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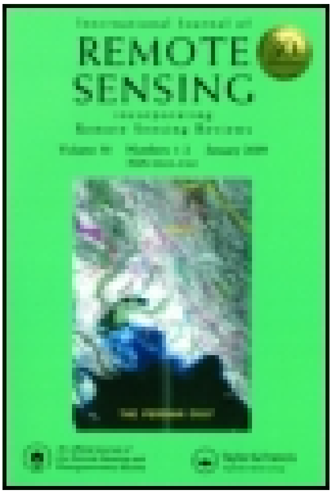

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Twenty-two years of ozonesonde measurements at the South Pole

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Since 1986, the Earth System Research Laboratory and its predecessors have been making weekly balloon ozone soundings at the South Pole Station in Antarctica. During the springtime ozone hole period, the sounding frequency is increased to 2–3 per week. The 2007 springtime minimum total column ozone at South Pole was 125 Dobson units, with the layer between 14 and 21 km showing a typical 95% loss of ozone. In contrast, the 2006 minimum total column ozone was 93 Dobson units and showed 99% ozone destruction in the 14–21 km layer. Owing to variations in meteorology and stability of the polar vortex, year to year variations in the severity of the ozone hole of this magnitude are expected. Analysis of the ozone loss rate in September indicates large interannual variability suggesting a dynamic component. Detailed analysis of the 22-year record is used to search for early signs of the beginning of ozone hole recovery. The conclusion is that up to the year 2007, no definitive signs of the beginning of ozone hole recovery have been detected at South Pole Station.

1. Introduction

While satellite remote sensing provides global coverage of ozone, balloon-borne ozone sensors provide an accurate measure of the vertical profile of ozone. They are very useful in defining sources and sinks of ozone. Together, satellite and balloon measurements have been very successful in studying the Antarctic ozone hole. This paper reports on ozonesonde measurments at the South Pole.

The first 10 years of ozonesonde studies from the South Pole, which began in 1986, were presented by Hofmann *et al.* (1997). They found that Antarctic springtime ozone depletion had worsened during the 1986–1995 period but had reached a pseudo-equilibrium during the 1992–1995 period, reaching nearly zero ozone in the 14–18 km region. They found that ozone depletion had extended into the 22–24 km region and identified the high altitude depletion region as a possibly useful indicator of future ozone hole recovery. They investigated the ozone loss rate in September when the ozone hole formed and showed that especially above 18 km it varied with the quasi-biennial oscillation in equatorial winds with the maximum loss occurring during the spring following a descending easterly transition in the tropical winds. Using early equivalent chlorine projections they estimated that the beginning of ozone hole recovery would likely not be detected

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before the 2010–2020 period. It is the purpose of this paper to update the 10-year record with an additional 12 years of ozonesonde observations.

2. Observations

Balloon sounding of the Antarctic ozone hole is important as it indicates the altitude region where chemical ozone depletion is occurring. It allows accurate estimates of total and partial column ozone amounts during darkness when most satellite measurements cannot be made. With adequate sounding during September, when the ozone hole is formed, the ozone loss rate, which is a function of the abundance of ozone-destroying chemicals, can be determined as a function of altitude. Balloons also allow investigation of the upper altitudes where the depletion phenomenon is not complete. For the past 22 years, the Earth System Research Laboratory and its predecessors have been making weekly balloon ozone soundings at the South Pole Station in Antarctica. During the springtime ozone hole period, the sounding frequency is increased to 2–3 per week, allowing resolution of the rapid decline in ozone experienced during September.

Figure 1 shows South Pole ozone profiles before ozone depletion began (generally August) and at the time of maximum ozone depletion (generally early October) for the 22 ozone holes of 1986 to 2007. In figure 2, profiles are shown for the year 2006 when the largest ozone hole both in area and severity occurred. The 14–21 km region of total ozone depletion is indicated in the figure and will be used to study the time variation of the severely depleted region. The upper (22–24 km) region, where ozone is only partially depleted, is also indicated in the figure. The latter may be a useful region to study ozone hole recovery (Hofmann *et al.* 1997).

Figure 3 shows the 14–21 km average temperartures and indicates no trend in winter with a minimum near –90°C. There is some evidence for a trend toward colder summers however. In figure 4 the winter–spring temperatures are broken out monthly and show that while no trends exist in July and August, there may be marginally significant trends in June (warming) and September (cooling). The unusually warm September 2002 temperature was related to the early splitting of the vortex that year.

Figure 5 shows the 14–21 km column ozone from 1986 to 2007. The near-zero ozone values that began in about 1993 ceased in the unusual year of 2002. Figure 6 shows the minimum 14–21 km column ozone measured each year from 1986 to 2007. This figure shows that while 2006 was the lowest at less than 2 DU, the years 1993 to 2001 were consistently low and that considerable variability set in following the major warming which split the vortex in 2002. This variablity is believed to be related to enhanced atmospheric wave activity which disturbs the polar vortex and disrupts the depletion phenomenon.

Figure 7 shows the annual cycle of column ozone in the 14–21 km region for each year from 1986 to 2007. This figure clearly displays the degree of variability of ozone in the 14–21 km altitude range throughout the year. The years 1988 and 2002 stand out as years of considerable vortex variability. The September data (day 244 to 273 in figure 7) shows the precipitice drop in ozone in the 14–21 km region during formation of the ozone hole. As in Hofmann *et al.* (1997), this region will be studied for variations in the ozone loss rate.

