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J. Kuttippurath[1]*, **F. Lefèvre**[2], S. Raj[1], P. Kumar[1] and K. Abbhishek[1]

[1] *CORAL, Indian Institute of Technology Kharagpur, Kharagpur–721302, India.*

[2] *LATMOS/IPSL, Sorbonne Université, UVSQ, CNRS, Paris, France*

* *To whom* ***correspondence*** *should be addressed. Email:* ***jayan@coral.iitkgp.ac.in***

Short title: Ozone hole at Maitri

ADDRESS FOR COMMUNICATIONS

Prof. J. Kuttippurath

Centre for Oceans, Rivers, Atmosphere and Land Sciences (CORAL)

Indian Institute of Technology Kharagpur, 721302 Kharagpur, India.

Email: jayan@coral.iitkgp.ac.in

Phone: 0091 9475472847

HIGHLIGHTS

- First-time analysis of chemical ozone loss at Maitri station in Antarctica
- Loss amounts to 170 DU or 40–50%,as for the Antarctic vortex average
- Largest loss in 2006 and smallest in 2002 in agreement with meteorology
- Maitri measurements are representative of the Antarctic vortex measurements

Abstract

Stratospheric ozone is a trace gas of great importance as it filters harmful ultraviolet radiations reaching the earth surface. Since ozone influences temperature and dynamics of the stratosphere, it is also a climate-relevant gas. Significant changes in the stratospheric ozone are, therefore, a great concern for human health and climate. India has a polar research programme and has two research stations in Antarctica; Maitri (70.4° S, 11.4° E, since 1989) and Bharati (69.2° S, 76.2° E). Semi-regular measurements of total column ozone (TCO) are carried out to monitor the changes in the ozone layer there. Here, we use the available TCO measurements from Maitri for the winters of 1999–2003 and 2006, to estimate the chemical ozone loss for the first time at the station. We estimate the largest ozone loss (59% or 180 DU) in 2006, and smallest in 2002 and 1999 (44% or 160 DU) among the winters; consistent with the meteorology, as the winter 2006 was the coldest and 2002 was the warmest with the first-ever sudden stratospheric warming over Antarctica. The Maitri ozone loss analysis is found to be representative for the whole Antarctica as assessed from the comparison with the average TCO from all Antarctic stations and satellite overpass TCO observations. The study, henceforth, demonstrates the value and significance of continuous monitoring of the ozone hole at Maitri to assist the policy decisions such as the Montreal Protocol and its amendments and adjustments.

Key words: Antarctic ozone hole; Stratosphere; Climate Change; Maitri; Bharati

1. Introduction

Ozone is a highly reactive triatomic molecule and is abundant in the stratosphere at about 10–50 km, with its peak around 25–35 km in the tropical latitudes. The concentration of ozone in the stratosphere (i.e. the ozone layer) protects the earth from harmful ultraviolet (UV) radiations. Due to the increase in chlorofluorocarbons (CFCs) in the atmosphere after industrialisation, stratospheric ozone started to decline in the polar regions by late 1970s (Farman et al., 1985; Bodeker et al., 2005; Müller et al., 2008; WMO, 2018). Measurements from the ground and space have confirmed that the depletion of ozone layer started in the late 1970s and deepened further and reached a point of saturation in the Antarctic in the early 1980s (Kuttippurath et al., 2018a). The space-based total column measurements exposed the spatial extent of ozone hole (Stolarski et al., 1986). This situation in Antarctica lead to the seasonal ozone loss and appearance of ozone hole over there (WMO, 2014). Since the stratospheric temperatures are lower, polar vortex is stronger and polar stratospheric clouds (PSCs) are more frequent and widespread, the ozone loss is strong in Antarctica as compared to that of the Arctic (WMO, 2018). The ozone loss is observed to be significant only in the colder Arctic winters such as 1995, 1996, 2000, 2005, 2011 and 2020 (Manney et al., 2011, 2020; Rex et al., 2004). In Antarctica, the ozone loss is severe in all winters and show similar loss of about 45–55% or around 175 DU (Kuttippurath et al., 2013; Sonkaew et al., 2013; Tilmes et al., 2006; Huck et al., 2004). There were a few exceptions to this too, such as the winters with significant warming in 1988, 2002 and 2019 (e.g. Kanzawa and Kawaguchi, 1990; Kuttippurath et al., 2015).

Significant reduction in ozone has also been observed in the mid-latitudes due to the high levels of halogen compounds in the atmosphere since the 1980s (Steinbrecht et al., 2011; Nair et al., 2013; Tully et al., 2015; WMO, 2018). Studies observe a decrease in ozone of about -0.7%/yr in the mid-latitudes and 4–5% in the subtropics prior to 1997 during which the halogens peaked in the mid-latitudes (Nair et al., 2015; Krzyścin, 2012; Steinbrecht et al., 2006; WMO, 2018). However, recovery of ozone is found afterwards, about −0.2±0.08 to −1±0.07%/yr in the mid-latitudes and −0.2±0.06 to −0.7±0.05%/yr in the subtropics in the upper stratosphere (e.g. Nair et al., 2015). Similar estimates were also found in other long-term ozone trend studies for the mid-latitudes (e.g. Weber et al., 2018; WMO, 2018). The increase in ozone is attributed to the dynamics related to the quasi-biennial oscillation, El Niño–Southern Oscillation. Therefore, the mid-latitude and low latitude ozone change will be decided by the dynamics and the amount of stratospheric chlorine in the regions (e.g. Randell et al., 2002). On the other hand, the ozone changes in the high latitudes were attributed to the reduction in halogen loading in the atmosphere (e.g. WMO, 2018). Also, there is a clear reduction in frequency for the occurrence of ozone loss saturation over the period 2001–2017 in the Antarctic, which underlines the impact of phasing out of ozone-depleting substances (ODSs) through Montreal protocol (Kuttippurath et al., 2018a). Although statistically significant positive trends are observed in the Antarctic (e.g. Chipperfield et al., 2017; Kuttippurath and Nair, 2017; Solomon et al., 2016; Salby et al., 2015), no clear trends are found in the Arctic ozone due to large dynamical variability there.

India has three research bases in Antarctica: the first station was established in 1980 as Dakshin Gangotri (70.4° S, 11.4° E), Maitri (70.4° S, 11.4° E) in 1989 and Bharati (69.2° S, 76.2° E) in 2012, and the latter two are only currently active. The Ministry of Earth Science (MoES) of India and its operational and research agencies make different types of observation at the stations. The station Maitri is located in the rocky coasts of Queen Maud Land at the edge of the Antarctic continent, which is devoid of snow throughout the year and experiences wind from both ocean and inland (Ganguly, 2012). There are semi-regular total column ozone (TCO) measurements at Maitri since the early 1990s using Brewer Spectrophotometer. There are studies using ozone measurements from Maitri, but mostly discussed the seasonal and interannual changes in ozone, and their relationship with meteorology such as temperature, pressure and winds (e.g. Ali et al., 2017; Ganguly and Joel, 2010; Ghude et al., 2005; Lal and Ram, 2013). In a long-term study using ground-based and satellite datasets for the period 1979–2001, the seasonal variation in TCO over Maitri was found to be more pronounced than other temporal variability. The study also found a declining trend in the monthly average TOC during the period 1979–1988 and was attributed to the increased CFCs in the stratosphere (Ganguly and Joel, 2010). In another study, TOC measured at Maitri showed good agreement with stratospheric temperature anomaly (Ghude et al., 2006, 2005). Although, there are studies using Maitri ozone measurements, the chemical ozone loss was never estimated with these measurements. The primary goal of the ozone measurements in Antarctica is ozone loss estimation and monitoring the temporal changes of ozone hole. Therefore, we estimate the chemical ozone loss analyses using the available measurements (6 years) of Maitri TCO measurements.

