Twenty Questions and Answers About the Ozone Layer: 2018 Update

Scientific Assessment of Ozone Depletion: 2018

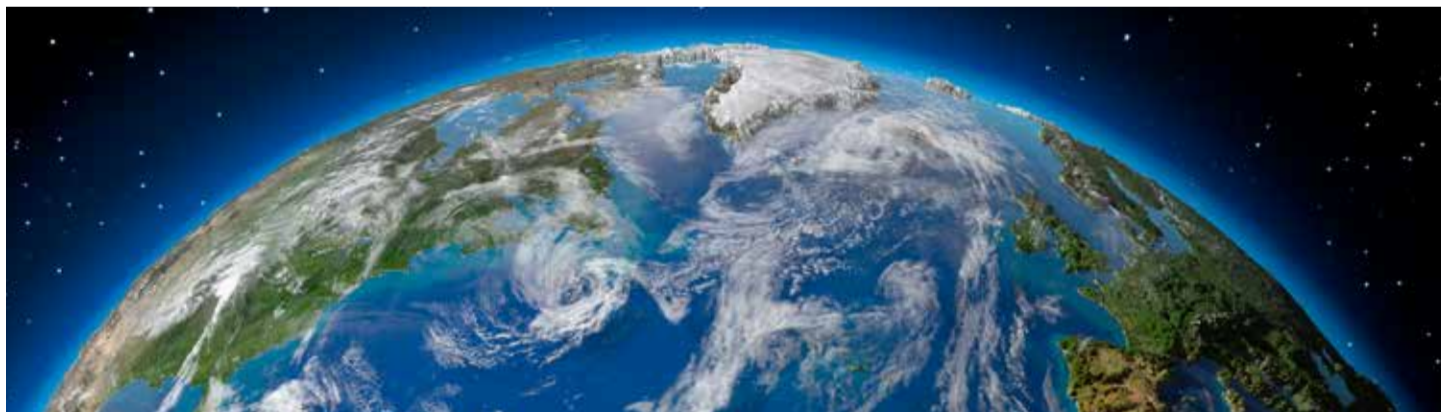### Lead Author

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Why has an "ozone hole" appeared over Antarctica when ozone-depleting substances are present throughout the stratosphere?

Ozone-depleting substances are present throughout the stratospheric ozone layer because they are transported great distances by atmospheric air motions. The severe depletion of the Antarctic ozone layer known as the "ozone hole" occurs because of the special meteorological and chemical conditions that exist there and nowhere else on the globe. The very low winter temperatures in the Antarctic stratosphere cause polar stratospheric clouds (PSCs) to form. Special reactions that occur on PSCs, combined with the isolation of polar stratospheric air in the polar vortex, allow chlorine and bromine reactions to produce the ozone hole in Antarctic springtime.

The severe depletion of stratospheric ozone in late winter and early spring in the Antarctic is known as the "ozone hole" (see Q10). The ozone hole appears over Antarctica because meteorological and chemical conditions unique to this region increase the effectiveness of ozone destruction by reactive halogen gases (see Q7 and Q8). In addition to a large abundance of these reactive gases, the formation of the Antarctic ozone hole requires temperatures low enough to form polar stratospheric clouds (PSCs), isolation from air in other stratospheric regions, and sunlight (see Q8).

Figure Q9-1. Arctic and Antarctic temperatures. Air temperatures in both polar regions reach minimum values in the lower stratosphere in the winter season. Average daily minimum values over Antarctica are as low as −92°C in July and August in a typical year. Over the Arctic, average minimum values are near −80°C in late December and January. Polar stratospheric clouds (PSCs) are formed in the ozone layer when winter minimum temperatures fall below their formation threshold of about −78°C. This occurs on average for 1 to 2 months over the Arctic and about 5 months over Antarctica each year (see heavy red and blue lines). Reactions on liquid and solid PSC particles cause the highly reactive chlorine gas ClO to be formed, which catalytically destroys ozone (see Q8). The range of winter minimum temperatures found in the Arctic is much greater than that in the Antarctic. In some years, PSC formation temperatures are not reached in the Arctic, and significant ozone depletion does not occur. In contrast, PSC formation temperatures are always present for many months somewhere in the Antarctic, and severe ozone depletion occurs each winter season (see Q10).

Minimum Air Temperatures in the Polar Stratosphere
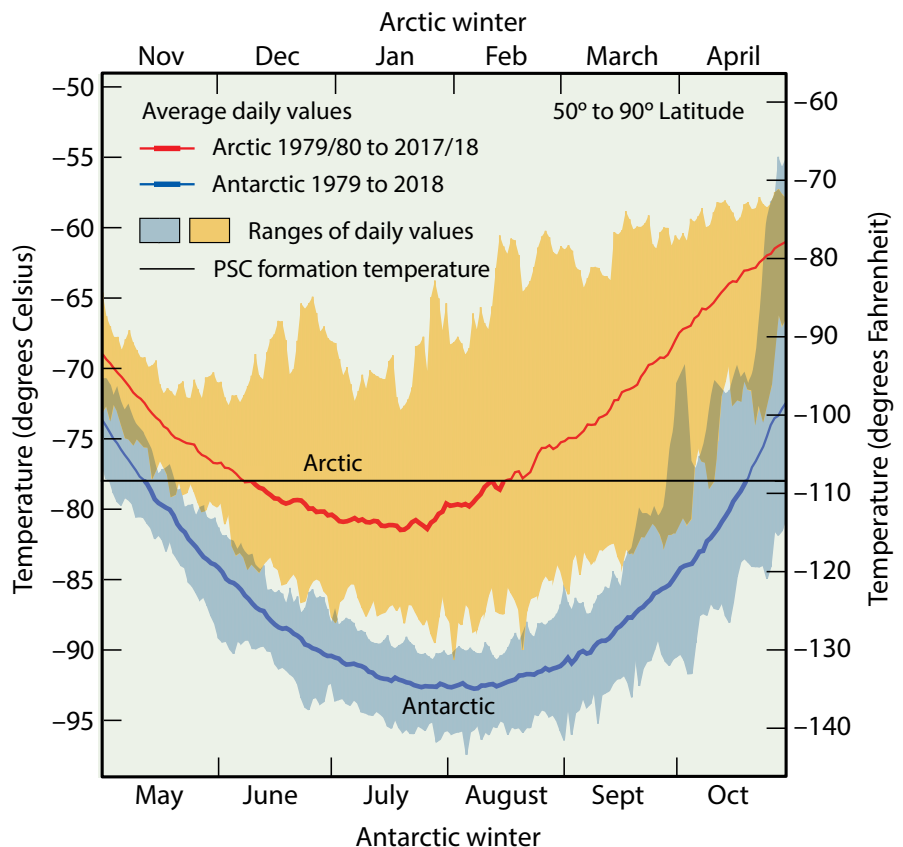
Distribution of halogen gases. Halogen source gases that are emitted at Earth's surface and have lifetimes longer than about 1 year (see Table Q6-1) are present in comparable abundances throughout the stratosphere in both hemispheres, even though most of the emissions occur in the Northern Hemisphere. The abundances are comparable because most long-lived source gases have no significant natural removal processes in the lower atmosphere, and because winds and convection redistribute and mix air efficiently throughout the troposphere on the timescale of weeks to months. Halogen gases (in the form of source gases and some reactive products) enter the stratosphere primarily from the tropical upper troposphere. Stratospheric air motions then transport these gases upward and toward the pole in both hemispheres.