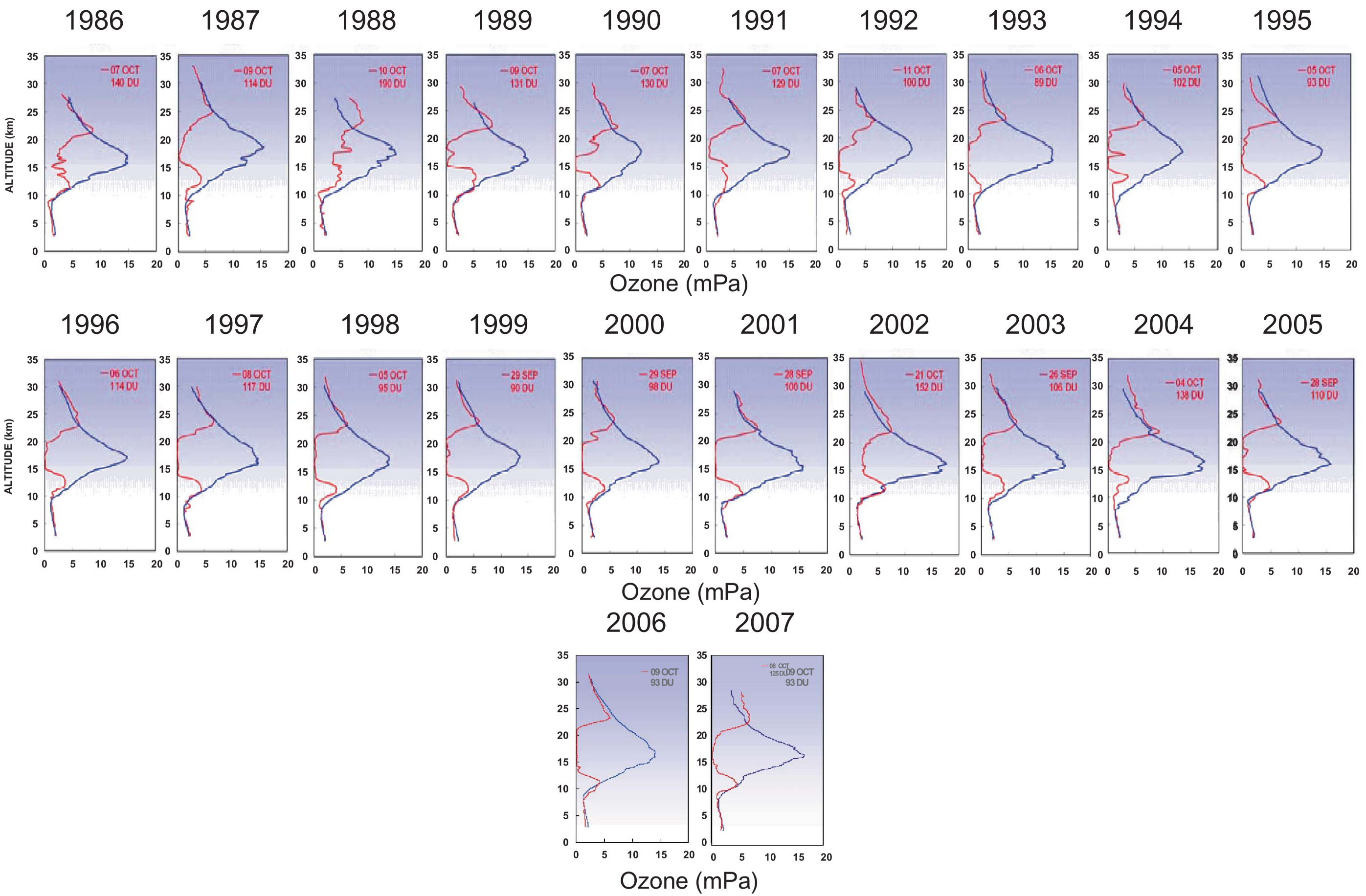

Figure 1. South Pole ozone profiles before the ozone hole developed (blue) and for the sounding that displayed the minimum ozone that year (red) for each year from 1986–2007.

