6h. 2021 Antarctic Ozone Hole

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The 2021 Antarctic ozone hole was the 13th largest in 42 years of satellite observations since 1979, with an area of 23.34 × 106 km2 (the average area for 7 September–13 October) and a minimum daily total ozone column of 92 DU. The 2021 polar stratospheric vortex was stable with consistently cold temperatures that created favorable conditions for ozone depletion. The meteorological conditions and seasonal development of the ozone hole in 2021 were similar to those in 2020. Weaker-than-usual amplitudes of planetary scale Rossby waves in the September–October period helped maintain a strong vortex and led to below-average Antarctic ozone columns in late austral spring and early summer.

Antarctic lower stratospheric temperatures were consistently near- or below average during austral winter and spring 2021 (Fig. 6.15a). Cold air facilitated formation of polar stratospheric clouds (PSCs; Fig. 6.15b), whose spatial volume was near-average in July–August and above average in September. PSC particles provide surfaces for heterogeneous chemical reactions that release active chlorine (Cl2) for ozone depletion as sunlight returns to polar latitudes in August–September. Concentrations of ClO (Fig. 6.15c) were near- or below average until mid-September and above average in early October, similar to those in 2020. *Aura* Microwave Limb Sounder (MLS) observations showed that the 2021 vortex-averaged ozone concentration (Fig. 6.15d) on the 440-K isentropic surface (~60 hPa) was substantially above the average. However, the change in ozone concentration between the first week of July and the first week of October indicated that seasonal ozone losses were about 2.22 ppmv, which is comparable to the losses in two other cold years: 2.18 ppmv in 2020 and 2.24 ppmv in 2006. The Antarctic ozone hole area, defined by the region with total ozone columns below 220 DU, reached its peak at 24.8 × 106 km2 on 7 October (Fig. 6.15e). The weaker-than-average amplitudes of planetary scale Rossby waves through austral spring (which propagate from the upper troposphere into the stratosphere, depositing momentum and warming the Antarctic stratosphere) produced colder temperatures inside the vortex and inhibited mixing across the vortex edge, allowing the ozone hole area to remain well above the average until it disappeared on 23 December. This was one of the longest-lasting ozone holes on record, second only to 2020 (Kramarova et al. 2021). In 2006 (orange line in Fig. 6.15e), the area of the ozone hole grew faster in August–September partly because the level of ozone depleting substances was ~3.7 ppbv, which is 0.4 ppbv higher than today (NASA 2022). Below-average temperatures in 2006 resulted in the largest ozone hole on record. The slower growth rate of the 2021 ozone hole is consistent with other indications of recovery, such as the delayed onset of the hole's appearance and its decreasing size in September, all attributable to decreasing levels of ozone depleting substances (Stone et al. 2021).

Sonde observations at South Pole station indicated that the lower stratospheric column between 12 and 20 km was near-average in July–September (Fig. 6.15f) but was below average from October through December. The lowest 12–20-km column measured was 7.6 DU on 15 October, about two weeks later than in most years. The minimum total column ozone over the Antarctic (60°–90°S) were detected on 7 and 8 October at 92 DU, and minimum total ozone columns were also consistently below the average from mid-September to December. This seasonal behavior is similar to that in 2006 and 2020 (orange and purple lines in Fig. 6.15, respectively)—the two prior years with similarly weak wave activity and cold temperatures that resulted in persistently large holes and low ozone columns in October–December. The ClO concentration and PSC volumes dropped to near zero by mid-October (Figs. 6.15b,c), marking the termination of seasonal ozone depletion (Fig. 6.15d), but the stable vortex in 2021 kept ozone columns below average for the rest of the year by preventing meridional mixing of ozone-rich air from the midlatitude stratosphere into polar latitudes.