Low polar temperatures. The severe ozone destruction that leads to the ozone hole requires low temperatures to be present over a range of stratospheric altitudes, over large geographical regions, and for extended time periods. Low temperatures are important because they allow liquid and solid PSCs to form. Reactions on the surfaces of these PSCs initiate a remarkable increase in the most reactive chlorine gas, chlorine monoxide (ClO) (see below as well as Q7 and Q8). Stratospheric temperatures are lowest in the polar regions in winter. In the Antarctic winter, minimum daily temperatures are generally much lower and less variable than those in the Arctic winter (see **Figure Q9-1**). Antarctic temperatures also remain below PSC formation temperatures for much longer periods during winter. These and other meteorological differences occur because of variations between the hemispheres in the distributions of land, ocean, and mountains at middle and high latitudes. As a consequence, winter temperatures are low enough for PSCs to form somewhere in the Antarctic for nearly the entire winter (about 5 months), and only for limited periods (10–60 days) in the Arctic for most winters.

Isolated conditions. Stratospheric air in the polar regions is relatively isolated for long periods in the winter months. The isolation is provided by strong winds that encircle the poles during winter, forming a *polar vortex*, which prevents substantial transport and mixing of air into or out of the polar stratosphere. This circulation strengthens in winter as stratospheric temperatures decrease. The Southern Hemisphere polar vortex circulation tends to be stronger than that in the Northern Hemisphere because northern polar latitudes have more land and mountainous regions than southern polar latitudes. This situation leads to more meteorological disturbances in the Northern Hemisphere, which increase the mixing in of air from lower latitudes that warms the Arctic stratosphere. Since winter temperatures are lower in the Southern than in the Northern Hemisphere polar stratosphere, the isolation of air in the polar vortex is much more effective in the Antarctic than in the Arctic. Once temperatures drop low enough, PSCs form within the polar vortex and induce chemical changes such as an increase in the abundance of ClO (see Q8) that are preserved for many weeks to months due to the isolation of polar air.

Polar stratospheric clouds (PSCs). Reactions on the surfaces of liquid and solid PSCs can substantially increase the relative abundances of the most reactive chlorine gases. These reactions convert the reservoir forms of reactive chlorine gases, chlorine nitrate ($ClONO_2$) and hydrogen chloride (HCl), to the most reactive form, ClO (see Figure Q7-3). The abundance of ClO increases from a small fraction of available reactive chlorine to comprise nearly all chlorine that is available. With increased ClO, the catalytic cycles involving ClO and BrO become active in the chemical destruction of ozone whenever sunlight is available (see Q8).

Different types of liquid and solid PSC particles form when stratospheric temperatures fall below about −78°C (−108°F) in polar regions (see Figure Q9-1). As a result, PSCs are often found over large areas of the winter polar regions and over significant

Arctic Polar Stratospheric Clouds (PSCs)

Figure Q9-2. Polar stratospheric clouds. This photograph of an Arctic polar stratospheric cloud (PSC) was taken in Kiruna, Sweden (67°N), on 27 January 2000. PSCs form in the ozone layer during winters in the Arctic and Antarctic, wherever low temperatures occur (see Figure Q9-1). The particles grow from the condensation of water, nitric acid (HNO_3), and sulfuric acid (H_2SO_4). The clouds often can be seen with the human eye when the Sun is near the horizon. Reactions on PSCs cause the formation of the highly reactive gas chlorine monoxide (ClO), which is very effective in the chemical destruction of ozone (see Q7 and Q8).

altitude ranges, with significantly larger regions and for longer time periods in the Antarctic than in the Arctic. The most common type of PSC forms from nitric acid (HNO_3) and water condensing on pre-existing liquid sulfuric acid-containing particles. Some of these particles freeze to form solid particles. At even lower temperatures (−85°C or −121°F), water condenses to form ice particles. PSC particles grow large enough and are numerous enough that cloud-like features can be observed from the ground under certain conditions, particularly when the Sun is near the horizon (see **Figure Q9-2**). PSCs are often found near mountain ranges in polar regions because the motion of air over the mountains can cause localized cooling in the stratosphere, which increases condensation of water and HNO_3.

When average temperatures begin increasing in late winter, PSCs form less frequently, which slows down the production of ClO by conversion reactions throughout the polar region. Without continued production, the abundance of ClO decreases as other chemical reactions re-form the reservoir gases, $ClONO_2$ and HCl. When temperatures rise above PSC formation thresholds, usually sometime between late January and early March in the Arctic and by mid-October in the Antarctic (see Figure Q9-1), the most intense period of ozone depletion ends.

Nitric acid and water removal. Once formed, the largest PSC particles fall to lower altitudes because of gravity. The largest particles can descend several kilometers or more in the stratosphere within a few days during the low-temperature winter/spring period. Because PSCs often contain a significant fraction of available HNO_3, their descent removes HNO_3 from regions of the ozone layer. This process is called *denitrification* of the stratosphere. Because HNO_3 is a source for nitrogen oxides (NO_x) in the stratosphere, denitrification removes the NO_x available for converting the highly reactive chlorine gas ClO back into

the reservoir gas $ClONO_2$. As a result, ClO remains chemically active for a longer period, thereby increasing chemical ozone destruction. Significant denitrification occurs each winter in the Antarctic and only for occasional winters in the Arctic, because PSC formation temperatures must be sustained over an extensive altitude region and time period to lead to denitrification (see Figure Q9-1).