2. Methods

2.1 Ground-based and satellite measurements

Since we estimate ozone loss at Maitri, we use the ground-based measurements from the station in the Antarctic. Measurements from other Antarctic stations are also considered to compare with that of Maitri (e.g. Kuttippurath et al., 2013). The co-coordinates of the stations including Maitri are shown in **Figure 1.** The figure also shows the potential vorticity (PV) maps on 22 September 2002 as the vortex was very much disturbed with a major warming and on

24 September 2006, when the Antarctic experienced the biggest ozone hole ever in the observed history. In both occasions, the Maitri station was inside the polar vortex, suggesting that the station is pretty much inside the vortex in most dynamical conditions. However, please note that the vortex position will be different at different altitudes. We use the measurements made by the Brewer Spectrometer (MkIV, 153) at Maitri. Brewer instruments employ differential absorption of ozone in the UV region for ozone measurements (Brewer et al., 1973). Individual observations are made by looking at the direct sun on a clear sky and are averaged to a daily mean and the measurements are limited to SZA (solar zenith angle) <80°. The measurements are better than that of the Dobson measurements and accuracy of the instruments are about 0.5% of TCO or 1 DU (Scarnato et al., 2010; Kuttippurath et al., 2018b). A comprehensive study on polar ozone measurements by different instruments with a detailed analysis on their strength and limitations are presented in Kuttippurath et al. (2018b).

We have used the winter measurements in Antarctica, which are considered from May through November. On the other hand, most Maitri measurements are performed during winter and spring months as compared to other stations in the Antarctic. The measurements are available for the years 1999–2006. However, the measurements in 2004 and 2005 were during the summer, which are not considered as we estimate the ozone loss in winter and spring. There are 40–64 days of measurements in each year and are mostly during the period September–November, because the observations were primarily aimed at monitoring the changes in Antarctic ozone hole. Additionally, the Brewer measurements are limited to the availability of sunlight and depend on SZA, which is why most measurements are done in spring.

The ground-based measurements at Maitri are compared to the TOMS (Total Ozone Mapping Spectrometer) and OMI (Ozone Monitoring Instrument) measurements of the respective years. The TOMS retrievals make use of two wavelengths: 331.2 and 360 nm, but 270–500 nm for OMI. The measurements during the period 1999–2003 are compared to the version 8.5 TCO from TOMS on-board Earth Probe (Wellemeyer et al., 2002). The 2006 measurements are however, compared to the OMI measurements as the TOMS instrument was not operational from 2005 onwards (e.g. McPeters et al., 2015). The uncertainty of satellite measurements (both TOMS and OMI) is about ±1–3% or the mean bias is about ±4 DU, which depends on the station and satellite instrument for for SZA < 84° (Kuttippurath et al., 2018b; Kroon et al., 2008; Balis et al., 2007; Leveltet al., 2006).

2.2 Ozone loss calculation

We apply the passive method (Goutail et al., 2005; Kuttippurath et al., 2010) to estimate ozone loss from TCO measurements at Maitri and other stations. However, note that there are different methods for estimating the ozone loss, as discussed in Harris et al. (2002). The method uses a passive tracer simulated by a chemical transport model (CTM) and we use the REPROBUS model simulations for the passive tracer simulations (Lefèvre et al., 1998). It is a three-dimensional CTM with a comprehensive description of stratospheric chemistry. The model runs were forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses, with 60 vertical levels from 1000 to 0.1 hPa. The model uses the hybrid sigma-pressure vertical coordinate and vertical advection is computed directly from the wind fields. Chemical species are transported by a semi-Lagrangian method (Williamson and Rasch, 1989). Note that we have considered only the passive tracer simulations from the model results. The tracer is initialised on first of July so that the ozone loss on that day would be zero. The chemical ozone loss is then estimated by subtracting the passive tracer from TCO measured by the ground-based instrument at respective stations.

Large changes in ozone in the polar regions are very much related to the circumpolar circulation, position of polar vortex, and the special meteorology related to the vortex in winter and spring there (e.g. Hood and Soukharev, 2005; Huck et al., 2004; Solomon, 1999). The polar vortex acts as a containment vessel and is effectively separated from the mid-latitude air. Very low temperatures inside the vortex and high winds at the edge of the vortex are the key feature of this dynamical system. This situation facilitates the formation of PSCs and the high winds at the vortex edge prevent mixing of air masses from the adjacent middle latitude regions (e.g., Drdla and Müller, 2012). This makes a unique heterogeneous chemistry inside the vortex and set conditions for chlorine activation and ozone loss. Therefore, the ozone loss has to be estimated within the vortex. We have used the ECMWF meteorological files (Dee et al., 2011) to compute the potential vorticity (PV) and then to estimate the edge of the vortex using the method defined by Nash et al. (1996) to segregate the vortex measurements. To avoid the PV filaments in vortex edge calculation, we have also used additional criteria of 35 PV units (pvu, and one pvu is $10^{-6}\,\mathrm{K m^2\,kg^{-1} s^{-1}}$) and 63° Equivalent Latitude (EqL, Müller et al., 2005). That is, the measurements are considered to be inside the vortex, when they satisfy the conditions of Nash et al. (1996) vortex edge criterion, > 35 pvu and > 63° S EqL conditions.

3. Results and Discussion

3.1 Meteorology of the winters

The Maitri station is located at 70° S, which is almost inside the polar vortex in most winters. **Figure 2** shows the average polar cap temperature in the Antarctic for different winters at 70 and 100 hPa. The temperature at 70 hPa (in the lower stratosphere) show about 195 K from July to mid-September in all winters, which gradually increases until the end of November. The temperatures from mid-September to November normally decide the ozone loss chemistry in the lower stratosphere and final warming of Antarctic winters. The temperatures below 195 K facilitate the formation of polar stratospheric clouds (PSCs) on which the halogens would be activated and make ozone loss when the vortex would be exposed to sunlight in spring. The evolution of lower stratospheric temperature is different in each winter (Kuttippurath et al., 2013; Tilmes et al., 2006; Huck et al., 2005). For instance, the temperature increases from 195 K in mid-September to 206–212 K by the end of November in 1999, 2001, 2003, and 2006. However, PSCs can still be present and thus, chlorine activation can drive ozone loss during the period (Grooß et al., 2011; Müller et al., 2018). There were minor warmings in early September 2000 and mid-September in 2006, about 2–5 K. Conversely, the winter 2002 was dynamically disturbed from July onwards with minor warmings and then this particular dynamical situation finally lead to a major warming with a vortex split event on 25 September 2002 (e.g. Hoppel et al., 2003). This was the first-ever vortex split major warming event recorded in the measurement era. The temperature increased from 198 to 217 K from mid- to the end of September in that winter. Therefore, the warmest was 2002 and the coldest was 2006 among the analysed winters. The evolution of temperature is similar at 100 hPa, but about 3 K higher until mid-September and about 1–5 K smaller afterwards, depending on the winter. These dynamical conditions are also reflected in the TCO measured from satellites (TOMS–OMI) as illustrated in **Figure 2**.