September is the key time period for Antarctic ozone depletion (e.g., Strahan et al. 2019). As the sunlight returns to polar latitudes, catalytic ozone destruction is initiated by reactions with active chlorine and bromine species produced on PSC surfaces during polar night. Colder September temperatures increase PSC surface area, leading to greater ozone depletion and a larger hole area. Figure 6.16a shows the interannual variability in the September vortex temperature with the coldest one-third of years shown in blue. The September ozone hole area also depends on levels of active chlorine (Fig. 6.16c). The effective equivalent stratospheric chlorine (EESC) represents an estimated concentration of human-produced and natural chlorine and bromine compounds in the stratosphere (Newman et al. 2007). EESC concentration reached its maximum level in the early 2000s and declined thereafter because of the implementation of the Montreal Protocol and its amendments. EESC levels were 13% lower in 2021 compared to the maximum. The impact of the slow rate of EESC decline on the ozone hole area is only observable on decadal or longer timescales, while the interannual variations are modulated by lower stratospheric temperatures: the ozone hole is larger in colder years and smaller in warmer years (Fig. 6.16c). To isolate the temperature effect, we fit a quadratic function of EESC with a 5.2 year mean age (shown as gray line in Fig. 6.16c) to the observed ozone hole areas, then determined the relationship between temperature and the deviation of the observed area from the fitted area (Fig. 6.16b). The September area anomalies are highly correlated with September temperatures ($r = 0.86$, Fig. 6.16b). Thus, the above-average area in September 2021 was largely the result of below-average temperatures.

Ozone depletion ceased by mid-October (Fig. 6.15d) because the ClO concentration and PSC volume dropped to near zero (Figs. 6.15b,c). Therefore, the ozone hole area in November fully depended on cold meteorological conditions that allowed the ozone-depleted air mass to persist over Antarctica. Figure 6.16d demonstrates a strong linear dependence between the area of the November ozone hole and lower stratospheric temperatures in November ($r = 0.88$).

While the 2021 Antarctic ozone hole was larger than average, it was smaller than ozone holes in the late 1990s and 2000s when the levels of ozone depleting substances were near their maximum. The weak amplitudes of planetary scale waves throughout spring 2021 slowed the winter-to-summer transition, resulting in one of the longest-lived ozone holes in the observational record. These results demonstrate that the changes in the Antarctic ozone hole area are consistent with our understanding of ozone depletion, and that ozone recovery due to the implementation of the Montreal Protocol has emerged despite large interannual fluctuations in stratospheric dynamics.