Ice particles form at temperatures that are a few degrees lower than those required for PSC formation from HNO_3. If ice particles grow large enough, they can fall several kilometers due to gravity. As a result, a significant fraction of water vapor can be removed from regions of the ozone layer over the course of a winter. This process is called *dehydration* of the stratosphere. Because of the very low temperatures required to form ice, dehydration is common in the Antarctic and rare in the Arctic. The removal of water vapor does not directly affect the catalytic reactions that destroy ozone. Dehydration indirectly affects ozone destruction by suppressing PSC formation later in winter, which reduces the production of ClO by PSC reactions.

Discovering the role of PSCs. Ground-based observations of PSCs were available many decades before the role of PSCs in polar ozone destruction was recognized. The geographical and altitude extent of PSCs in both polar regions was not known fully until PSCs were observed by a satellite instrument in the late 1970s. The role of PSC particles in converting reactive chlorine gases to ClO was not understood until after the discovery of the Antarctic ozone hole in 1985. Our understanding of the chemical role of PSC particles developed from laboratory studies of their surface reactivity, computer modeling studies of polar stratospheric chemistry, and measurements that directly sampled particles and reactive chlorine gases, such as ClO, in the polar stratosphere.

The Discovery of the Antarctic Ozone Hole

The first decreases in Antarctic total ozone were observed in the early 1980s over research stations located on the Antarctic continent. The measurements were made with ground-based Dobson spectrophotometers (see box in Q4) installed as part of the effort to increase observations of Earth's atmosphere during the International Geophysical Year that began in 1957 (see Figure Q0-1).The observations showed unusually low total ozone during the late winter/early spring months of September, October, and November. Total ozone was lower in these months compared with previous observations made as early as 1957. The early published reports came from the Japan Meteorological Agency and the British Antarctic Survey. The results became widely known to the world after three scientists from the British Antarctic Survey published their observations in the prestigious scientific journal *Nature* in 1985. They suggested that rising abundances of atmospheric CFCs were the cause of the steady decline in total ozone over the Halley Bay research station (76°S) observed during successive Octobers starting in the early 1970s. Soon after, satellite measurements confirmed the spring ozone depletion and further showed that for each late winter/early spring season starting in the early 1980s, the depletion of ozone extended over a large region centered near the South Pole. The term "ozone hole" came about as a description of the very low values of total ozone, apparent in satellite images, that encircle the Antarctic continent for many weeks each October (spring in the Southern Hemisphere) (see Q10). Currently, the formation and severity of the Antarctic ozone hole are documented each year by a combination of satellite, ground-based, and balloon observations of ozone.

Very early Antarctic ozone measurements. The first total ozone measurements made in Antarctica with Dobson spectrophotometers occurred in the 1950s following extensive measurements in the Northern Hemisphere and Arctic region. Total ozone values observed in the Antarctic spring were found to be around 300 Dobson units (DU), lower than those in the Arctic spring. The Antarctic values were surprising because the assumption at the time was that the two polar regions would have similar values. We now know that these 1950s Antarctic values were not anomalous; in fact, similar values were observed near the South Pole in the 1970s, before the ozone hole appeared (see Figure Q10-3). Antarctic total ozone values in early spring are systematically lower than those in the Arctic early spring because the Southern Hemisphere polar vortex is much stronger and colder and, therefore, much more effective in reducing the transport of ozone-rich air from midlatitudes to the pole (compare Figures Q10-3 and Q11-2).

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.

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.
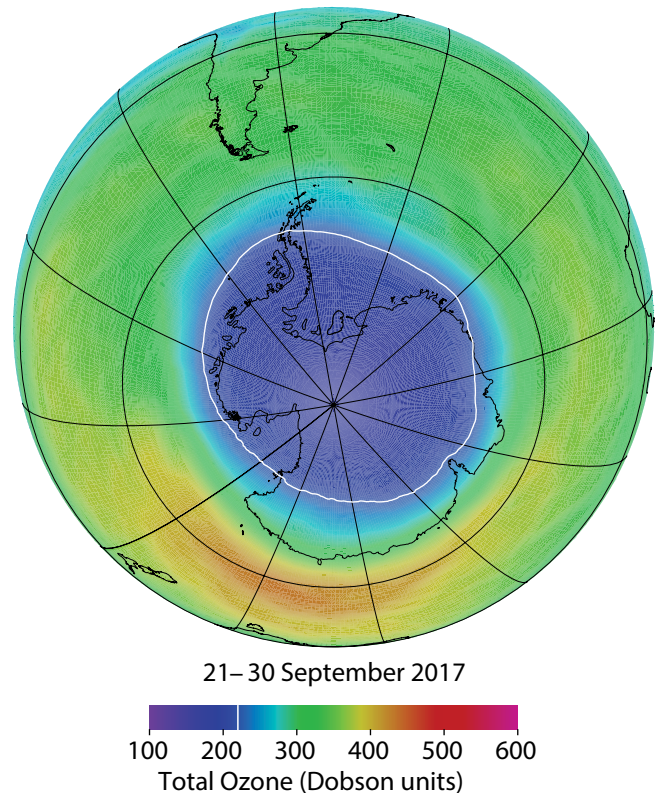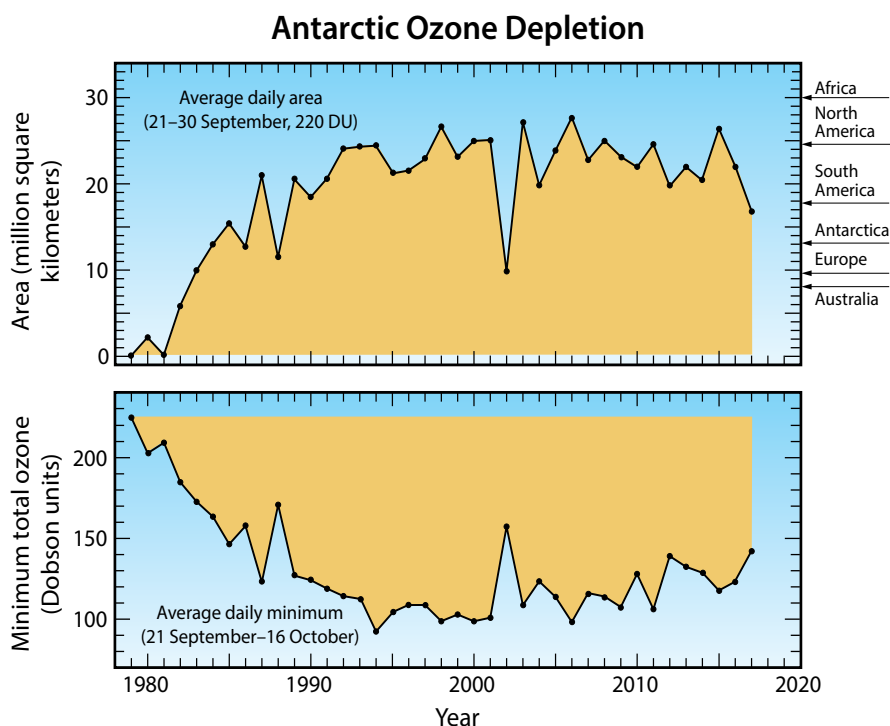

