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 during polar night, 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 polar stratospheric air, which allows time for chemical destruction processes to occur after the return of sunlight. The severity of Antarctic ozone depletion as well as long-term changes can be seen using satellite observations of total ozone and profiles of ozone versus altitude.

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**).

Antarctic Ozone Hole

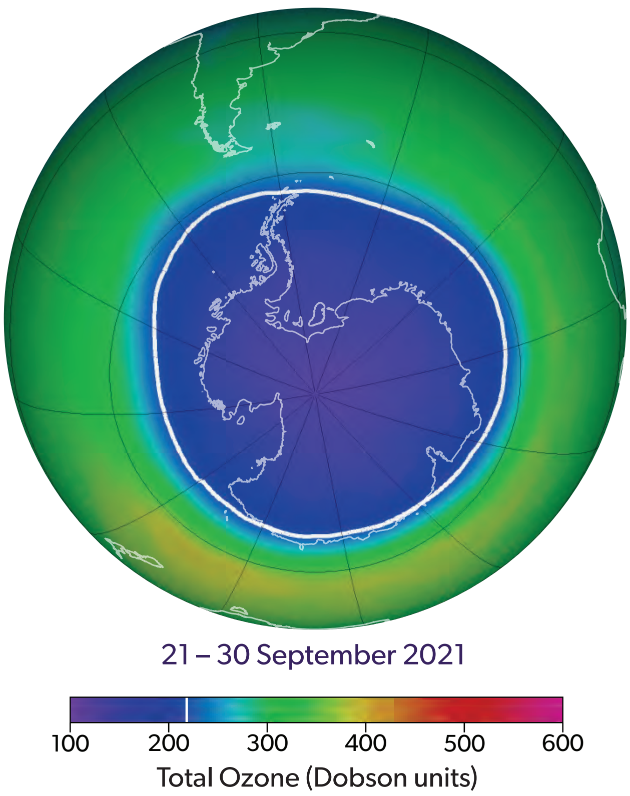

Figure Q10-1. Antarctic ozone hole. Total ozone values as measured by a satellite instrument are shown for high southern latitudes averaged over 21 to 30 September 2021. The dark blue and purple regions over the Antarctic continent show the severe ozone depletion or "ozone hole" now found every austral 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 (thick 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 (better seen in Figure Q10-3) 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 cessation of the ozone-depleting chemical reactions and the transport of ozone-enriched air masses towards the pole.

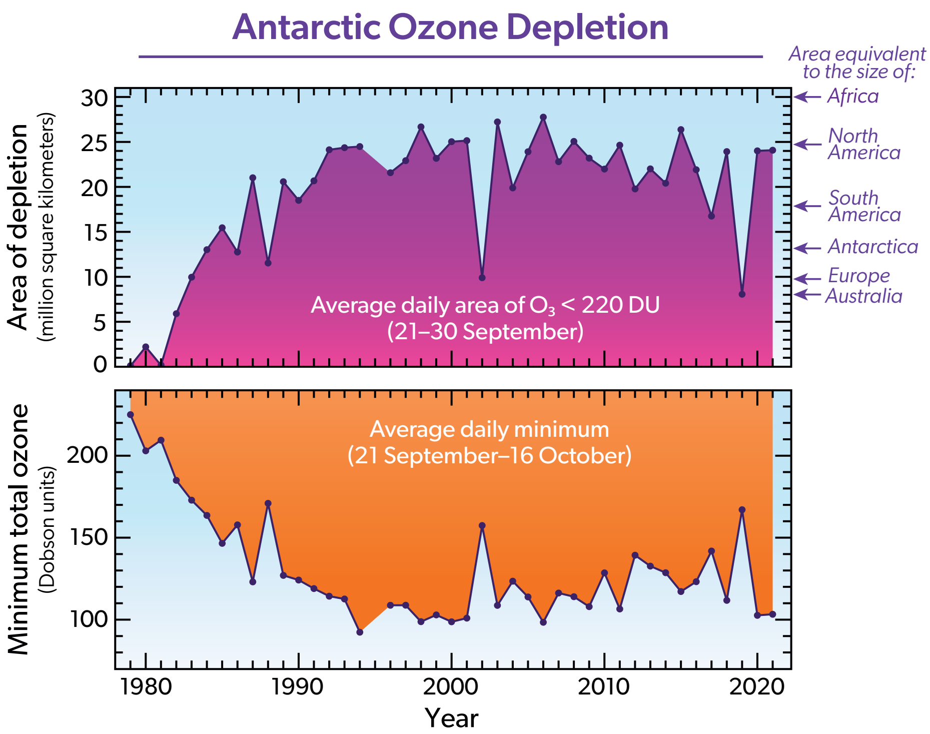

Figure Q10-2. Antarctic ozone hole features. Long-term changes are shown for key aspects of the Antarctic ozone hole: the area enclosed by the 220-DU contour on maps of total ozone (upper panel) and the minimum total ozone amount measured over Antarctica (lower panel). The values are from satellite observations 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 and 2019 (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 the mid-2060s (see Q20).

