

Q10

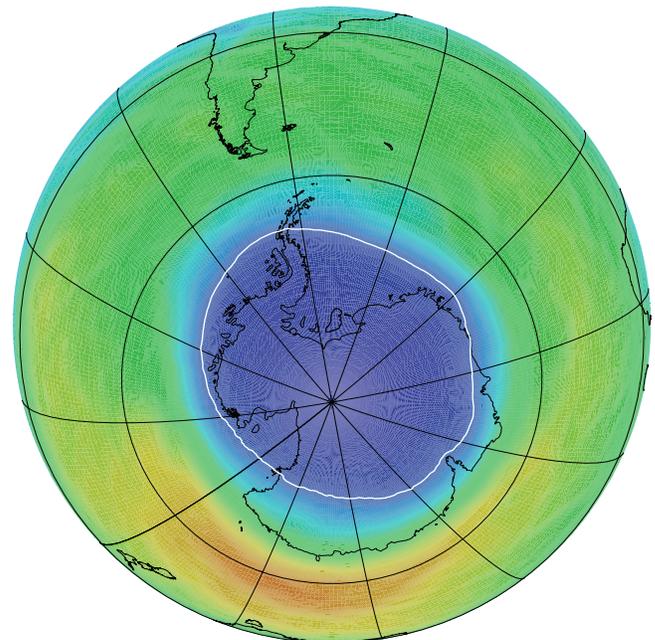
How severe is the depletion of the Antarctic ozone layer?

Severe depletion of the Antarctic ozone layer was first reported in the mid-1980s. Antarctic ozone depletion is seasonal, occurring primarily in late winter and early spring (August–November). Peak depletion occurs in early October when ozone is often completely destroyed over a range of stratospheric altitudes, thereby reducing total ozone by as much as two-thirds at some locations. This severe depletion creates the “ozone hole” apparent in images of Antarctic total ozone acquired using satellite instruments. In most years the maximum area of the ozone hole far exceeds the size of the Antarctic continent.

The severe depletion of Antarctic ozone, known as the “ozone hole”, was first reported in the mid-1980s (see box in Q9). The depletion is attributable to chemical destruction by reactive halogen gases (see Q7 and Q8), which increased everywhere in the stratosphere in the latter half of the 20th century (see Q15). Conditions in the Antarctic winter and early spring stratosphere enhance ozone depletion because of (1) the long periods of

extremely low temperatures, which cause polar stratospheric clouds (PSCs) to form; (2) the large abundance of reactive halogen gases produced in reactions on PSCs; and (3) the isolation of stratospheric air, which allows time for chemical destruction processes to occur. The severity of Antarctic ozone depletion as well as long-term changes can be seen using satellite observations of total ozone and ozone altitude profiles.