The winters show minor warmings in mid-September and consequently resulted in distortion or elongation of the polar vortex in 2000, 2001, 2003 and 2006. However, a very quiet and calm September was evident in 1999 and therefore, an undisturbed, concentric and circular polar vortex is evident in that winter. In 2002, the first-ever vortex split event occurred in the southern polar region and is clearly captured by TCO map, as shown in Figure 2. Apart from that, we also wanted to show the position of Maitri station in different types of vortex disturbances. The maps depict that the station is always inside the vortex even during the vortex split event. This would make the station ideal for ozone loss and ozone trend studies in the southern polar region. We have also marked the Indian station Bharti in the maps to compare the position of both stations in terms of their vortex representation. It exhibits that Bharti station resides at the vortex edge on most occasions when the vortex is slightly disturbed. Note that we have shown the TCO with ozone hole 220 DU contour, not the vortex edge to demonstrate the position of polar vortex in the maps.

3.2 Temporal evolution of ozone

Figure 3 shows the ozone measurements at Maitri compared to the TOMS–OMI and the average of all ground-based station measurements (without Maitri) in Antarctica. In general, the Maitri measurements are made in September, October and November months. Therefore, the measurements show below 220 DU in September and early October. The measurements in November or even mid-October onwards show large interannual variability. This is an expected result as the minimum ozone in Antarctica usually occurs during the period (Huck et al.,2005; Müller et al., 2008; Grooß et al., 2011; Kuttippurath et al., 2013). Ozone increases gradually afterwards due to mixing with the mid-latitude air. Therefore, the ozone shows a steep decline in September, from about 250–200 DU to 150–110 DU, depending on winters. The smallest ozone measurements in the winter are found in October, about around 100–120 DU in the coldest winters of 1999, 2003 and 2006. However, the ozone values show a slight increase (10–20 DU) from mid-October onwards such as in 2000. The November measurements exhibit ozone values between 150 and 300 DU in different winters. The situation in warm winters is slightly different as shown by the ozone distribution in 2002. As demonstrated by temperature, the winter was highly disturbed with minor warmings from July through September and then ended up with a major warming in late September with a vortex split. Therefore, excursion of vortex to mid-latitudes, and distortion, elongation and split of the vortex would cause such large and episodic changes in ozone distribution. There was an unusual chlorine deactivation, which is also one of the reasons of the high ozone values in 2002 (Grooß et al., 2005). The intermittent high values of ozone throughout the winter months show the intense dynamical activity in the winter. Also, the high ozone values associated with the minor warmings in other winters (e.g. late September in 1999 and mid-September in 2006) and final warming (e.g. end of November in 2001, 2002 and 2003) are clearly captured by the Maitri measurements. A similar distribution of ozone can be also found in the measurements at the Sejong station (62° S, 58° W) in the western Antarctica (Koo et al., 2018). Note that the total ozone changes inside the vortex are largely decided by diabatic descent inside the vortex, the adiabatic motions related to planetary wave activity, and convergence or divergence related to the changes of tropospheric height. Therefore, the variations of ozone values are expected in daily measurements due to the dynamics.

Figure 3 also shows the comparison between Maitri measurements and TOMS-OMI overpass ozone measurements at Maitri. In addition, the Maitri measurements are also compared to the average of all other ground-based station measurements in Antarctica. The details of other station measurements are given in Figure 1 and Table 1 of Kutippurath et al. (2013). However, please note that we have exempted Dumont d'Urville and Concordia measurements from the averaged data. Therefore, the other seven station measurements are used for the station average. The averaged data show the complete evolution of ozone in the winter, as the Maitri data start only in September. The comparison with station-averaged data with Maitri data would allow us to assess the spatial variability of TOC in Antarctica and representativeness of the individual station measurements (e.g. Maitri) for the entire region. On top of these, the use of multiple data displays the synergetic use of various types of observations for better interpretation of analysed results.

The TOMS-OMI measurements start by mid-August over the Antarctica and the overpass at Maitri shows good agreement with the ground-based observations throughout the winters. The differences are mostly within 5%, which is also the uncertainty of the satellite overpass measurements (McPeters et al., 2008; Kroon et al., 2008; Kuttippurath et al., 2018b). Nevertheless, the difference between the Brewer and satellite measurements at Maitri is slightly larger during warming periods as shown by the measurements in November 2003 and 2006. Previous analyses have also found similar results when ground-based measurements are compared to the satellite measurements. For example, Balis et al. (2007) found an overestimation (about 2%) of TOMS measurement with ground-based measurements in the southern hemisphere. Similar results were also found when satellite measurements were compared to that of ground-based measurements in the southern latitudes for the period 1996–2000, where the estimation was about 3.3% (Bramstedt et al., 2003). An analogous result was observed when Zhongshan measurements were compared to EP-TOMS measurements for which the satellite measurements were 2.55% higher than that of ground-based measurements. The OMI measurements were also found to be overestimated (2–7%) the ground-based measurements at Marambio and Belgrano (Balis et al., 2007; Kuttippurath et al., 2018b). The satellite overpass measurements are the area-averaged value of about 100 km, which would be slightly different from the point-measurements made by the Brewer or ground-based instrument at the station. In addition, when the temperature increases in spring, the ozone loss stops and ozone hole reduces its size by November. This vortex erosion would be another reason of the differences between ground-based and space-based observations in spring and during warm winters.

On the other hand, the all station averaged data show the complete seasonal evolution of TOC in Antarctica. The ozone starts to decrease in early July, the reduction in ozone gradually progresses in August and the rate of decrease peaks in September. The lowest ozone values are observed during the end of September and early October, and the ozone picks up due to mixing with mid-latitude air afterwards until the end of November, as also found in the Maitri ground-based measurements. The station average and Maitri data show very good agreement up to the minimum ozone period (early October). The average data show slightly higher values as these data include measurements from the edge stations such as Marambio, Rothera and San Martin, where the ozone values are relatively higher than other stations (e.g. Kuttippurath et al., 2013; Zhang et al., 2017). As stated previously, the planetary wave activity can disturb the polar vortex at times, which would make some stations outside the vortex (e.g. Marambio and Rothera) and thus show slight differences in ozone measurements between satellite and ground-based measurements during warming periods and at the end of spring, as found in the figure.