This region has come to be called the "ozone hole" because of the near-circular contours of low ozone values in the maps. The reported area of the ozone hole for a given year 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. 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 only one-third of the 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 broad geographic region with values of total ozone around 350 DU surrounds the ozone hole in September 2021, revealing 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 ozone 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, ozonesonde 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 10 October 2020 (see red line in left panel of Figure Q11-3), ozone abundances are essentially zero over the altitude region from 14 to 20 km. The lowest winter temperatures and highest abundances of reactive chlorine (ClO) occur in this altitude region (see Figure Q7-3). The differences in the South Pole ozone profiles averaged over 1967–1971 and over 1990–2021 in Figure Q11-3 show how reactive halogen gases have dramatically altered the ozone layer. For the 1967–1971 time period, a normal ozone layer is clearly evident in the October average profile, with a peak near 16 km altitude. In the 1990–2021 average profile, a broad minimum centered near 16 km is observed, with ozone values reduced at some altitudes 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 research station (76°S) (see box in Q9) during each October first became apparent in the early 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 Q10-3). Computer model simulations indicate that Antarctic ozone depletion actually began in the early 1960s. Until the early 1980s, depletion of total ozone 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

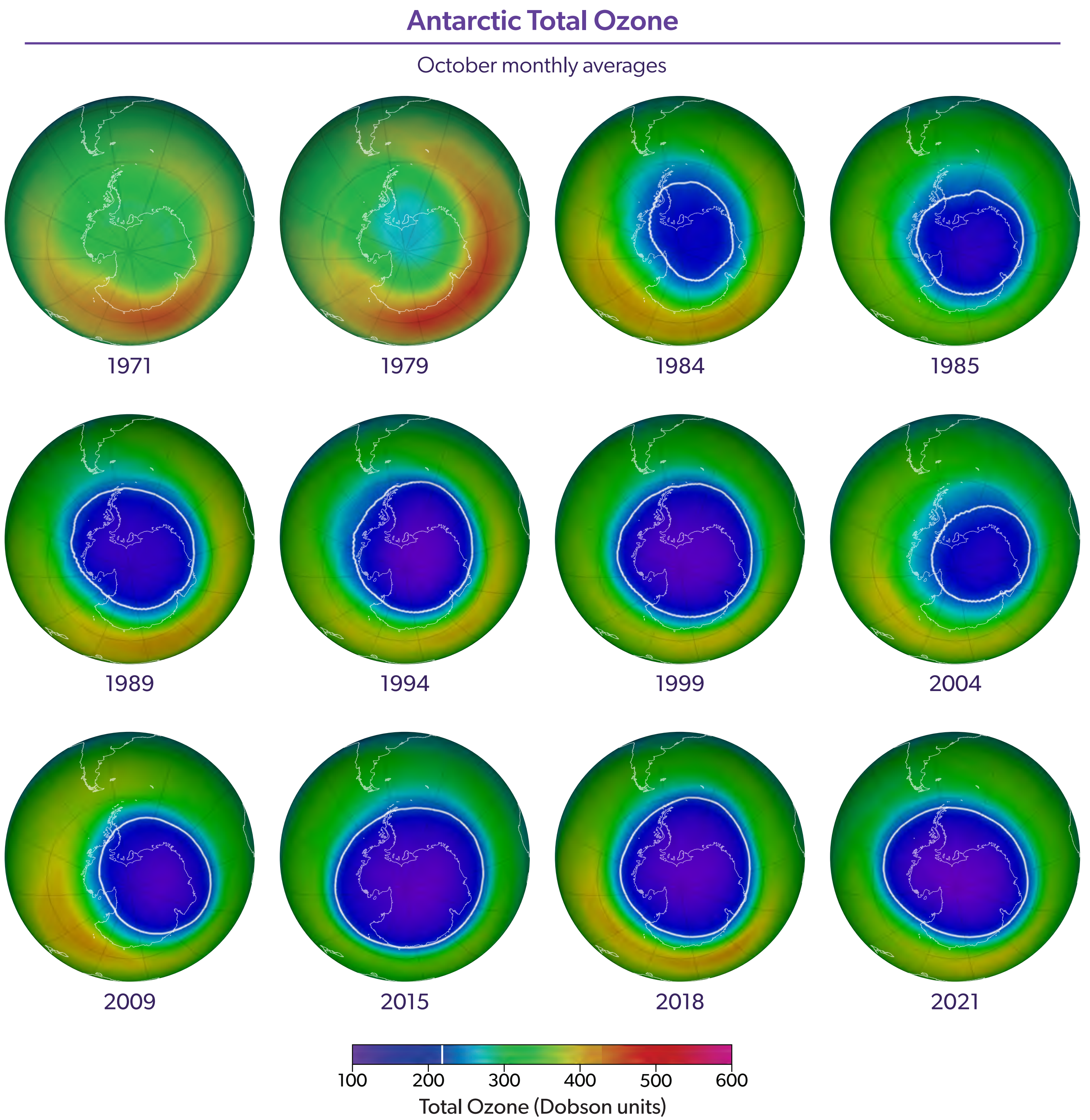

Figure Q10-3. Antarctic total ozone. Long-term changes in Antarctic total ozone are demonstrated with this series of total ozone maps derived from satellite observations. Each map is an average during October, the month of maximum ozone depletion over Antarctica. In the 1970s an ozone hole, as defined by a significant region with total ozone values less than 220 DU (thick white line), was not observed. 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 mid-1980s 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 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.

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 the area of depletion increased after 1980, then became fairly stable in the 1990s, 2000s, and into the mid-2010s, often reaching an area of 25 million square km (about the size of North America). Exceptions are the unexpectedly low areas of depletion observed in 2002 and 2019, which are explained in the box at the end of this Question.