Antarctic Ozone Hole

21– 30 September 2017

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

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 Depletion

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
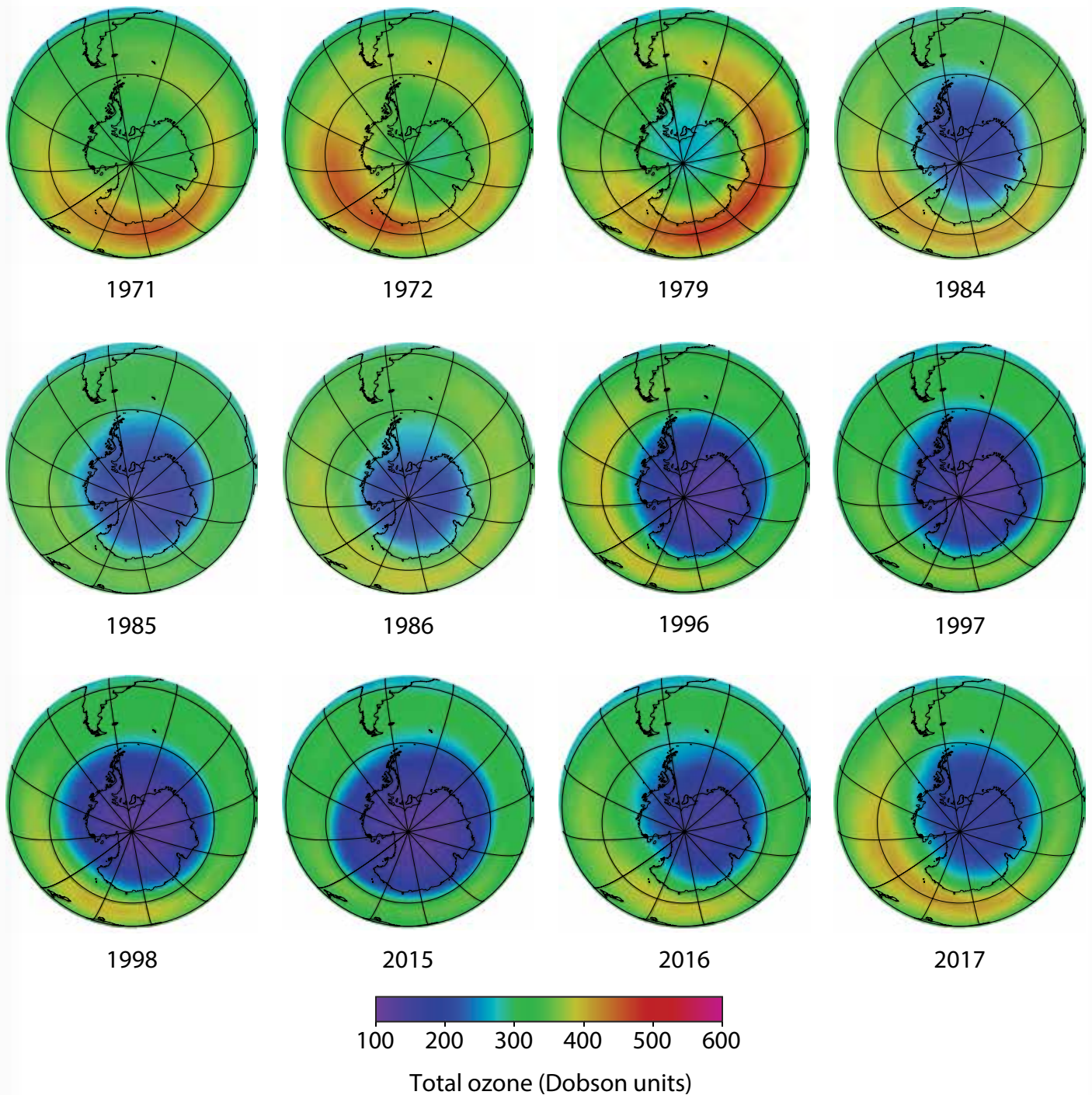## (October monthly averages)

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 circumpolar 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 $ClONO_2$ (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

24 September 2001   24 September 2002   24 September 2003

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

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).
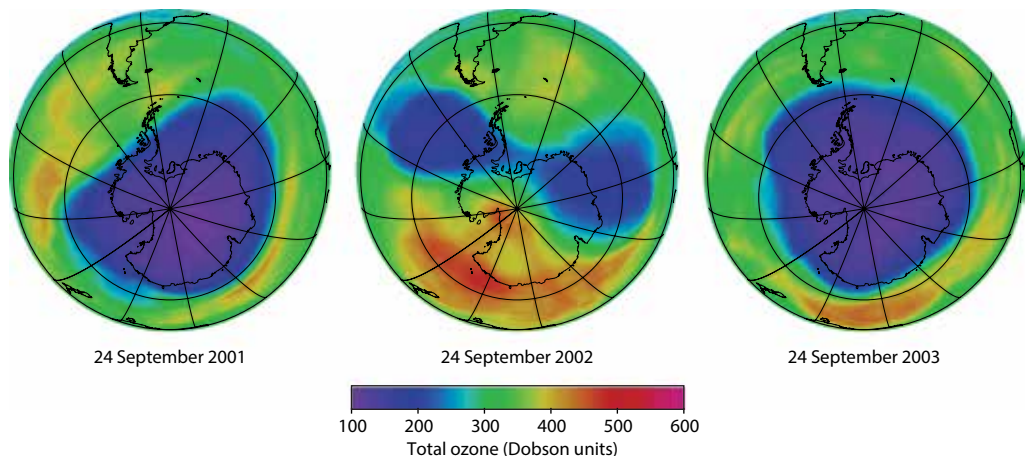
Q11

Is there depletion of the Arctic ozone layer?

