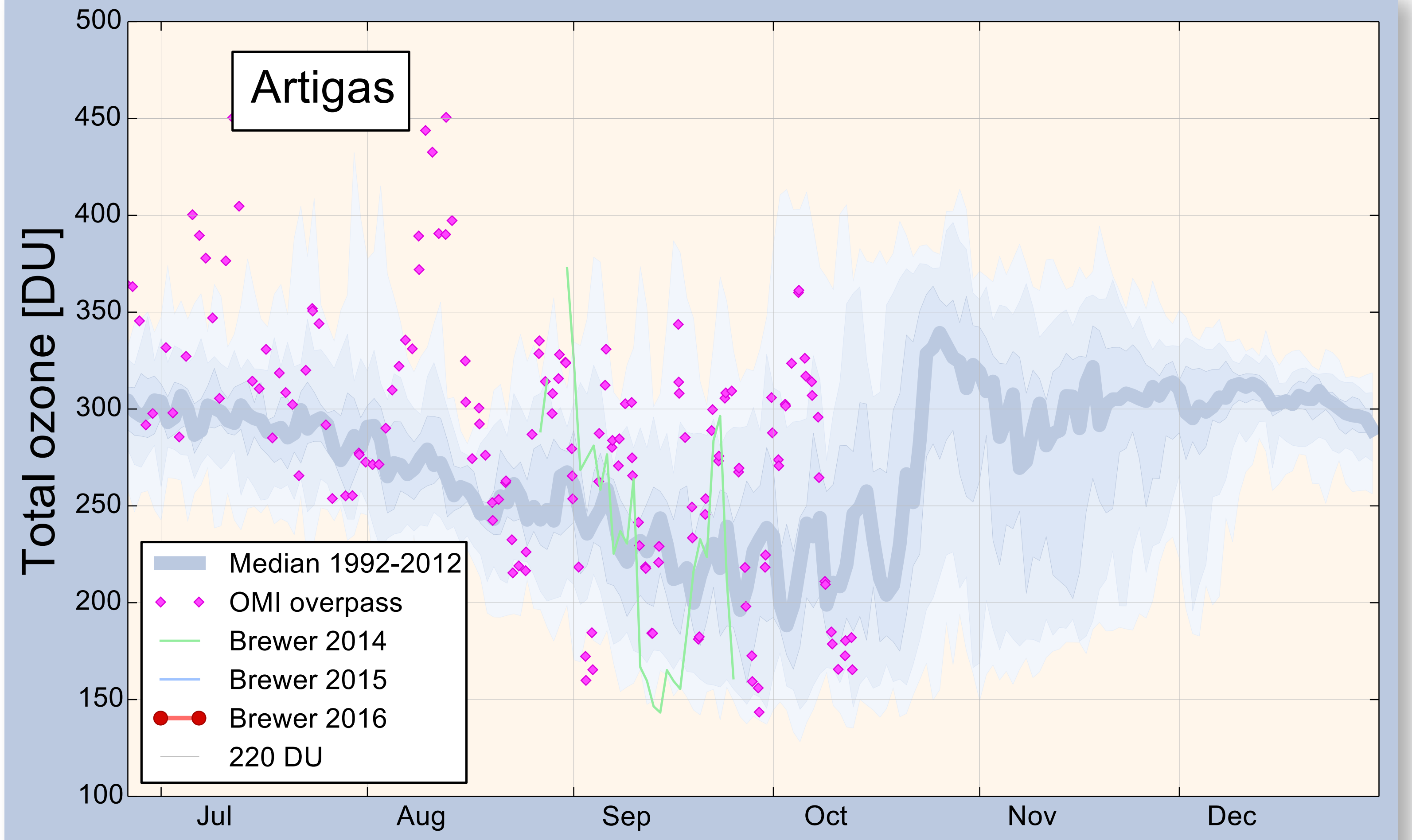
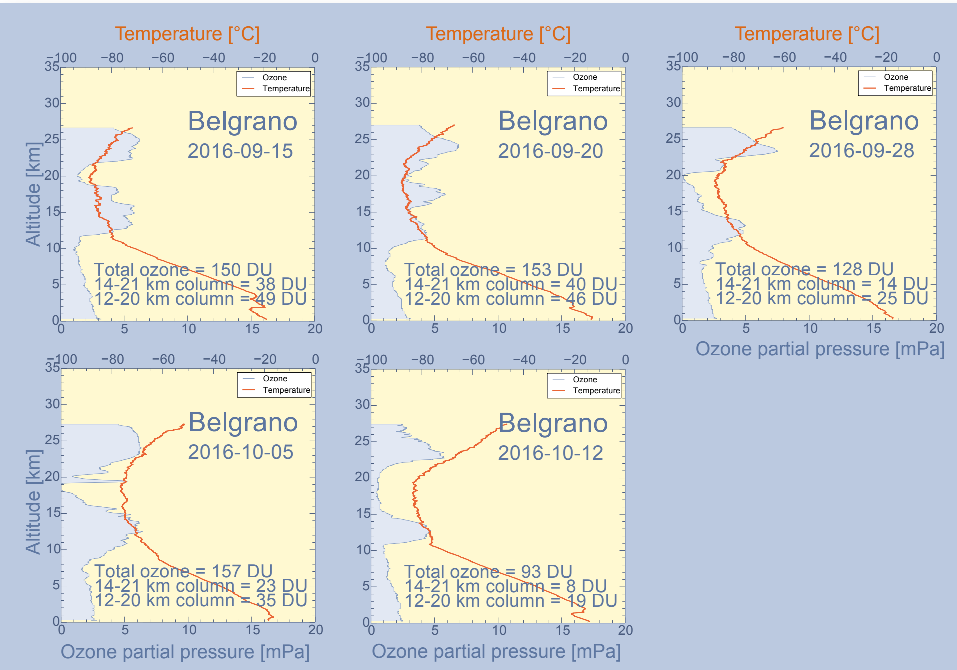


Figure 9. Brewer observations at the Uruguayan station Artigas, located on King George Island, just off the coast of the Antarctic Peninsula. The OMI data have been downloaded from the TEMIS site at KNMI.

Belgrano

Ozonesonde launch at Belgrano.

The vertical distribution of ozone is measured at the Argentine GAW station Belgrano (77.88°S, 34.63°W) with electrochemical ozonesondes. Four sondes were launched in August and four in September. One of the September sondes had suspiciously low ozone and is hence not shown here. Two sondes have been launched so far in October. The profiles are shown in **Figure 10**. No clear sign of ozone depletion can be seen in the first two profiles, but all the others show some degree of ozone loss. The most depleted profile is the one of 12 October with a 14-21 km partial column of 8 DU. Among all the profiles recorded in Antarctica this year, only the 5 October profile from the South Pole had less with 7 DU.



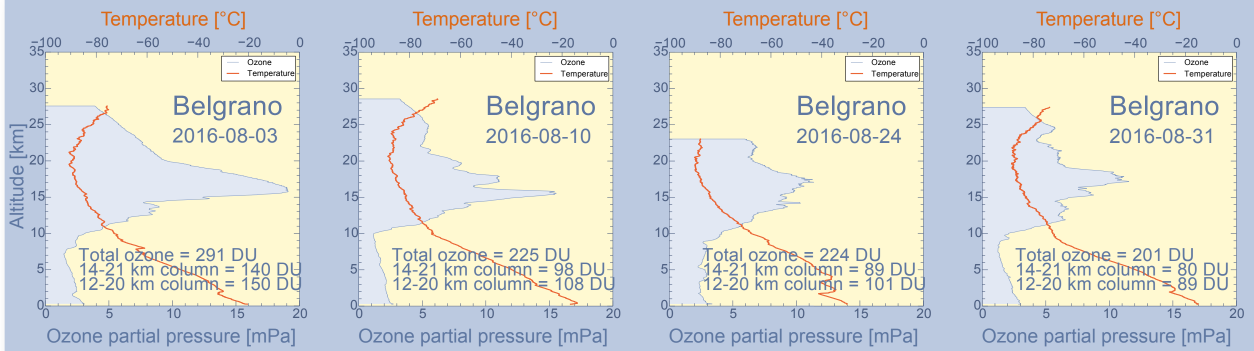


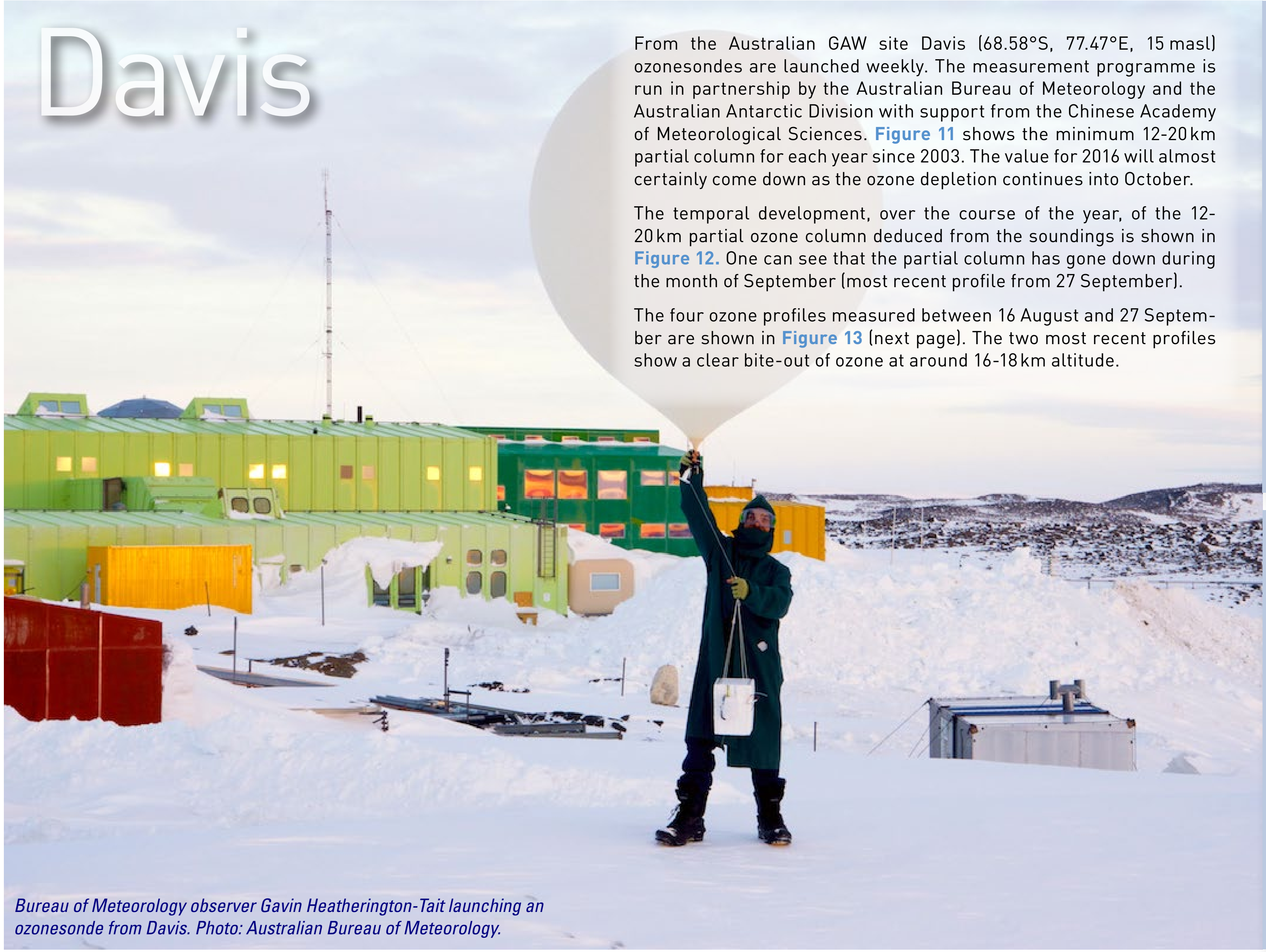
Figure 10. Ozonesonde profiles measured at Belgrano in August, September and October 2016.

Davis

From the Australian GAW site Davis (68.58°S, 77.47°E, 15 masl) ozonesondes are launched weekly. The measurement programme is run in partnership by the Australian Bureau of Meteorology and the Australian Antarctic Division with support from the Chinese Academy of Meteorological Sciences. **Figure 11** shows the minimum 12-20 km partial column for each year since 2003. The value for 2016 will almost certainly come down as the ozone depletion continues into October.

The temporal development, over the course of the year, of the 12-20 km partial ozone column deduced from the soundings is shown in **Figure 12.** One can see that the partial column has gone down during the month of September (most recent profile from 27 September).

The four ozone profiles measured between 16 August and 27 September are shown in **Figure 13** (next page). The two most recent profiles show a clear bite-out of ozone at around 16-18 km altitude.



Bureau of Meteorology observer Gavin Heatherington-Tait launching an ozonesonde from Davis. Photo: Australian Bureau of Meteorology.

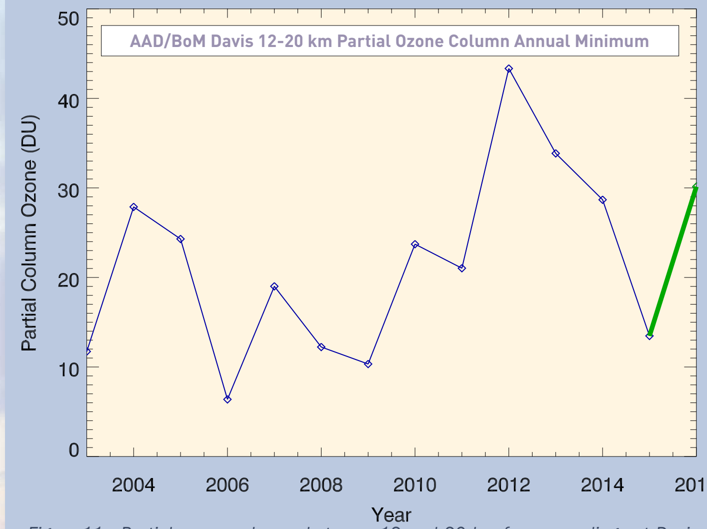


Figure 11. Partial ozone columns between 12 and 20 km from soundings at Davis. The blue curve shows the minimum values of this partial ozone column for each season from 2003 until 2015. The green curve shows the minimum so far in 2016 (X September). The plot has been provided by Matt Tully, Australian Bureau of Meteorology.

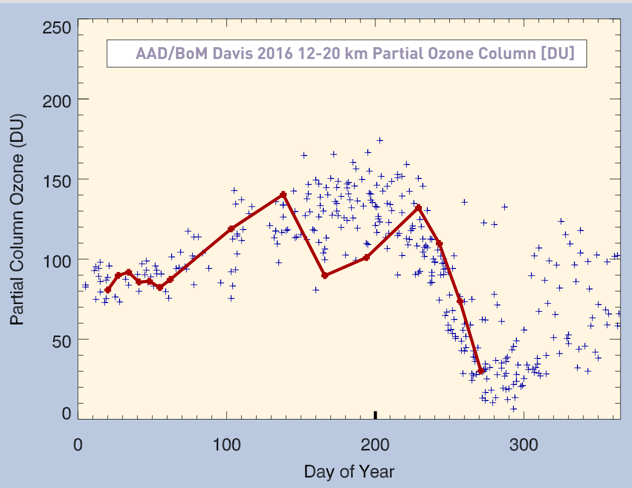


Figure 12. Partial ozone columns between 12 and 20 km from soundings at Davis. The thick red curve shows the data from 2016. The blue crosses show all data from 2003-2015. The plot has been provided by Matt Tully, Australian Bureau of Meteorology.

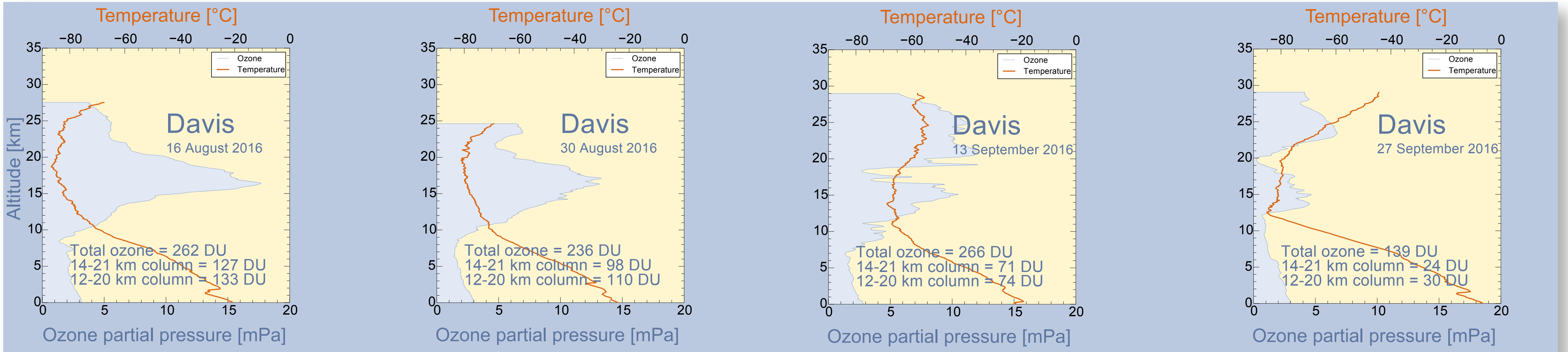


Figure 13. Ozonesonde profiles measured at Davis from 16 August to 27 September 2016.

The twin buildings at Dôme Concordia. Photo: Marco Maggiore.

Total ozone is measured with a SAOZ spectrometer at the French/Italian GAW/NDACC station at Dôme Concordia (75.0998870°S, 123.333487°E, 3250 masl) on the Antarctic ice cap. The measurements started up again on 18 August after the polar night. **Figure 14** shows the 2016 measurements in comparison with OMI overpass data and data from the two previous years. Long term (1992-2012) statistics is also shown. So far, total ozone has, on most days, been larger than the long term median, but the last few days have seen total ozone values below the long term median.

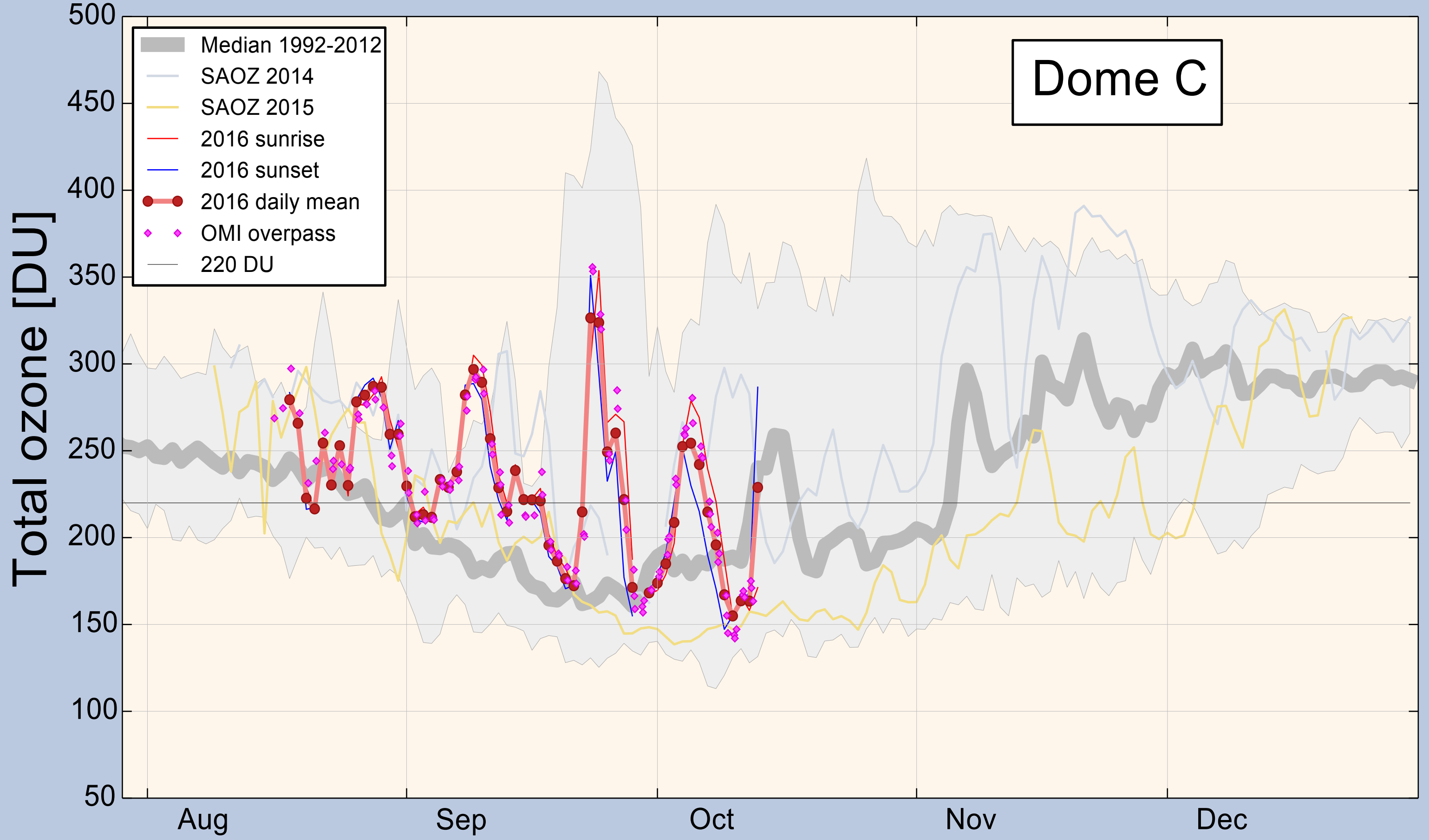


Figure 14. Time series of daily mean total ozone in 2016, together with sunrise and sunset values, in comparison to earlier years, as measured by a SAOZ spectrometer at Dôme Concordia. The grey shaded area shows the range of values and the thick grey line shows the median from the MSR2 data from KNMI during the 1992-2012 time period.

Aerial view of the Dumont d'Urville station.

