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Trends in Antarctic ozone hole metrics 2001–17

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Abstract. Linear trends over the years 2001–17 are reported of a number of standard metrics used to describe the severity of the Antarctic ozone hole, both with and without a simple adjustment to account for meteorological variability. The trends were compared to those from the years 1979–2001. All metrics considered showed a trend towards reduced ozone depletion since 2001, at significance levels ranging from 2.4 to 3.9 standard errors of the trend after the adjustment was performed. The adjustment for meteorological variability had little effect on the values of the trends but did substantially reduce the scatter and, therefore, uncertainty of the trends.

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1 Introduction

It has been recognised for many years (Schoeberl *et al.* 1996; Newman and Nash 2000; Newman *et al.* 2004, 2006) that although stratospheric halogen concentration (the essential cause of the Antarctic ozone hole) is the dominant driver of decadal-scale variability in Antarctic ozone, the year to year variation is mostly due to stratospheric dynamics. Colder temperatures in the polar stratosphere in austral winter and spring are associated with a more stable polar vortex, a greater volume of polar stratospheric clouds, fuller and more widespread chlorine activation and thus a deeper and longer lasting ozone hole. Temperature variations should, therefore, be taken into account when assessing ozone hole variations over time, particularly, systematic temperature changes that could be induced by increasing greenhouse gas emissions or radiative feedback from the ozone hole itself (Solomon *et al.* 2017).

Apart from polar temperature, there do exist a number of additional factors which also contribute to interannual ozone hole variability. These include the transport of chlorine to the poles (Strahan *et al.* 2014), which has been shown to be modulated by the equatorial Quasi Biennial Oscillation (Strahan *et al.* 2015), and increased stratospheric aerosol amounts resulting from large volcanic eruptions (Ivy *et al.* 2017; Stone *et al.* 2017). The contribution of very short-lived halogenated substances has also been recently studied (Yang *et al.* 2014; Sinnhuber and Meul 2015; Oman *et al.* 2016; Fernandez *et al.* 2017; Falk *et al.* 2017; Hossaini *et al.* 2017). Further, trends in ozone hole metrics can also be affected by nonlinear saturation effects (Bodeker 2002; Newman *et al.* 2006; Yang *et al.* 2008). However, it is shown below that temperature alone can account for the majority of the interannual variability.

Using a variety of approaches and selections of data, recent work has attempted to establish the existence of a statistically significant decrease in ozone depletion over Antarctica which can be attributed to declining halogen levels (Kuttippurath *et al.* 2013; Knibbe *et al.* 2014; de Laat *et al.* 2015; Solomon *et al.* 2016; Kuttippurath and Nair 2017; de Laat *et al.* 2017; Strahan and Douglass 2018; Pazmino *et al.* 2017; Keeble *et al.* 2017).

Here, we consider four representative metrics reported on in the series of papers by Klekociuk *et al.* (2011, 2014*a*, 2014*b*, 2015) and Tully *et al.* (2008, 2011): maximum 15-day averaged ozone hole area, minimum 15-day averaged total column ozone, integrated ozone deficit and the duration of the ozone hole. For each of the four metrics, we compute the linear trend over the time period 2001–17. We then adjust each metric for meteorological variability, using a simple linear fit to an appropriate choice of temperature time series from the MERRA-2 reanalysis, and recompute the trends after adjustment. For comparison, we also compute the linear trends over the earlier 1979–2001 period using the same approach.

2 Methods

The four Antarctic ozone hole metrics have been calculated using total column ozone measurements from the Total Ozone Mapping Spectrometer (TOMS) series of instruments on a number of satellite platforms, the Ozone Monitoring Instrument (OMI) onboard the Aura satellite and the Ozone Mapping Profiler Suite (OMPS) on Suomi National Polar-orbiting Partnership satellite. These measurements now span the years 1979–2017; however, no data are available for 1995 and only limited