Yes, significant depletion of the Arctic ozone layer now occurs in most years in the late winter and early spring period (January–March). However, Arctic ozone depletion is less severe than that observed in the Antarctic and exhibits larger year-to-year differences as a consequence of the highly variable meteorological conditions found in the Arctic polar stratosphere. Even the most severe Arctic ozone depletion does not lead to total ozone amounts as low as those seen in the Antarctic, because Arctic ozone abundances during early winter before the onset of ozone depletion are much larger than those in the Antarctic. Consequently, an extensive and recurrent "ozone hole", as found in the Antarctic stratosphere, does not occur in the Arctic.

Significant depletion of ozone has been observed in the Arctic stratosphere in recent decades. The depletion is attributable to chemical destruction by reactive halogen gases (see Q8), which increased in the stratosphere in the latter half of the 20th century (see Q15). Arctic depletion also occurs in the late winter/ early spring period (January–March), however over a somewhat shorter period than in the Antarctic (July–October). Similar to the Antarctic (see Q10), Arctic ozone depletion occurs because of (1) periods of very low temperatures, which lead to the formation of polar stratospheric clouds (PSCs); (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.

Arctic ozone depletion is much less than that observed each Antarctic winter/spring season. Extensive and recurrent ozone holes as found in the Antarctic stratosphere do not occur in the Arctic. Stratospheric ozone abundances during early winter, before the onset of ozone depletion, are naturally higher in the Arctic than in the Antarctic because transport of ozone from its source region in the tropics to higher latitudes is more vigorous in the Northern Hemisphere. Furthermore, ozone depletion is limited because, in comparison to Antarctic conditions, average temperatures in the Arctic stratosphere are always significantly higher (see Figure Q9-1) and the isolation of polar stratospheric air is less effective (see Q9). These differences occur because northern polar latitudes have more land and mountainous regions than southern polar latitudes (compare Figures Q10-3 and Q11-2 at 60° latitude), which creates more meteorological disturbances that warm the Arctic stratosphere (see box in Q10). Consequently, the extent and timing of Arctic ozone depletion varies considerably from year to year. In a few of the Arctic winters for the years shown in Figure Q11-1, PSCs did not form because temperatures were never sufficiently low. Ozone depletion in some winter/spring seasons occurs over many weeks, in others only for brief early or late periods, and in some not at all.

Long-term total ozone changes. Two important ways in which satellite observations can be used are to examine the average total ozone abundances in the Arctic region for the last half century and to contrast these values with Antarctic abundances:

- First, *total ozone averaged poleward of 63°N* for each March shows how total ozone has changed in the Arctic (see **Figure Q11-1**). The seasonal poleward and downward transport of ozone-rich air is naturally stronger in the Northern Hemisphere. As a result, total ozone values at the *beginning* of each winter season in the Arctic are considerably higher than those in the Antarctic. Before ozone depletion begins, normal Arctic values are close to 450 DU while Antarctic values are close to 330 DU. Decreases from pre-ozone-hole average values (1970–1982) were observed in the Arctic by the mid-1980s, when larger changes were already occurring in the Antarctic. The decreases in total ozone in the Arctic are generally much smaller than those found in the Antarctic and lead to total ozone values that are typically about 10 to 20% below normal. Maximum decreases in total ozone of about 30% observed in March 1997 and 2011 for considerable regions of the Arctic (see Figure Q11-2) are the most comparable to Antarctic depletion. In both of these Arctic winters, meteorological conditions inhibited transport of ozone-rich air to high latitudes, and in 2011 persistently low temperatures facilitated severe chemical depletion of ozone by reactive halogens (see Q8).

Overall, Arctic total ozone values exhibit larger year-to-year variability than those in the Antarctic. Ozone differences from the 1970–1982 average value are due to a combination of chemical destruction by halogens and meteorological (natural) variations. In the last quarter century, these two

Figure Q11-1. Average total ozone in polar regions. Long-term changes in average total ozone are shown for the Antarctic and Arctic, defined by latitudes poleward of 63°. Total ozone is measured with satellite instruments. The reference values (red lines) are averages of springtime total ozone from observations acquired between 1970 and 1982. Each point represents a monthly average for October in the Antarctic or March in the Arctic. After 1982, significant ozone depletion is found in most years in the Arctic and all years in the Antarctic. The largest average depletions have occurred in the Antarctic since 1990. The ozone changes arise from a combination of chemical destruction and natural variations in meteorological conditions that influence the year-to-year values of ozone, particularly in the Arctic. The influence of natural variations on Antarctic ozone has increased since 2000. For example, an increase in stratospheric particles following the volcanic eruption of Calbuco in southern Chile coupled with a cold, stable polar vortex played a prominent role in the low values of total ozone observed over Antarctica in October 2015, whereas the 2017 ozone hole was less extensive than prior years due to the presence of a less stable polar vortex. Essentially all of the ozone decrease in the Antarctic and usually about 50% of the decrease in the Arctic each year are attributable to chemical destruction by reactive halogen gases. In the Arctic, the other 50% is attributable to natural variations in the amounts of ozone transported towards the northern polar region before and during winter. Average total ozone values over the Arctic are naturally larger than over the Antarctic at the beginning of each winter season because, in the preceding months, more ozone is transported poleward in the Northern Hemisphere than in the Southern Hemisphere.
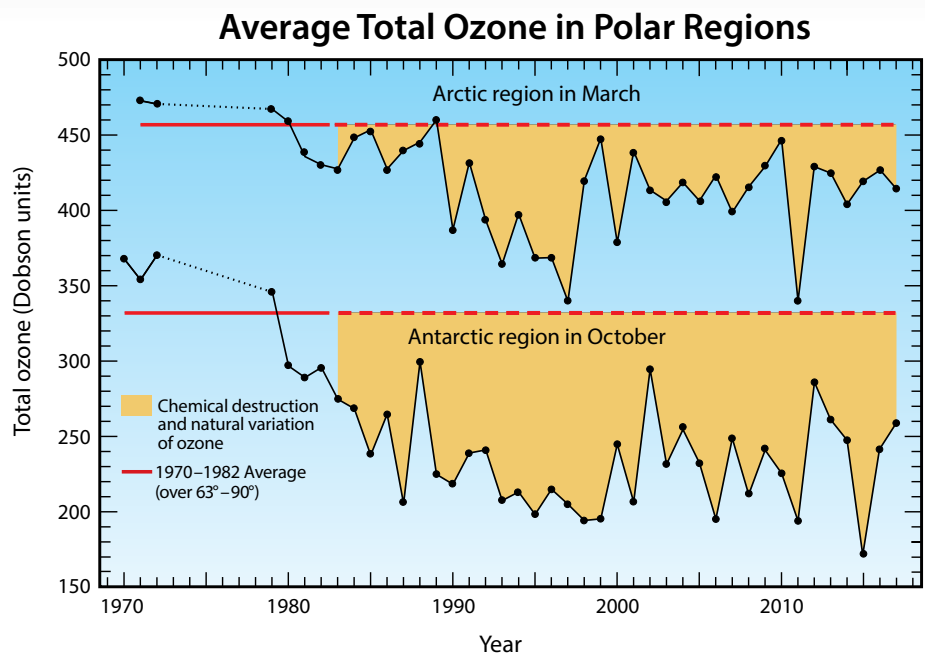
aspects have contributed about equally to observed ozone changes. The amount of chemical destruction depends in large part on stratospheric temperatures. Meteorological conditions determine how well Arctic stratospheric air is isolated from ozone-rich air at lower latitudes and also influence the extent and persistence of low temperatures.