Antarctic Ozone Hole

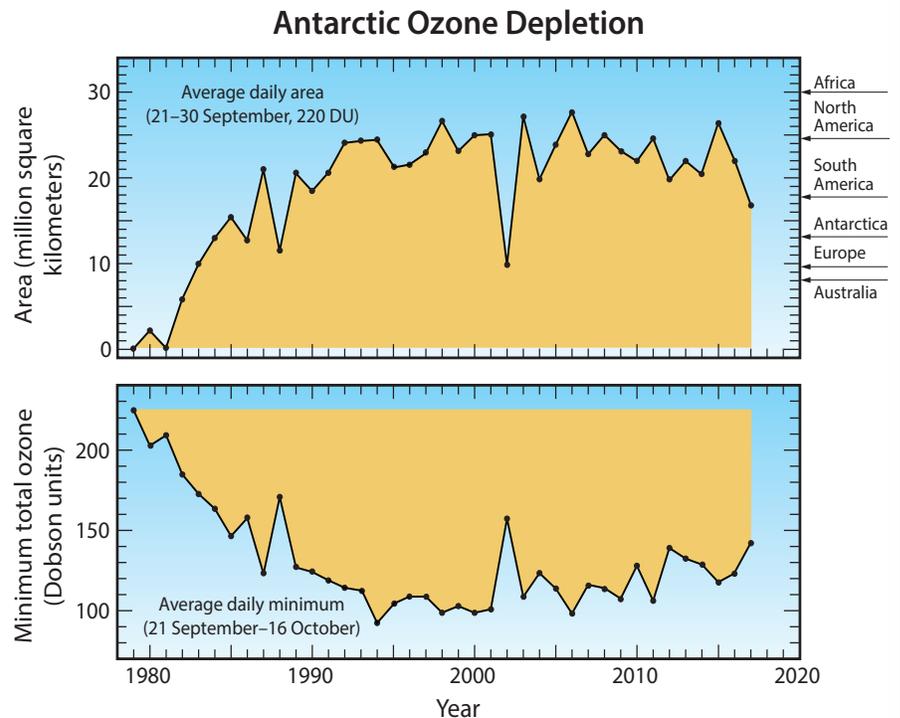


21–30 September 2017

100 200 300 400 500 600
Total Ozone (Dobson units)

Figure Q10-1. Antarctic ozone hole. Total ozone values are shown for high southern latitudes between 21 and 30 September 2017 as measured by a satellite instrument. The dark blue and purple regions over the Antarctic continent show the severe ozone depletion or “ozone hole” now found every austral spring. Minimum values of total ozone inside the ozone hole are close to 150 Dobson units (DU) compared with Antarctic springtime values of about 350 DU observed in the early 1970s (see Figure Q10-3). The area of the ozone hole is usually defined as the geographical region within the 220-DU contour (see white line) on total ozone maps. The maximum values of total ozone in the Southern Hemisphere in late winter/early spring are generally located in a crescent-shaped region that surrounds and is isolated from the ozone hole, due to stratospheric winds at the boundary of the polar vortex. In late spring or early summer (November–December), these atmospheric winds weaken and the ozone hole disappears due to the transport of ozone-enriched air masses towards the pole.

Figure Q10-2. Antarctic ozone hole features. Long-term changes are shown for key aspects of the Antarctic ozone hole: the area enclosed by the 220-DU contour on maps of total ozone (upper panel) and the minimum total ozone amount measured over Antarctica (lower panel). The values are based upon satellite observations and averaged for each year at a time near the peak of ozone depletion, as defined by the dates shown in each panel. The areas of continents are included for reference in the upper panel. The magnitude of Antarctic ozone depletion gradually increased beginning in 1980. In the past two and a half decades the depletion reached steady year-to-year values, except for the unusually small amount of depletion in 2002 (see Figure Q10-4 and following box). The magnitude of Antarctic ozone depletion will steadily decline as ODSs are removed from the atmosphere (see Figure Q15-1). The return of Antarctic total ozone to 1980 values is expected to occur around 2060 (see Q20).



Antarctic ozone hole. The most widely used images of Antarctic ozone depletion are derived from measurements of total ozone made with satellite instruments. A map of Antarctic early spring measurements shows a large region centered near the South Pole in which total ozone is highly depleted (see **Figure Q10-1**). This region has come to be called the “ozone hole” because of the near-circular contours of low ozone values in the maps. The area of the ozone hole is defined here as the geographical region within the 220-Dobson unit (DU) contour in total ozone maps (see white line in Figure Q10-1) averaged between 21–30 September for a given year. The area reached a maximum of 28 million square km (about 11 million square miles) in 2006, which is more than twice the area of the Antarctic continent (see **Figure Q10-2**). Minimum values of total ozone inside the ozone hole averaged in late September to mid-October are near 120 DU, which is nearly two-thirds below springtime values of about 350 DU observed in the early 1970s (see **Figures Q10-3** and **Q11-1**). Low total ozone inside the ozone hole contrasts strongly with the distribution of much larger values outside the ozone hole. This common feature can be seen in Figure Q10-1, where a crescent-shaped region with values around 400 DU surrounds a significant portion of the ozone hole in September 2017, and reveals the edge of the polar vortex that acts as a barrier to the transport of ozone-rich midlatitude air into the polar region (see Q9).