3.3 Chemical ozone loss in the winters 1999–2003 and 2006

We have analysed the ozone loss in 6 winters; 1999–2003 and 2006, and have averaged the ozone loss values for 7 days to suppress the daily variations in ozone to make a more robust ozone loss estimate. In 1999, the winter was not very cold as compared to other winters. The measurements are mostly restricted to October and November, and there is a constant ozone loss of about 150 DU during the period. In 2000, the ozone loss was 60 DU in August and it increased to 130 DU in early September and peaked to 160 DU by end of September. The ozone loss in 2001 was very severe and the loss was about 60 DU in mid-August, 80 DU in early September and the loss peaked by early October to 160 DU. The ozone loss in the warm winter also show a similar loss of about 170 DU in October. The ozone loss evolution shows similar features and loss values in 2003 and 2006, about 80 DU in September to 150–160 DU in October. The loss in peak period in October was relatively higher in 2006 and 2003, about 170 DU. The maximum ozone loss is generally found in early October as the PSCs terminates with relatively higher temperatures during the period.

We have also estimated the peak ozone loss in relative units for the period 15 September – 15 October (ozone loss/passive tracer multiplied by 100). The maximum loss estimated in 1999 is about 43% in 1999, 57% in 2000, 56% in 2001, 46% in 2002, 57% in 2003 and 59% in 2006. The ozone loss in 2002 was slightly different from other winters, as the winter was warmer than all other winters. The year witnessed the first major warming with a vortex split event in the observational record, which occurred on 25 September 2002. The ozone loss shows a sharp decline afterwards (e.g. Feng et al., 2005; Kuttippurath et al., 2013). Therefore, the ozone loss was similar to that of other winters and the peak ozone loss in DU observed by mid-September was lower (10–20 DU) than that of other winters, about 46%.

The ozone loss estimated at Maitri compares very well with TOMS-OMI satellite measurements (mostly within 2 DU) in all winters, as also shown in Kuttippurath et al. (2010, 2013). It is interesting to note that the ozone loss estimated at Maitri is very similar to that of the all station average of other ground-based measurements in Antarctica. The differences are mostly about 1–2 DU throughout the winter, except for one or two measurements in some winters such as the loss estimated at Maitri for November 2003. This suggests that the Maitri measurements are representative of the entire Antarctic vortex and the measurements are highly valuable for monitoring the temporal changes in the Antarctic ozone hole. The ozone loss estimated for the winters show comparable values to that estimated by previous studies.

For instance, our results are comparable to the values estimated by Huck et al. (2007) and are about 105–120±10 DU for the winters discussed. The ozone loss at Maitri for the winters 1999 and 2000 are also comparable to that found from the POAM satellite measurements (Hoppel et al., 2003) and SLIMCAT model simulations (Feng et al., 2005), as they also estimate similar ozone loss values. Our analyses are in good agreement with the partial column loss estimated (130–145±10) by Tilmes et al. (2006) for 1996 and 2003. The Maitri results are in very good agreement with that of Kuttippurath et al. (2013) as they also estimate a loss of about 150-170±10 DU for the winters 1999–2003 and 2006. However, our results for 2000–2001 are also comparable to the total column ozone loss estimated by Sinnhuber et al. (2002) and the partial column ozone loss found in Strahan and Douglas (2018).

4. Conclusions

India has a well-planned polar research programme and has ozone measurements since 1990s in Antarctica. We have considered TCO measurements from the Maitri station of Antarctica. The winter TCO measurements by the Brewer instrument are used for the winters 1999–2003 and 2006. The winters 2000, 2001, 2003 and 2006 were colder winters of Antarctica, and 2006 was coldest among them, in which the largest ozone hole was observed. Therefore, ozone loss amounted to 170 DU or 57–59% in 2006. The winters 1999 and 2002 were relatively warm and thus ozone loss was restricted, about 43–46%, and the winter 2002 experienced the first vortex split event in the southern polar region in the observational era. This dynamical situation led to the smallest ozone hole with lower ozone loss (43% in September) in that winter. The observed ozone loss matches very well with the all station average that includes measurements from nine stations in the Antarctic continent; implying that the Maitri measurements very much represent the ozone loss of the entire Antarctic region. This suggest that the station is inside the polar vortex in most winters. However, the differences in spring measurements and during warming periods indicate that the erosion of polar vortex. The analyses presented suggest the continued monitoring of ozone in the region to monitor one of the important trace gases on the earth that influences public health and changes in climate.

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Data availability

The data used in this study are publicly available (https://woudc.org/). The analyses codes can be provided on request. The OMI data are available on https://earthdata.nasa.gov/earth-observation-data/near-real-time/download-nrt-data/omi-nrt. Since the satellite data used are already freely available on public domains, the analysed data can also be provided for any scientific study.

Code availability

The analyses codes are available on request.

Competing Interests

The authors confirm that there are no known conflicts of interest and no competing interests.

References

Ali, K., Trivedi, D.K., Sahu, S.K., 2017. Surface ozone characterization at Larsemann Hills and Maitri, Antarctica. Sci. Total Environ. 584–585, 1130–1137, https://doi.org/10.1016/j.scitotenv.2017.01.173.

Balis, D., M. Kroon, M.E. Koukouli, E.J. Brinksma, G. Labow, J.P. Veefkind, R.D. McPeters, 2007. Validation of Ozone Monitoring Instrument Total Ozone Column Measurements Using Brewer and Dobson Spectrophotometer Ground-Based Observations. J. Geophys. Res. 112, doi:10.1029/2007JD008796.

Basher R.E. (1985) Review of the Dobson Spectrophotometer and its Accuracy. In: Zerefos C.S., Ghazi A. (eds) Atmospheric Ozone. Springer, Dordrecht. https://doi.org/10.1007/978-94-009-5313-0_78.

Bramstedt, K., J. Gleason, D. Loyola, W. Thomas, A. Bracher, M. Weber, J.P. Burrows, 2003. Comparison of total ozone from the satellite instruments GOME and TOMS with measurements from the Dobson network 1996–2000. Atmos. Chem. Phys. 3 1409-1419

Brewer, A.W., Mcelroy, C.T., Kerr, J.B., 1973. Nitrogen dioxide concentrations in the atmosphere. Nature 246, 129–133.

Chipperfield, M. P., S. Bekki, S. Dhomse, N. R. P. Harris, B. Hassler, R. Hossaini, W. Steinbrecht, R. Thiéblemont, M. Weber, 2017. Detecting Recovery of the Stratospheric Ozone Layer. Nature 549, 211–218. doi:10.1038/nature23681.