- Second, *total ozone maps* over the Arctic and surrounding regions (see **Figure Q11-2**) show year-to-year changes in total ozone during March. In the 1970s, total ozone values were near 450 DU when averaged over the Arctic region in March. Beginning in the 1990s and continuing into the mid-2010s, values above 450 DU were increasingly absent from the March average maps. A comparison of the maps in the 1970s and early to mid-2010s, for example, shows a striking reduction of total ozone throughout the Arctic region. The large geographical extent of low total ozone in the maps of March 1997 and March 2011 represent exceptional events in the Arctic observational record of the last four decades as noted above in the discussion of Figure Q11-1. The high values of total ozone observed throughout the Arctic during March 2018 followed a meteorological warming event in late February that disrupted the polar vortex circulation

and transported large amounts of ozone to high northerly latitudes. The large-scale differences between Arctic ozone distributions observed in March 2011, 2014, and 2018 are a prime example of the influence of meteorology in driving year-to-year variations in Arctic ozone depletion.

Altitude profiles of Arctic ozone. Arctic ozone is measured using a variety of instruments (see Q4), as in the Antarctic, to document daily to seasonal changes within the ozone layer. Spring Arctic and Antarctic balloon-borne measurements are shown in Figure Q11-3. Arctic profiles were obtained from the Ny-Ålesund research station at 79°N. For 1990–2018, the March average reveals a substantial ozone layer, contrasting sharply with the severely depleted Antarctic ozone layer in the October average over a similar time period. This contrast further demonstrates how higher stratospheric temperatures and more variable meteorology have protected the Arctic ozone layer from the greater ozone losses that occur in the Antarctic, despite similar abundances of reactive halogen gases (see Q7) in the two regions.

The Arctic profiles shown in Figure Q11-3 for 29 March 1996 and 1 April 2011 are two of the most severely depleted in the 30-year

Arctic Total Ozone
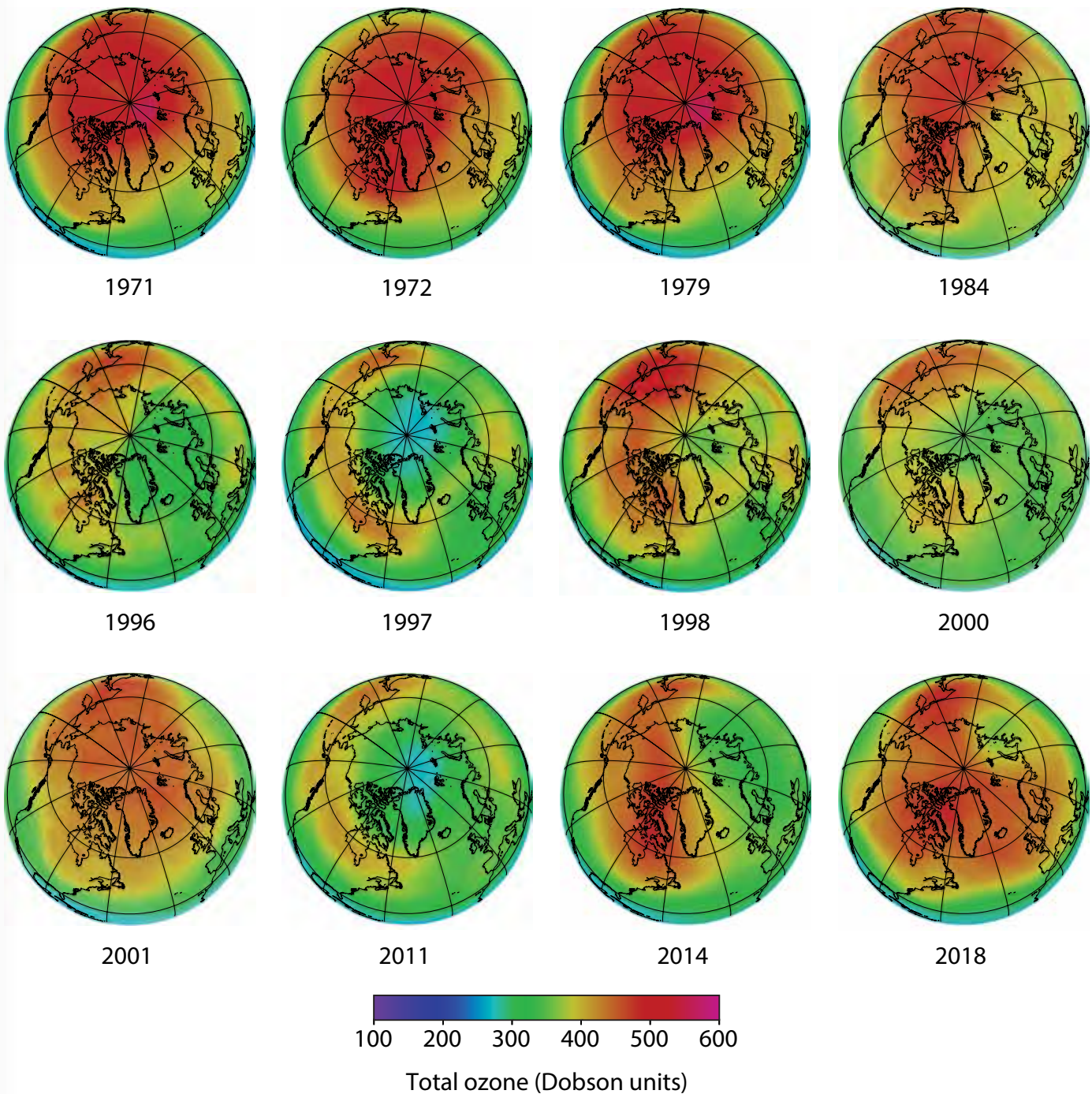## (March monthly averages)