Altitude profiles of Antarctic ozone. The low total ozone values within the ozone hole are caused by nearly complete removal

of ozone in the lower stratosphere. Balloon-borne instruments (see Q4) demonstrate that this depletion occurs within the ozone layer, the altitude region that normally contains the highest abundances of ozone. At geographic locations with the lowest total ozone values, balloon measurements show that the chemical destruction of ozone has often been complete over an altitude region of up to several kilometers. For example, in the ozone profile over South Pole, Antarctica on 9 October 2006 (see red line in left panel of Figure Q11-3), ozone abundances are essentially zero over the altitude region of 14 to 21 km. The lowest winter temperatures and highest reactive chlorine (ClO) abundances occur in this altitude region (see Figure Q7-3). The differences in the average South Pole ozone profiles between the decade 1962–1971 and the years 1990–2018 in Figure Q11-3 show how reactive halogen gases have dramatically altered the ozone layer. In the 1960s, a normal ozone layer is clearly evident in the October average profile, with a peak near 16 km altitude. In the 1990–2018 average profile, a broad minimum centered near 16 km now occurs, with ozone values reduced by up to 90% relative to normal values.

Long-term total ozone changes. Prior to 1960, the amount of reactive halogen gases in the stratosphere was insufficient to cause significant chemical loss of Antarctic ozone. Ground-based observations show that the steady decline in total ozone over the Halley Bay, Antarctic research station (76°S) (see box in Q9) during each October first became apparent in the early 1970s.

Antarctic Total Ozone (October monthly averages)