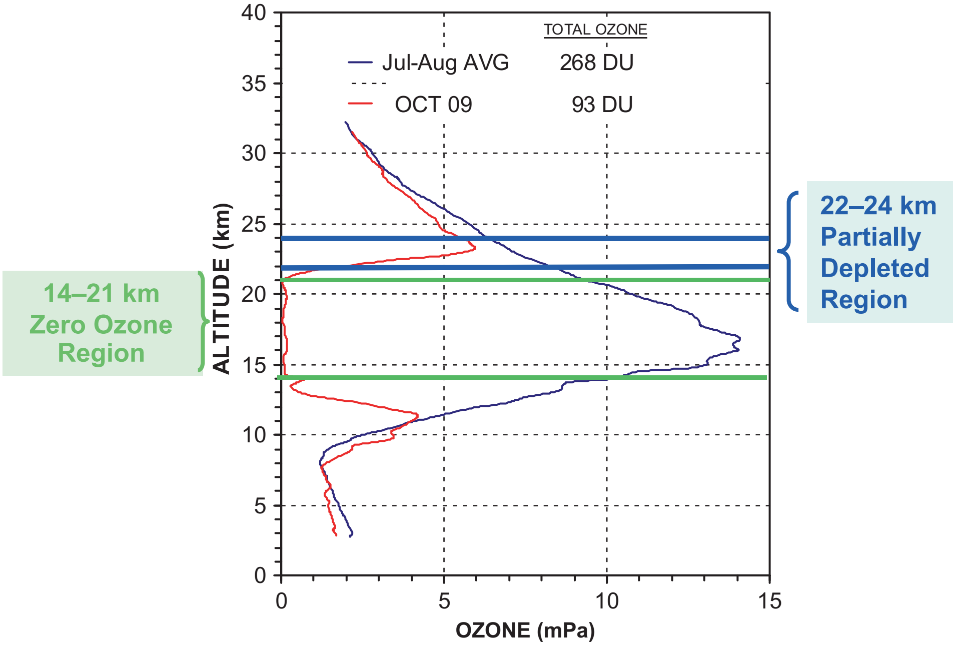

Figure 2. South Pole ozone profiles in 2006 before the ozone hole developed (blue) and for the sounding that displayed the minimum ozone (red). Regions of interest at 14–21 km and 22–24 km are delineated.

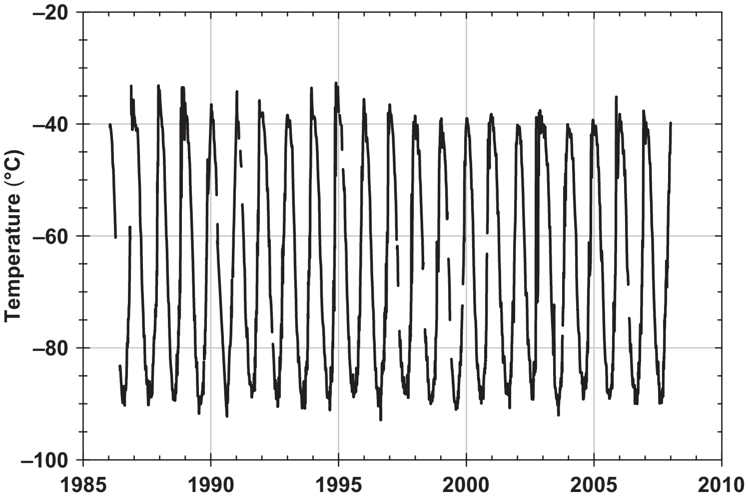

Figure 3. South Pole 14–21 km average temperatures for all the soundings from 1986–2007.

Figure 8 shows ozone column data versus time for both total column ozone and 14–21 km ozone during September of 2006. The ozone loss rate (Dobson units per day) and its standard error can be determined from curves such as these for each year. Figure 9 shows the profile of ozone loss rates and standard errors for 2-km averages from 10–12 km to 22–24 km from 12 soundings during September 2006.

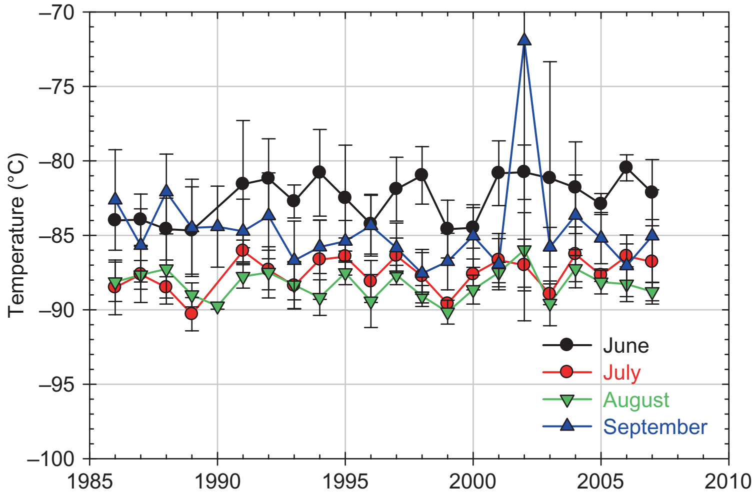

Figure 4. South Pole 14–21 km average temperatures and standard errors for the months of June, July, August and September for the period 1986–2007.

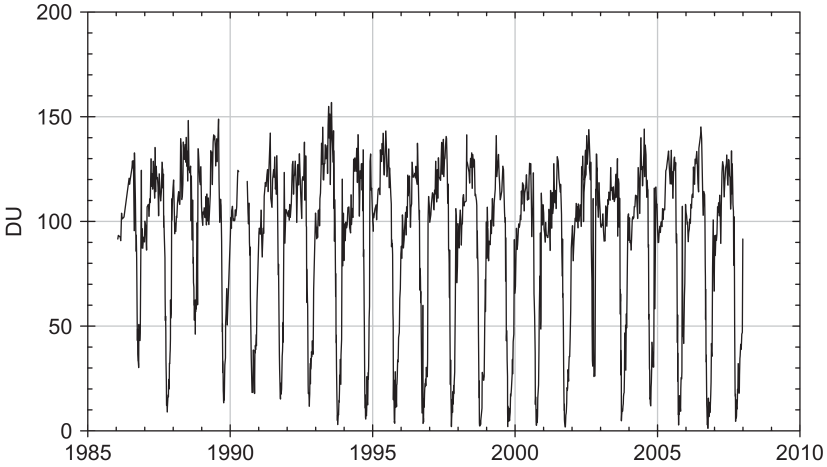

Figure 5. South Pole 14–21 km column ozone for all the soundings (1383) from 1986–2007. The annual springtime minimum is clear in the figure.