The French GAW/NDACC station Dumont d'Urville (66.662929°S, 140.002546°E) is located at the polar circle, which allows for SAOZ measurements around the year. **Figure 15** shows the progression of daily averaged total ozone together with sunrise and sunset values. The daily average value is calculated as the mean of the total ozone values at sunrise and sunset. On some days, when the vortex edge is over the station, the difference between the sunrise and sunset values can reach several tens of DU. Total ozone has come down more or less gradually over the course of July and the first days of August. At the end of August there was a sudden increase where total ozone went above 400 DU before returning to around 220 DU and then increasing to above 400 DU again. Then in dropped well below 300 DU before rising to above 400 DU once again. In early October total ozone dropped rapidly to around 200 DU before increasing again. Such sudden excursions in total ozone is typical for a station located close to the edge of the polar vortex, sometimes observing vortex air and sometimes observing mid-latitude air.

Ozone soundings carried out since early July are shown in **Figure 16**. Most of these profiles are quite representative of middle latitude air masses. However, the 19 August profile show a little ozone bite-out just above 20 km and the 13 September profile shows clear signs of ozone depletion between 15 and 20 km. On 22 September one can also see a bite-out of ozone, but the affected layer is quite shallow. On 5 October, the ozone profile is characteristic of middle latitude air masses.

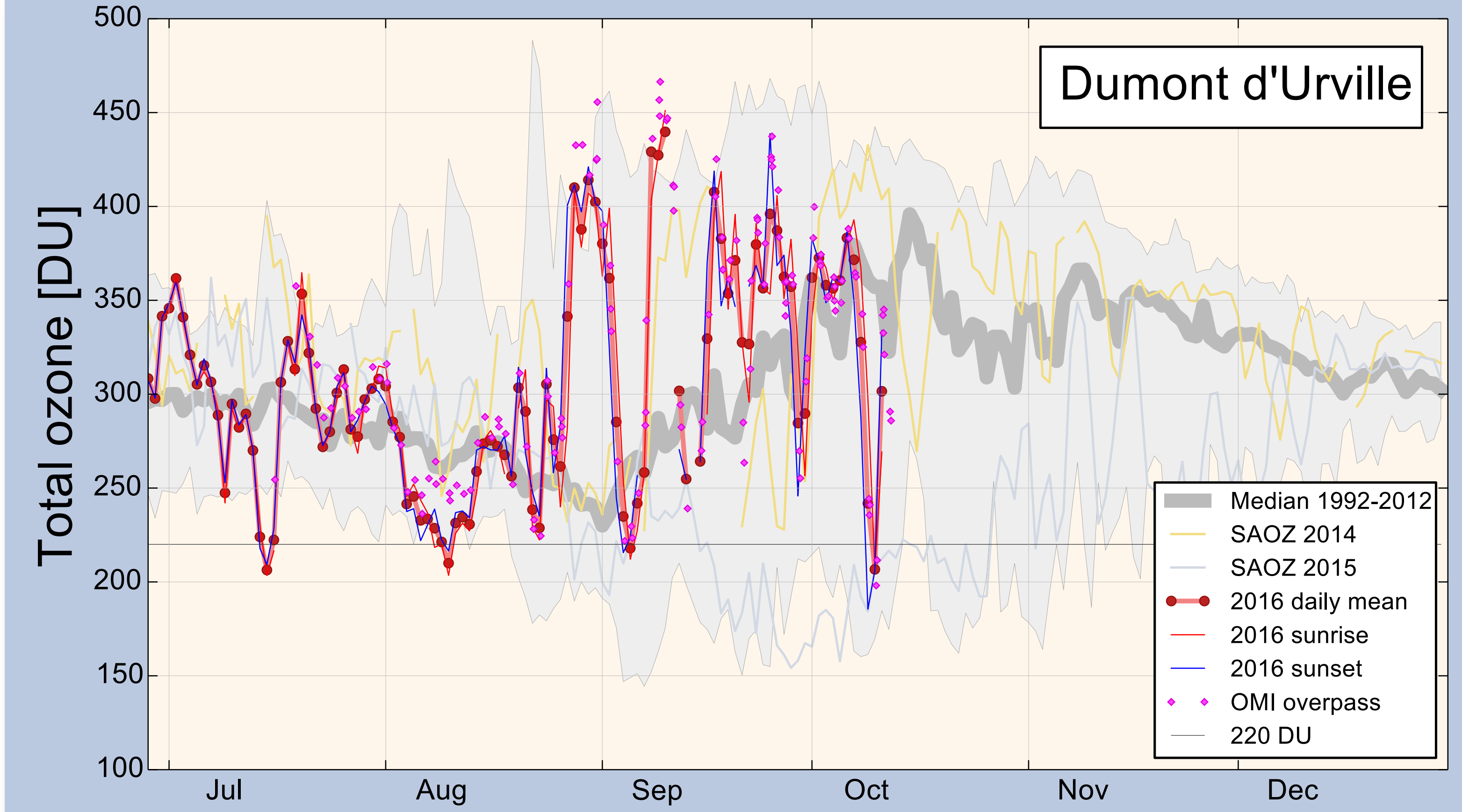


Figure 15. Time series of daily mean total ozone in 2016, in comparison to earlier years, as measured by a SAOZ spectrometer at Dumont d'Urville. Sunrise and sunset values for 2016 are also shown. The long term statistics (1992-2012) is based on the MSR2 data from KNMI.

The total ozone and PV maps in **Figure 17** show the location of Dumont d'Urville with respect to the ozone hole. One can see that on 1 September the station is just outside of the ozone hole and influenced my mid-latitude air masses. On 13 September, on the other hand, the station is just inside the ozone hole and this explains the relatively low 14-21 km partial ozone column of 69 DU, which is characteristic of an ozone hole situation. On 5 October, the station is well outside the vortex, explaining the typical mid latitude ozone profile measured on that day. The SAOZ data show a rapid plunge in ozone around 9 October and in **Figure 17** (rightmost panel) one can see that the station is well inside the vortex on that day.

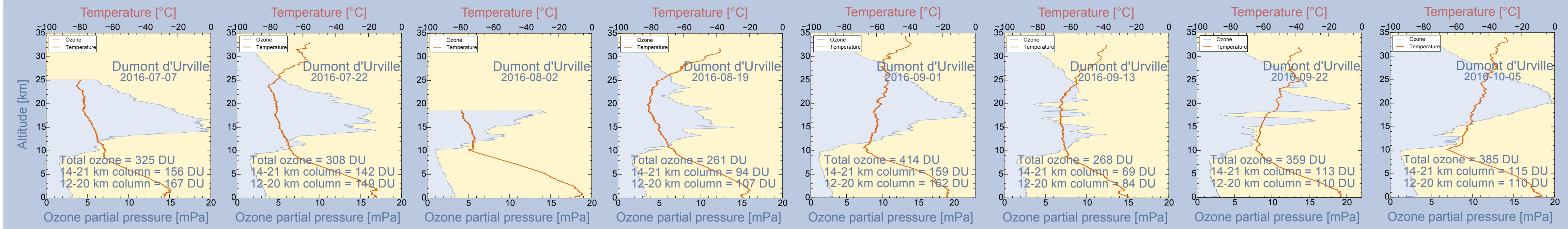


Figure 16. Ozone soundings performed at Dumont d'Urville since July 2016.

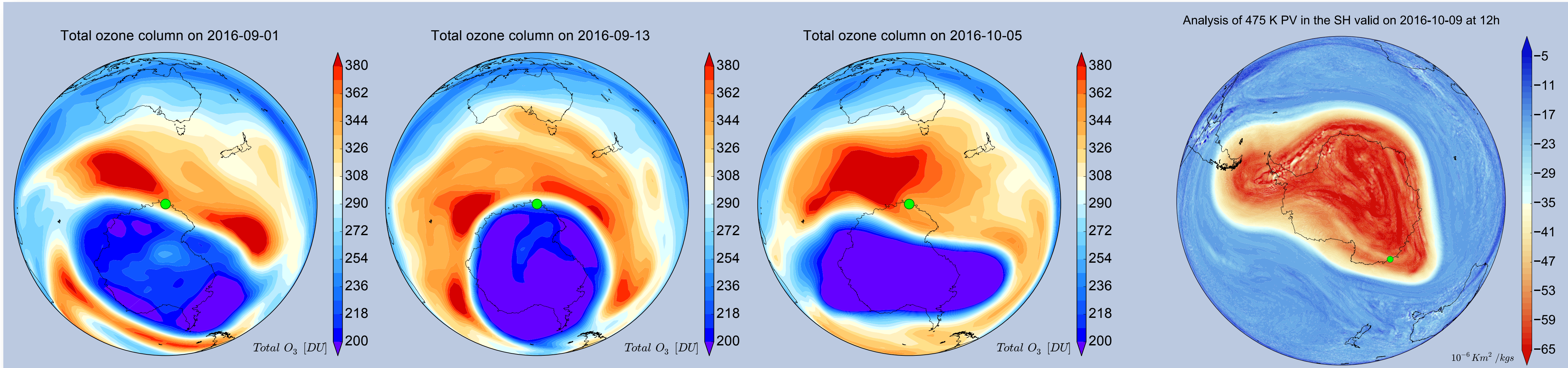


Figure 17. Three leftmost maps: Total ozone from the BASCOE data assimilation model for 1 and 13 September and 5 October. The BASCOE model assimilates data from the MLS instrument on board the AURA satellite. Rightmost map: Potential vorticity at the 475 K isentropic level on 9 October, showing Dumont d'Urville well inside the vortex. This is in agreement with the low total ozone column measured by the SAOZ instrument on that day.

Halley

Total ozone has been measured with a Dobson spectrophotometer at the UK GAW station Halley (75.6052°S, 26.2100°W, 33 masl) since 1957. Due to its high latitude, the measurement season starts in late August, and the first measurement after the polar winter was carried out on 22 August. The Dobson observations are shown on the next page in **Figure 18**. Since the measurements started up again in late August, total ozone has been below the 220 DU threshold on almost every day, and in late September and early October total ozone dropped to 124 DU.

In early 2013 a SAOZ spectrometer was put into service at Halley. The SAOZ instrument measures the scattered light from zenith around sunrise and sunset. This allows for measurements at higher solar zenith angles, which leads to a longer measurement season. In 2016 the SAOZ measurements started up again on 3 August after the polar winter with a total ozone value of 292 DU. In September and so far in October, total ozone has been lower than the long term (1992-2012) median and values down to 106 DU have been observed.

The SAOZ data are somewhat lower than the Dobson and OMI data, and since the data are preliminary they should be used with caution. **Figure 19** shows the SAOZ total ozone time series at Halley for 2016 together with long term statistics (1992-2012) and OMI overpass data.

The new Halley Research station (Halley VI). Photo: Jonathan Shanklin, British Antarctic Survey. More information about the new Halley Station can be found at: http://en.wikipedia.org/wiki/Halley_Research_Station

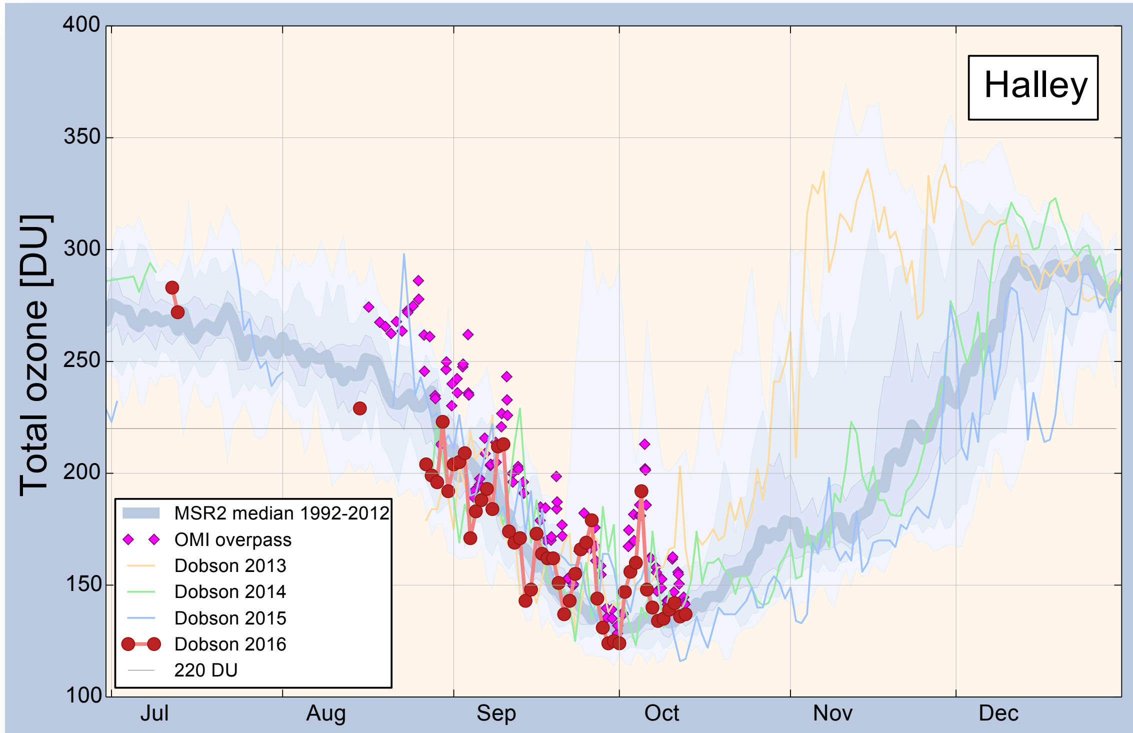


Figure 18. Time series of daily mean total ozone in 2016, as measured by a Dobson spectrophotometer at Halley. Data from the three previous years are also shown. The thick grey line shows the median ozone column for the 1992-2012 time period based on MSR2 data from KNMI. The light grey shaded area shows historical maxima and minima calculated for the 1992-2012 time period. The somewhat darker shaded regions show the 10-90th percentile and the 30-70th percentile. The plot is produced at WMO based on data downloaded from WOUDC, from Jonathan Shanklin's Antarctic web site at British Antarctic Survey and from the TEMIS web site at KNMI.

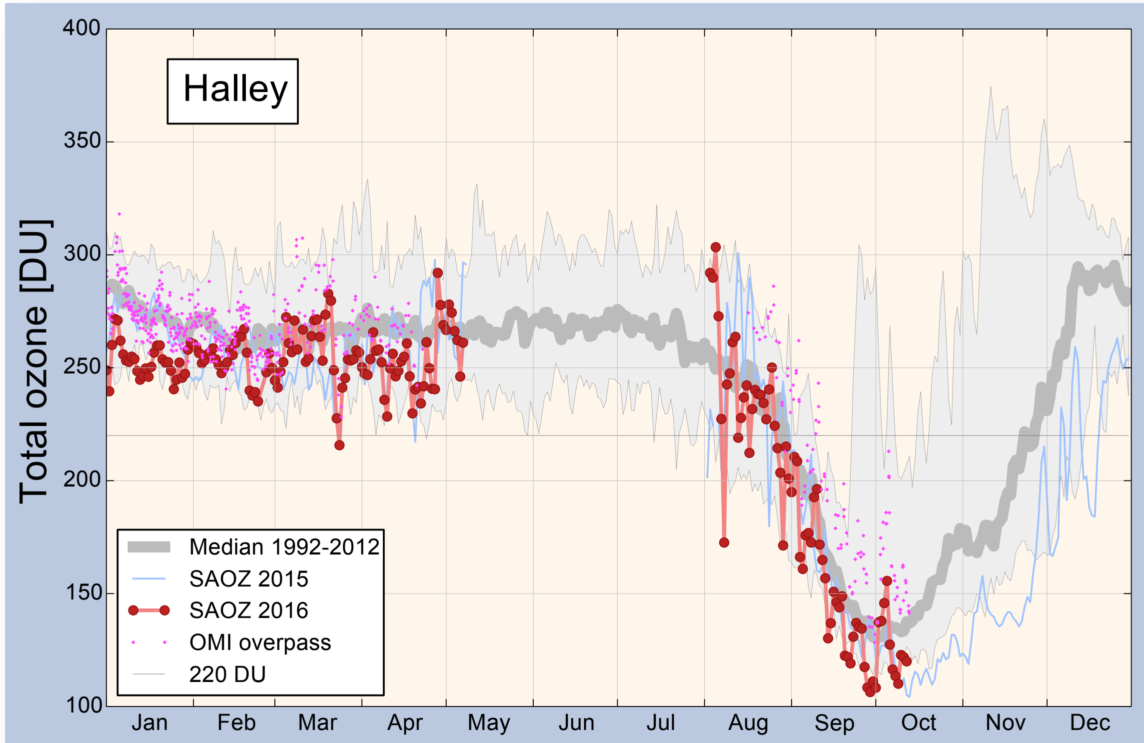


Figure 19. Time series of total ozone in 2015 and 2016, as measured by a SAOZ spectrometer at Halley. The pink line with dark red circles shows the daily average ozone column for 2016. The thin, light blue line shows SAOZ measurements from 2015. The magenta diamonds show the OMI overpass data. The plot is produced at WMO based on data downloaded from Jonathan Shanklin's Antarctic web site at the British Antarctic Survey.

Kerguelen

Aerial view of the French research station at the Kerguelen Islands

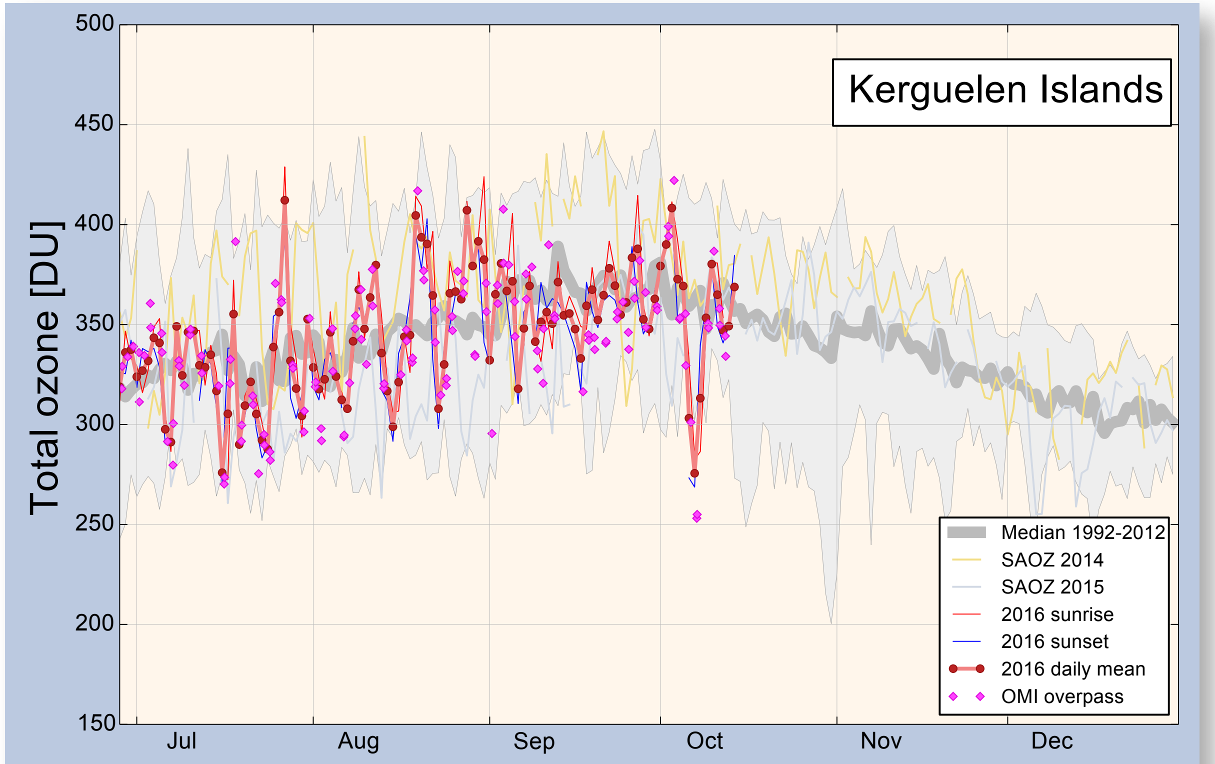


Figure 20. Total ozone above Kerguelen Islands starting July 2016. The red and blue lines show SAOZ morning and evening total ozone values, respectively, and the pink line with dark red circles shows the daily mean values. Daily mean observations from 2014 and 2015 are also shown together with OMI overpass data.

The Kerguelen Islands, also known as the Desolation Islands, are a group of islands in the southern Indian Ocean constituting one of the two emerged parts of the mostly submerged Kerguelen Plateau. Among the most isolated places on Earth, they are more than 3,300 km away from the nearest populated location. The islands, along with Adélie Land, the Crozet Islands and the Amsterdam and Saint Paul Islands are part of the French Southern and Antarctic Lands and are administered as a separate district. There are no indigenous inhabitants, but France maintains a permanent presence of 50 to 100 engineers and researchers.

At Kerguelen Islands there is a GAW/NDACC station (49.35°S, 70.28°E, 29 masl) equipped with a SAOZ spectrometer. Usually, Kerguelen is well outside the polar vortex, but on rare occasions the vortex might pass over the islands. The SAOZ ozone observations for 2016 are shown in **Figure 20** together with data from 2014 and 2015. Until the end of September, total ozone oscillated around the long term (1992-2012) median. In early October, total ozone made a dip down to around 270 DU. The potential vorticity maps in **Figure 21** (next page) show that the edge of the polar vortex was very close to the station on 7 October.