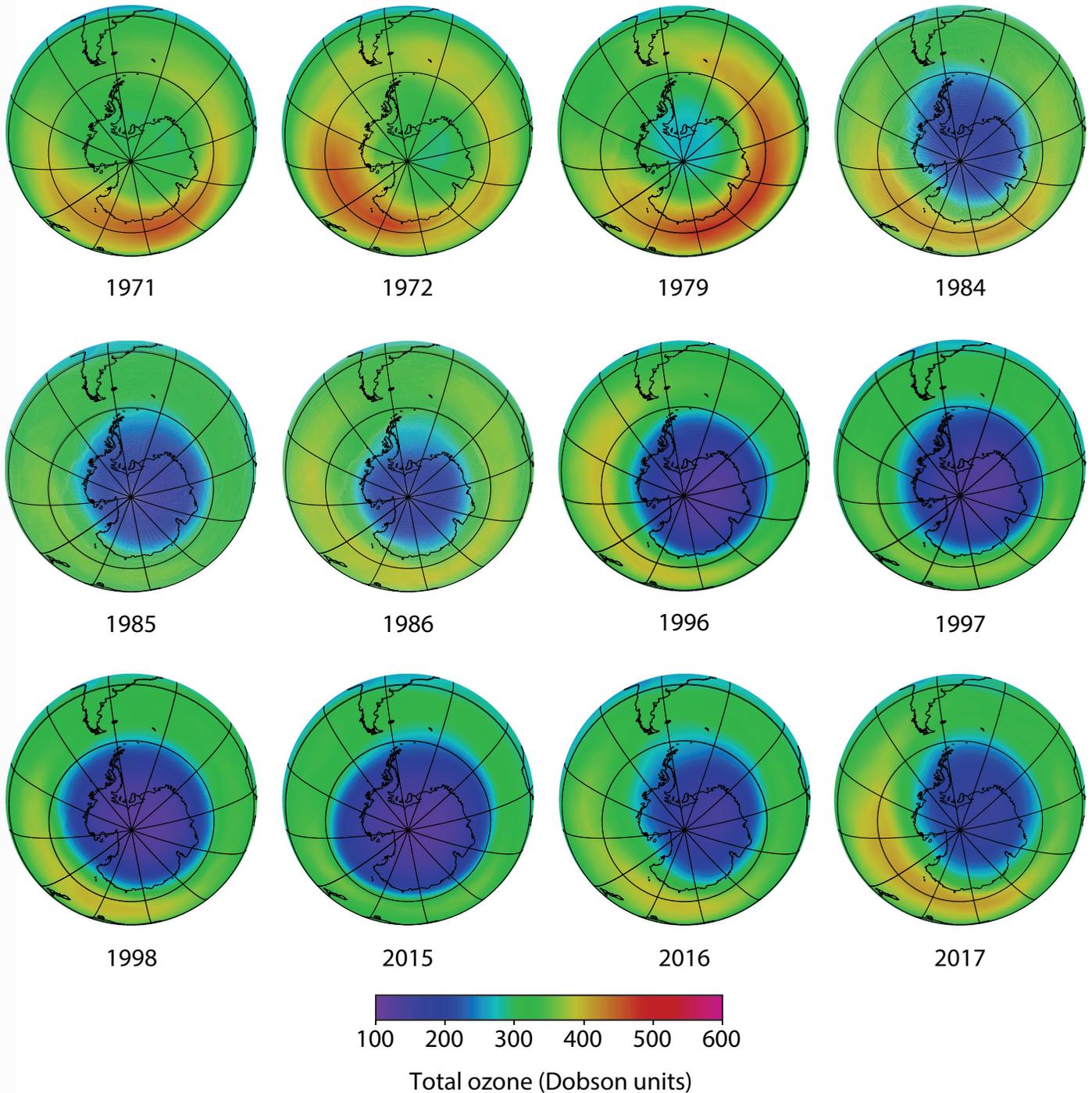


Figure Q10-3. Antarctic total ozone. Long-term changes in Antarctic total ozone are demonstrated with this series of total ozone maps derived from satellite observations. Each map is an average during October, the month of maximum ozone depletion over Antarctica. In the 1970s, no ozone hole was observed, as defined by a significant region with total ozone values less than 220 DU (dark blue and purple colors). The ozone hole initially appeared in the early 1980s and increased in size until the early 1990s. A large ozone hole has occurred each year since the early 1990s as shown in Figure Q10-2. Maps from the mid-2010s show the large extent (about 25 million square km) of recent ozone holes. The largest values of total ozone in the Southern Hemisphere during October are still found in a crescent-shaped region outside of the ozone hole. The satellite data show that these maximum values and their geographic extent have significantly diminished since the 1970s.

Satellite observations reveal that in 1979, total ozone during October near the South Pole was slightly lower than found at other high southerly latitudes (see Figure 10-3). Computer model simulations indicate Antarctic ozone depletion actually began in the early 1960s. Until the early 1980s, total ozone depletion was not large enough to result in minimum values falling below the 220 DU threshold that is now commonly used to denote the boundary of the ozone hole (see Figure Q10-1). Starting in the mid-1980s, a region of total ozone well below 220 DU centered over the South Pole became apparent in satellite maps of October total ozone (see Figure Q10-3). Observations of total ozone from satellite instruments can be used in multiple ways to examine how ozone depletion has changed in the Antarctic region over the past 50 years, including:

- First, *ozone hole areas* displayed in Figure Q10-2 show that depletion increased after 1980, then became fairly stable in the 1990s, 2000s, and into the mid-2010s, often reaching an area of 24 million square km (about the size of North America). An exception is the unexpectedly low depletion
- in 2002, which is explained in the box at the end of this Question. The ozone hole area was larger in 2015, compared to 2014 and 2016, due to the presence of an unusually cold and stable polar vortex in 2015 as well as an increase in stratospheric particles due to the Calbuco volcanic eruption in southern Chile during April 2015.
- Second, *minimum Antarctic ozone* amounts displayed in Figure Q10-2 show that the severity of the depletion increased beginning around 1980 along with the rise in the ozone hole area. Fairly constant minimum values of total ozone, near 110 DU, were observed in the 1990s and 2000s, with the exception of 2002. There is some indication of an increase in the minimum value of total ozone since the early 2010s.
- Third, *total ozone maps* over the Antarctic and surrounding regions show how the ozone hole has developed over time in Figure Q10-3. October averages show the absence of an ozone hole in the 1970s, the extent of the ozone hole

The 2002 Antarctic Ozone Hole

The 2002 Antarctic ozone hole showed features that looked surprising at the time (see **Figure Q10-4**). That year exhibited much less ozone depletion as measured by the area of the ozone hole or minimum total ozone amounts in comparison with ozone holes in 2001 and 2003. The 2002 values now stand out clearly in the year-to-year changes in these quantities displayed in Figure Q10-2. There were no forecasts of an ozone hole with unusual features in 2002 because the meteorological and chemical conditions required to deplete ozone, namely low temperatures and available reactive halogen gases, were present that year and did not differ substantially from those in previous years. The ozone hole initially formed as expected in August and early September 2002. Later, during the last week of September, a rare meteorological event occurred that dramatically reshaped the ozone hole into two separate depleted regions (see Figure Q10-4). As a result of this disturbance, the combined area of these two regions in late September and early October was significantly less than that observed for the previous or subsequent ozone holes.