Chipperfield, M. P., Dhomse, S. S., Feng, W., McKenzie, R. L., Velders, G. J. M., and Pyle, J. A.: Quantifying the ozone and ultraviolet bene_ts already achieved by the Montreal Protocol,

Nat. Commun. 6, 7233, https://doi.org/10.1038/ncomms8233, 2015.
Dee, et al., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. Roy. Meteorol. Soc. 137, 553–597.
Drdla, K. and Müller, R., 2012. Temperature thresholds for chlorine activationand ozone loss in the polar stratosphere. Ann. Geophys. 30, 1055–1073, https://doi.org/10.5194/angeo-30-1055-2012.
Farman, J. C., Gardiner, B.G., Shanklin, J.D., 1985. Large losses of total ozone in Antarctica reveal seasonal ClO x/NOx interaction. Nature 315, 207–210.
Feng, W. et al., 2005. Three-dimensional model studyof the Arctic ozone loss in 2002/2003 and comparison with 1999/2000 and 2003/2004. Atmos. Chem. Phys. 5, 139–152.
Ganguly, N.D., 2012. Comparative Study of the Influence of Air Pollution on UVI at Maitri in Antarctica and New Delhi in India 2012. International Schol. Res. Notes 2012, https://doi.org/10.5402/2012/315859.
Ganguly, N.D., Joel, V., 2010. Long Term Trend, Diurnal and Seasonal Variations of Atmospheric Ozone at Indian Antarctic Station Maitri, Earth Science India 3, 174-180.
Ghude, S.D., Jain, S.L., Kulkarni, P.S., Kumar, A., Arya, B.C., 2006. Year-to-year variation of ozone hole over Schirmacher region of East Antarctica: A synopsis of four-year measurement, Indian Journal of Radio Space Physics 35, 253–258.
Ghude, S.D., Kumar, A., Jain, S.L., Arya, B.C., Bajaj, M.M., 2005. Comparative study of the total ozone column over Maitri, Antarctica during 1997, 2002 and 2003. Int. J. Remote Sens. 26, 3413–3421.
Grooß, J.-U., Konopka, P., and Müller, R.: Ozone chemistry during the 2002 Antarctic vortex split, J. Atmos. Sci., 62, 860–870, 2005.
Grooß, J.-U., Brautzsch, K., Pommrich, R., Solomon, S., and Müller, R., 2011. Strato-spheric

ozone chemistry in the Antarctic: What controls the lowest values thatcan be reached and their recovery?, Atmos. Chem. Phys. 11, 12217–12226.

Goutail, F. et al., 2005. Early unusual ozoneloss during the Arctic winter 2002/2003 compared to other winters. Atmos. Chem. Phys. 5, 665–677, doi:10.5194/acp-5-665-2005, 2005.10778,10789

Harris, N. R. P. et al., 2002. Comparison of empirically derived ozone lossrates in the Arctic vortex. J. Geophys. Res. 107, 8264, https://doi.org/10.1029/2001JD000482.

Hood, L. L., B. E. J. Soukharev, 2005. Interannual Variations of Total Ozone at Northern Midlatitudes Correlated with Stratospheric EP Flux and Potential Vorticity. J. Atmos. Sci. 62, 3724–3740. doi:10.1175/JAS3559.1.

Hoppel, K., Bevilacqua, R., Allen, D., Nedoluha, G., Randall, C., 2003. POAM III observations of the anomalous 2002 Antarctic ozone hole. Geophys. Res. Lett. 30, https://doi.org/10.1029/2003GL016899.

Huck, P. E., McDonald, A. J., Bodeker, G. E., Struthers, H., 2005. Interannual variability in Antarctic ozone depletion controlled by planetary waves and polar temperature. Geophys. Res. Lett. 3, doi:10.1029/2005GL022943.

Kanzawa, H., Kawaguchi, S., 1990. Large stratospheric sudden warming in Antarctic late winter and shallow ozone hole in 1988: observation by Japanese Antarctic Research Expedition. Dyn. Transp. Photochem. middle Atmos. South. Hemisphere. Proc., Work. San Fr. 1989 135–148.

Kuttippurath, J., Godin-Beekmann, S., Lefèvre, F., Santee, M.L., Froidevaux, L., Hauchecorne, A., 2015. Variability in Antarctic ozone loss in the last decade (2004–2013): high-resolution simulations compared to Aura MLS observations. Atmos. Chem. Phys 15, 10385–10397.

Kuttippurath, J., Lefèvre, F., Pommereau, J.-P., Roscoe, H.K., Goutail, F., Pazmiño, A., Shanklin, J.D., 2013. Antarctic ozone loss in 1979–2010: first sign of ozone recovery. Atmos. Chem. Phys. 13, 1625–1635.

Kuttippurath, J. and Nair, P. J., 2017. The signs of Antarctic ozone hole recovery, Sci. Rep., 7, 585, https://doi.org/10.1038/s41598-017-00722-7.

Kuttippurath, J. et al., 2018a. Emergence of ozone recovery evidenced by reduction in the occurrence of Antarctic ozone loss saturation. npj Clim. Atmos. Sci. 1, 42, https://doi.org/10.1038/s41612-018-0052-6

Kuttippurath, J., Kumar, P., Nair, P.J., Chakraborty, A., 2018b. Accuracy of satellite total column ozone measurements in polar vortex conditions: Comparison with ground-based observations in 1979–2013. Remote Sens. Environ. 209, 648–659.

Koo, J. H., et al., 2018. Total ozone characteristics associated with regional meteorology in West Antarctica. Atmos. Environ. 195, 78–88. https://doi.org/10.1016/j.atmosenv.2018.09.056

Kroon, M., Veefkind, J.P., Sneep, M., McPeters, R.D., Bhartia, P.M., Levelt, P.F., 2008. Comparing OMI-TOMS and OMI-DOAS total ozone column data, J. Geophys. Res. 113, D16S28, doi:10.1029/2007JD008798.

Krzyścin, J. W., 2012. Onset of the total ozone increase based on statistical analyses of global ground-based data for the period 1964–2008. Int. J. Climatol. 32, 240–246, doi:10.1002/joc.2264.

Lal, R. P., Ram, S., 2013. Compilation of ozonesonde observation over Schirmacher oasis east Antarctic from 1999–2007, Mausam 64, 613–624.

Lefèvre, F., Figarol, F., Carslaw, K.S., Peter, T., 1998. The 1997 Arctic ozone depletion quantified from three-dimensional model simulations. Geophys. Res. Lett. 25, 2425–2428.

Levelt, P.F., van den Oord, G.H.J., Dobber, M.R., Mlkki, A., Visser, H., de Vries, J.,Stammes, P., Lundell, J., Saari, H., 2006. The Ozone Monitoring Instrument. IEEETrans. Geosci. Remote Sens. 44, 1093–1101.

Manney et al., 2011. Unprecedented Arctic ozone lossin 2011. Nature 478, 469–475, doi:10.1038/nature10556, 2011.

McPeters, R., M. Kroon, G. Labow, E. Brinksma, D. Balis, I. Petropavlovskikh, J. P. Veefkind, P. K. Bhartia, and P. F. Levelt, 2008. Validation of the Aura Ozone Monitoring Instrument total column ozone product. J. Geophys. Res. 113, D15S14, doi:10.1029/2007JD008802

McPeters, R. D., S. Frith, G. J. Labow., 2015. OMI Total Column Ozone: Extending the Long-Term Data Record. Atmos. Meas. Tech. 8, 4845–4850, doi:10.5194/amt-8-4845-2015.

Müller, R., Grooß, J.-U., Lemmen, C., Heinze, D., Dameris, M., and Bodeker, G., 2008. Simple measures of ozone depletion in the polar stratosphere. Atmos.Chem. Phys. 8, 251–264.