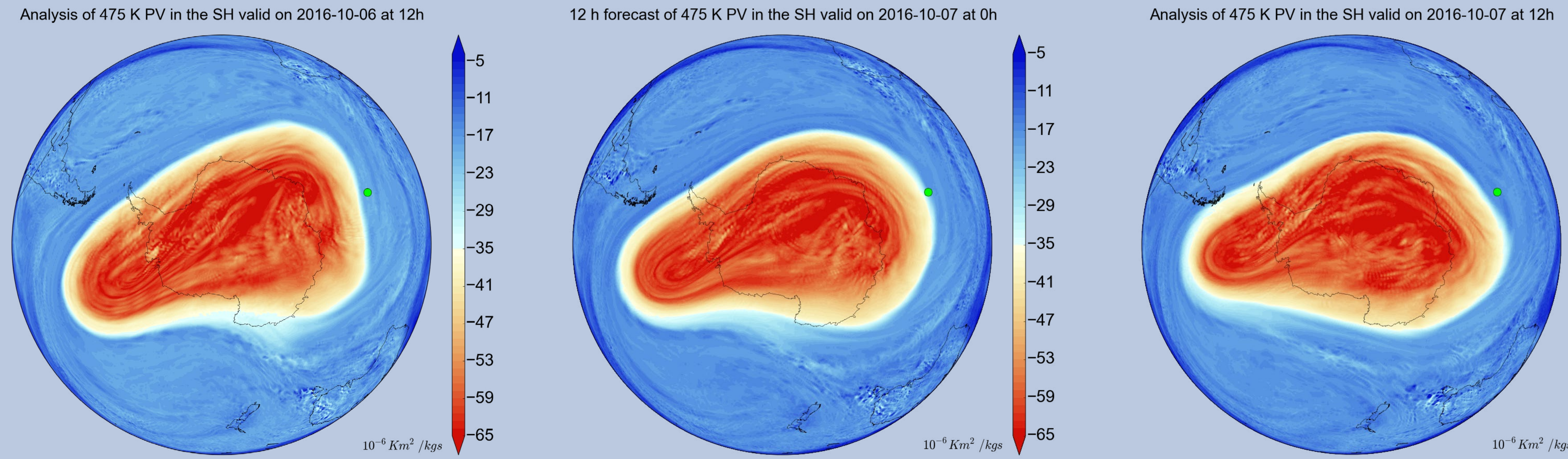


Figure 21.Maps of potential vorticity (PV) showing the position of the Kerguelen Islands (green circle). One can see that at 0 h on 7 October, the station was on the edge of the polar vortex. The PV data originate from ECMWF and are made available by the Norwegian Institute for Air Research (NILU). The plots are produced at WMO.

Macquarie Island

Ozonesonde launch at Macquarie Island. Photo: BoM.

Macquarie Island or "Macca" as it is often called is a Nature Reserve managed by the Tasmanian Parks and Wildlife Service. The island and surrounding waters out to 12 nautical miles were inscribed on the World Heritage List in 1997 as a site of major geoconservation significance, as an island of unique natural diversity and one of the truly remarkable places on earth. The land under the sea, all flora and fauna including fish and marine plants are completely protected. The GAW/NDACC station on Macquarie Island is located at 54.499531°S and 158.937170°E. Dobson observations of total ozone have been made there since 1957 by the Australian Bureau of Meteorology.

The plot (**Figure 22**) shows daily total ozone values in July and August,

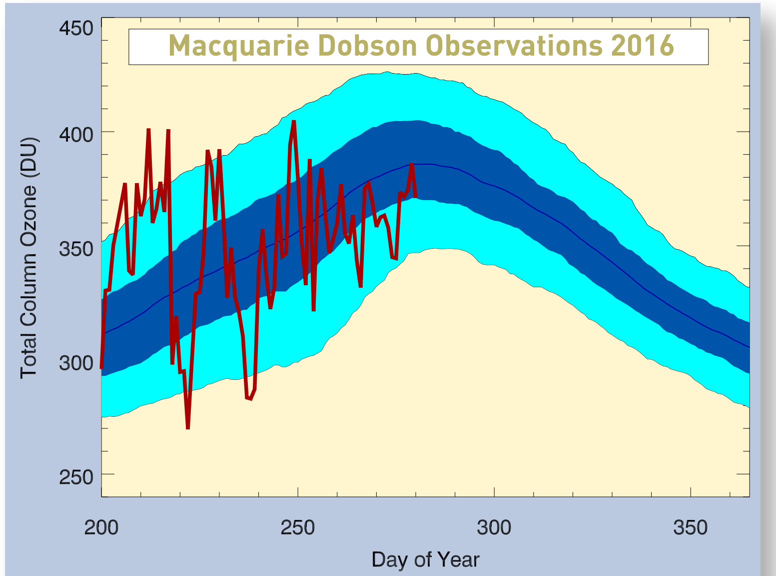


Figure 22. Dobson observations carried out at Macquarie Island in 2016 in comparison with long term (1987-2015) statistics.

2016 (dark red line) compared to the 1987-2015 climatology. The light blue area represents the 10th-90th percentile range, the medium blue the 30th-70th percentile range and the blue line the daily mean.

Ozonesondes are launched at Macquarie approximately once per week. **Figure 23** shows profiles from flights launched in late August and in September. On 6 September one can see some small bite-outs at the altitudes where one expects ozone depletion. **Figure 24** shows a map of potential vorticity on 6 September. The location of Macquarie Island is given with a green circle. One can see that the stations was close to the vortex edge on this date.

Recently, it was decided to close down the around-the-year activities at Macquarie Island. Pressure from the scientific community helped to reverse the decision and the activities will continue as before. More about this can be found here: http://www.abc.net.au/news/2016-09-20/federal-minister-shifts-blame-on-macquarie-island-shutdown/7861416

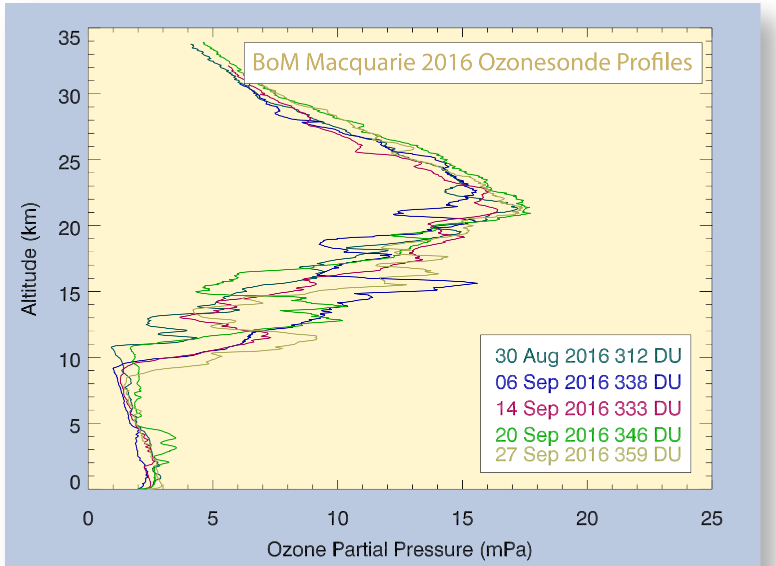


Figure 23. Ozone profiles over Macquarie Island measured with electrochemical ozonesondes.

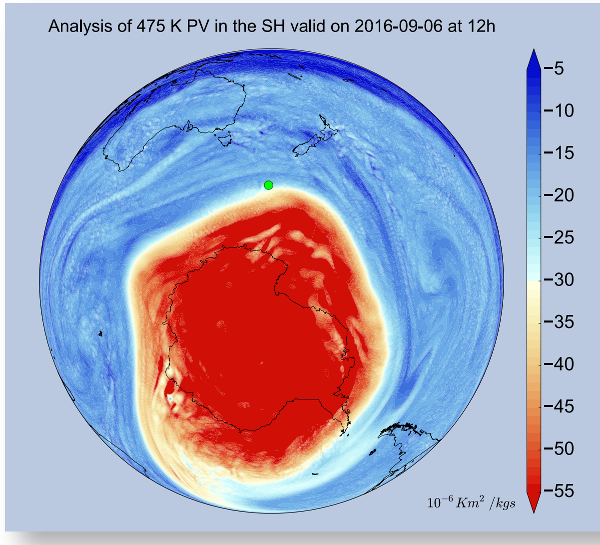


Figure 24. Map of potential vorticity on 6 September showing that Macquarie Island was near the vortex edge on this date.

Marambio

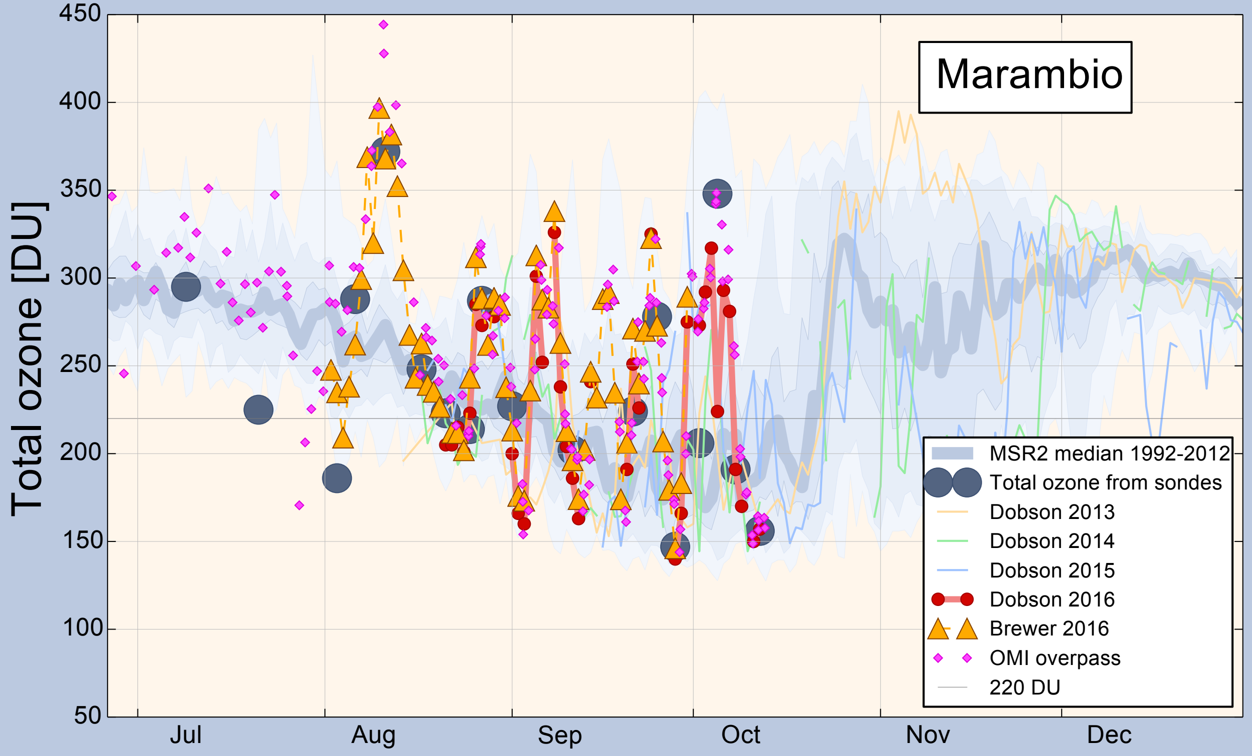


Figure 25. Total ozone over Marambio as measured by Dobson and Brewer spectrophotometers (Dobson: orange line with red dots; Brewer: cyan dashed line with cyan triangles) and by ozonesondes (large dark blue dots). For comparison satellite over pass data from OMI are also shown (small magenta diamonds). The median and maximum and minimum values from satellite measurements for the 1992-2012 period are shown to put current data into context.

Total ozone is measured at the Argentine GAW station Marambio (64.2°S, 56.6°W) both with a Brewer MkIII instrument and with a Dobson instrument. The data for 2016 are shown in **Figure 25** together with satellite overpass data and Dobson data from 2013 to 2015. Total ozone derived from ozonesondes is also shown. Long term statistics based on the MSR2 data set is shown for comparison.

Ozone profiles are observed with ozonesondes at Marambio. Soundings are carried out approximately twice per week during the ozone depletion period. Two sondes were launched in July, seven in August, six in September and four so far in October. Soundings from 9 July 2016 onwards are shown in **Figure 26** (next page). The soundings launched on 21 and 25 August show some first signs of ozone depletion, and the soundings on 1 and 11 September show clear signs of ozone depletion with large bite-outs in the 19-23 km altitude region. On 2 and 5 October, the ozone profiles are typical of mid latitude air masses. On 8 October, the vortex is back over Marambio and the profile measured on that day is characteristic of ozone depletion around 20 km. The profile observed on 12 October shows the most depleted profile so far this year with a 14-21 km column of 16 DU. On this day, Marambio is deep inside the polar vortex.

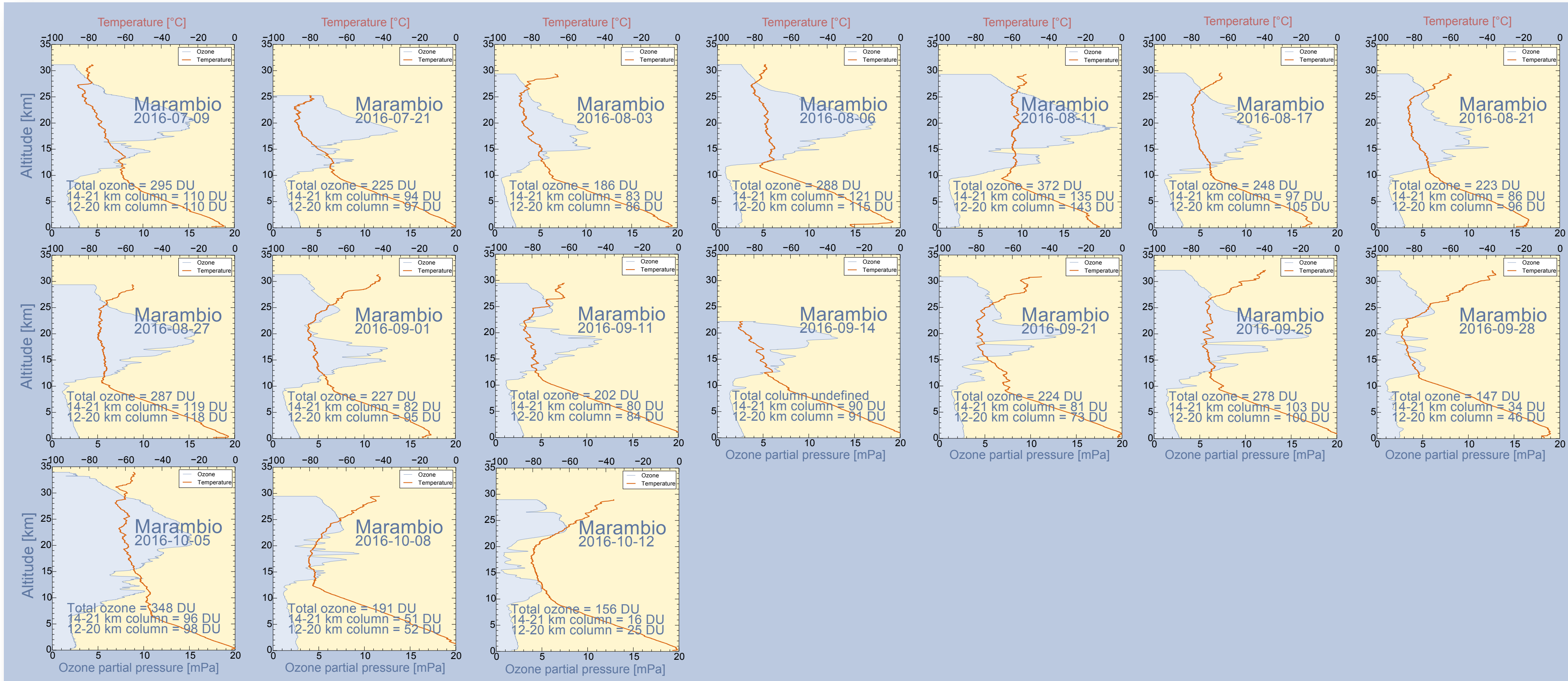


Figure 26. Ozone profiles measured with electrochemical ozonesondes launched from the Argentinian GAW station Marambio from 9 July to 12 October 2016.

At the Russian GAW station Mirny (66.558270°S, 93.001017°E) total ozone is measured with a filter instrument (M-124). The observations for 2016 started on 2 August and these data are shown together with data for the previous three years in **Figure 27**. On several days total ozone has been below the 220 DU threshold, as shown by the M-124 data and also by the satellite data from OMI. The large variations in total ozone are typical of a station located near the vortex edge. The station alternates between being inside and outside of the polar vortex.

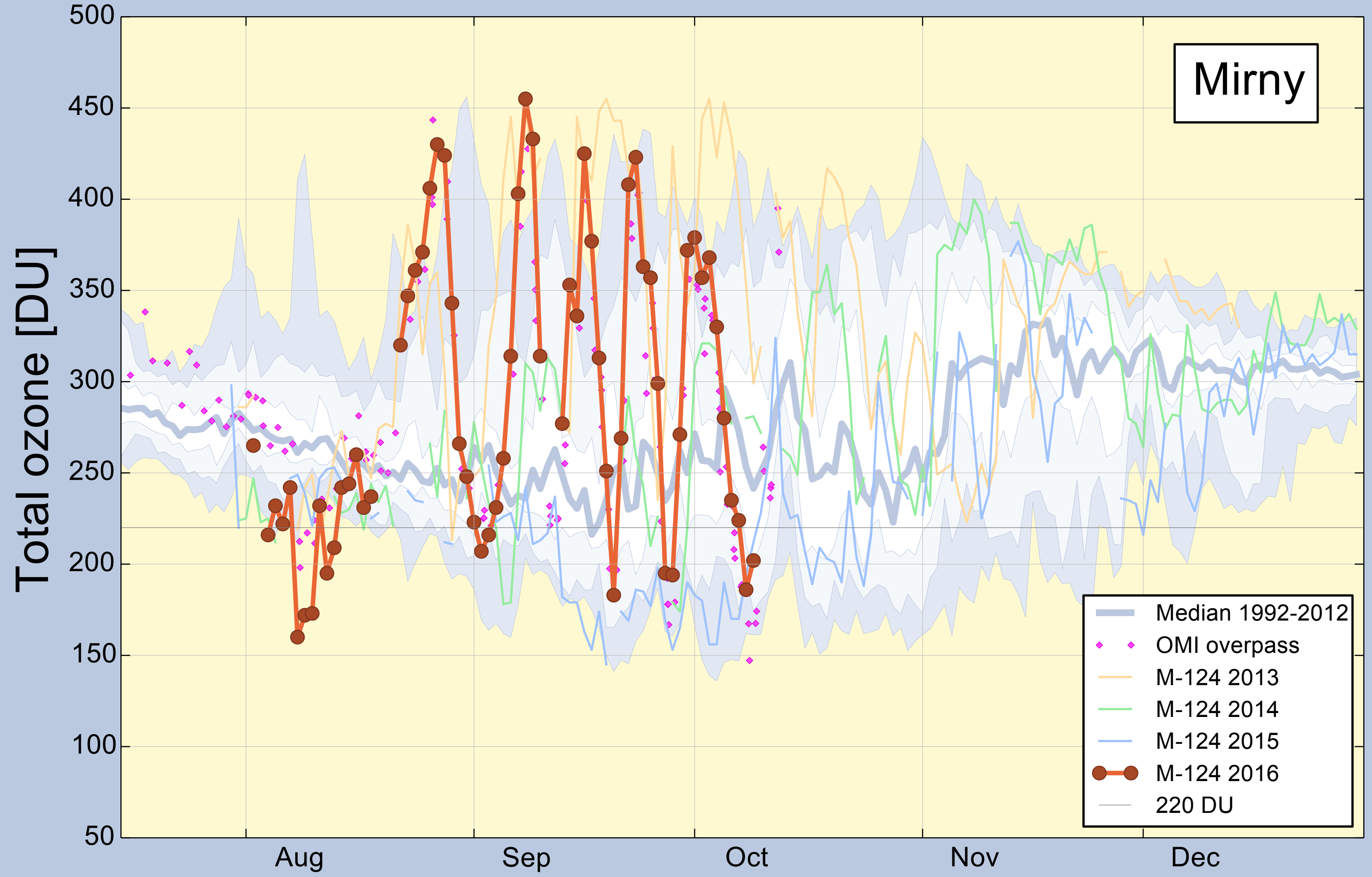


Figure 27. Total ozone above Mirny as measured by a M-124 filter instrument and by the OMI instrument on board the AURA satellite.

Neumayer

The vertical distribution of ozone is measured with ozonesondes from the German GAW/NDACC station at Neumayer (70.666°S, 8.266°W). Fifteen sondes have been launched since 7 July, as shown on the next page in **Figure 28**. Total ozone dipped below 220 DU on 4 September and the soundings after that, with the exception of 7 September, all show total ozone well below 220 DU. All the September and October soundings show ozone bite-outs at various altitudes, both above and below 20 km. The most depleted profile observed so far this year is the one of 9 October with a 14-21 km partial column of 14 DU.

The Neumayer III station. Photo: AWI

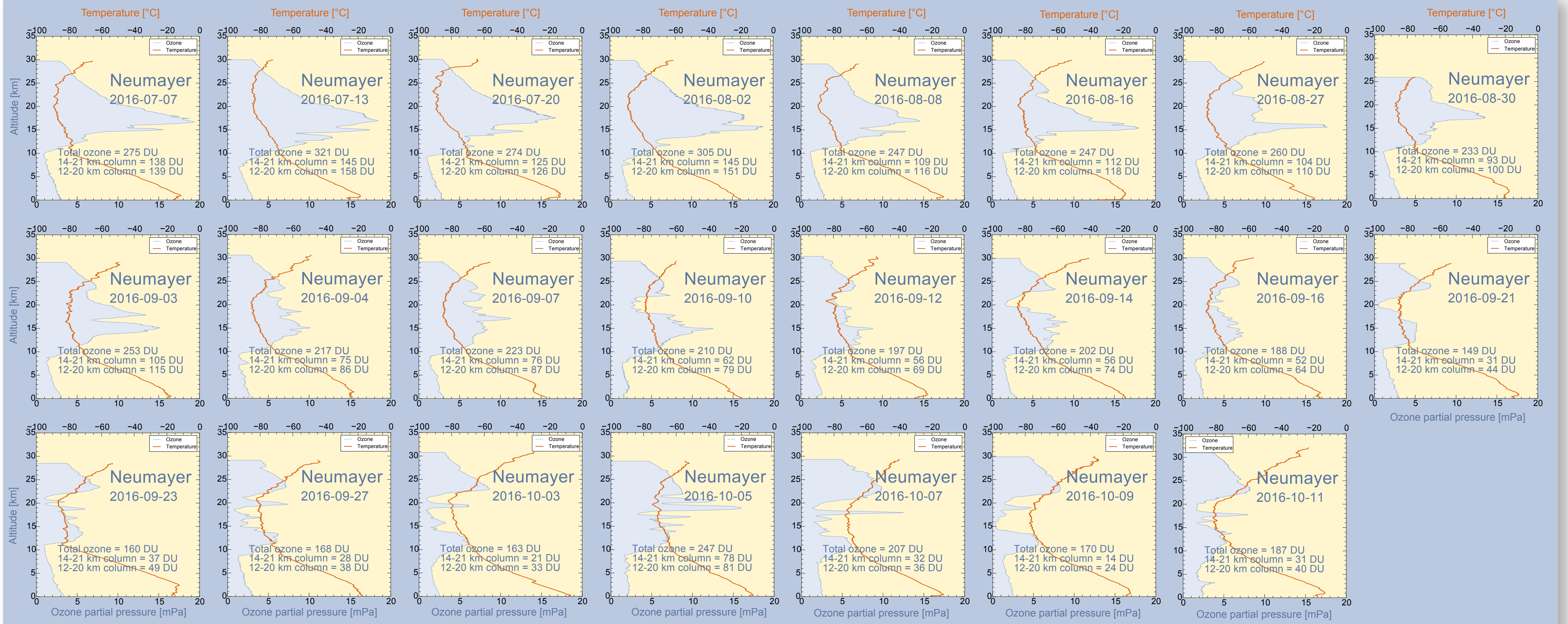


Figure 28. Ozone profile measured with electrochemical ozonesondes launched from the German GAW station Neumayer between 7 July and 11 October 2016.