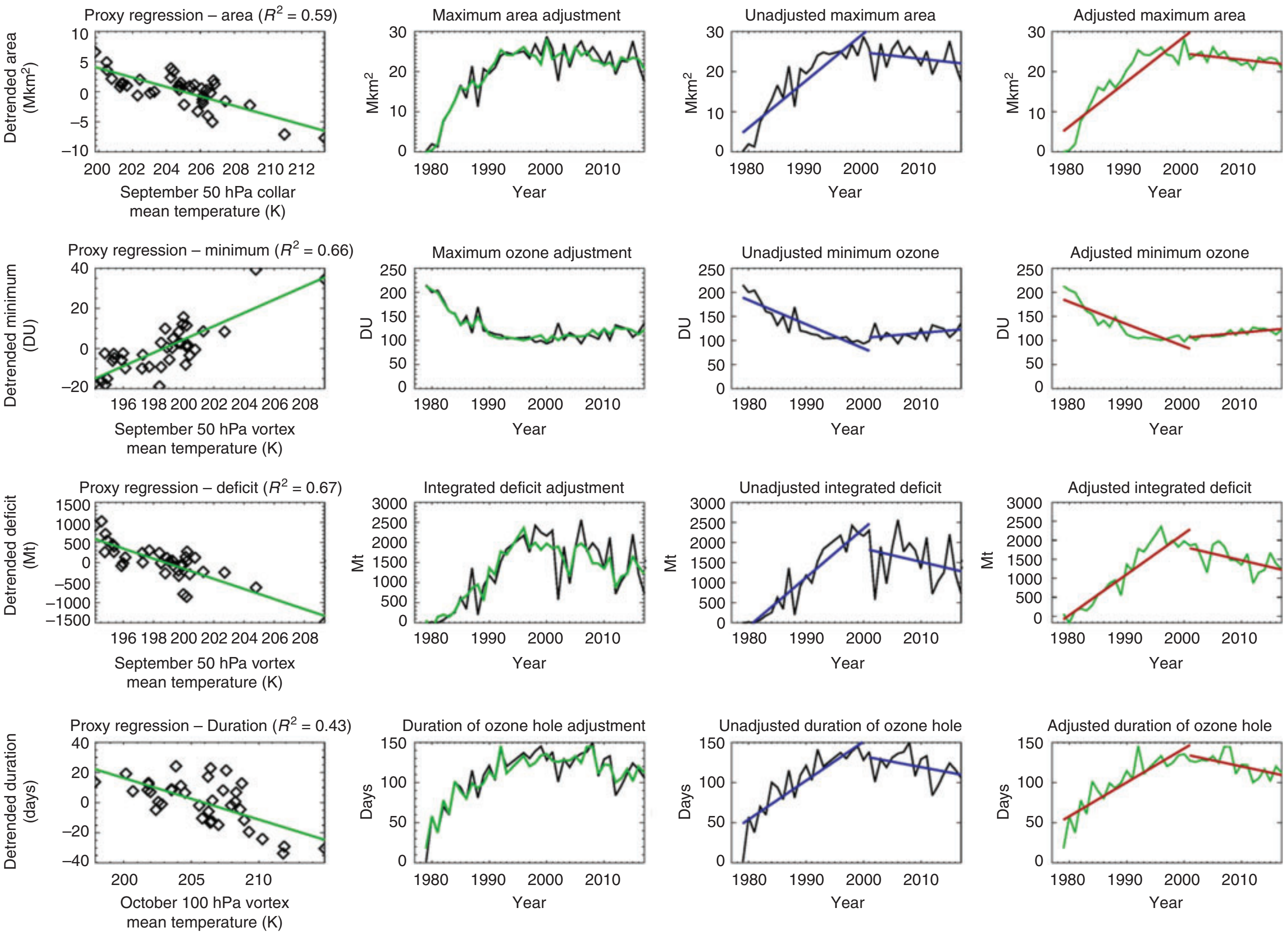

Fig. 1. For each of the four metrics – maximum 15-day averaged area of ozone hole, minimum 15-day averaged total column ozone, integrated ozone deficit and duration of ozone hole – scatter plot of detrended metric vs selected temperature proxy and the linear fit (green); the adjusted (green) and unadjusted (black) proxy time series; linear 1979–2001 and 2001–17 trends (blue) of the unadjusted time series; linear 1979–2001 and 2001–17 trends (red) of the adjusted time series.

data for 1994. OMI data have been used here for 2005 in preference to TOMS which was also in operation at the same time.