- 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 exceptions of 2002 and 2019. There is some indication of an increase in the minimum value of total ozone since the early 2010s. However, in 2020 and 2021 unusually cold conditions produced large and long-lasting ozone holes, whereas in 2019 a weather disturbance resulted in a small, shallow ozone hole (see box). The ozone holes of 2019, 2020, and 2021 demonstrate the importance of year-to-year variability in ozone hole conditions, which challenges the identification of recovery due to declining levels of ODSs.
- Third, ***total ozone maps*** over the Antarctic and surrounding regions (Figure Q10-3) show how the ozone hole has developed over time. October averages show the absence of an ozone hole in the 1970s, the extent of the ozone hole around the time of its discovery in 1985 (see box in Q9), followed by the progression throughout the 1990s, the 2010s, and into the early 2020s.
- Fourth, ***values of total ozone averaged poleward of 63°S*** for each October (Figure Q11-1) show how total ozone has changed in the Antarctic region. 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). Increased year-to-year variability in Antarctic-region ozone is evident since 2000.

Disappearance of the Antarctic ozone hole. Severe depletion of Antarctic ozone occurs each spring. In mid-October, temperatures in the polar lower stratosphere begin to increase (see Figure Q9-1), eventually rising to a level that prevents the formation of PSCs and production of ClO. Consequently, the most effective chemical cycles that destroy ozone are curtailed (see Q8). Typically, the polar vortex breaks down during late November or early December, ending the isolation of high-latitude air and increasing the exchange of air between the Antarctic stratosphere and lower latitudes. This exchange allows substantial amounts of ozone-rich air to be transported poleward, where it displaces or mixes with air depleted in ozone. As a result of these large-scale transport and mixing processes, the ozone hole typically disappears by mid-December.

Long-term recovery of the Antarctic ozone hole. There are emerging indications that the size and maximum ozone depletion (severity) of the Antarctic ozone hole has diminished since 2000. The signature of recovery is clearest during September, which is early spring in the Southern Hemisphere. Although accounting for the effect of natural variability on the size and depth of the ozone hole is challenging, the weight of evidence suggests that the decline in the amount of reactive halogen gases in the stratosphere since 2000 has made a substantial contribution to the observed reductions in the size and depth of the ozone hole during September. The reduction of Antarctic ozone depletion leading to full recovery of total ozone back to the value observed in the early 1980s requires continued, 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 the mid-2060s (see Q20).