Novolazarevskaya

At the Russian GAW station Novolazarevskaya (70.776739°S, 11.822138°E) total ozone is measured with an M-124 filter instrument. The data are submitted by Elena Sibir and Vladimir Radionov of the Arctic and Antarctic Research Institute, St. Petersburg. The data for 2016, together data from satellite overpasses are shown in **Figure 29.** Total ozone has been close to the long term median so far this season.

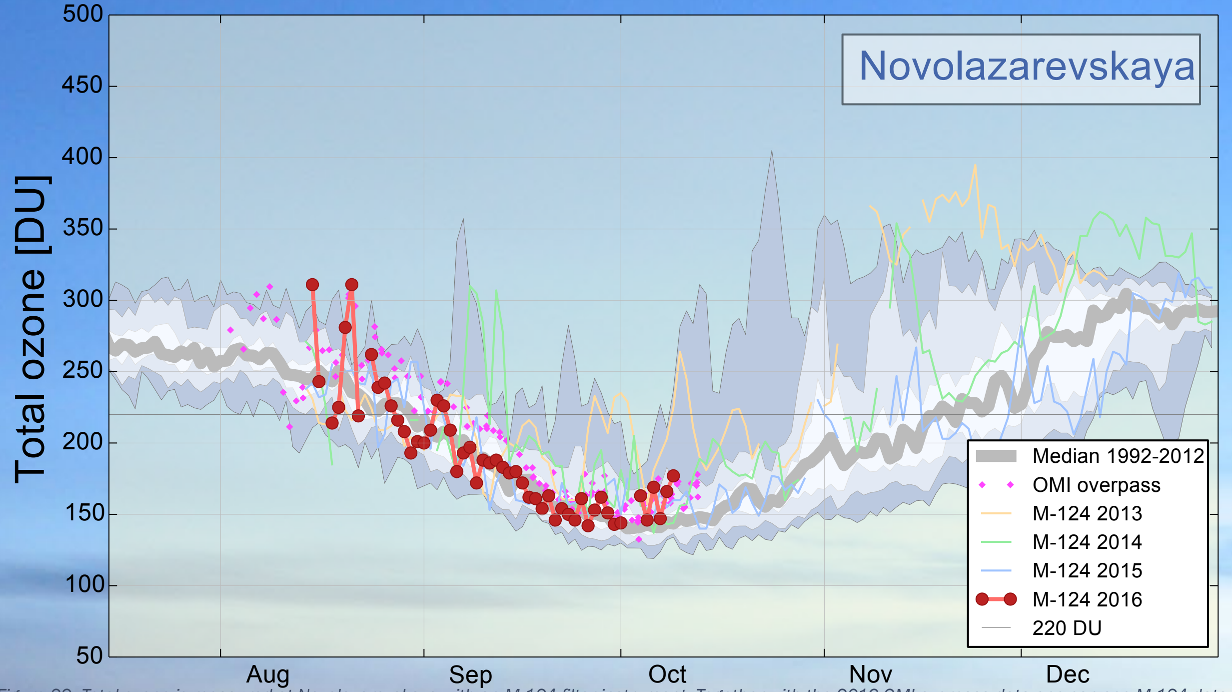
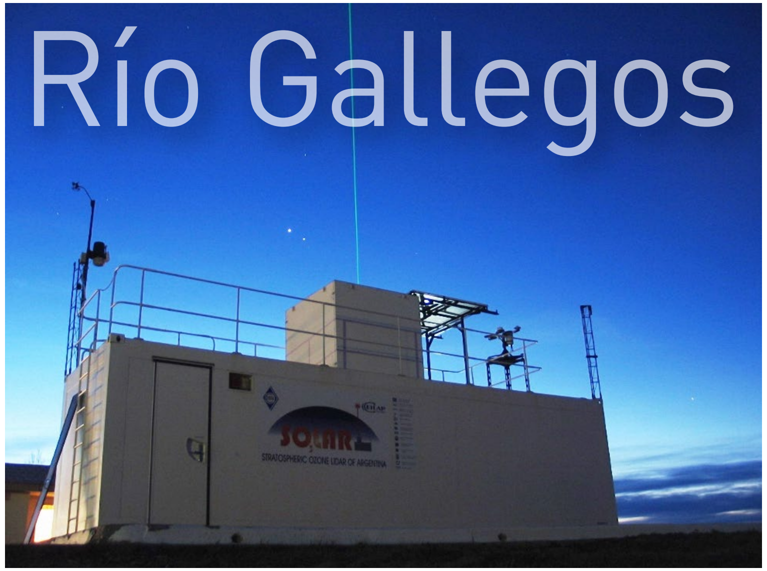


Figure 29. Total ozone is measured at Novolazarevskaya with an M-124 filter instrument. Together with the 2016 OMI overpass data one can see M-124 data from 2016, 2015, 2014 and 2013. Long term statistics is shown for comparison. The light grey-blue shaded region shows the maximum and minimum values between 1992 and 2012 together with 30-70th and 10-90th percentiles based on the MSR2 data set from KNMI.



The differential absorption lidar (DIAL) to measure ozone profiles.

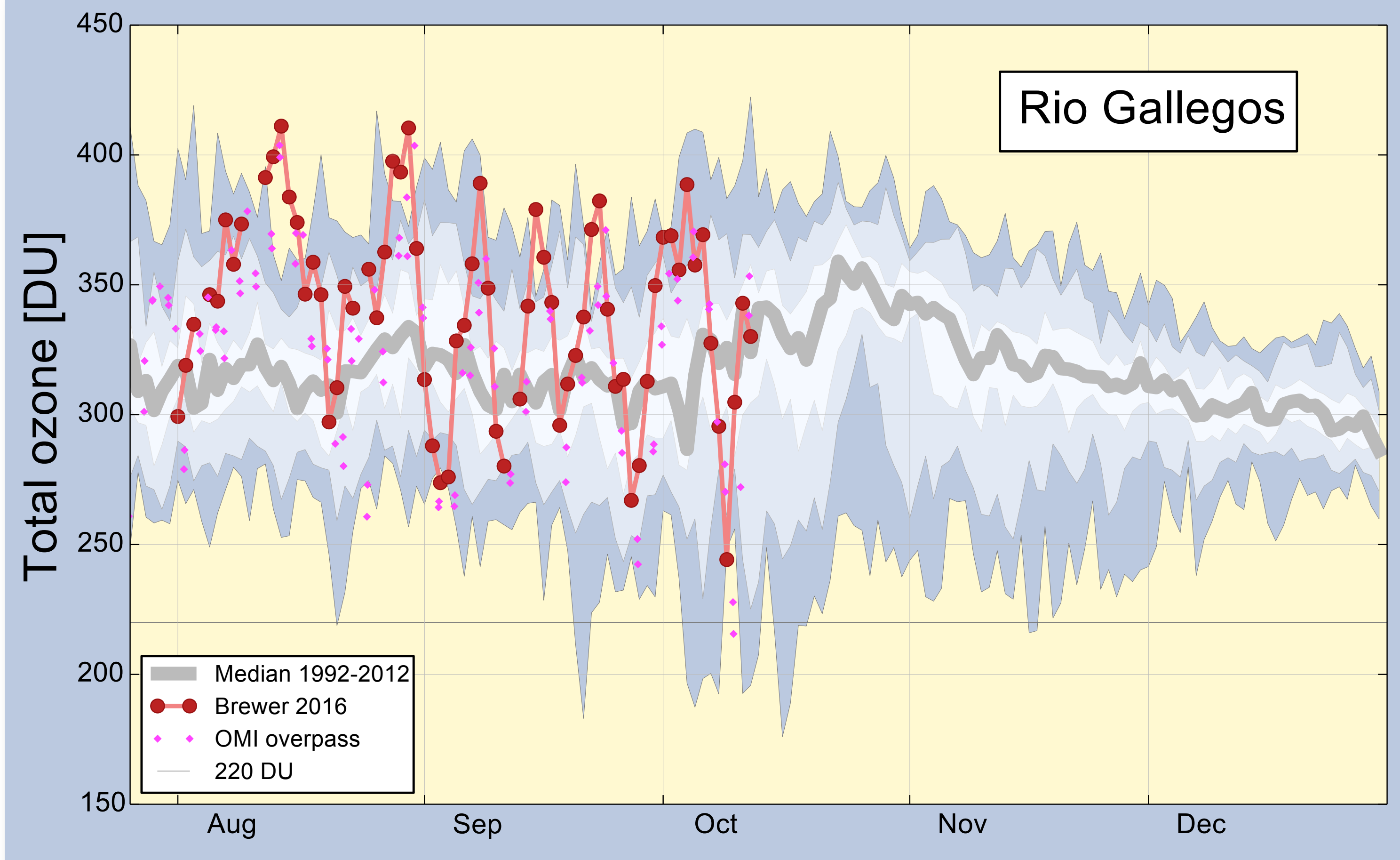


Figure 30.Total ozone over Río Gallegos as measured with a Brewer spectrophotometer.

The GAW and NDACC station "Observatorio Atmosférico de la Patagonia Austral (UNIDEF-OAPA)" located in Río Gallegos (51.600496°S, 69.31946°W) is equipped with a differential absorption lidar (DIAL) to measure ozone profiles and with a SAOZ spectrometer to record total columns of ozone and NO_2. Moreover, a GUV-541 filter radiometer is installed to take measurements of solar UV radiation. The station is operated by the Lidar Division of CEILAP (Laser and Applications Research Center), which belongs to UNIDEF (MINDEF, (Ministerio de Defensa) and CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina). It is also supported by JICA. CEILAP is associated with LATMOS, France through a collaboration agreement (UMI - CNRS 3351). The Nagoya University operates a millimeter-wave radiometer for mesospheric ozone profile measurements, which is operated by the Lidar División of OAPA.

A Brewer spectrophotometer was installed in Río Gallegos in February 2016 and data from this instrument is shown in **Figure 30**. One can see an episode in early October when total ozone dipped below 250 DU, which is much lower than the long term (1992-2012) median.

A SAOZ spectrometer has been in operation in Río Gallegos since 2008. This instrument measures when the sun is near the horizon, i.e. around sunrise and sunset. Data from 2016 together with data from the last two years are shown in **Figure 31** (next page). Also here the low-ozone episode on 9-10 October can be seen, and, since both morning and evening values are plotted, one can see that the morning value on 10 October is much lower than the evening value on that day (222 DU vs 308 DU). This is characteristic for a situation where the station is

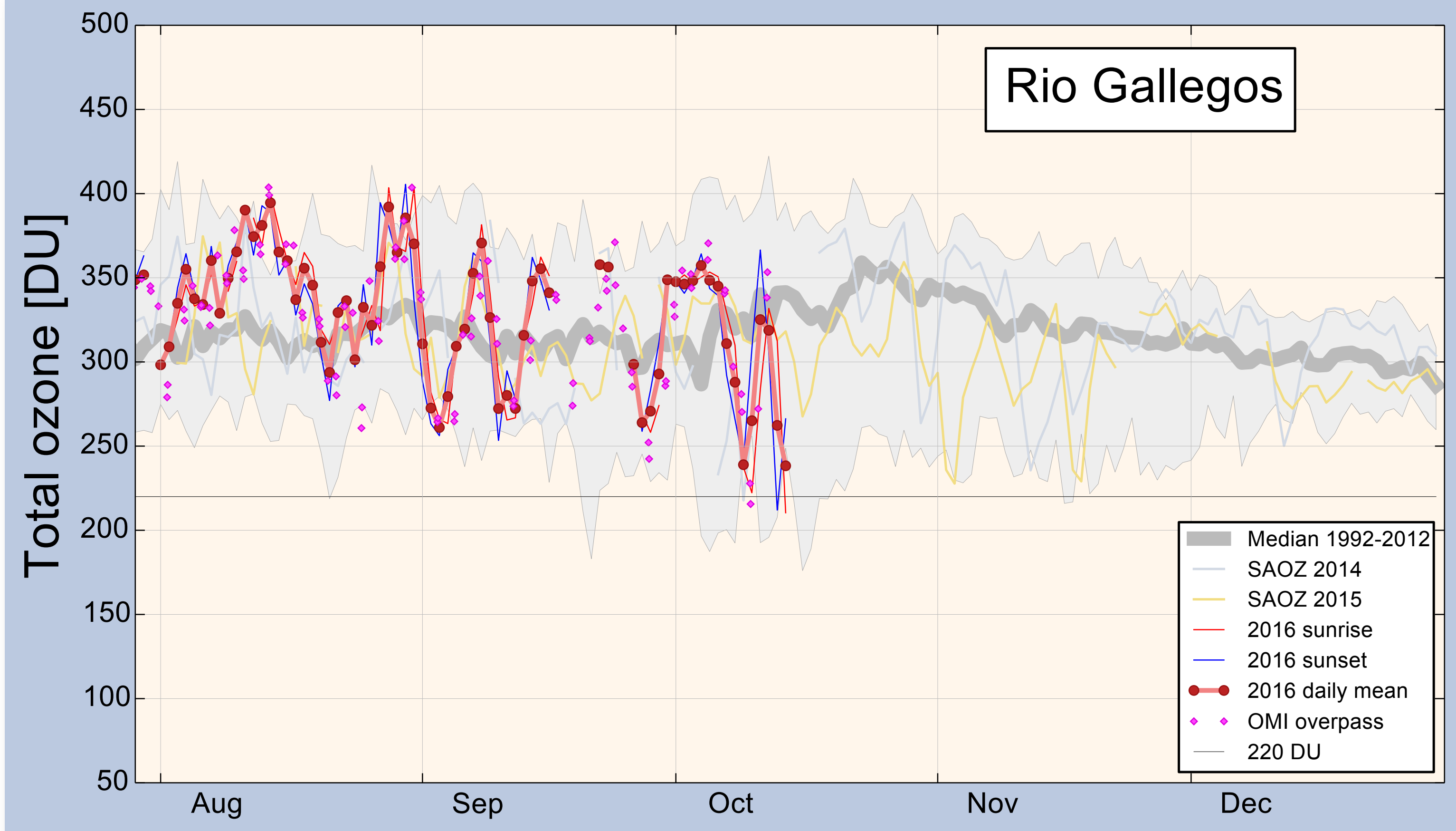


Figure 31. Total ozone over Río Gallegos as measured with a SAOZ spectrometer. Daily mean values from 2016 are shown with a light red line and dark red dots. Sunrise and sunset values are shown in red and blue, respectively. Data from 2014 and 2015 are also shown. Satellite overpass data from OMI are shown as small magenta diamonds. One can clearly see the dip in total ozone around 9-10 October.

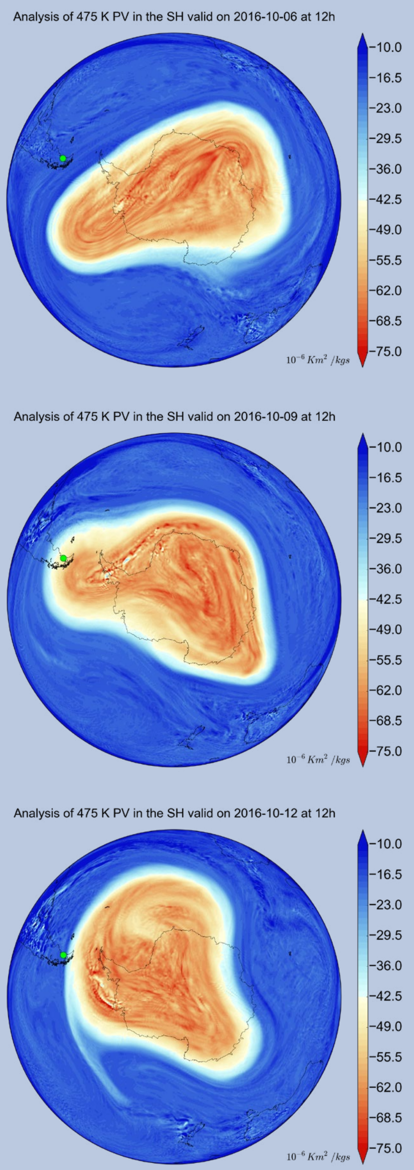


Figure 32. Potential vorticity at the isentropic level of 475 K. The three maps show the situation on 6, 9 and 12 October, respectively. The position of Río Gallegos is indicated with the green circle. On 6 October, the station is clearly outside of the vortex, whereas on 9 October the station is inside. On 12 October the station is outside again. The PV data originate from ECMWF and are made available by the Norwegian Institute for Air Research (NILU). The plots are produced at WMO.

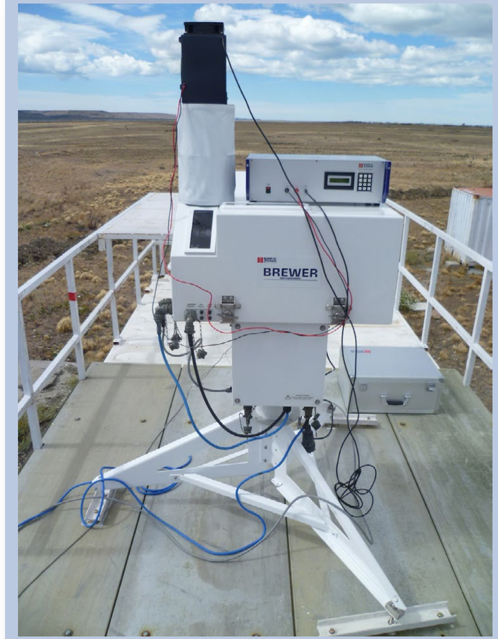
on the edge of the vortex, looking into the vortex in the morning and looking out of the vortex in the evening.

Figure 32 shows maps of potential vorticity at the 475 K isentropic level (around 19 km altitude) for three dates around the low-ozone episode. One can see how the vortex moves during this time period, and that on 9 October, the station is just inside the vortex. Total ozone drops more than 100 DU during the days from 6 to 9 October.

In addition to measuring total ozone, the Brewer spectrophotometer also measures UV radiation. From those measurements one can deduce the UV Index. **Figure 33** shows the daily progression and diurnal variation of the UV Index from 2 October to 12 October. As the vortex passes over the station around 9-10 October, one can see a clear increase in the daily maximum of the UV Index, going up from a typical noon-time value of around 3 to a value just above 6 on the 9th of October.

The Brewer spectrophotometer is also programmed to do Umkehr measurements, and this results in vertical profiles. The vertical resolution is not as high as with ozonesondes or an ozone lidar, but still high enough to detect the ozone depleted region between 15 and 25 km altitude.

The observational programme in Río Gallegos is supported through the project entitled "Development of Atmospheric Environmental Risk Management System in South America" (2013-2018) financed by JICA-JST through Science and Technology Research Partnership for Sustainable Development (SATREPS)."



Brewer #229, deployed in Río Gallegos.

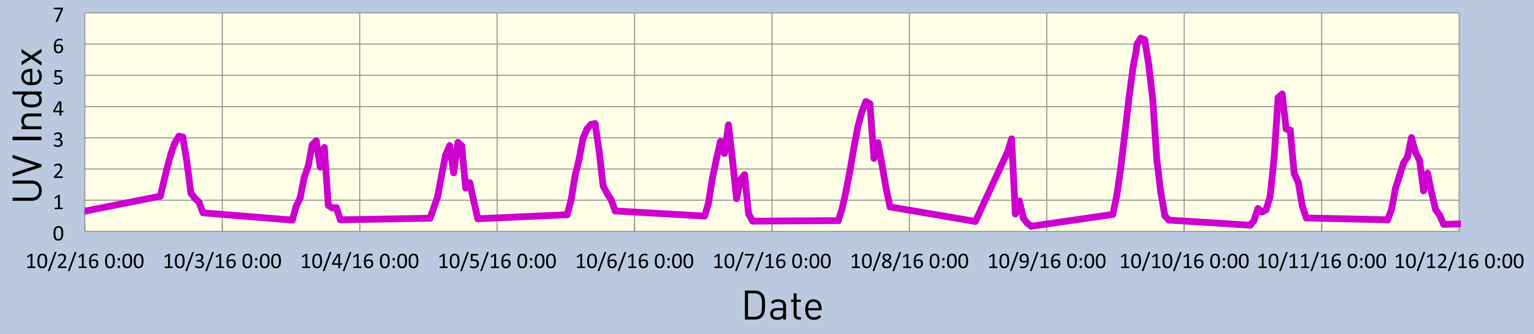


Figure 33.UV Index as measured with the Brewer spectrophotometer in Río Gallegos. One can see how the UV Index increases from a typical value around 3 to a value above 6 as the vortex touches the station. The plot has been provided by Jacobo Salvador, UNIDEF (MINDEF-CONICET)-Observatorio Atmosférico de la Patagonia Austral.