Figure Q11-2. Arctic total ozone. Long-term changes in Arctic total ozone are evident in this series of total ozone maps derived from satellite observations. Each map is an average during March, the month when some ozone depletion is usually observed in the Arctic. In the 1970s and 1980s, the Arctic region had normal ozone values in March, with values of 450 DU and above (red colors). Ozone depletion on the scale of the Antarctic ozone hole does not occur in the Arctic. Instead, late winter/early spring ozone depletion has eroded the normal high values of total ozone. For most years starting in the 1990s, the extent of ozone values of 450 DU and above is greatly reduced in comparison with the 1970s. The large regions of low total ozone in 1997 and 2011 (blue colors) are unusual in the Arctic record, although not unexpected. Meteorological conditions led to below-average stratospheric temperatures and a strong polar vortex in these winters, conditions favorable to strong ozone depletion.
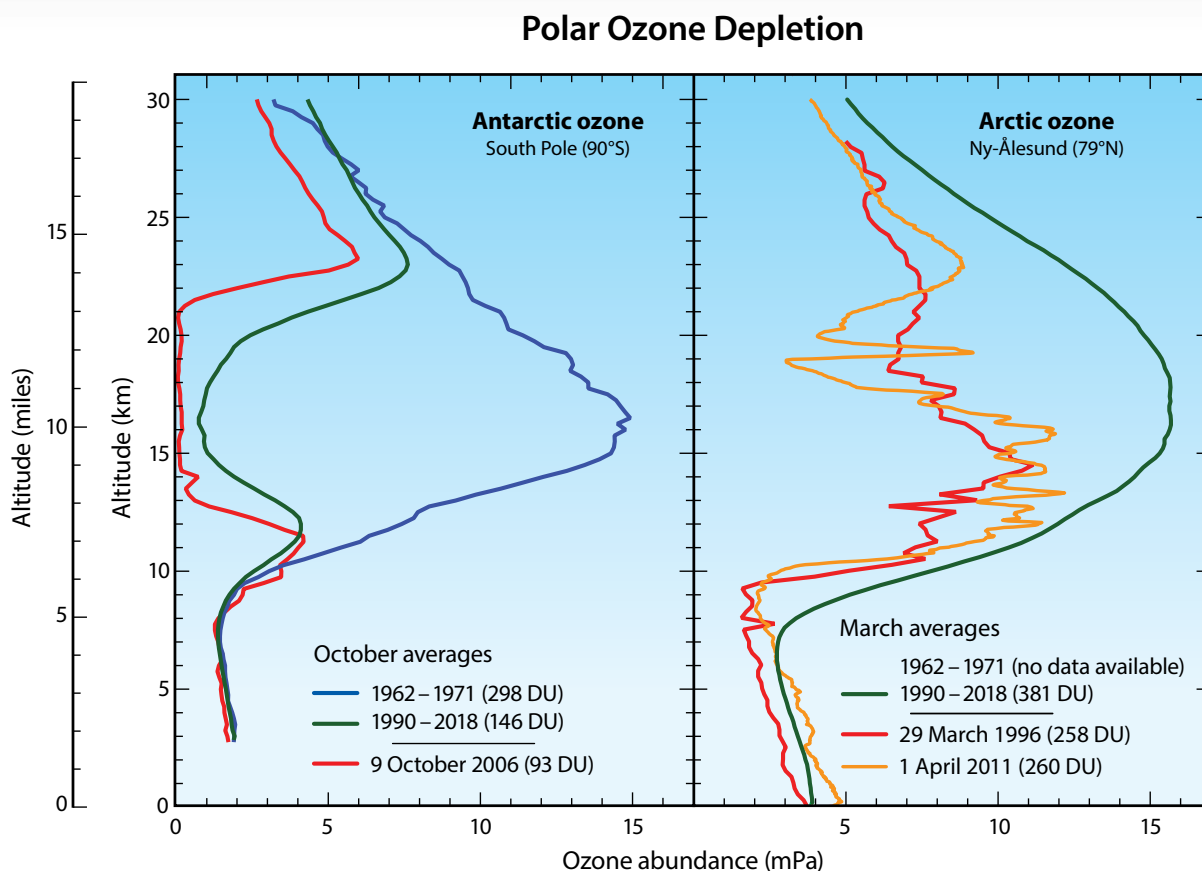
Figure Q11-3. Vertical distribution of Antarctic and Arctic ozone. At high latitudes during winter and spring, most stratospheric ozone resides between about 10 and 30 km (6 to 19 miles) above Earth's surface. Long-term observations of the ozone layer with balloon-borne instruments also allow vertical profiles of ozone during winter to be compared between the Antarctic and Arctic regions. In the Antarctic at the South Pole (left panel), a normal ozone layer was observed to be present between 1962 and 1971. As shown here, ozone was almost completely destroyed between 14 and 21 km (9 to 13 miles) over the South Pole on 9 October 2006. Average October values of ozone in the last three decades (1990–2018) are 90% lower than pre-1980 values at the peak altitude of the ozone layer (16 km). The Arctic ozone layer is shown by the average March profile for 1990–2018 obtained over the Ny-Ålesund research station (right panel). No data from Ny-Ålesund are available for the 1962–1971 period. Some profiles reveal significant depletion, as shown here for 29 March 1996 and 1 April 2011. In such years, winter minimum temperatures are generally lower than normal, allowing for formation of PSCs and increases in ClO over longer periods of time. The number in parentheses for each profile is the total ozone value in Dobson units (DU) (see box in Q4). On 9 October 2006 at the South Pole, the total ozone value of 93 DU was less than one-third of the October average ozone measured at the South Pole between 1962 and 1971. Depletion of ozone of this magnitude has never been observed in the Arctic. Ozone abundances are shown here as the pressure of ozone at each altitude using the unit "milli-Pascals" (mPa) (100 million mPa = atmospheric sea-level pressure).

record from Ny-Ålesund. Although significant, the depletion during both events is smaller in comparison to that routinely observed in the Antarctic, such as in the profile from 9 October 2006. In the Antarctic stratosphere, near-complete depletion of ozone over many kilometers in altitude and over areas almost as large as North America is a common occurrence. Ozone depletion of this magnitude has never been observed in the Arctic stratosphere.