The peak in ozone loss rate is well-resolved in the 16–19 km region. Figure 10 shows similar data for each September for the 22 years. The uncertainties are similar to those in figure 9. There appears to be no time variation in the height of the peak loss rate.

Figure 11 shows the time variation of the ozone loss rates for total ozone and for the 14–21 km column ozone. The re-analysed data for the years 1986 to 1995 are essentially identical to those presented in Hofmann *et al.* (1997) because they are from the same raw dataset. However, the increasing severity in the ozone loss rate from 1986 to 1995, identified in Hofmann *et al.* (1997), surprisingly shows large variations after 1995, both for total ozone and for the 14–21 km column.

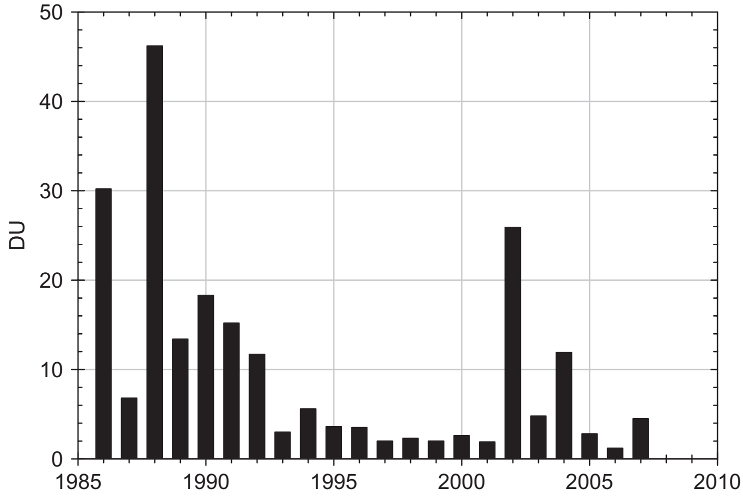

Figure 6. South Pole 14–21 km annual minimum column ozone in the ozone hole from 1986–2007. Following stable low values from 1993 to 2001, the variability has increased.

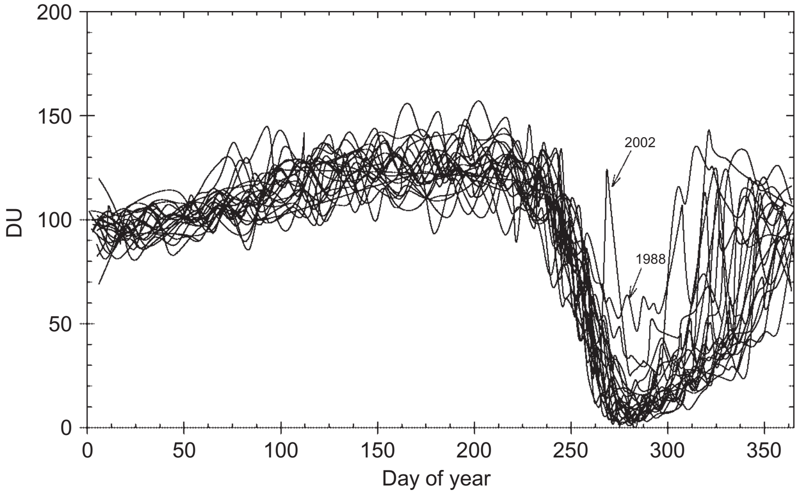

Figure 7. South Pole 14–21 km annual column ozone from all the soundings for each year from 1986–2007. The figure indicates the degree of variability in this quantity. The polar vortex was unusually disturbed in 1988 and 2002.

3. Discussion

In the following we will examine possible sources for the ozone loss rate variability and investigate further the evidence or non-evidence for the beginning of ozone hole recovery. The slope of the ozone versus time curves (see figure 8) can be affected by several variables. Obviously, an important variable is the amount of active ozone-destroying chemicals that are present in the vortex during September. It can also be affected by the winter temperature and the stability of the polar vortex during September. Winter temperature appears not to have

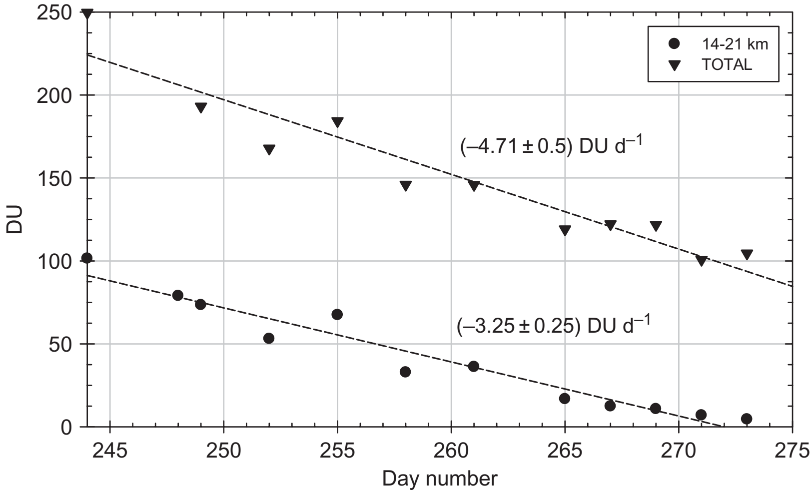

Figure 8. South Pole column ozone decline during September 2006 for the 14–21 km region and for total ozone.