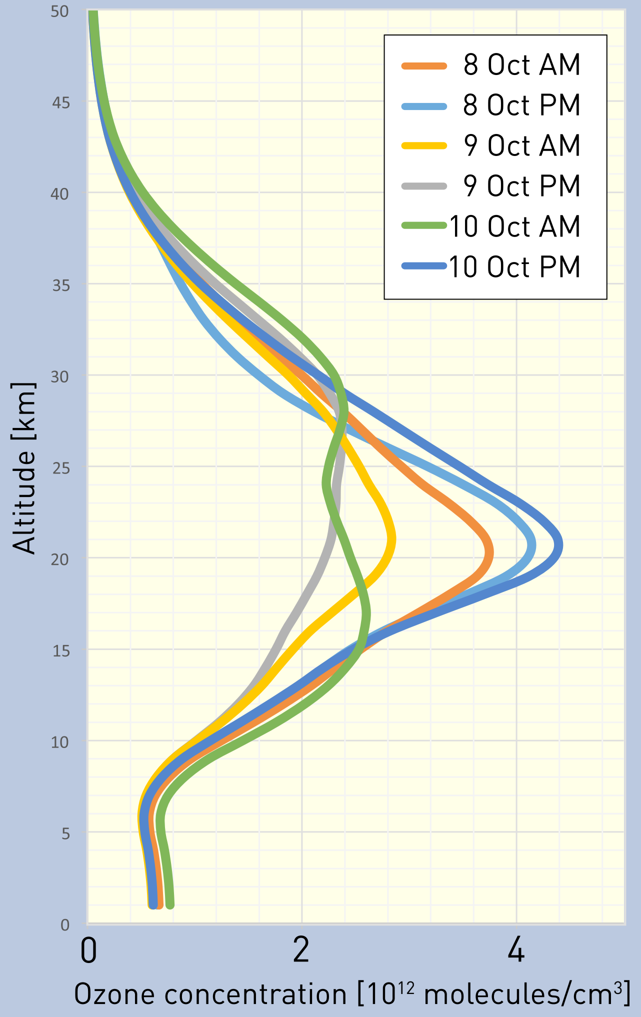


Figure 34. Vertical profiles of ozone on three consecutive days from 8 to 10 October based on Umkehr measurements carried out with the Brewer spectrophotometer in Río Gallegos. The plot has been provided by Jacobo Salvador, UNIDEF (MINDEF-CONICET)-Observatorio Atmosférico de la Patagonia Austral.

The approach to the Rothera Research Station. Photo: Beth Simmons.

At the British GAW/NDACC station Rothera (67.5695°S, 68.1250°W) total ozone is measured with a SAOZ spectrometer. The data are up to date as of mid October. Since the station is close to the polar circle, observations can be carried out around the year. Total ozone was oscillating between approximately 220 and 380 DU in June. In July, total ozone varied between 150 and 330 DU. In August total ozone has been more variable as ozone depletion has started and the polar vortex edge moves back and forth over the station. The highest value observed in August was 375 DU and the lowest was 164 DU. In September, the ozone decline has continued and the lowest value observed was 123 DU on 2 September. After that, ozone has oscillated as the station moves in and out of the polar vortex. Low ozone was observed in late September and also in mid October as the station was inside the vortex on those dates.

Figure 35 shows the 2016 data in comparison to earlier years and long term statistics.

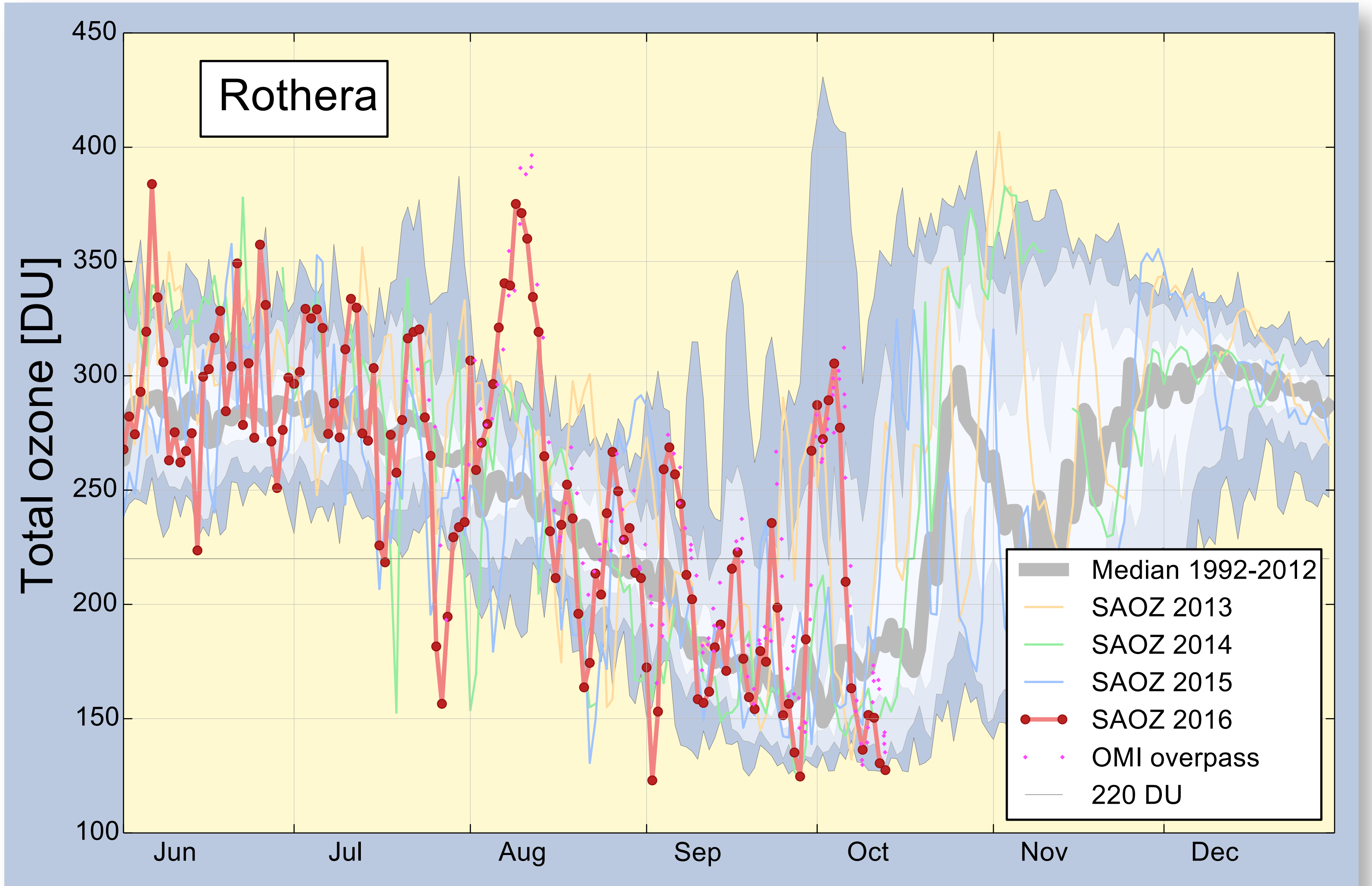


Figure 35. Total ozone measured at Rothera with a SAOZ spectrometer. The plot includes data until mid October 2016. The data should be considered preliminary. SAOZ data from the three previous years are also shown as well as satellite overpass data from the OMI instrument. The long-term statistics (median, maximum, minimum, 30-70th percentile and 10-90th percentile are based on the MSR2 reanalysis from KNMI.

San Martín

The GAW station San Martin (68.12°S, 67.10°W), operated by Argentina, is situated 76 km from the Rothera station. Total ozone is measured with a Brewer spectrophotometer. The instrument has been out of order since 2011, but is back in operation since 2015. As seen in **Figure 36**, total ozone was mostly above or near the median in late August, but declined during most of September. After a rapid increase to more than 300 DU in late September and early October, total ozone declined again down to around 150 DU.

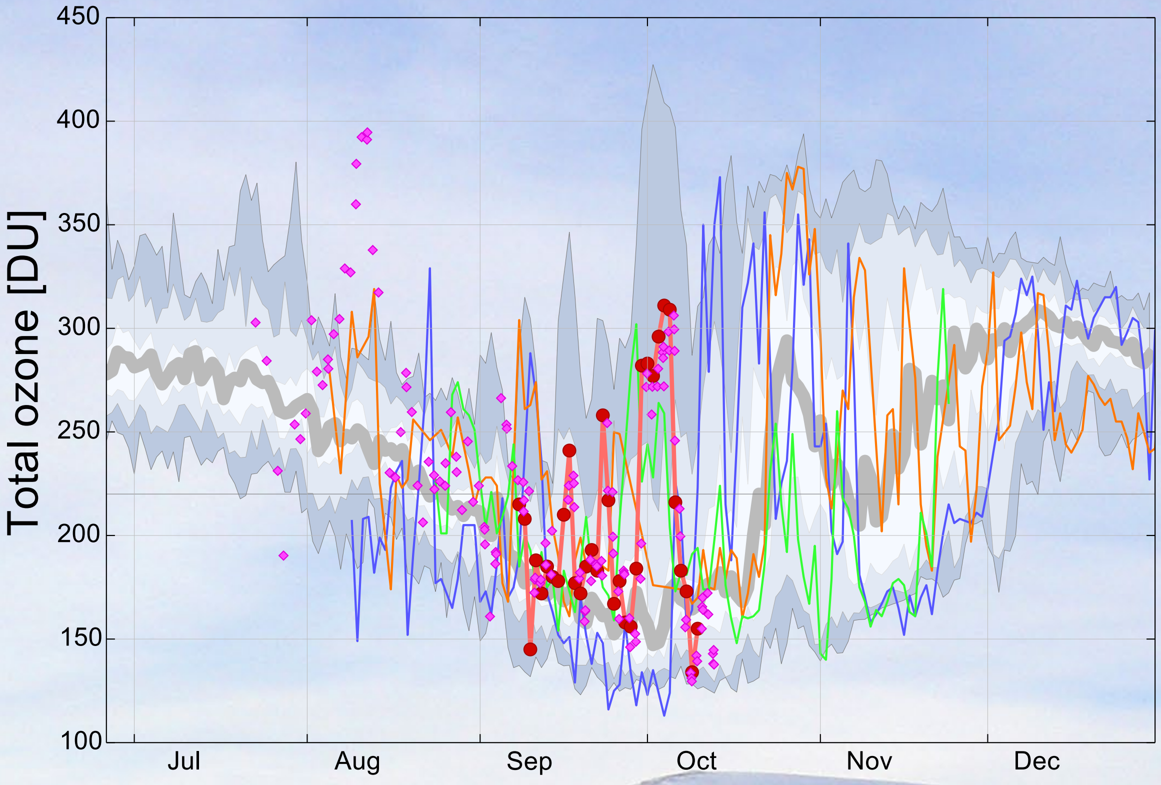


Figure 36. Total ozone in 2016, measured at the Argentine station San Martin with a Brewer spectrophotometer. The thin grey line shows the 220 DU limit. For comparison is shown data for the three previous years when the instrument was in operation, namely 2009, 2010 and 2015. The three shaded regions show range, 10-90th percentile and 30-70th percentile, respectively.

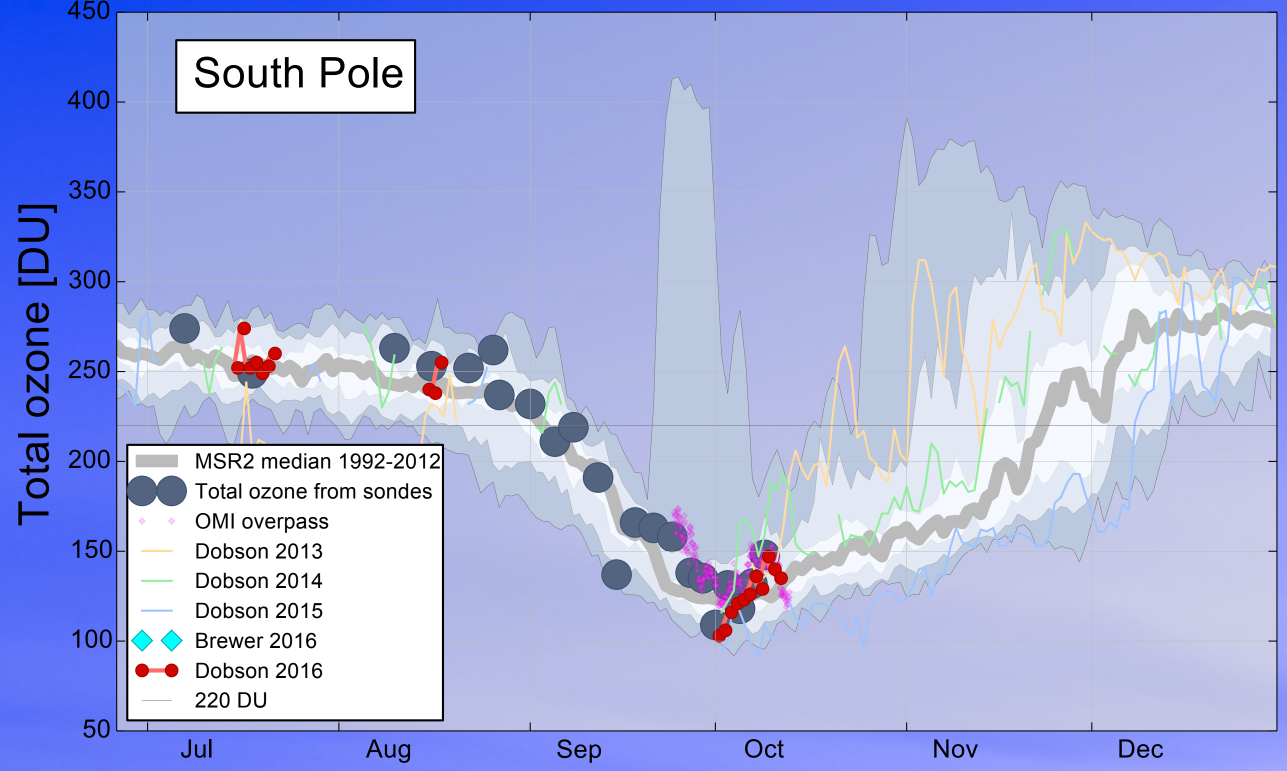


Figure 37. Total ozone measured at the South Pole from late June until mid October 2016.

South Pole

The total ozone column at the GAW/NDACC South Pole station (Amundsen-Scott base) has been measured by NOAA/ESRL with a Dobson spectrophotometer since December 1963. The vertical distribution of ozone has been measured by NOAA/ESRL with electrochemical concentration cell (ECC) ozonesondes since 1986. During the polar night, Dobson measurements can be carried out for a few days around the full moon. The direct sun Dobson measurements started in early October, and there are also moon observations from mid July and mid August. **Figure 37** shows total ozone measurements at the South Pole. On the plot are shown moon observations from mid July and mid August 2016 and data from the three previous years together with long term statistics based on the MSR2 data set from KNMI. Total ozone calculated from ozonesonde observations are also shown. These data show that total ozone so far this season are very near the long term median.

Figure 38 (next page) shows the individual ozone soundings carried out between 7 July and 11 October. One can see the progressive decline in the partial ozone columns (12-20 km and 14-21 km). On 5 October the partial ozone columns are lower than at the same time last year.

During the polar night stratospheric temperatures over the South Pole drop below -90°C. For example, a temperature of -92.9°C was observed at 20.5 km on 18 July. Temperatures remained cold in the stratosphere into the spring; On 27 August the temperature was -89.5°C at 18.4 km and on 21 September it was -86.5°C at 18.5 km above the South Pole.

Total ozone is measured with a Brewer spectrophotometer operated by Environment and Climate Change Canada (ECCC) and NOAA and that belongs to ECCC. This instrument was installed at the South Pole in February 2008. The measurements will start up again in early October after the polar night.

Time-lapse photo of an ozonesonde launch at the South Pole. Photo: Christian Krueger, IceCube

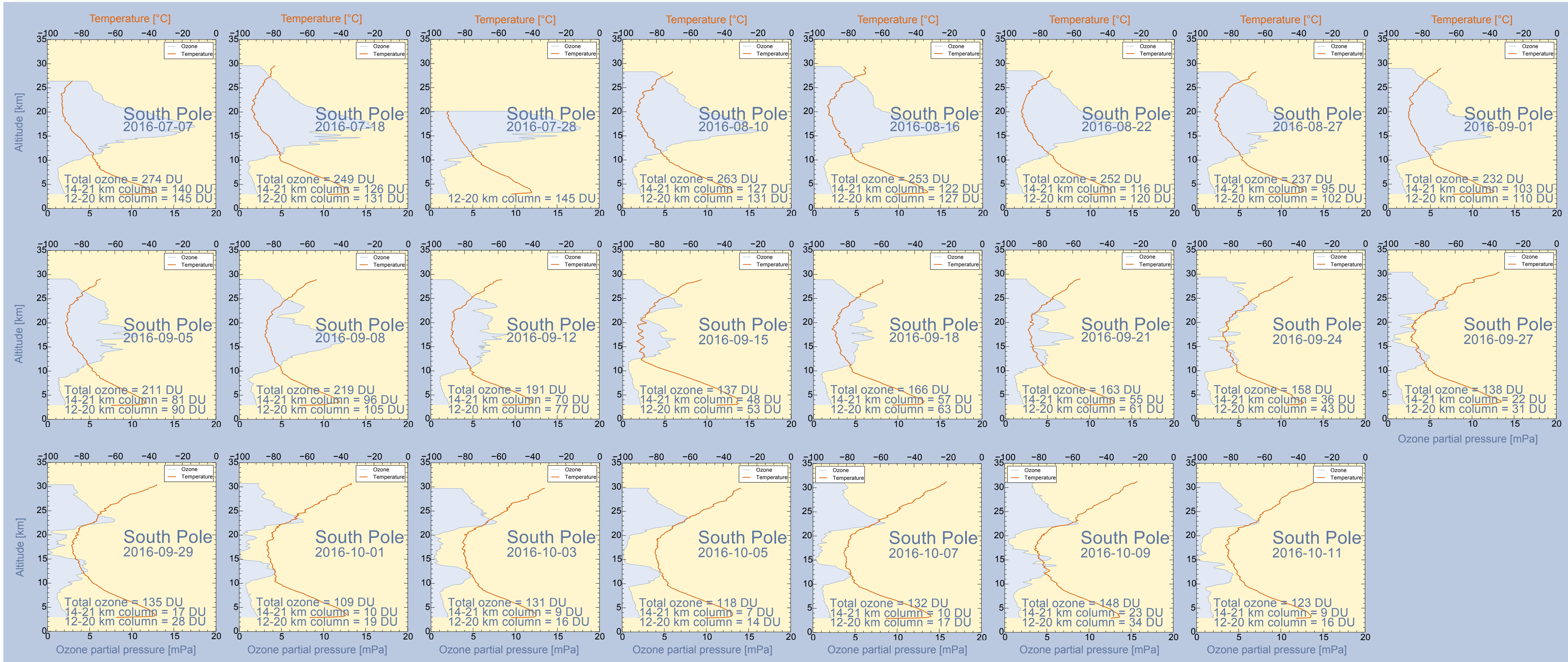


Figure 38. Ozonesonde profiles measured at the South Pole from 7 July until 11 October 2016.

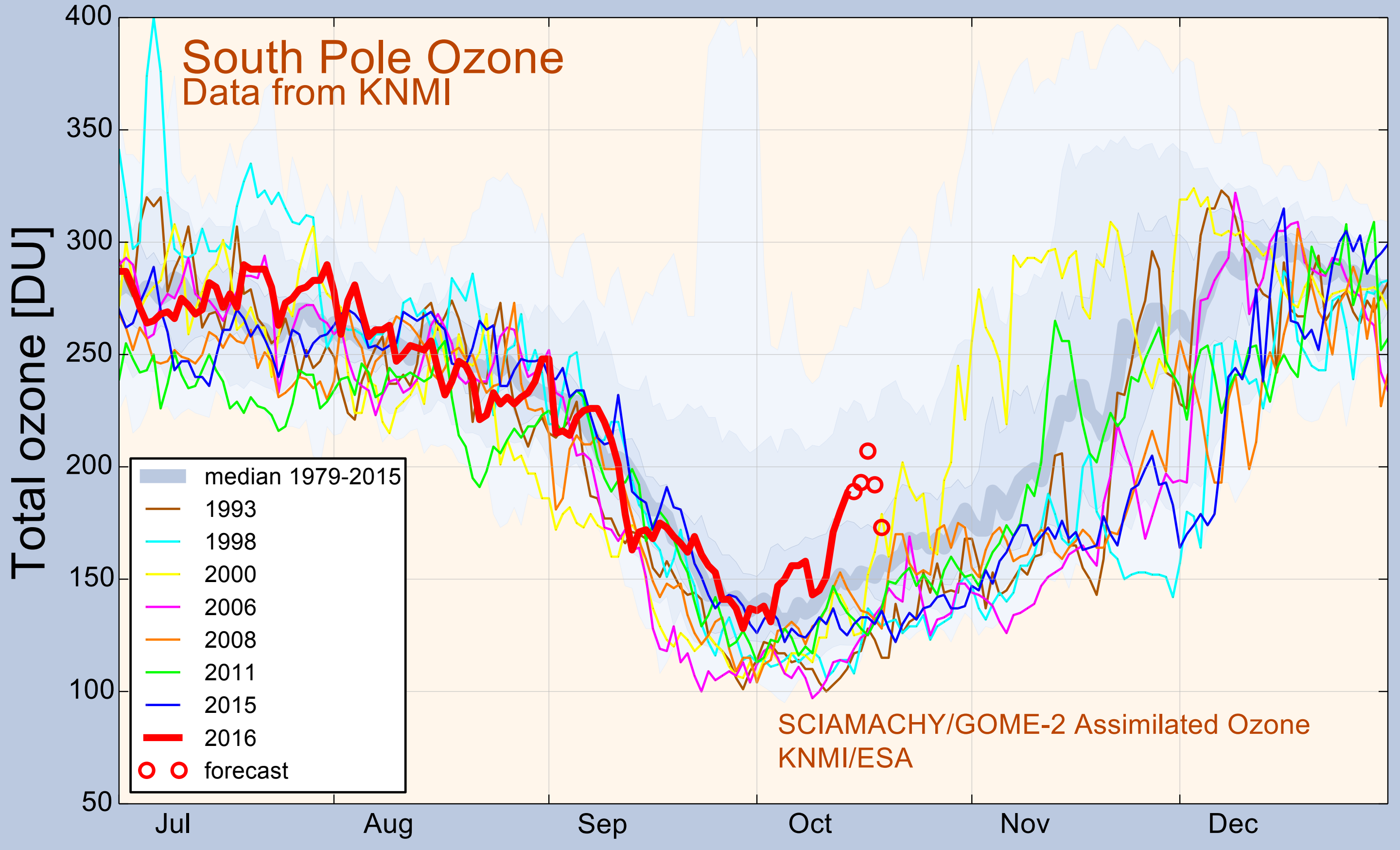


Figure 39.Total ozone at the South Pole from the data assimilation model at KNMI. This model uses data from various satellites. The red curve and the open red circles show 2016. Earlier years with substantial ozone loss are shown for comparison.