Müller, R., Grooß, J.-U., Zafar, A. M., Robrecht, S., and Lehmann,R., 2018. The maintenance of elevated active chlorine levels in theAntarctic lower stratosphere through HCl null cycles. Atmos. Chem.Phys. 18, 2985–2997, https://doi.org/10.5194/acp-18-2985-2018,

Nair, P.J., Froidevaux, L., Kuttippurath, J., Zawodny, J.M., Russell, J.M., Steinbrecht, W., Claude, H., Leblanc, T., Gijsel, J.A.E., Johnson, B., Swart, D.P.J., Thomas, A., Querel, R., Wang, R., Anderson, J., 2015. Subtropical and mid-latitude ozone trends: implications for recovery. J. Geophys. Res. 120, 7247–7257, doi:10.1002/2014JD022371.

Nair, P.J., et al., 2013. Ozone trends derived from the total column and vertical profiles at a northern mid-latitude station. Atmos. Chem. Phys. 13, 10373–10384.

Nash, E.R., Newman, P.A., Rosenfield, J.E., Schoeberl, M.R., 1996. An objective determination of the polar vortex using Ertel's potential vorticity, J. Geophys. Res. 101, 9471–9478, 1996.

Randel et al., 2002. Changes in Column Ozone Correlated with the Stratospheric EP Flux. J. Meteorol. Soc. Japan 80, 849–862.

Rex, M., Salawitch, R.J., von der Gathen, P., Harris, N.R.P., Chipperfield, M.P., Naujokat, B., 2004. Arctic ozone loss and climate change. Geophys. Res. Lett. 31, L04116,doi:10.1029/2003GL018844, 2004.

Salby, M., Titova, E., Deschamps, L., 2011. Rebound of Antarctic ozone. Geophysical Research Letters 38(9). doi:10.1029/2011GL047266

Scarnato, B., Staehelin, J., Stübi, R., Schill, H., 2010. Long-term total ozone observationsat Arosa (Switzerland) with Dobson and Brewer instruments (1988–2007). J.Geophys. Res. 115 (D13).

Sonkaew, T. et al., 2013. Chemicalozone losses in Arctic and Antarctic polar winter/spring season derived from SCIAMACHY limb measurements 2002–2009, Atmos. Chem.Phys. 13, 1809–1835, https://doi.org/10.5194/acp-13-1809-2013.

Solomon, S.: Stratospheric ozone depletion: A review of concepts and history,Rev. Geophys. 37, 275–316, https://doi.org/10.1029/1999RG900008, 1999.

Solomon, S., Ivy, D.J., Kinnison, D., Mills, M.J., Neely, R.R., Schmidt, A., 2016. Emergence of healing in the Antarctic ozone layer. Science 353, 269–274.

Steinbrecht, W. et al., 2006. Long-term evolution of upper stratospheric ozone at selected stations of the Network for the Detection of Stratospheric Change (NDSC). J. Geophys. Res. 111, https://doi.org/10.1029/2005JD006454.

Stolarski, R. S. et al., 1986. Nimbus 7 satellite measurements of the springtimeAntarctic ozone decrease, Nature 322, 808–811, 1986.

Strahan, S.E., A.R. Douglass, 2018. Decline in Antarctic Ozone Depletion and Lower

Stratospheric Chlorine Determined from Aura Microwave Limb Sounder Observations. Geophys. Res. Lett. 45, 382–390. doi:10.1002/2017GL074830.

Tilmes, S., Müller, R., Engel, A., Rex, M., Russell III, J., 2006. Chemical ozone loss in the Arctic and Antarctic stratospherebetween 1992 and 2005. Geophys. Res. Lett. 33, L20812, doi:10.1029/2006GL026925.

Tully, M. B., A.R. Klekociuk, S.K. Rhodes, 2015. Trends and Variability in TotalOzone from a Mid-Latitude Southern Hemisphere Site: The Melbourne Dobson Record 1978–2012. Atmosphere-Ocean 53, 58–65, doi: 10.1080/07055900.2013.869192

Weber, M. et al., 2018. Total Ozone Trends from 1979 to 2016 Derived from Five Merged Observational Datasets – The Emergence into Ozone Recovery. Atmos. Chem. Phys. 18, 2097–2117, doi:10.5194/acp-18-2097-2018.

Wellemeyer, C.G., Bhartia, P.K., Taylor, S.L., Qin, W., Ahn, C., 2004. Version 8 Total Ozone Mapping Spectrometer (TOMS) Algorithm, paperpresented at Quadrennial Ozone Symposium, Eur. Comm., Kos, Greece.

Williamson, D.L., Rasch, P.J., 1989. Two-Dimensional Semi-Lagrangian Transport with Shape-Preserving Interpolation. Mon. Weather Rev. 117, 102–129.

World Meteorological Organization (WMO), 2014. Scientific Assessment of Ozone Depletion: 2014 Global Ozone Research and Monitoring Project—Report No. 55, Geneva, Switzerland.

World Meteorological Organization (WMO), 2018. Scientific assessment of ozone depletion: 2018, Global Ozone Research and Monitoring Project-Report No. 58, Geneva, Switzerland.

Zhang, L., J. Li, L. Zhou, 2017. The relationship between polar vortex and ozone depletion in the Antarctic stratosphere during the period 1979–2016. Adv. Meteorol. 2017, 1–12, doi:10.1155/2017/3078079.

FIGURE CAPTIONS

Fig. 1: The ozone measurement stations in Antarctica. The Maitri station together with other ozone observing stations in Antarctica. The stations are represented by their first three letters (e.g. MAR – Marambio, MCM – Arrival Heights/McMudro, MIR – Mirny, DAV – Davis, SYO – Syowa, MAI – Maitri, NEU – Neumayer and SPL – South Pole). The potential vorticity maps for 24 September 2002 and 24 September 2006 are also shown.

Fig. 2: Temporal evolution of wintertime polar meteorology. Evolution of polar cap (60°–90° S) temperatures at 100 and 70 hPa in Antarctica. The total column ozone (TCO) measurements from satellite measurements (TOMS–OMI) on 25 September and October mean for each year are also shown. The vortex split event occurred in the Antarctic was on 25 September 2002 and is selected to represent the dynamics of polar vortex. The ozone hole criterion of 220 DU is also demarcated on the ozone maps. The horizontal dotted lines in temperature graphs (left0 represent 195 K (i.e. Polar Stratospheric Cloud threshold).

Fig. 3: Ozone measurements at Maitri and other Antarctic stations. The ozone measurements at Maitri in Antarctica for the period 1999–2003 and 2006. The measurements averaged for all other stations in Antarctica and TOMS–OMI satellite overpass at Maitri are also shown. The dotted horizontal line represents the ozone hole criterion 220 DU, and 100, 200 and 300 DU.

Fig. 4: Ozone loss at Maitri and the Antarctic ozone hole. The chemical ozone loss estimated with the Maitri measurements in Antarctica together with that of the mean-ozone computed from the measurements of other Antarctic stations for the period 1999–2003 and 2006. The ozone loss estimated with the TOMS–OMI satellite overpass observations at Maitri are also shown. The dotted horizontal line represents the ozone loss of 50, 100, 150, 200 and 250 DU.