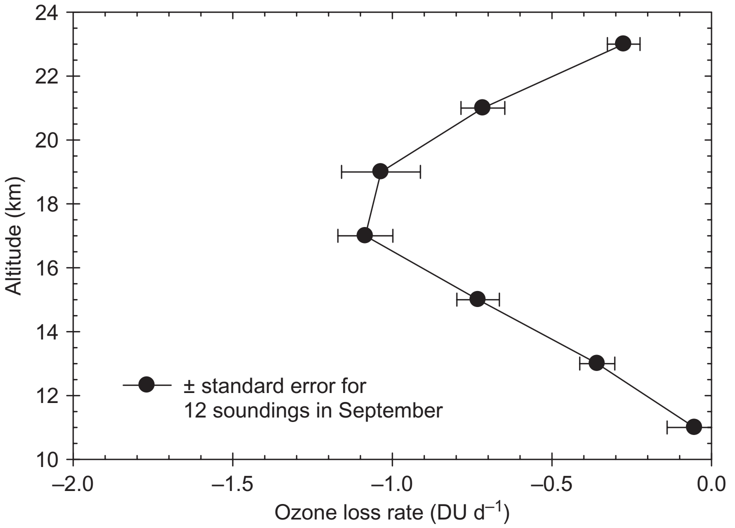

Figure 9. South Pole 2-km average September 2006 ozone loss rates with standard errors.

varied substantially in the depletion region. Fortunately, due to the South Pole's generally vortex-centred position, vortex stability was not a factor in determining the September ozone versus time slope. Even in 2002 when the vortex split (Varotsos 2002), data prior to 22 September could be used to obtain a valid slope. The value of ozone in August, prior to the September depletion period, could have an affect on the slope if the depletion process were dependent on the ozone concentration. To test this, we have plotted the average August ozone at 14–21 km versus the ozone loss rate at that height in figure 12 for the 22 years of data. There appears to be a slight dependence (larger ozone loss rates for higher

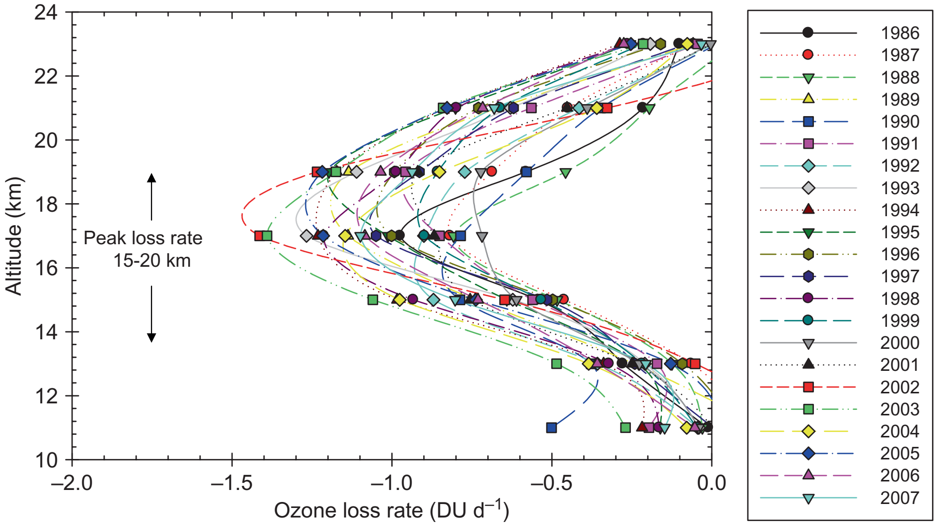

Figure 10. South Pole 2-km average September ozone loss rates for each year from 1986–2007.

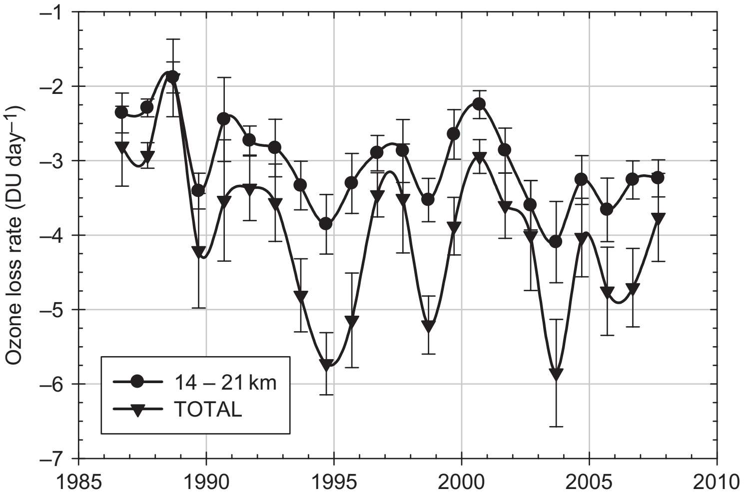

Figure 11. South Pole September ozone loss rates for the 14–21 km region and for total column ozone from 1986–2007.

August ozone) but the dependence is rather weak and should not have a major effect on ozone loss rates. Thus it appears that the variability of September ozone loss rate from year to year is related mainly to the amount of ozone-destroying chemicals present.