Total ozone over the South Pole, calculated with the data assimilation model at KNMI, is shown in **Figure 39**. One can see that total ozone has passed through the minimum for this year and is on the way up again.

Total ozone is measured at the Japanese GAW station Syowa (69.006°S, 39.577°E) with a Dobson spectrophotometer. These measurements have been carried out since 1961. Measurements started up on 11 August after the winter, as shown in **Figure 40**. One can see that so far (until mid October) the total ozone values are close to the long term median.

Ozone profiles are measured at Syowa with ozonesondes. So far, eleven soundings have been carried out (**Figure 41**). All these profiles show ozone bite-outs and one can see how the bite-out progresses quite steadily from 17 August to 10 October with the latter as the most depleted profile with a 14-21 km partial column of 19 DU.

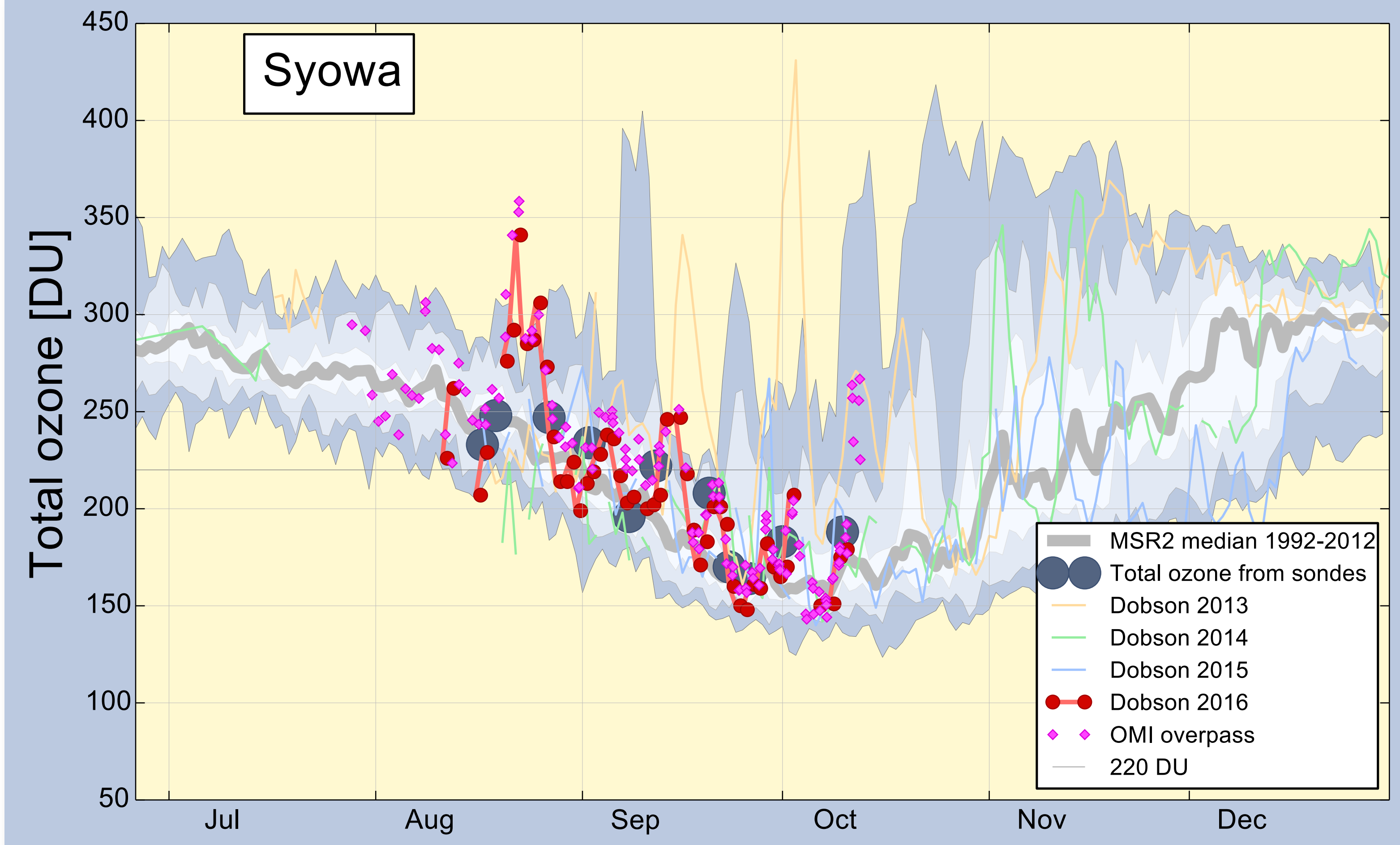


Figure 40.Dobson measurements from Syowa. Data from the current year and the three previous years are shown. For comparison total ozone from OMI overpass data are also shown (small magenta diamonds) as well as total ozone calculated from ozonesondes (blue circles).

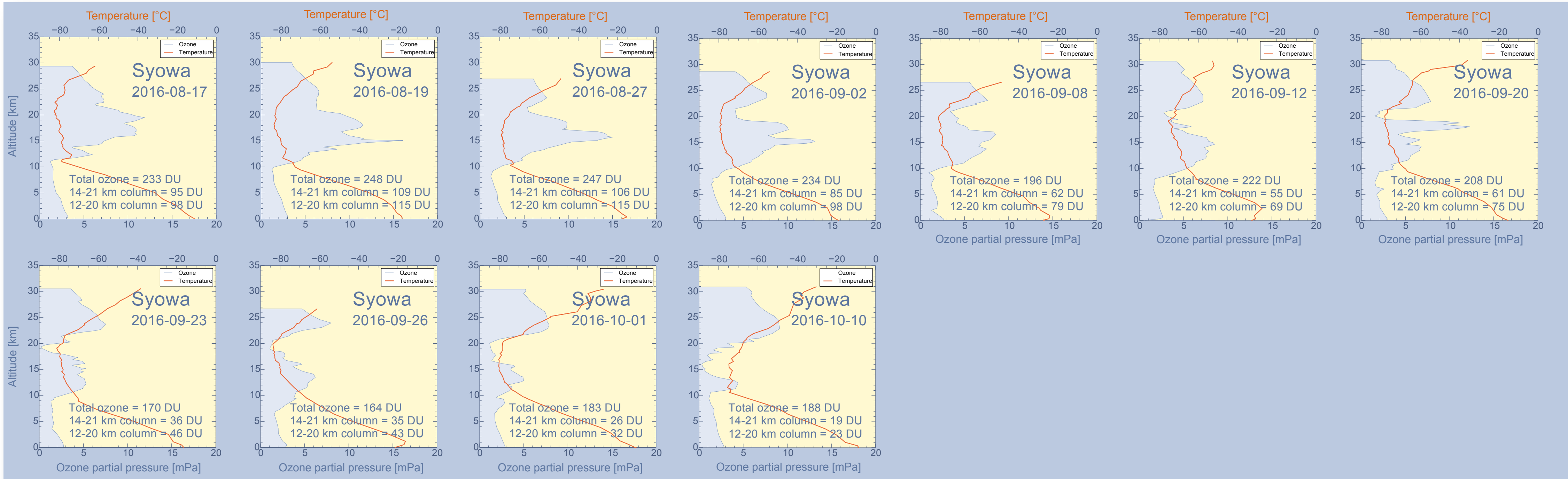


Figure 41. Ozonesonde observations at Syowa from 17 August until 10 October.

Ushuaia

Ozonesonde launch at Ushuaia. Photo: SMN.

The GAW Global station Ushuaia (54.848334°S, 68.310368°W) is operated by the Servicio Meteorológico Nacional of Argentina. This station is mainly influenced by middle latitude air masses, but on certain occasions the south polar vortex sweeps over the southern tip of the South American continent. On such occasions Ushuaia can be on the edge of or even inside the ozone hole.

Total ozone is measured with a Dobson spectrophotometer and the measurement from June 2016 until now are shown in **Figure 42** together with OMI overpass data and total ozone derived from ozonesondes. One can see the good agreement between total ozone from the Dobson measurement and the total ozone derived from the ozonesondes.

Ozone profiles are measured with electrochemical ozonesondes approximately twice per month from June until the end of the ozone hole season. The ozonesonde data for 2016 are shown in **Figure 43**. Most of the profiles are typical of mid-latitude air masses and show no sign of ozone depletion. However, the profile observed on 12 September shows a characteristic ozone bite-out in the 19-23 km height interval. Satellite data for this date show that the ozone hole touched Ushuaia on this day. On 9 October it is clear that the ozone hole is over Ushuaia again with a total ozone column of 188 DU (observed with the Dobson spectrophotometer, 186 DU deduced from the balloon sounding) and a 14-21 km partial column of 34 DU. Once again, on 14 October, the vortex is back over Ushuaia and this time the station is even deeper inside the vortex. The ozone sounding carried out on that day shows a 14-21 km partial column of 29 DU.

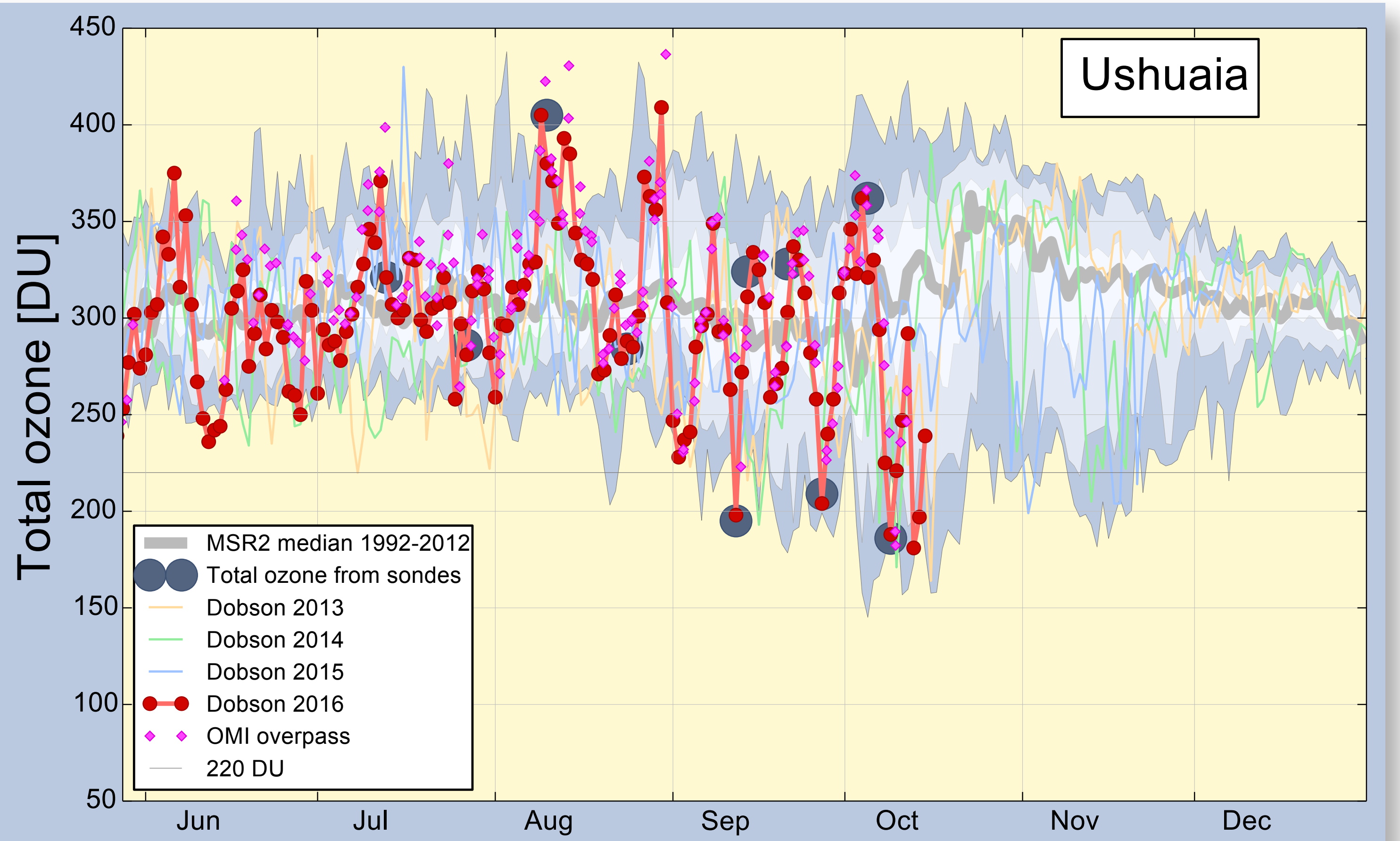


Figure 42. Total ozone over Ushuaia in 2016. The dark blue-grey circles show total ozone deduced from ozone balloon soundings, and the light red curve with dark red dots shows the Dobson observations in 2016. Dobson data from the three previous years are shown in blue, green and orange for 2015, 2014 and 2013, respectively. The magenta diamonds show OMI overpass data. The thick grey line shows the median total ozone value for each day based on MSR version 2 data for the 1992-2012 time period. The shaded areas in various shades of grey shows the range of total ozone values over the same time period together with the 10th to 90th and 30th to 70th percentiles for the 1992-2012 time period. One can clearly see the excellent agreement between total ozone from the Dobson instrument and from the ozonesondes.

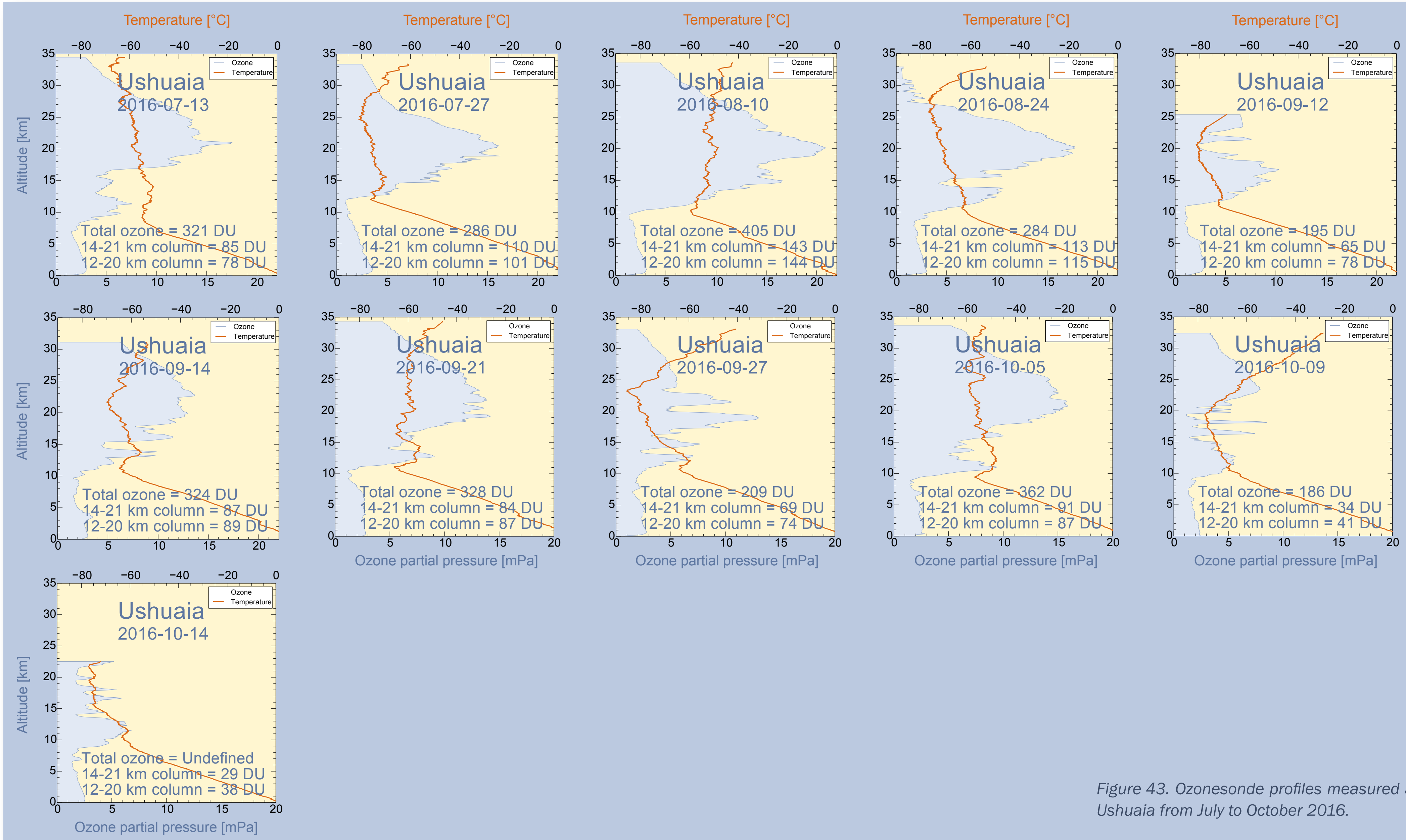


Figure 43. Ozonesonde profiles measured at Ushuaia from July to October 2016.

Vernadsky station (65.15°S, 64.16°W) is run by the National Antarctic Scientific Centre of Ukraine. The data are processed by the British Antarctic Survey. Total ozone observations have been carried out here since mid 1957. Total ozone is measured with a Dobson spectrophotometer. Observations recommenced after the polar night on 21 July, with initial results around 280 DU. In August total ozone values oscillated between approximately 200 and 350 DU. Also in September, total ozone oscillated between these two values, but the first few days of the month total ozone dropped to around 180 DU. In October, total ozone first rose to over 350 DU but then plummeted to the lowest values seen so far this year (153 DU on 13 October). The Dobson observations and OMI overpass data for 2016 are shown in **Figure 44** together with long term statistics (1992-2012) and Dobson data for the three previous years.

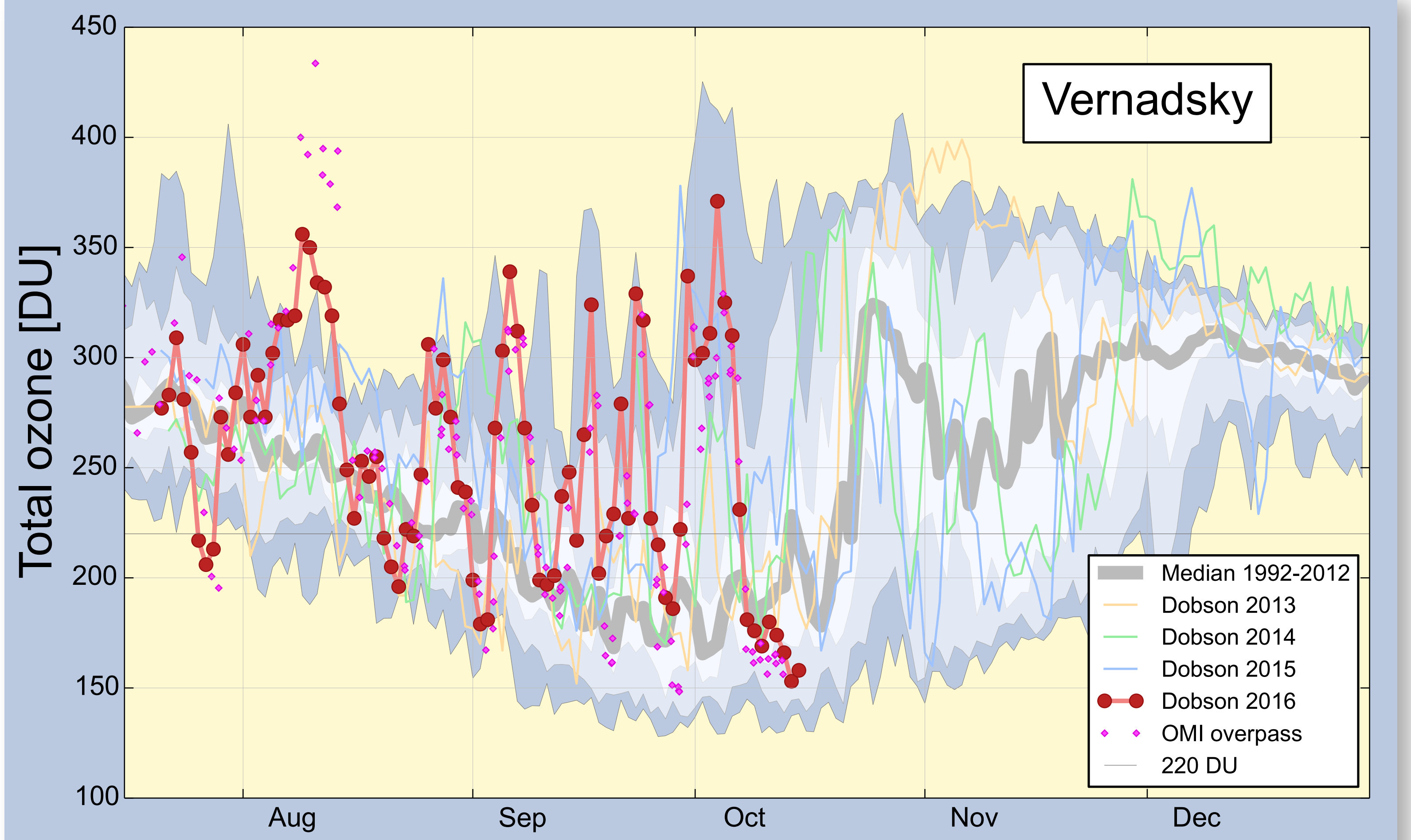


Figure 44. Total ozone over Vernadsky in 2016. The red line with dark red dots shows the Dobson observations (until 13 October) and the small magenta diamonds show OMI overpass data (until 16 September). The grey line shows the 1992-2012 median. It can be seen that total ozone varies with the position of the station with respect to the vortex edge.