Figure 1

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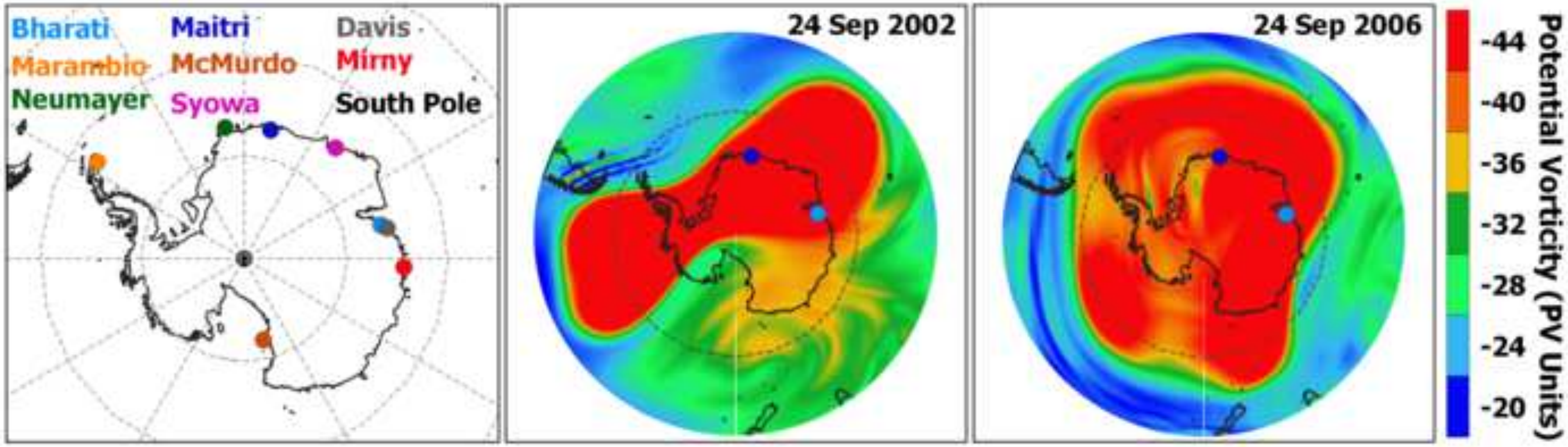

Figure 2

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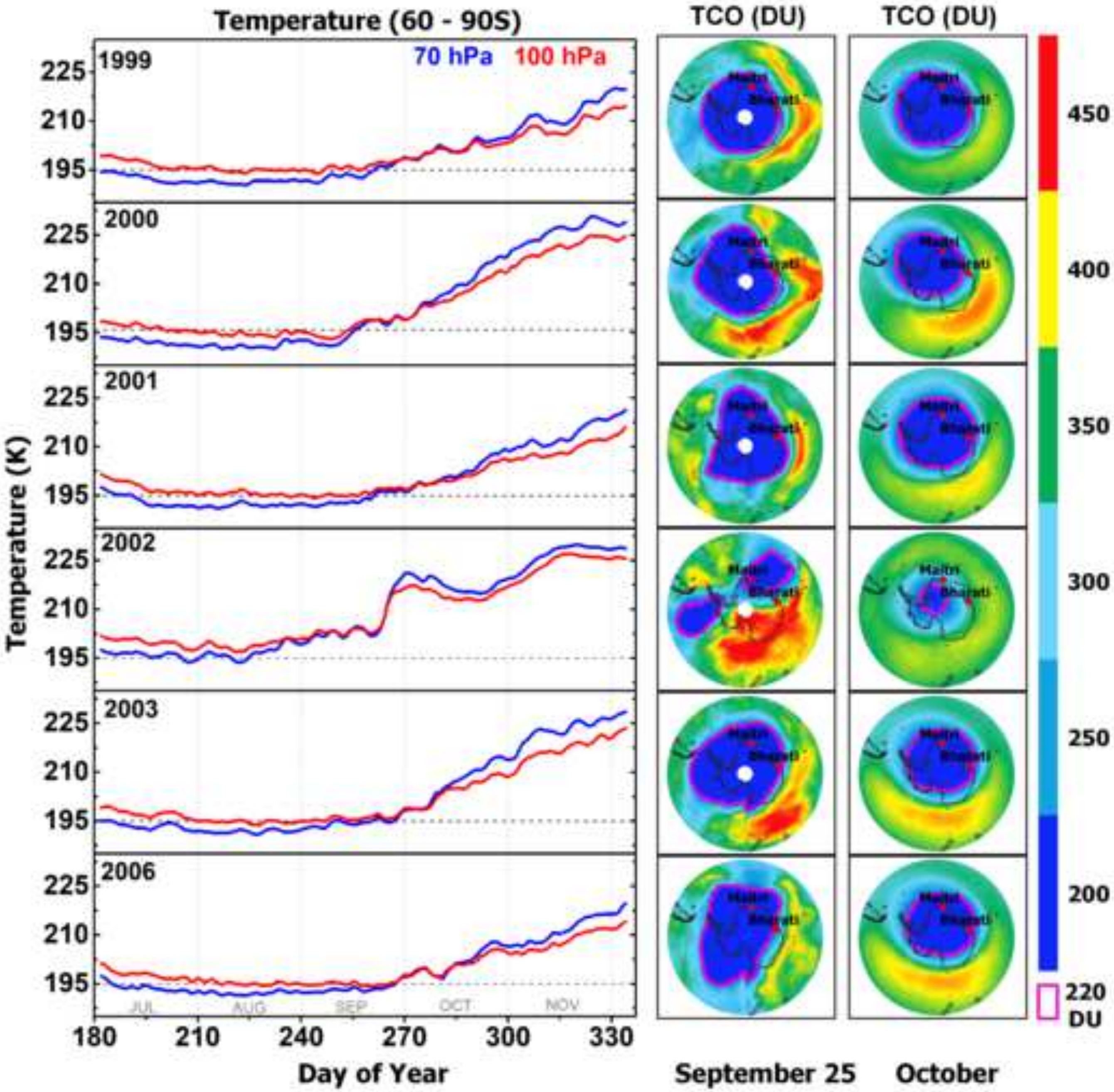