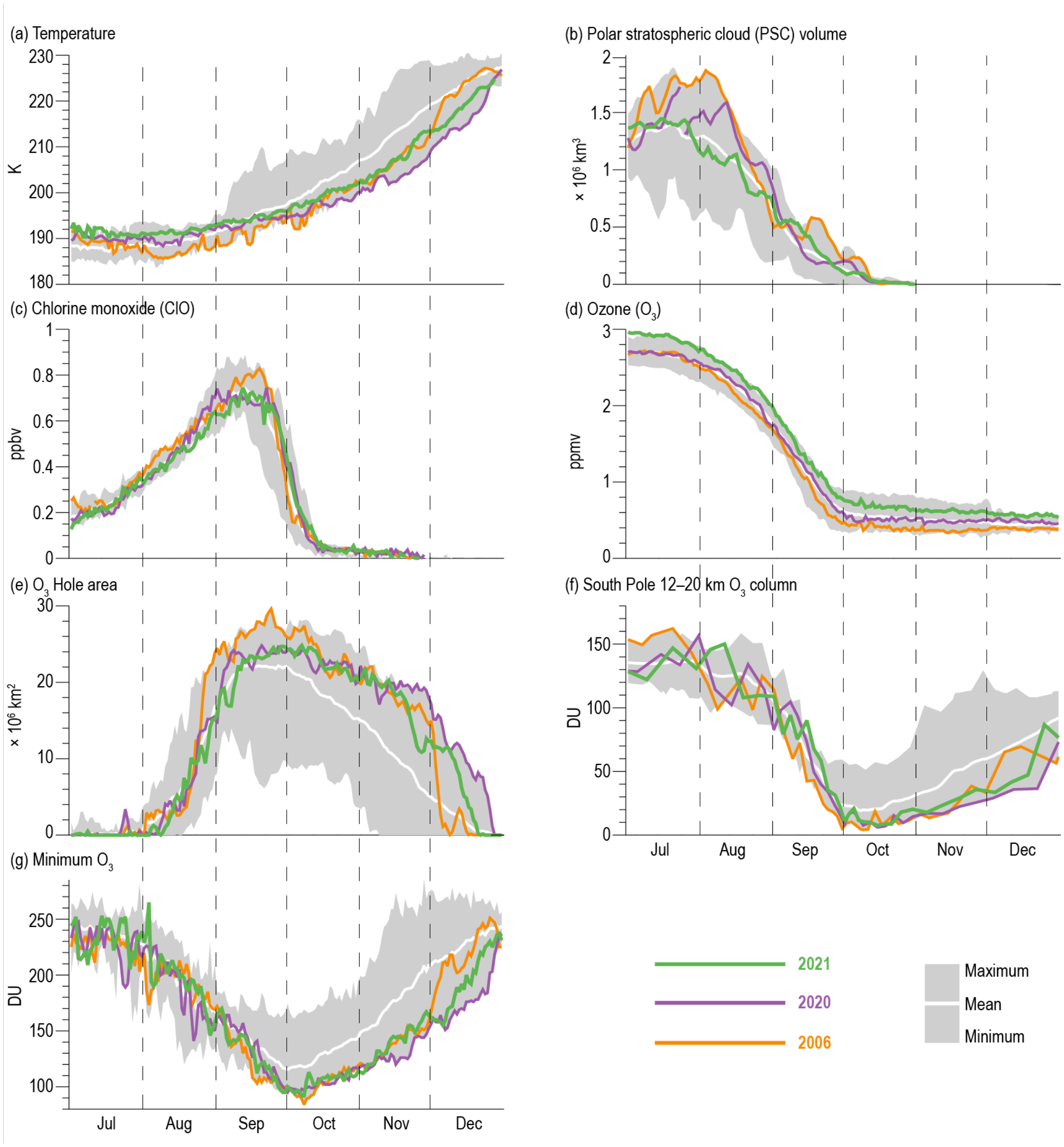

Fig. 6.15. Antarctic values of (a) vortex-averaged MERRA-2 temperature (K), (b) CALIPSO PSC volume (× 106 km3) updated from Pitts et al. (2018), (c,d) vortex-averaged ClO (ppbv) and O3 (ppmv) measured by Aura MLS (updated from Manney et al. 2011), (e) OMI/OMPS Antarctic ozone hole area (× 106 km2, area with ozone total column less than 220 DU), (f) lower stratospheric ozone columns (DU, 12–20 km) based on sonde measurements at South Pole, and (g) minimum total ozone columns (DU) over 60°–90°S from OMI/OMPS. MERRA-2 temperature and MLS averages are made inside the polar vortex on the 440-K potential temperature surface (~19 km or 60 hPa). Gray shading shows the range of daily Antarctic values for 2005 (for all but (b), which starts in 2006) through 2020. The white curve indicates the 2005–20 long-term mean.