Unusual 2019 Antarctic Ozone Hole

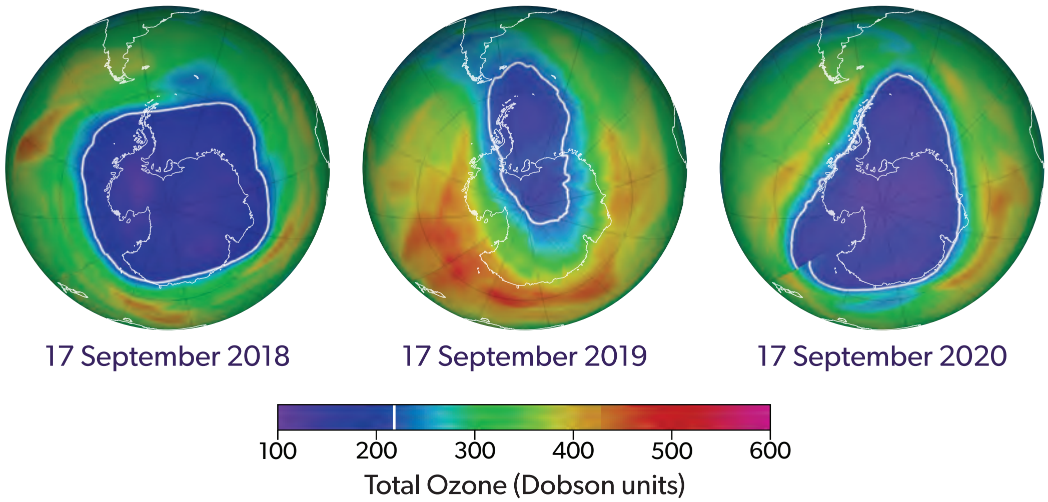

Figure Q10-4. Unusual 2019 ozone hole. Views from space of the Antarctic ozone hole are shown for 17 September for three consecutive years: 2018, 2019, and 2020. The ozone holes in 2018 and 2020 are considered typical of those observed since the late 1990s. An initially circular hole in 2019 was transformed by the significant transport of air from midlatitudes into the region of the ozone hole starting in late August. This unusual event, initiated by meteorological disturbances in the midlatitude troposphere, transported high amounts of ozone from midlatitudes into the region of the ozone hole and led to higher temperatures that reduced the rate of ozone depletion in 2019 compared to most other years. Consequently, the region of low total ozone in 2019 was displaced from the normal circumpolar position, and the amount of ozone depletion in 2019 as measured by the area of the ozone hole or minimum total ozone amounts was much less than in either 2018 or 2020 (see Figure Q10-2).

The 2019 Antarctic Ozone Hole

The 2019 Antarctic ozone hole 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 2018 and 2020. The 2019 values, along with those observed in 2002, stand out clearly in the year-to-year changes in these quantities displayed in Figure Q10-2. Both of these anomalies are due to unusually warm meteorological conditions.

The ozone hole initially formed as expected in August 2019. At the end of August, an unusual weather pattern occurred that resulted in the transport of air from midlatitudes into the region of the ozone hole. As a result of this meteorological disturbance, the region of low total ozone was displaced from the normal circular position centered over the South Pole during September 2019 (see **Figure Q10-4**). Air with anomalously large amounts of ozone was transported from midlatitudes into the Antarctic stratosphere during the first two weeks of September 2019, resulting in the smallest ozone hole in the 21st century and one of the smallest ever observed in September since 1984, when the ozone hole was discovered (see Figure Q10-2).

The unexpected meteorological influence in 2019 resulted from specific atmospheric air motions that sometimes occur in polar regions. Meteorological analyses show that the 2019 disturbance was initiated by strong, large-scale weather systems that originated in the lower atmosphere (troposphere) at midlatitudes earlier in the year. This tropospheric weather system extended poleward and upward into the stratosphere, disturbing the normal circumpolar wind (polar vortex), transporting air with high levels of ozone into the vortex, and warming the lower stratosphere where ozone depletion was ongoing. The impact of this weather disturbance during late winter/early spring, when ozone loss processes are normally most effective, resulted in less Antarctic ozone depletion in 2019.

A similar stratospheric warming event occurred in 2002, resulting in ozone hole area and minimum total ozone amount values that are comparable to those observed in 2019 (see Figure Q10-2). Another warming event in 1988 caused somewhat smaller changes in the ozone hole features than those observed in 2002 and 2019. 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 in 2020 and 2021 returned to values similar to those observed since the late 1990s (see Figures Q10-2 and Q10-3).