Figure 3

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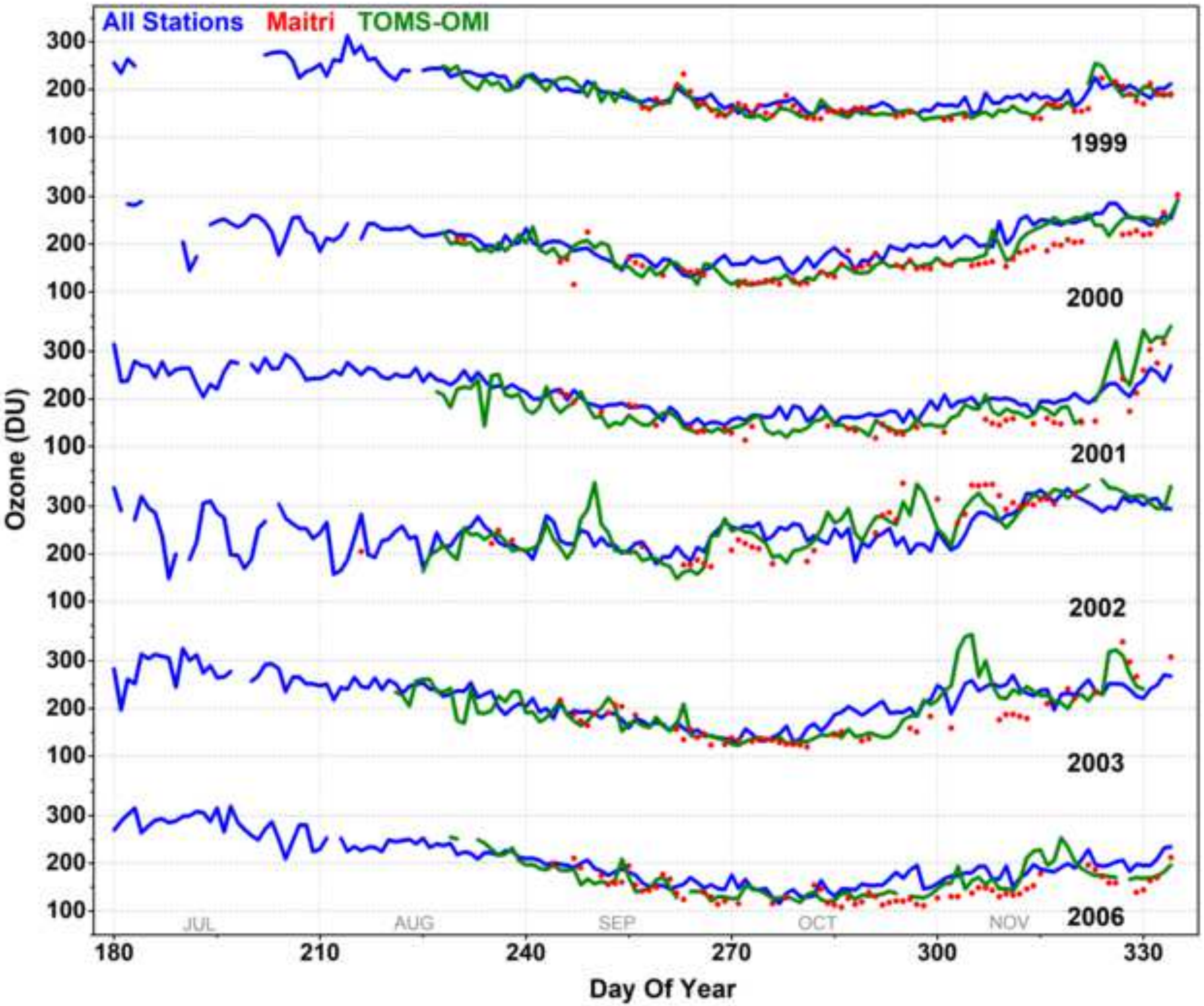

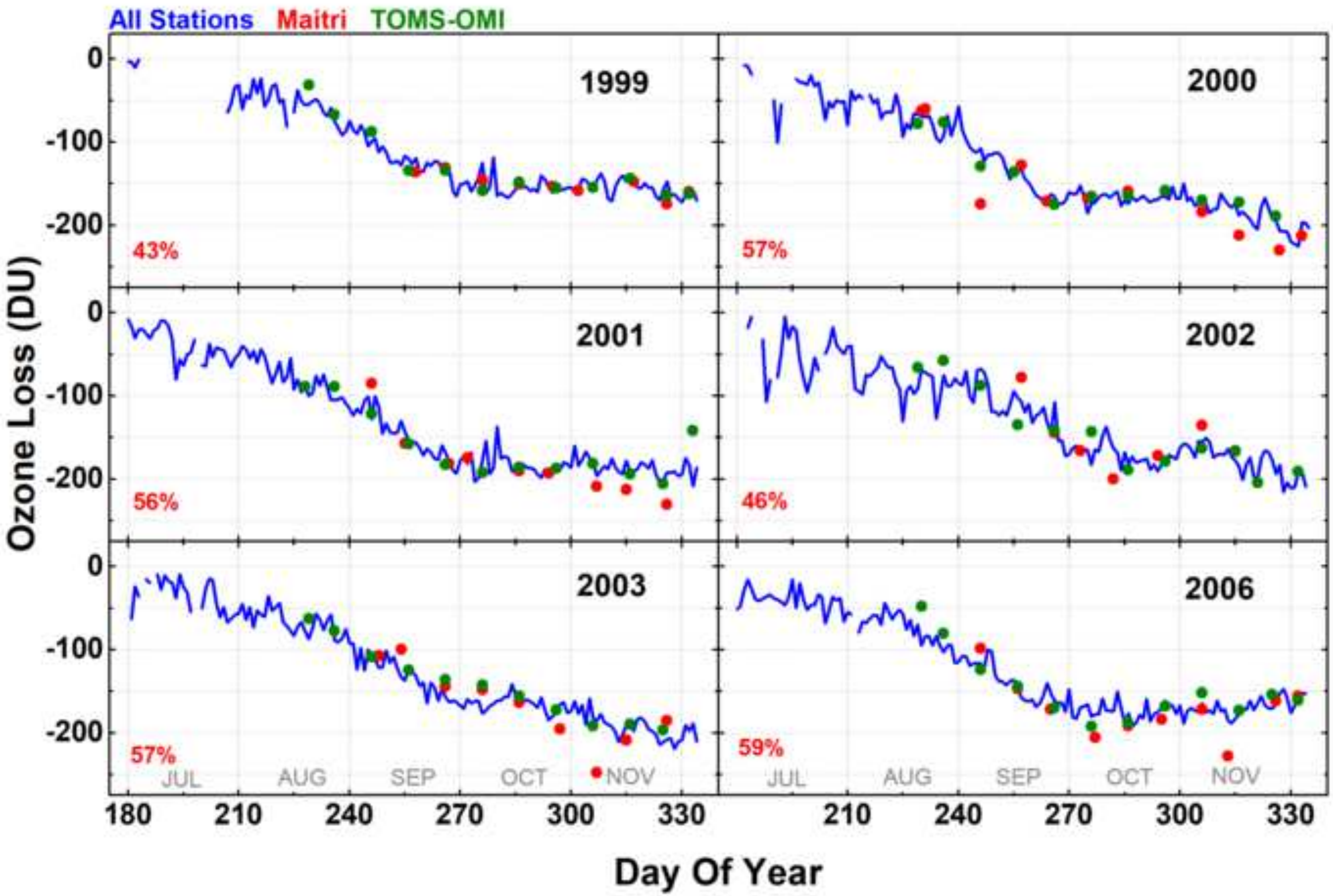
All Stations Maitri TOMS-OMI
Ozone Loss (DU)
0
-100
-200
1999
43%
2000
57%
2001
56%
2002
46%
2003
57%
2006
59%
JUL
AUG
SEP
OCT
NOV
180
210
240
270
300
330
Day Of Year