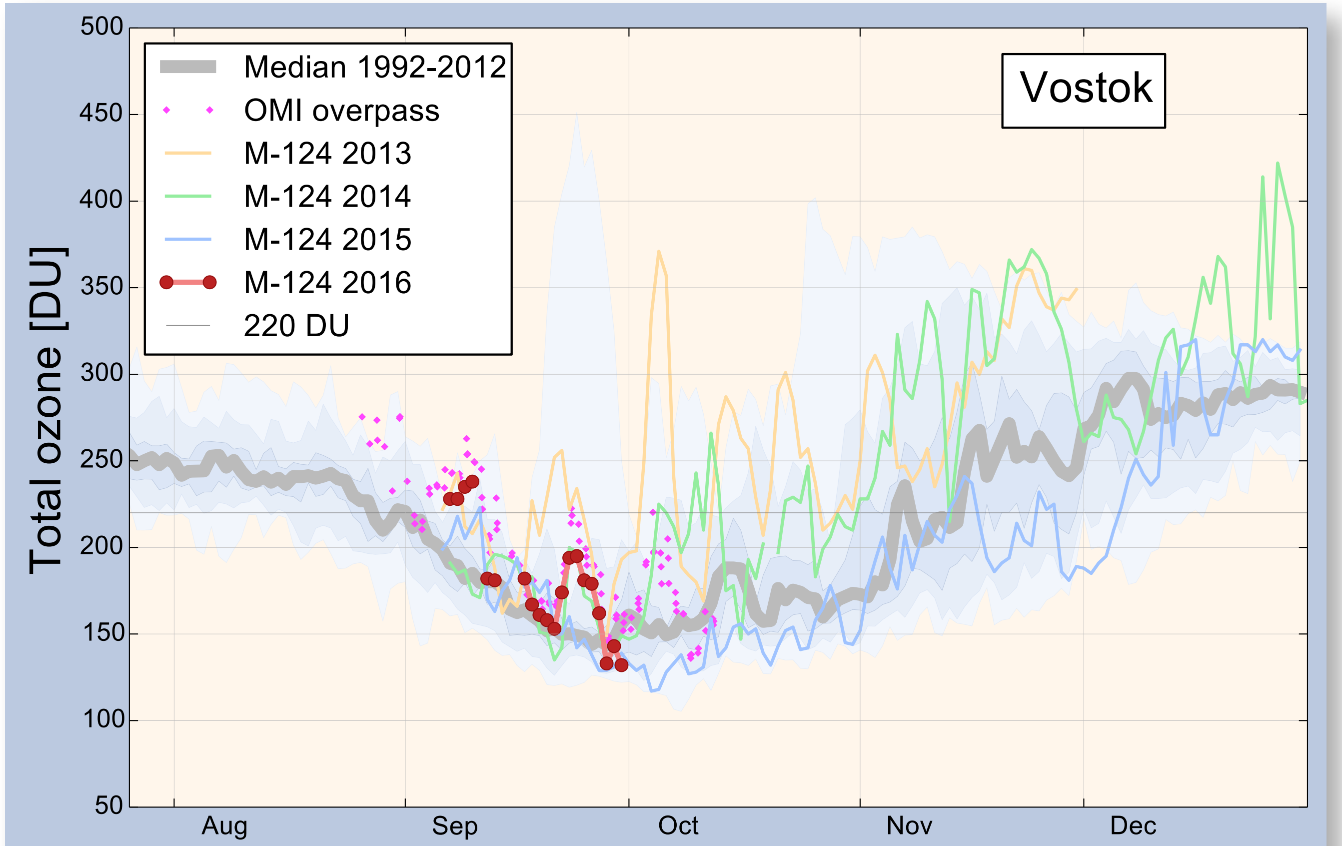


Figure 45. Total ozone observations carried out at the Vostok ice drilling site in 2016 with an M-124 filter instrument compared to satellite overpass data from OMI. Also shown is statistics for the 1992-2012 time period. The thick grey curve shows the median total ozone column for this time period. The grey shaded area shows the range of values for the 1992-2012 time period. The observations made in 2013, 2014 and 2015 are also shown.

Vostok (78.464422°S, 106.837328°E, 3448 masl) is located near the South Geomagnetic Pole, at the center of the East Antarctic ice sheet. Although this is a Russian research station, scientists from all over the world conduct research here. One of the primary projects at this site, a coordinated Russian, French and American effort, is drilling ice cores through the 3,700 m thick ice sheet. These ice cores contain climate records back to almost half a million years before present.

Total ozone is measured at Vostok with a M-124 filter instrument. Data for September are currently available. The minimum value measured so far in 2016 was on 30 September with 132 DU. **Figure 45** shows the M-124 data for 2016 together with data from 2013-2015 and 2016 satellite overpass data from the OMI instrument on board the AURA satellite.

Zhong Shan

At the Chinese GAW station Zhong Shan (69.3731°S, 76.3724°E) total ozone is measured with a Brewer spectrophotometer. The measurement series dates back to March 1993. In 2016, the observations started on 23 August after the polar night. **Figure 46** shows the Brewer data (dark red circles connected with pink lines) together with OMI overpass data (magenta diamonds). Long term statistics for the 1992-2012 time period is also shown. The data show that total ozone was unusually high for some days in late August. Except for a couple of days in mid September and in early October, total ozone has been above the long term median so far in 2016.

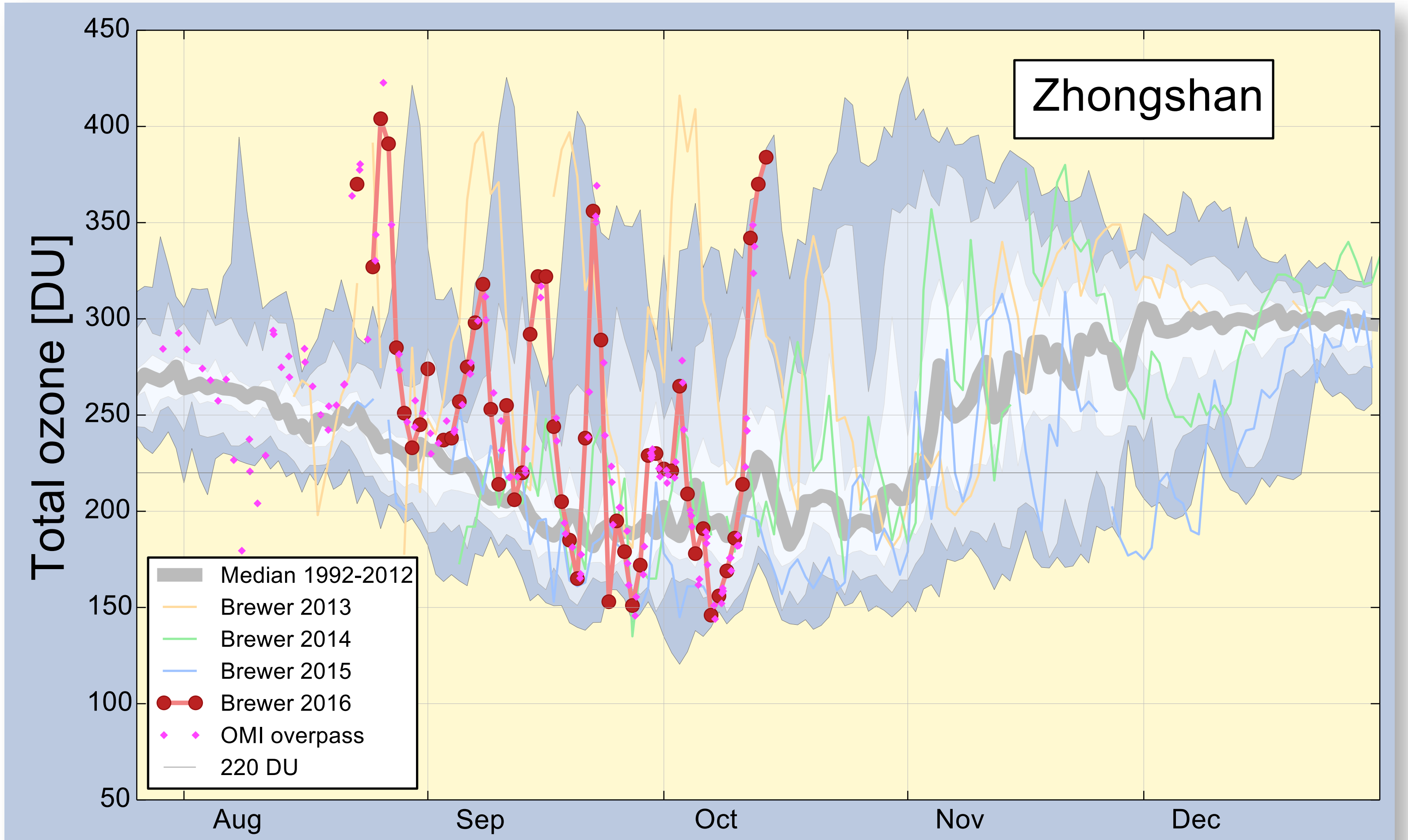


Figure 46. Total ozone observations carried out at Zhong Shan in 2016 with a Brewer instrument compared to satellite overpass data from OMI.

Chemical activation of the vortex

Results from a data assimilation model

As of 5 October, the vortex is still depleted in nitric acid. Hydrochloric acid has reformed and there is almost no active chlorine left. Ozone remains low inside the vortex.

Figure 47 (next page) shows the progression of four key species from 1 May until 5 October at the level of 45.4 hPa. The plots are made from output from the BASCOE model at the Belgian Institute for Space Aeronomy (BIRA-IASB). BIRA-IASB is in charge of the monitoring and evaluation of the stratospheric composition products delivered by the European MACC projects. In this context, the BASCOE assimilation system was setup to deliver near real-time analyses and forecasts of ozone and related species for the stratosphere. The version used here was originally developed in the framework of the past GSE-PROMOTE program of the European Space Agency. The BASCOE data assimilation system assimilates the offline dataset (level-2, v3.3) retrieved from the Aura-MLS instrument. While delivered a few days later than the NRT stream, the offline dataset includes several species: O_3, H_2O, HNO_3, HCl, ClO, $(ClO)_2$, HOCl and N_2O. More information about the MACC projects and the BASCOE model with references can be found here: http://macc.aeronomie.be/4_NRT_products/3_Models_changelogs/BASCOE.php

One can see from the figure how gaseous nitric acid (HNO_3) is gradually removed, starting in May when PSC temperatures set in, and continuing through June and July. HNO_3 removal is essentially complete by 1 August and is still very low on 5 October. Removal of gaseous HNO_3 is an indication that this compound is condensated in the form of polar stratospheric clouds (nitric acid trihydrate, $HNO_3{\cdot}3H_2O$).

At the same time hydrochloric acid is removed as it reacts with chlorine nitrate ($ClONO_2$) and forms active chlorine. One can see how hydrochloric acid (second row) is being depleted as it is being converted on the PSC particles. Extensive conversion of HCl has already taken place by 1 July, and by 1 August essentially the whole vortex is entirely devoid of HCl. It remains very low also on 1 September, but on 17 September some HCl has reformed. From that date until 5 October, the amount of HCl has increased substantially and is higher inside the vortex than outside.

A good indicator of vortex activation is the amount of chlorine monoxide (ClO). It should be noted, however, that ClO dimerises and forms $(ClO)_2$ in darkness. The dimer is easily cracked in the presence of sunlight. ClO will therefore be present in the sunlit parts of the vortex, whereas the dark areas will be filled with $(ClO)_2$, which is not observed by Aura-MLS, but calculated by the BASCOE model. By looking at the sum of the monomer and dimer ($ClO + 2Cl_2O_2$) one gets a better impression of the degree of chlorine activation. This is shown in the third row on the figure. First signs of activation is visible already on 1 June. The maximum degree of activation happens during the month of August. By 17 September, the degree of activation is waning and on 5 October there is almost no active chlorine left.

The bottom row shows the mixing ratio of ozone at the 45.4 hPa level. Up until July there is no indication of ozone depletion, but on 1 August one can see that some ozone destruction has taken place along the edge of the vortex. By 1 September the depletion has progressed and is now affecting the whole vortex. By 17 September the whole vortex has less than 1.2 ppm of ozone at this level and this remains the case also on 5 October.

Figure 48 (page after next) compares the situation for four species on the date of 30 September for the years 2013, 2014, 2015 and 2016. The four species are the same as in **Figure 47**. One can see from the figure that the degree of activation and ozone depletion are quite similar for the three years shown here. Ozone depletion seems a bit more advanced in 2015, though.

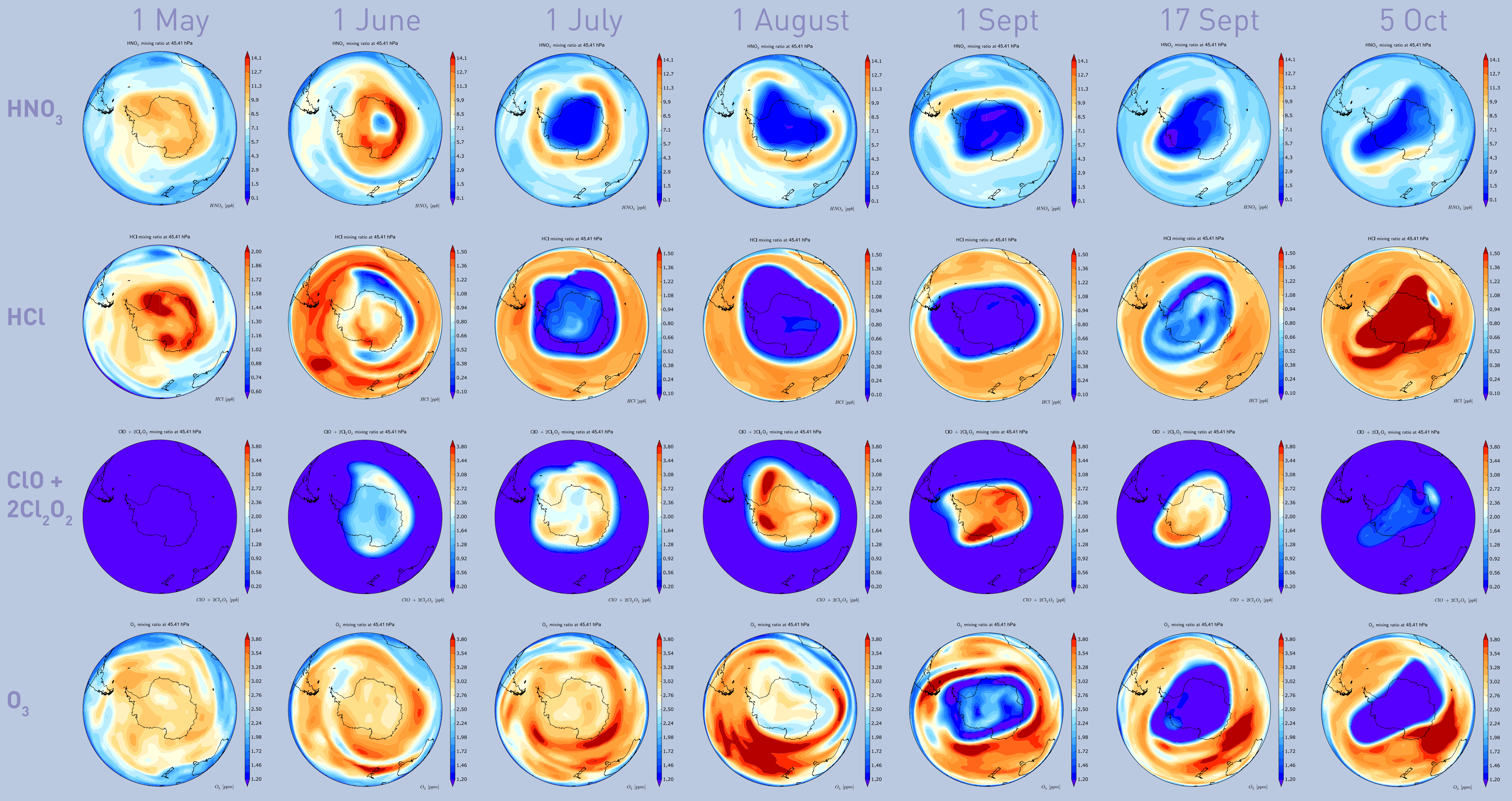


Figure 47. Results from the BASCOE data assimilation model at the level of 45.4 hPa. This model is run as part of the MACC-III project, which is funded by the European Commission and coordinated by ECMWF. The upper row shows the mixing ratio of nitric acid, the second row shows the mixing ratio of hydrochloric acid, the third row shows the sum of chlorine monoxide and its dimer ($ClO + 2Cl_2O_2$), and the bottom row shows the mixing ratio of ozone. All four rows show the temporal development from 1 May to 5 October with intermediate frames shown for 1 June, 1 July, 1 August, 1 September and 17 September. Please note that the upper and lower limits of the HCl scale is different from the other dates on 1 May.

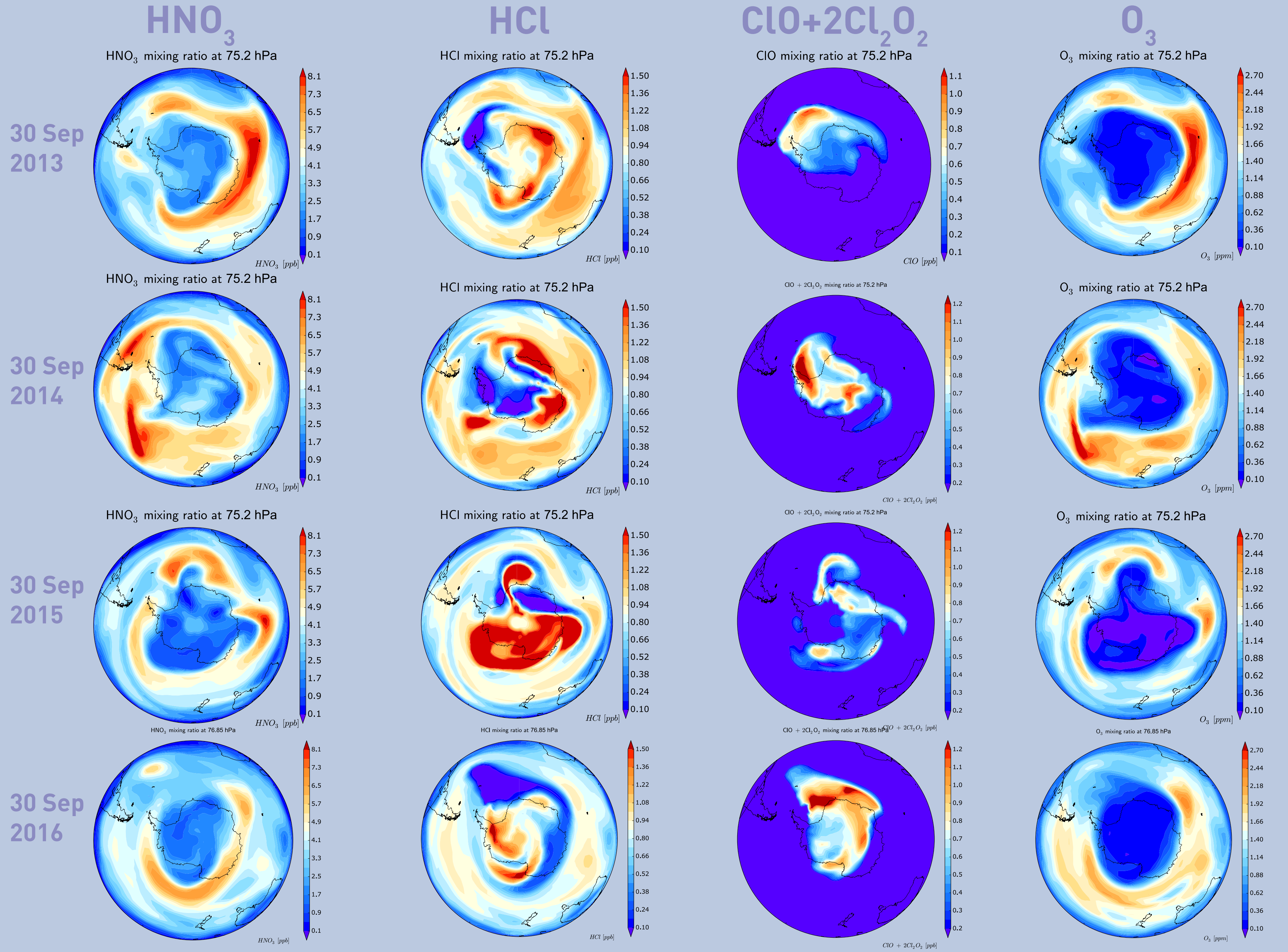


Figure 48. Results from the BASCOE data assimilation model at the level of 75.2 hPa (76.9 hPa in 2016). This model is run as part of the MACC-III project, which is funded by the European Commission and coordinated by ECMWF. This figure compares the degree of processing in the south polar vortex on 30 September for the four years 2013, 2014, 2015 and 2016. It can be seen that the removal of nitric acid (HNO_3) is similar for the four years, with a hint of more removal in 2015 as compared to 2013, 2014 and 2016. Hydrochloric acid (HCl) is reforming at this time of the season, but this process is less complete in 2016 as compared to the other years. The active chlorine dimer (Cl_2O_2) is more abundant in 2016 that at the same time in 2013-2015, which means that ozone destruction is still ongoing. The rightmost column compares the ozone mixing ratio for the four years. One can see that ozone depletion is less complete in 2016 as compared to 2015, and quite similar to that observed in 2013 and 2014.

Ozone hole area and mass deficit

Ozone hole area

The area of the region where total ozone is less than 220 DU ("ozone hole area") as deduced from the GOME-2 instrument on Metop (and SCIAMACHY on Envisat in the past) is shown in Figure 49. A similar plot, based on data from the OMI instrument is shown in Figure 50. During the last two weeks of August, the area increased more rapidly than at the same time last year. During the first few days of September, the ozone hole area followed quite exactly the development of 2015. From then on the 2016 ozone hole area is lagging behind relative to 2015 and is quite similar to the long term (1979-2015) average.

Ozone mass deficit

The ozone mass deficit is defined as the amount of ozone (measured in megatonnes) that has to be added to the ozone hole in order for total ozone to come up to 220 DU in those regions where it is below this threshold. Figure 51 and Figure 52 (next page) show the ozone mass deficit as deduced from GOME-2 and OMI, respectively. The development of this parameter follows very closely the long term (1979-2015) average and, as of mid October, is smaller than in 2015 and near the long term average. The data from KNMI and NASA diverge somewhat both in absolute numbers and also in comparison to the long term average.