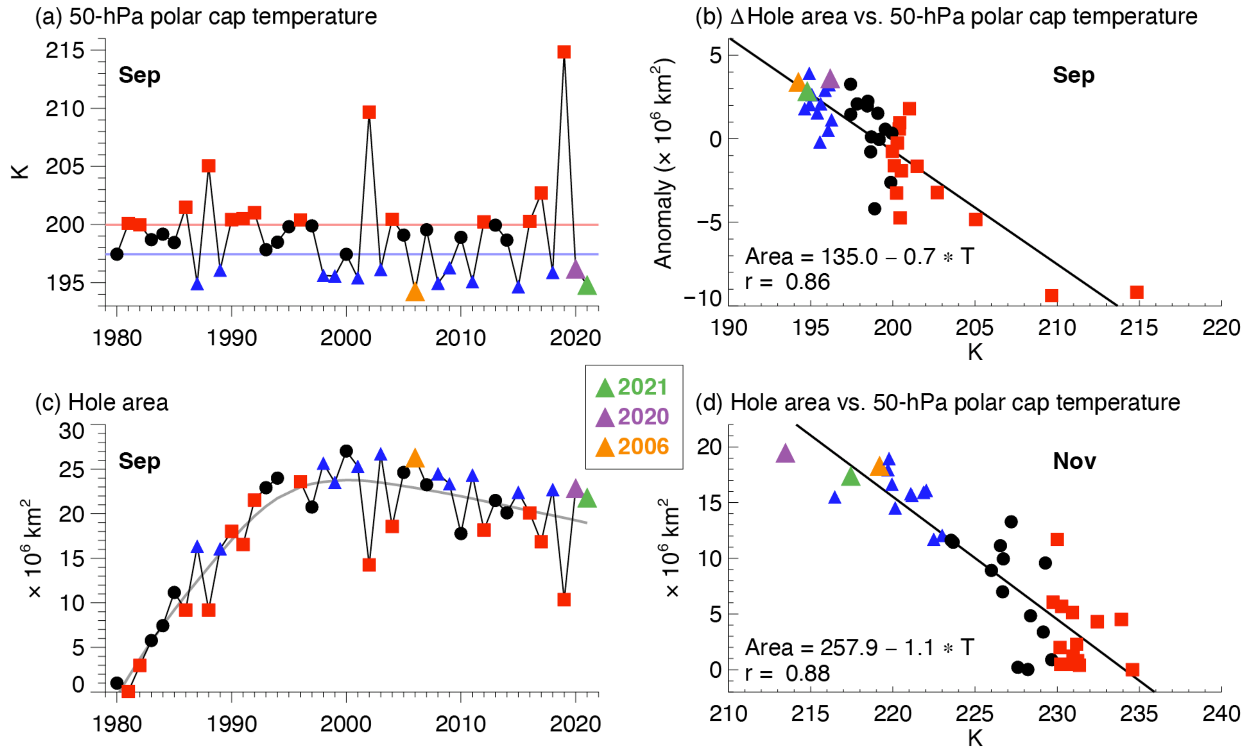

Fig. 6.16. (a) MERRA-2 50-hPa Sep temperature (K) averaged over 60°–90°S, (b) inter-annual anomalies of the ozone hole area (× 106 km2) in Sep (see text) vs. 50-hPa temperature (K), (c) Sep average Antarctic ozone hole area (× 106 km2), and (d) Nov ozone hole areas (× 106 km2) vs. 50-hPa Nov temperature (K). Years with temperatures in the lowest (highest) third are shown as blue triangles (red squares), and three cold years 2006, 2020, and 2021 are highlighted in orange, purple, and green, respectively. The horizontal blue and red lines in (a) indicate 33% and 66% percentiles. The gray curve in (c) shows a quadratic fit of EESC with a 5.2 year mean age (Newman et al. 2007) to the Sep hole areas. Ozone data for 1979–92 are from Total Ozone Mapping Spectrometer (TOMS) Nimbus-7, 1993–94 are from TOMS Meteor-3, 1996–2004 are from EPTOMS, 2005–15 are from Aura Ozone Monitoring Instrument (OMI), and 2015–21 are from Suomi National Polar-orbiting Partnership (SNPP) Ozone Mapping and Profiler Suite (OMPS). There were no satellite total ozone observations for 1995. The black lines in (b) and (d) show the linear fit, with a correlation of 0.86 and 0.88 (statistically significant at > 99.9% confidence level) for Sep and Nov, respectively.

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Data sources:

Aura MLS data
http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/MLS/index.shtml

South Pole sonde measurements
https://www.esrl.noaa.gov/gmd/dv/spo_oz/

Total column ozone data from NASA satellite instruments
https://ozoneaq.gsfc.nasa.gov/data/ozone/

Ozone hole images and data
http://ozonewatch.gsfc.nasa.gov

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10.5067/QBZ6MG944HW0.