As indicated earlier (see figure 11), the South Pole September ozone loss rates show significant interannual variability. As in Hofmann *et al.* (1997) we have examined the data for a quasi-biennial oscillation (QBO) variation in the ozone loss rates. The results are shown in figure 13. Except for QBO cycles which do not have a well-defined

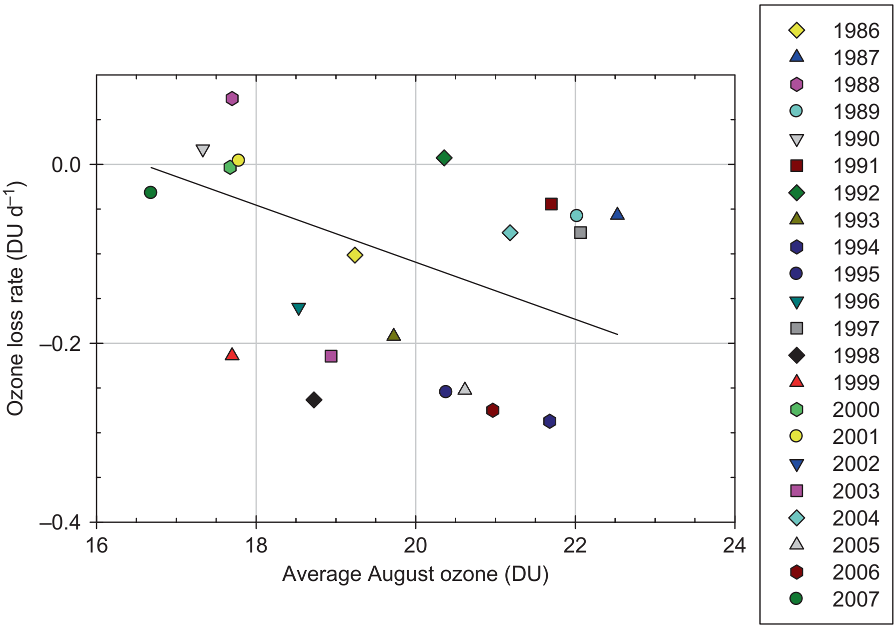

Figure 12. South Pole ozone loss rate versus average August ozone at 14–21 km for 1986–2007.

easterly to westerly transition time at high altitude (e.g. 1992 and 2001), high ozone loss rates occur in the austral spring following the descending east to west transition in the tropical winds. The 1996 transition was the only exception to this. A general correlation with the QBO suggests that there is a dynamic component to the variability in September ozone loss rates. This could result if the transport of ozone depleting chemicals into the vortex was affected by rapid change in the tropical wind phase at high altitude.

We will now examine the data in more detail for evidence of a beginning of ozone hole recovery. Figure 14 shows the time variation of all chlorine and bromine atoms measured in various molecules at the surface of the earth, converted to an ‘equivalent’ chlorine value using a factor of 60 applied to the more reactive bromine atoms (Montzka *et al.* 1996, Hofmann and Montzka 2009). This equivalent chlorine (ECl) parameter peaked at the surface in 1994. It is believed that it requires about 6 years (Newman *et al.* 2006) for gases emitted at the surface in the northern hemisphere (the predominant source) to reach high southern latitudes, enter the vortex at high altitudes and descend into the ozone depletion region. Thus, the maximum in chemical ozone depleting potential should have occurred in the Antarctic stratosphere about the year 2000.

Figure 15 shows the time variation of the 14–21 km ozone loss rate, the measured ECl parameter, the World Meteorological Organization (WMO) scenario for future levels of ECl (WMO 2007), and equivalent effective stratospheric chlorine (EESC) (Newman *et al.* 2006). It is clear from the figure that there is only a general relation between the ozone loss rate in the heart of the ozone hole and EESC, becoming, on average, greater as EESC increased in the early 1990s. While full recovery of the ozone loss rate to pre-1980 values is not expected until