Restoring ozone in spring. As in the Antarctic, ozone depletion in the Arctic is largest in the late winter/early spring season. In spring, temperatures in the polar lower stratosphere increase (see Figure Q9-1), halting the formation of PSCs, the production of ClO, and the chemical cycles that destroy ozone. The breakdown of the polar vortex ends the isolation of air in the high-latitude region, allowing more ozone-rich air to be transported poleward where it displaces or mixes with air in which ozone may have been depleted. As a result of these large-scale transport and mixing processes, any ozone depletion at high northern latitudes typically disappears by April or earlier.

Terminology

CCM	chemistry-climate model
CFC	chlorofluorocarbon, a group of industrial compounds that contains at least one chlorine, fluorine, and carbon atom
CFC-11-equivalent	a unit for the measure of the mass of emission of an ODS, equal to the product of the actual mass emission of the ODS times its ODP
CO_2-equivalent	a unit for the measure of the mass of emission of a GHG, equal to the product of the actual mass emission of the GHG times its GWP
DU	Dobson unit, a measure of total column ozone; 1 DU = 2.687×10^{16} molecules/cm^2
EESC	equivalent effective stratospheric chlorine, a measure of the total amount of reactive chlorine and bromine gases in the stratosphere that is available to deplete stratospheric ozone
GHG	greenhouse gas
gigatonne	1 billion (10^9) metric tons = 1 trillion (10^{12}) kilograms
GWP	global warming potential, a measure of the effectiveness of the emission of a gas to cause an increase in the radiative forcing of climate, relative to the radiative forcing caused by the emission of the same mass of CO_2; all GWPs used here are for a 100-year time interval
halon	a group of industrial compounds that contain at least one bromine and carbon atom; may or may not contain a chlorine atom
HCFC	hydrochlorofluorocarbon, a group of industrial compounds that contain at least one hydrogen, chlorine, fluorine, and carbon atom
HFC	hydrofluorocarbon, a group of industrial compounds that contain at least one hydrogen, fluorine, and carbon atom and no chlorine or bromine atoms
HFO	hydrofluoroolefin, a group of industrial compounds that contain at least one hydrogen, fluorine, and carbon atom and no chlorine or bromine atoms, and also include a double carbon bond that causes these gases to be more reactive in the troposphere than other HFCs
IPCC	Intergovernmental Panel on Climate Change
kilotonne	1000 metric tons = 1 million (10^6) kilograms
megatonne	1 million (10^6) metric tons = 1 billion (10^9) kilograms
mPa	millipascal; 100 million mPa = atmospheric sea-level pressure
nm	nanometer, one billionth of a meter (10^{-9} m)
ODP	ozone-depletion potential, a measure of the effectiveness of the emission of a gas to deplete the ozone layer, relative to the ozone depletion caused by the emission of the same mass of CFC-11
ODS	ozone-depleting substance
ozone layer	the region in the stratosphere with the highest concentration of ozone, between about 15 and 35 km altitude
ppb	parts per billion; 1 part per billion equals the presence of one molecule of a gas per billion (10^9) total air molecules
ppm	parts per million; 1 part per million equals the presence of one molecule of a gas per million (10^6) total air molecules
ppt	parts per trillion; 1 part per trillion equals the presence of one molecule of a gas per trillion (10^{12}) total air molecules
PFC	perfluorocarbon, a group of industrial compounds that contain only carbon and fluorine atoms
PSC	polar stratospheric cloud
RCP	Representative Concentration Pathway
RF	radiative forcing of climate
SAOD	stratospheric aerosol optical depth
stratosphere	layer of the atmosphere above the troposphere that extends up to around 50 km altitude, and that includes the ozone layer
TEAP	Technology and Economic Assessment Panel of the Montreal Protocol
troposphere	lower layer of the atmosphere that extends from the surface to about 10-15 km (6-9 miles) altitude
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

UV	ultraviolet radiation
UV-A	ultraviolet radiation between wavelengths of 315 and 400 nm
UV-B	ultraviolet radiation between wavelengths of 280 and 315 nm
UV-C	ultraviolet radiation between wavelengths of 100 and 280 nm
WMO	World Meteorological Organization

Chemical Formulae

Bromine Compounds:

$CBrClF_2$	halon-1211
$CBrF_3$	halon-1301
$CBrF_2CBrF_2$	halon-2402
CH_2Br_2	dibromomethane
$CHBr_3$	bromoform
CH_3Br	methyl bromide
Br	atomic bromine
BrO	bromine monoxide
BrCl	bromine monochloride

Chlorine Compounds:

CCl_3F	CFC-11
CCl_2F_2	CFC-12
CCl_2FCClF_2	CFC-113
CCl_4	carbon tetrachloride
CH_2Cl_2	dichloromethane
CH_3CCl_3	methyl chloroform
CH_3Cl	methyl chloride
CHF_2Cl	HCFC-22
CH_3CCl_2F	HCFC-141b
CH_3CClF_2	HCFC-142b
Cl	atomic chlorine
ClO	chlorine monoxide
$(ClO)_2$	chlorine monoxide dimer, chemical structure ClOOCl
$ClONO_2$	chlorine nitrate
HCl	hydrogen chloride

Other Halogens:

CHF_3	HFC-23
CH_2F_2	HFC-32
CHF_2CF_3	HFC-125
CH_2FCF_3	HFC-134a
CH_3CF_3	HFC-143a
CH_3CHF_2	HFC-152a
$CF_3CF=CH_2$	HFO-1234yf
CF_4	carbon tetrafluoride
C_2F_6	perfluoroethane
IO	iodine monoxide
SF_6	sulfur hexafluoride

Other gases:

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H	atomic hydrogen
H_2O	water vapor
HNO_3	nitric acid
H_2SO_4	sulfuric acid
N_2	molecular nitrogen
N_2O	nitrous oxide
NO_x	nitrogen oxides
O	atomic oxygen
O_2	molecular oxygen
O_3	ozone