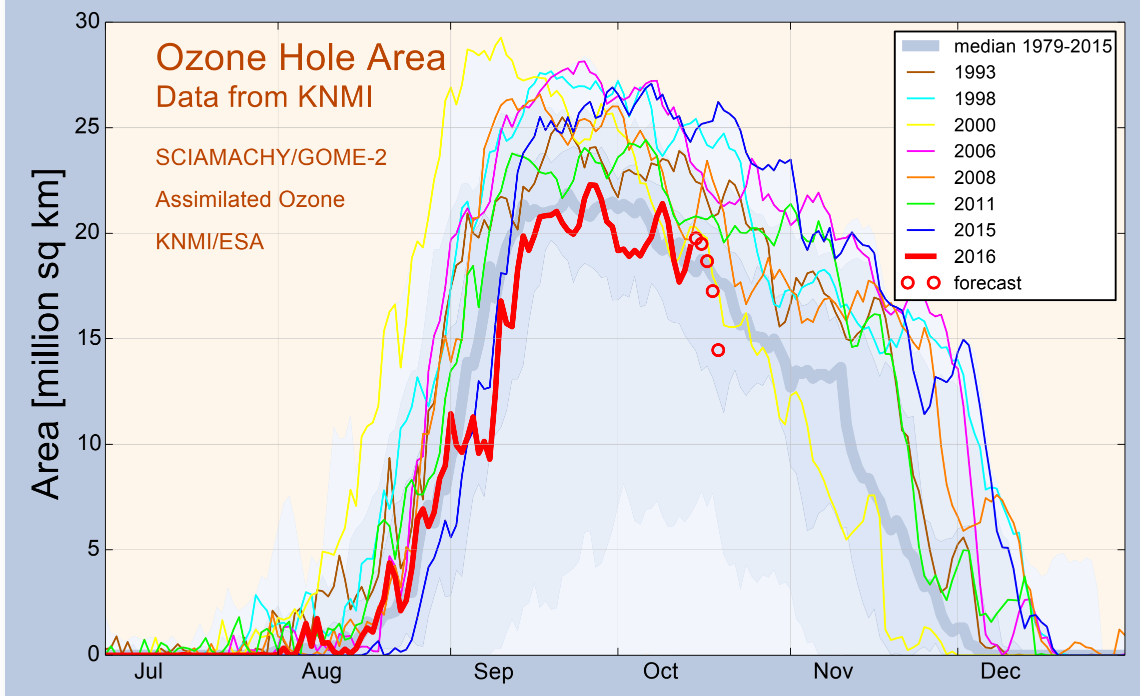


Figure 49. Ozone hole area for the years from 2006 to 2016 (red curve and open circles). The ozone hole area is the area of the region where total ozone is below 220 DU. The open circles represent a forecast for the five next days. The data are provided by KNMI and is based on data from the GOME-2 and SCIAMACHY satellite instruments. This plot is produced by WMO.

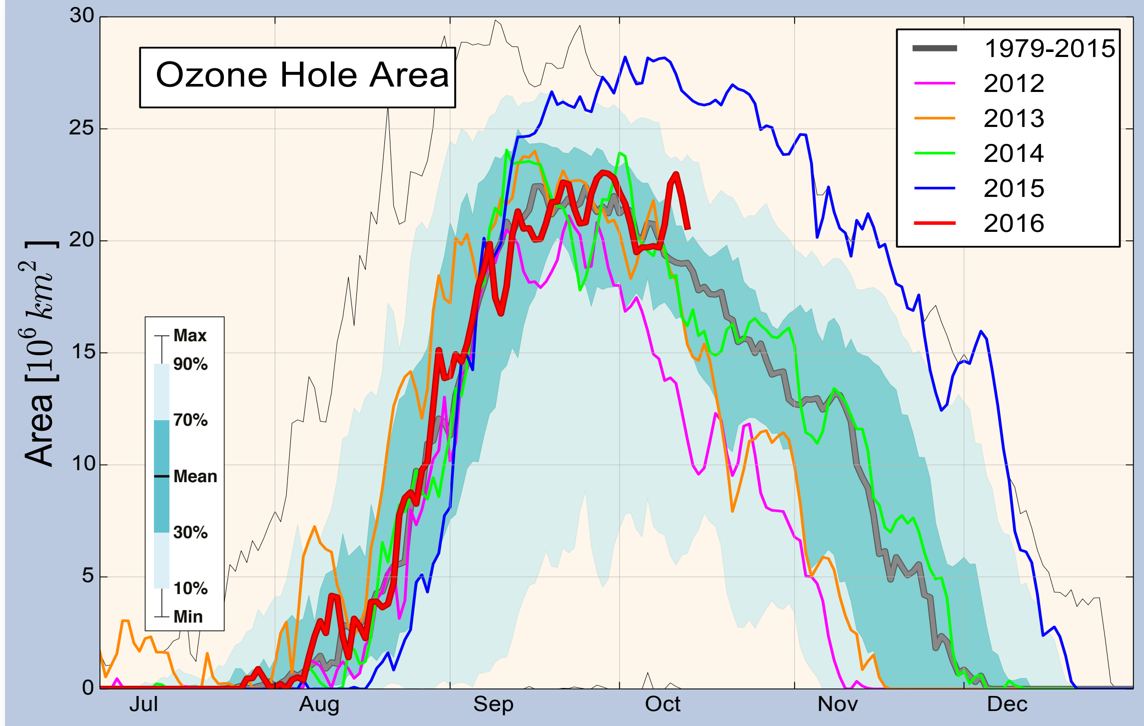


Figure 50. Area (millions of km²) where the total ozone column is less than 220 Dobson units. 2016 is showed in red (until 14 October). 2015 is shown in blue, 2014 in green, 2013 in orange and 2012 in magenta. The smooth grey line is the 1979-2015 average. The dark green-blue shaded area represents the 30th to 70th percentiles and the light green-blue shaded area represents the 10th and 90th percentiles for the time period 1979-2015. The ozone hole area on 27 August is 5.1 million km², which is about half the long term average for that particular date. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA, which are based on data from NOAA/NCEP.

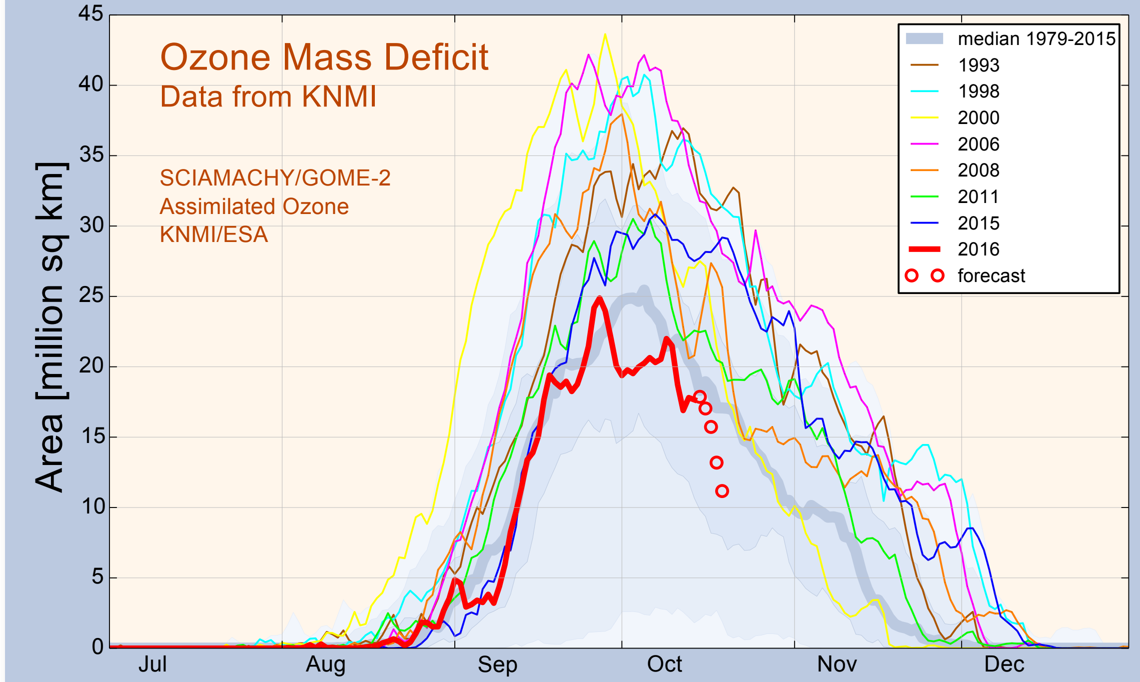


Figure 51. Ozone mass deficit for 2016 (red curve and dots (five-day forecast)). Some other selected years with substantial ozone loss are shown for comparison. The ozone mass deficit is defined as the mass of ozone that would have to be added to the ozone hole in order to bring the total ozone column up to 220 DU in those areas where total ozone is less than 220 DU. The open circles represent a forecast for the five next days. The thick grey line is the 1979-2015 median. The three grey shaded areas show range, 10th to 90th percentile and the 30th to 70th percentile, respectively. This plot is produced by WMO and is based on data from the TEMIS web site at KNMI.

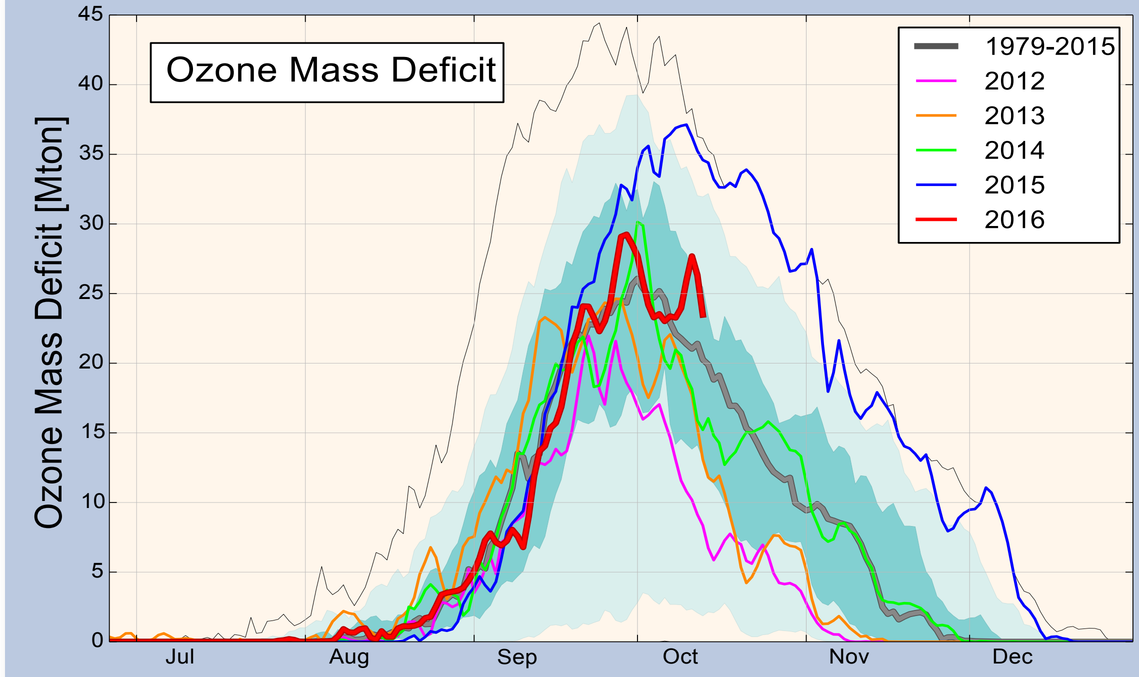


Figure 52. Ozone mass deficit (megatons) inside the Antarctic ozone hole for the years from 2012 to 2016 together with 1979-2015 statistics. Data for 2016 are shown in red. The ozone mass deficit is defined as the mass of ozone that would have to be added to the ozone hole in order to bring the total ozone column up to 220 DU in those areas where total ozone is less than 220 DU. The plot is made at WMO based on data downloaded from the Ozonewatch web site at NASA. The data are based on ozone observations from the OMI instrument (for recent data) and from various TOMS instruments (historical data).

Long term statistics

In order to assess the severity of the ozone hole, one can average the ozone hole area over various representative time periods. Several time periods have been used by various investigators, and four such time periods are commonly used to calculate the average ozone hole area for the years 1979 to present. Calculations are done at KNMI, based on the Multi-Sensor Reanalysis, and SCIAMACHY and GOME-2 data, and at NASA based on TOMS and OMI data. Averages for two different time periods (last ten days of September, 7 September to 13 October) have been calculated. These results are shown in **Figure 53** with results from KNMI in the left column and from NASA in the right column.

It can be seen that the ozone hole area averaged over the ten last days of September was smaller in 2016 than in 2015, yet larger than in 2012-2014. The result for 2016 is a bit smaller than the median of the ten previous years.

The ozone hole area averaged over the period 7 September to 13 October is also smaller in 2016 than in 2015, similar to 2013 and 2014 and a bit bigger than in 2010 and 2012.

Rather than looking at the area of the region where total ozone is below 220 DU one can also calculate the amount of ozone that one would have to add to the ozone hole in order to bring total ozone up to 220 DU in those regions where total ozone is inferior to this value. This quantity is called the ozone mass deficit (OMD). The result of this analysis, again based on the Multi-Sensor Reanalysis data and SCIAMACHY and GOME-2 from KNMI, is shown together with NASA data (based on OMI and TOMS) in the two lower figures of **Figure 53**. The time periods are the same as those used for the ozone hole area calculations. According to this metric, the OMD averaged over the 21-30 September time period is smaller in 2016 than in 2011 and 2015, but larger than in 2010, 2012, 2013 and 2014. Looking at OMD averaged over the 7 September to 13 October time period gives about the same result as the 21-30 September period.

All in all, these results make the 2016 ozone hole an average year in comparison to the ten previous years.

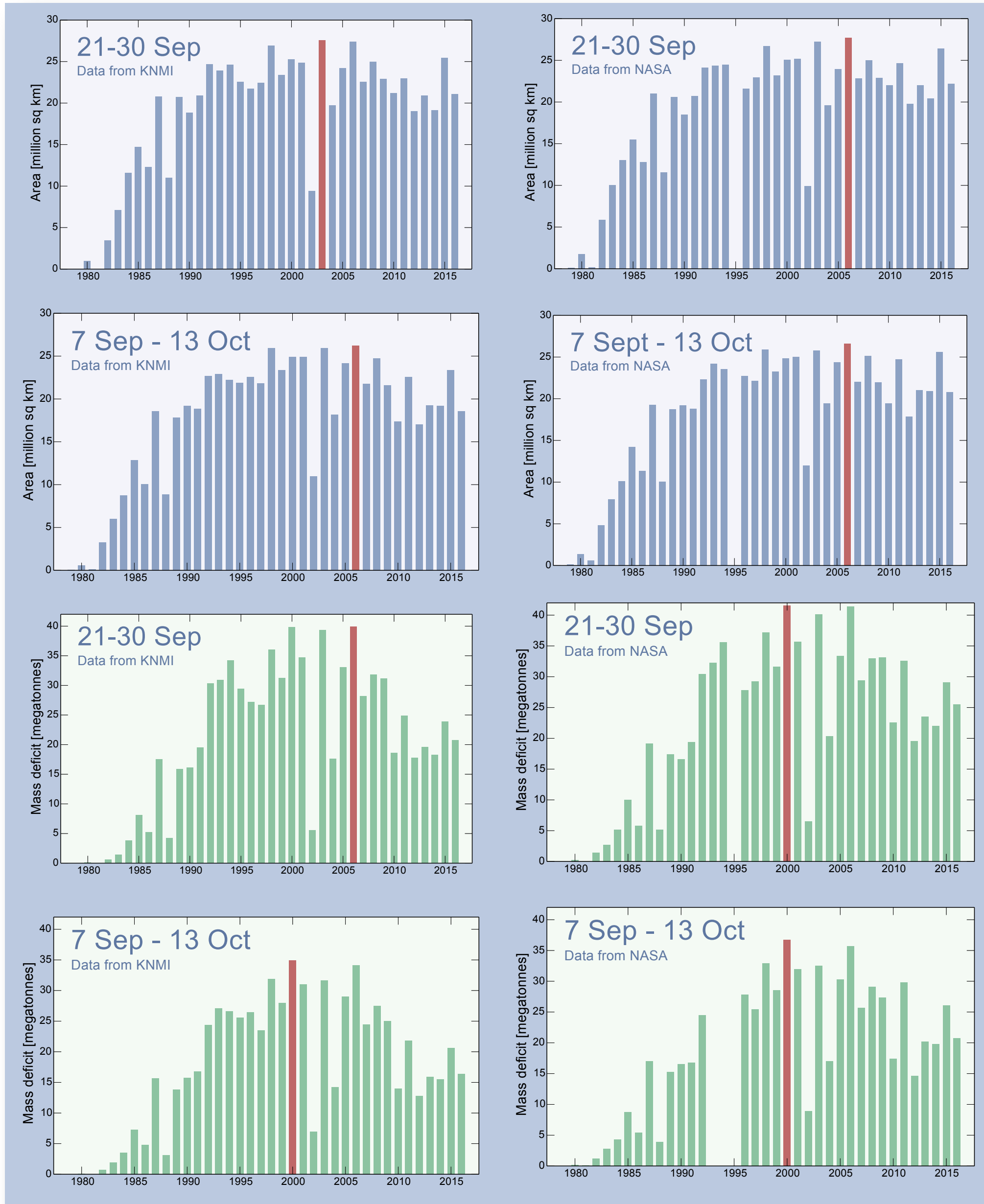


Figure 53. Two upper rows: Area of the ozone hole for the years 1979-2016, averaged over two different time periods. Two lower rows: Ozone mass deficit for the same time periods. The data for the 7 September to 13 October time period are preliminary. The plots are produced at WMO, based on data from KNMI (left column) and NASA.

UV radiation

UV radiation is measured by various networks covering the southern tip of South America and Antarctica. There are stations in Southern Chile (Punta Arenas), southern Argentina (Ushuaia) and in Antarctica (Belgrano, Marambio, McMurdo, Palmer, South Pole). Reports on the UV radiation levels will be given in futures issues when the sun comes back to the south polar regions. Links to sites with data and graphs on UV data are found in the "Acknowledgements and Links" section at the end of the Bulletin.

Distribution of the bulletins

The Secretariat of the World Meteorological Organization (WMO) distributes Bulletins providing current Antarctic ozone hole conditions beginning late August of each year. The Bulletins are available through the Global Atmosphere Watch programme web page at http://www.wmo.int/pages/prog/arep/gaw/ozone/index.html. In addition to the National Meteorological Services, the information in these Bulletins is made available to the national bodies representing their countries with UNEP and that support or implement the Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol.

Acknowledgements and links

These Bulletins use provisional data from the WMO Global Atmosphere Watch (GAW) stations operated within or near Antarctica by: Argentina (Comodoro Rivadavia, Rio Gallegos, San Martin, Ushuaia), Argentina/Finland (Marambio), Argentina/Italy/Spain (Belgrano), Australia (Macquarie Island and Davis), China/Australia (Zhong Shan), France (Dôme Concordia, Dumont d'Urville and Kerguelen Is), Germany (Neumayer), Japan (Syowa), New Zealand (Arrival Heights), Russia (Mirny, Novolazarevskaja and Vostok), Ukraine (Vernadsky), UK (Halley, Rothera), Uruguay (Artigas and Salto) and USA (South Pole). More detailed information on these sites can be found at the GAWSIS web site (http://www.empa.ch/gaw/gawsis).

Satellite ozone data are provided by NASA (http://ozonewatch.gsfc.nasa.gov), NOAA/TOVS (http://www.cpc.ncep.noaa.gov/products/stratosphere/tovsto/), NOAA/SBUV/2 (http://www.cpc.ncep.noaa.gov/products/stratosphere/sbuv2to/) and ESA/Sciamachy (http://envisat.esa.int). Satellite data on ozone, ClO, HCl and a number of other relevant parameters from the MLS instrument on the Aura satellite can be found here: http://mls.jpl.nasa.gov/plots/mls/mls_plot_locator.php and here: http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=MLS

Potential vorticity and temperature data are provided by the European Centre for Medium Range Weather Forecasts (ECMWF) and their daily T_{106} meteorological fields are analysed and mapped by the Norwegian Institute for Air Research (NILU) Kjeller, Norway, to provide vortex extent, PSC area and extreme temperature information. Meteorological data from the US National Center for Environmental Prediction (NCEP) are also used to assess the extent of PSC temperatures and the size of the polar vortex (http://www.cpc.ncep.noaa.gov/products/stratosphere/polar/polar.shtml). NCEP meteorological analyses and climatological data for a number of parameters of relevance to ozone depletion can also be acquired through the Ozonewatch web site at NASA (http://ozonewatch.gsfc.nasa.gov/meteorology/index.html).

SAOZ data in near-real time from the stations Dôme Corncordia and Dumont d'Urville can be found here:
http://saoz.obs.uvsq.fr/SAOZ-RT.html

Ozone data analyses and maps are prepared by the World Ozone and UV Data Centre at Environment Canada (http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap), by the Royal Netherlands Meteorological Institute (http://www.temis.nl/protocols/O3global.html) and by the University of Bremen (http://www.doas-bremen.de/). UV indices based on the SCIAMACHY instrument on Envisat can be found here: http://www.temis.nl/uvradiation/

UV and ozone data from New Zealand can be found here:
http://www.niwa.co.nz/our-services/online-services/uv-and-ozone

Plots of daily total ozone values compared to the long term average can be found here:
http://ftpmedia.niwa.co.nz/uv/ozone/ozone_lauder.png?1234

Forecasts of the UV Index for a number of sites, including the South Pole and Scott Base can be found here:
http://www.niwa.co.nz/our-services/online-services/uv-and-ozone/forecasts

Ultraviolet radiation data from the Dirección Meteorológica de Chile can be found here: http://www.meteochile.cl

Data on ozone and UV radiation from the Antarctic Network of NILU-UV radiometers can be found here: http://polarvortex.dyndns.org

NRT results from the BASCOE data assimilation model can be found here: ftp://ftp-ae.oma.be/dist/macc/BASCOE/NRT

The 2014 WMO/UNEP Scientific Assessment of Ozone Depletion can be found here: http://www.wmo.int/pages/prog/arep/gaw/ozone_2014/ozone_asst_report.html

Questions regarding the scientific content of this Bulletin should be addressed to Geir O. Braathen,
mailto:GBraathen@wmo.int, tel: +41 22 730 8235.

The next WMO Antarctic Ozone Bulletin is planned for 28 October 2016.