Temperature values are taken from the MERRA-2 reanalysis (Gelaro *et al.* 2017), as made available from the NASA Ozone Watch website (http://ozonewatch.gsfc.nasa.gov/, accessed 21 April 2020). For each of the metrics considered, linear correlations were established between monthly mean temperatures in either the 'vortex' (60–90°S) or the 'collar' (55–75°S) regions, and the detrended 1979–2017 time series for each metric. The detrending was performed by subtracting the record of each metric from a smoothed version of itself obtained with a LOESS smoothing (11-point window). (Alternative methods of producing a smoothed representative curve would serve equally well for the purpose of detrending.)

We select temperature parameters as shown below that were best correlated with the individual ozone hole metrics, although it should be noted that there is generally a high degree of correlation between polar temperatures at different heights, latitude ranges and months of the year, meaning that different choice of temperature parameters would give similar results to those presented here:

- Maximum 15-day averaged area – September 50 hPa collar mean ($R^2 = 0.59$)
- Minimum 15-day averaged total column ozone – September 50 hPa vortex mean ($R^2 = 0.66$)
- Integrated ozone deficit – September 50 hPa vortex mean ($R^2 = 0.67$)
- Duration of ozone hole – October 100 hPa vortex mean ($R^2 = 0.43$)

Scatter plots for the four correlations are shown in Fig. 1. The simple linear fit to temperature is able to explain up to two-thirds of the variance, in the case of ozone hole mass deficit. The weakest correlation is found for ozone hole duration, which is influenced by temperature in early winter as well as late spring.

Independent linear trends are derived following Steinbrecht *et al.* (2017) and Chipperfield *et al.* (2017) rather than alternatives such as piecewise linear or fits to equivalent effective

Table 1. Linear trends of the four metrics, both adjusted and unadjusted for temperature, with uncertainty expressed as two standard errors, for the time periods 1979–2001 and 2001–17

Metric	1979–2001 trend	1979–2001 trend (adjusted)	2001–17 trend	2001–17 trend (adjusted)
Maximum 15 day averaged area (Mkm^2 year^{-1})	1.17 ± 0.24	1.12 ± 0.24	-0.16 ± 0.32	-0.15 ± 0.13
Minimum 15 day averaged total column ozone (DU year^{-1})	-5.00 ± 1.16	-4.62 ± 1.16	1.03 ± 1.26	1.08 ± 0.55
Integrated ozone deficit (Mt year^{-1})	126.6 ± 18.4	107.4 ± 17.1	-33.3 ± 60.2	-35.2 ± 27.4
Duration of ozone hole (days year^{-1})	4.84 ± 1.22	4.22 ± 1.07	-1.34 ± 1.66	-1.52 ± 1.05