The unexpected meteorological influence in 2002 resulted from specific atmospheric air motions that sometimes occur in polar regions. Meteorological analyses of the Antarctic stratosphere show that it was warmed by very strong, large-scale weather systems that originated in the lower atmosphere (troposphere) at midlatitudes in late September. At that time, Antarctic temperatures are generally very low (see Q9) and ozone destruction rates are near their peak values. The influence of these tropospheric systems extended poleward and upward into the stratosphere, disturbing the normal circum-polar wind (polar vortex) and warming the lower stratosphere where ozone depletion was ongoing. Higher temperatures in late September reduced the rate of ozone depletion and led to the higher minimum value for total ozone shown in Figure Q10-2. The greater-than-normal impact of these weather disturbances during late winter/early spring when ozone loss processes are normally most effective resulted in less Antarctic ozone depletion in 2002.

The 2002 stratospheric warming event is the strongest in the many decades of Antarctic meteorological observations. Another warming event in 1988 caused somewhat smaller changes in the ozone hole features than in 2002. Large warming events are difficult to predict because of the complex conditions leading to their formation.

The size and maximum ozone depletion (depth) of the ozone hole from 2003 through 2017 returned to values similar to those observed from the mid-1990s to 2001 (see Figure Q10-2). The high ozone depletion found since the mid-1990s, with the exception of 2002, is expected to be typical of coming years. A significant, sustained reduction of Antarctic ozone depletion, leading to full recovery of total ozone, requires comparable, sustained reductions of ozone-depleting substances in the stratosphere. Even with the halogen source gas reductions already underway (see Q15), the return of Antarctic total ozone to 1980 values is not expected to occur until around 2060 (see Q20).

around the time of its discovery in 1985 (see box in Q9), and the annual occurrence throughout the 1990s and 2010s.

- Fourth, values of *total ozone averaged poleward of 63°S* for each October show how total ozone has changed in the Antarctic region in Figure Q11-1. After decreasing steeply in the early years of the ozone hole, polar-cap averages of total ozone are now approximately 30% smaller than those in pre-ozone hole years (1970–1982). These Antarctic-region ozone values exhibit larger year-to-year variability than the other ozone measures noted above because this average includes areas outside the ozone hole. Increased year-to-year variability in Antarctic-region ozone is evident over the past decade. As noted above, the exceptionally low value of total ozone in 2015 is attributed in part to the effects of the Calbuco volcanic eruption, whereas the 2017 ozone hole was less extensive than prior years due to unusual meteorological conditions in the Southern Hemisphere. The maps in Figure Q10-3 show how the maximum in total ozone surrounding the ozone hole each year has also diminished

over the last four decades, adding to the decreases noted in Figure Q11-1.

Disappearance of the Antarctic ozone hole in spring. The severe depletion of Antarctic ozone occurs in the late winter/early spring season. In austral spring (mid-October), temperatures in the polar lower stratosphere increase (see Figure Q9-1), stopping the formation of PSCs and production of ClO and, consequently, the most effective chemical cycles that destroy ozone (see Q8). The polar vortex breaks down, ending the wintertime isolation of high-latitude air and increasing the exchange of air between the Antarctic stratosphere and lower latitudes. This allows substantial amounts of ozone-rich air to be transported poleward, where it displaces or mixes with air depleted in ozone. The midlatitude air also contains higher abundances of nitrogen oxide gases (NO_x), which help convert the most reactive chlorine gases (ClO) back into the chlorine reservoir gas ClONO₂ (see Q7 and Q9). As a result of these large-scale transport and mixing processes, the ozone hole typically disappears by mid-December.

Unusual 2002 Antarctic Ozone Hole

Figure Q10-4. Unusual 2002 ozone hole. Views from space of the Antarctic ozone hole are shown for 24 September in the years 2001, 2002, and 2003. The ozone holes in 2001 and 2003 are considered typical of those observed since the early 1990s. An initially circular hole in 2002 was transformed into two smaller, depleted regions in the days preceding 24 September. This unusual event is attributable to an early warming of the polar stratosphere caused by meteorological disturbances that originated in the troposphere at midlatitudes. Higher temperatures reduced the rate of ozone depletion in 2002. As a consequence, total ozone depletion was unusually low that year in comparison with 2001 and 2003 and all other years since the early 1990s (see Figure Q10-2).