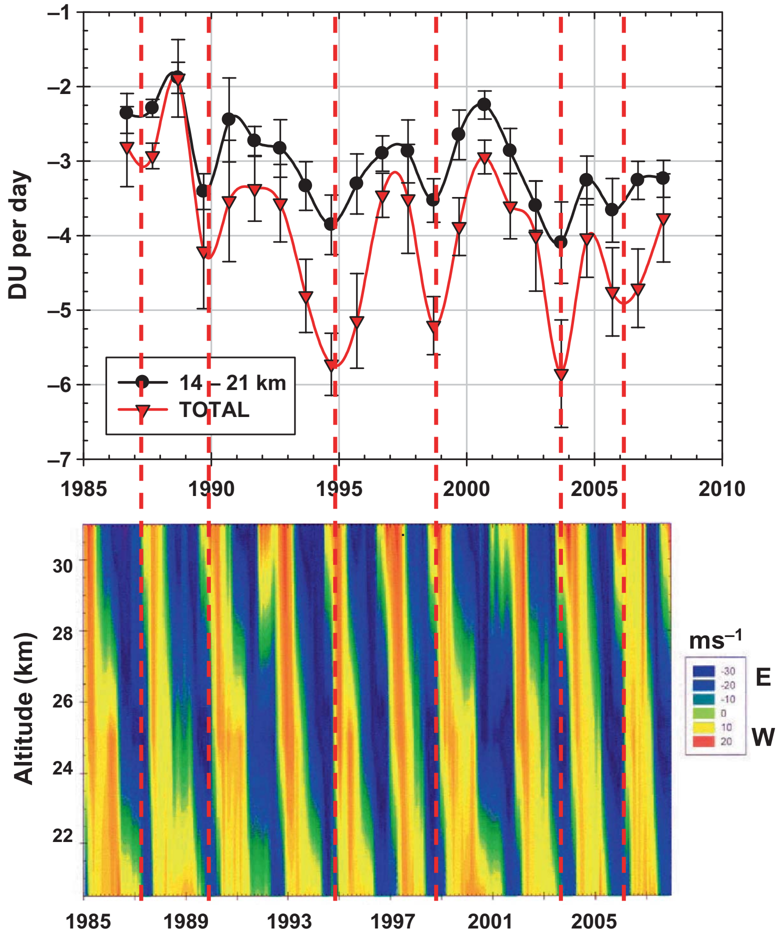

Figure 13. South Pole September ozone loss rates for 14–21 km and total column ozone (top) and quasi-biennial oscillation (QBO) winds at Singapore (bottom). Vertical dashed lines delineate periods of high ozone loss rates which are correlated with the westerly phase of the QBO at high altitude.

the decade of the 2080s, a reduction in ozone loss rate should be observable before 2050, but not as early as suggested from the pre-1996 data (Hofmann *et al.* 1997) owing to the increased variability in ozone loss rates after 1995.

We can explore other possible indicators of the beginning of ozone hole recovery. Figure 16 shows the September ozone loss rate at the top of the ozone hole at 22–24 km. In this region, ozone depletion was not present before 1993. Similar to the 14–21 km region, the ozone loss rate displays significant variability in the 22–24 km region, again likely related to interannually varying dynamic effects. It is expected that ozone depletion in the 22–24 km region will cease as the ozone hole begins its expected recovery in the future. As suggested by the variability in the loss rates in the figure, five or more consecutive years of no ozone loss at 22–24 km would be required to confirm this expected event.

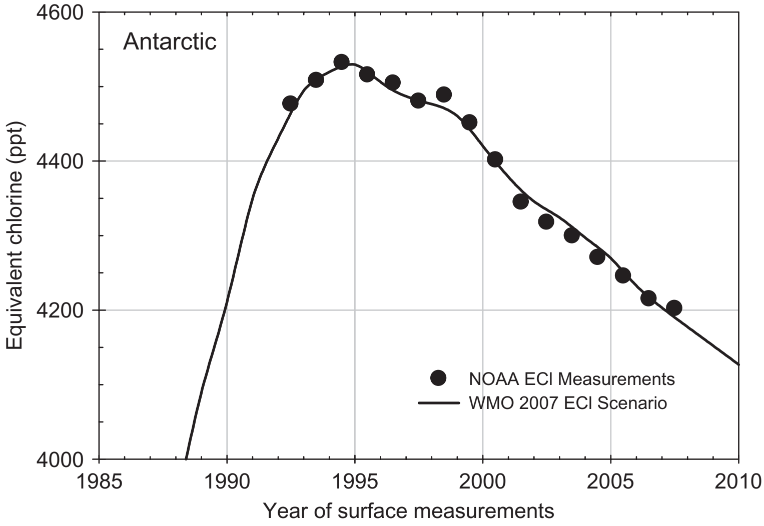

Figure 14. Equivalent chlorine determined from surface measurements of all the chlorine and bromine molecules that lead to destruction of stratospheric ozone. The smooth curve is a WMO scenario for equivalent chlorine.

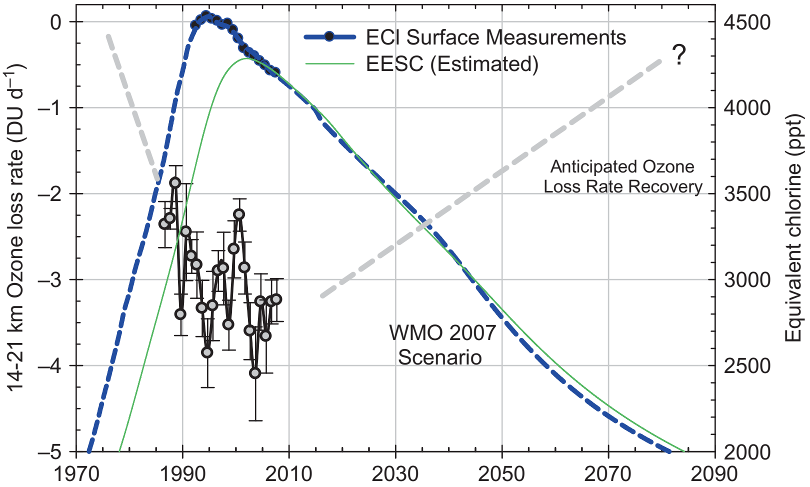

Figure 15. Time variation of the South Pole 14–21 km September ozone loss rate, equivalent chlorine (ECl) and equivalent effective stratospheric chlorine (EESC) which takes into account the time for chlorine and bromine molecules to reach the Antarctic stratosphere.