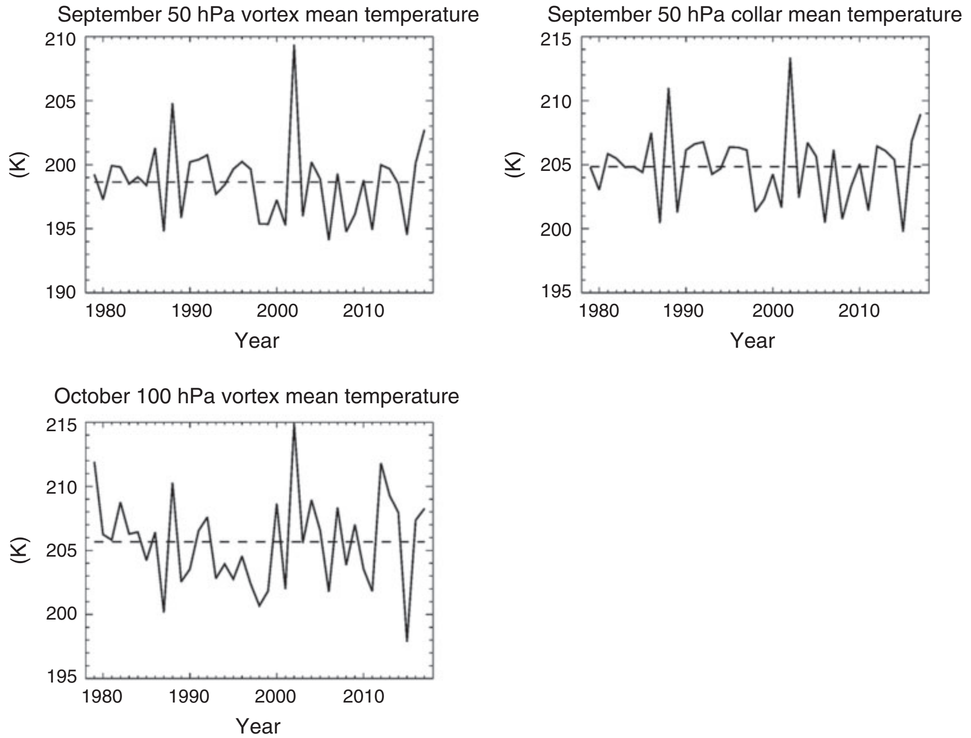

Fig. 2. Mean temperature in the polar vortex at 50 hPa for September (upper left panel), for the vortex collar at 50 hPa in September (upper right panel) and polar vortex mean at 100 hPa in October (lower left panel). The dashed line represents the mean over the 1979–2017 period.

stratospheric chlorine (EESC). Since the ozone hole was particularly severe in the year 2000 with respect to most metrics, a conservative choice has been made to consider only the 2001–17 trends.

Figure 1 shows, for each of the four metrics, the fit to the chosen temperature proxy, the proxy time series with and without adjustment according to the fit, and then 1979–2001 and 2001–17 trends with and without adjustment. Table 1 gives the values of the resulting trends with uncertainty limits of two standard errors. Auto-correlation of the residuals is minimal, less than 0.2 for all four metrics, resulting in negligible effect on the significance of the trends.

Figure 2 shows time series of the polar temperatures used in the regressions. The magnitude of temperature variability is noticeably greater in October, which supports the preferred use of September to establish ozone trends specifically related to ozone depleting substance decline (Solomon *et al.* 2016). Although the sign of the temperature fluctuations (i.e., whether a year is warmer or cooler than the long-term average) is generally consistent between the 2 months, the relative magnitudes can differ somewhat, such as in 2012. For both months, the interannual variability is significantly greater than long-term changes.

For all four metrics considered, the calculated trend since 2001 is in the direction of increased ozone (or equivalently, reduced ozone depletion). The reduction of scatter following adjustment for meteorological variability substantially increases the significance of the trends, at levels ranging from 2.4 to 3.9 standard errors. The magnitude of the trends, however, is not greatly affected by the temperature adjustment, attributable to the lack of any large systematic changes in temperature over this period.

For the earlier 1979–2001 period, the linear trend of decreasing ozone is significant at a much higher significance level than the ozone increase in the second period. Neither the magnitude nor uncertainty of the 1979–2001 trends is very dependent on the temperature adjustment. It is evident in Fig. 1 that the quality of the fit is limited more by the nonlinearity of the metrics in the early and later years than the inter-annual scatter. Although all four metrics displayed significant change over this period, the rate of change was not constant. This is to be expected, since the growth rate of stratospheric chlorine, represented by EESC (Newman *et al.* 2006), slowed considerably by the end of the century due to the success of the Montreal Protocol. Further, the use of a threshold (220 DU) to define the ozone hole metrics also necessarily introduces nonlinearity in the early years, seen most clearly in ozone hole area and ozone hole duration.

3 Conclusions

Linear trends, over the years 2001–17 of four standard metrics used to describe the severity of the Antarctic ozone hole, have been presented, both with and without a simple adjustment to account for meteorological variability. The simple linear fit of each metric to a selected Antarctic temperature proxy is able to account for the majority of the interannual variability in the metrics related to ozone hole area, minimum value of ozone, and integrated ozone mass deficit, but not ozone hole duration.

Adjusting the metrics for temperature substantially increases the significance of the observed trends. However, the magnitude of trends is not greatly dependent on whether the adjustment has been applied. For all four metrics considered, trends of reduced ozone depletion over the 2001–17 period become significant at the 2 standard error level once the temperature adjustment has been performed, but not without.

For comparison, the linear trends in each metric of the earlier period 1979–2001 have also been calculated, which are highly significant regardless of temperature adjustment.

The method of analysis employed is clearly limited to identifying a significant increase or decrease in ozone, and not establishing the underlying physical cause, apart from excluding meteorological variability. However, the ratios of pre- to post-2001 trends given in Table 1 are quite consistent, within uncertainties, with the ratio of increase and decrease of stratospheric chlorine loading in Antarctica, which for these time ranges is estimated as -4.

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