The temperature in the ozone depletion region is a useful parameter to compare ozone values from different time periods as it partially compensates for dynamic effects (Solomon *et al.* 2005). Figure 17 shows the ozone mixing ratio versus temperature at two levels (70 and 30 hPa) and for four different time periods from 1966 to 2007. The early data (1966–1972), obtained from ozonesonde measurements made at the South Pole over 40 years ago, show ozone mixing ratios above 1 ppm for typical stratospheric temperatures. The 1986–1989 period

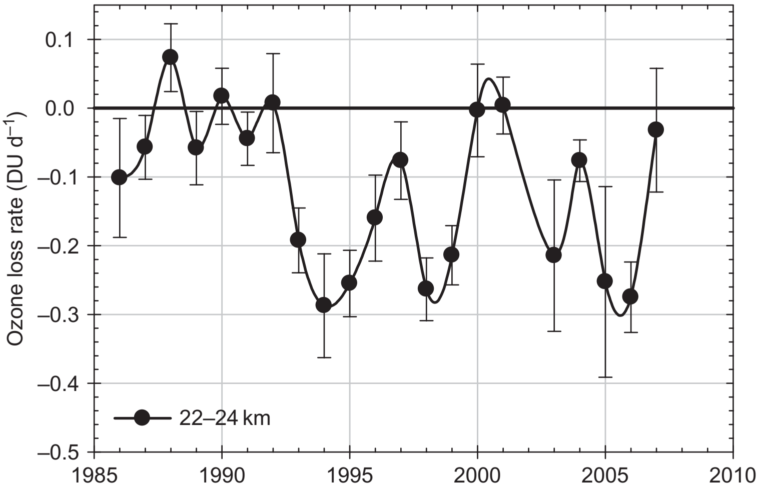

Figure 16. South Pole September ozone loss rates at 22–24 km from 1986–2007.

showed the beginning of ozone depletion with depressed mixing ratios while the severe depletion years of 1990–2004 showed ozone mixing ratio reductions by a factor of 10 or more in the coldest regions. The 2005–2007 data are shown separately in figure 17 and indicate no change from the 1990–2004 data, another piece of evidence that the beginning of recovery of the Antarctic ozone hole has not yet begun at the South Pole.

4. Summary and conclusions

In total, 22 years of ozonesonde measurements (approximately 1400 soundings) at the South Pole from 1986 to 2007 have been analysed in order to characterize the time variation of the springtime Antarctic ozone depletion process. Following a developmental stage from 1986 to 1992, the ozone hole minimum, which occurs in late September to early October, reached a low plateau averaging about 5 DU in the 14–21 km region from 1993 to about 2001. A sizable degree of variability followed; however, the lowest ozone minimum observed, about 2 DU, occurred in 2006. This observation, and comparisons of ozone mixing ratios versus temperature in the ozone hole, lead us to conclude that the beginning of the recovery of the ozone hole has not yet been observed at South Pole Station. It was also observed that the September ozone loss rate, when the ozone hole is forming, has become highly variable since about 1996. This variability correlates with the quasi-biennial oscillation (QBO) in tropical winds, suggesting a dynamic cause of the variability. The measurements of ozone by balloon at the South Pole have contributed considerably to our knowledge of the Antarctic ozone hole and the success of the Montreal Protocol in lessening the severity of ozone depletion in Antarctica. Adherence to the Protocol will assure recovery of the Antarctic ozone hole in the future and continued monitoring of the ozone hole will verify this recovery.

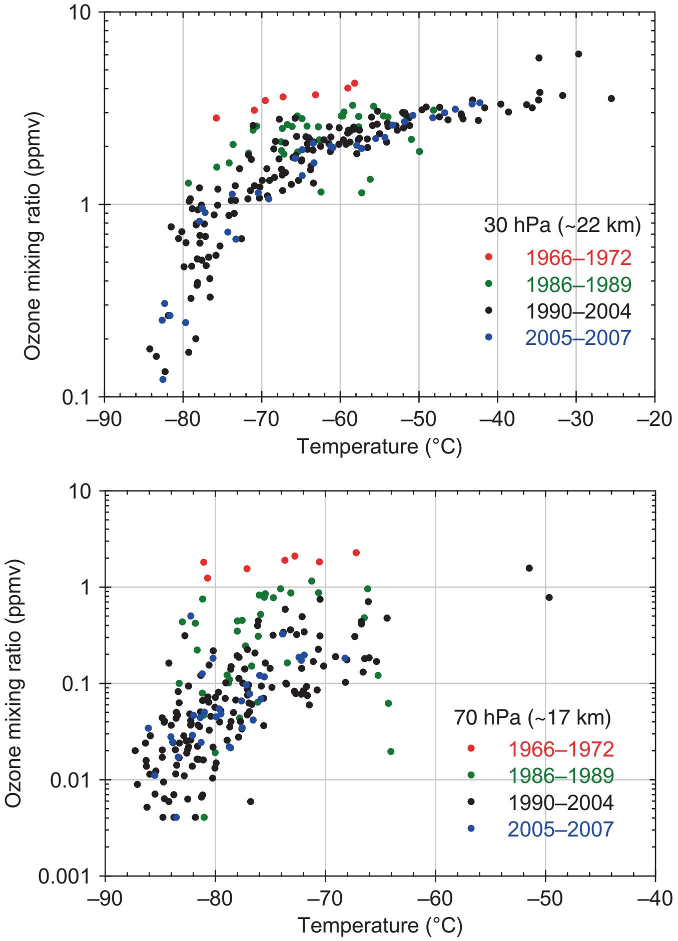

Figure 17. South Pole ozone mixing ratio versus temperature at 30 hPa (top) and 70 hPa (bottom) for four time periods over the range 1966 to 2007.

Acknowledgements

The authors are indebted to the many personnel who conducted the balloon flights over the 22-year period at the South Pole in extreme conditions. Without their dedicated service to the US National Oceanic and Atmospheric Administration this work would have been impossible.

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