

# Q9

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

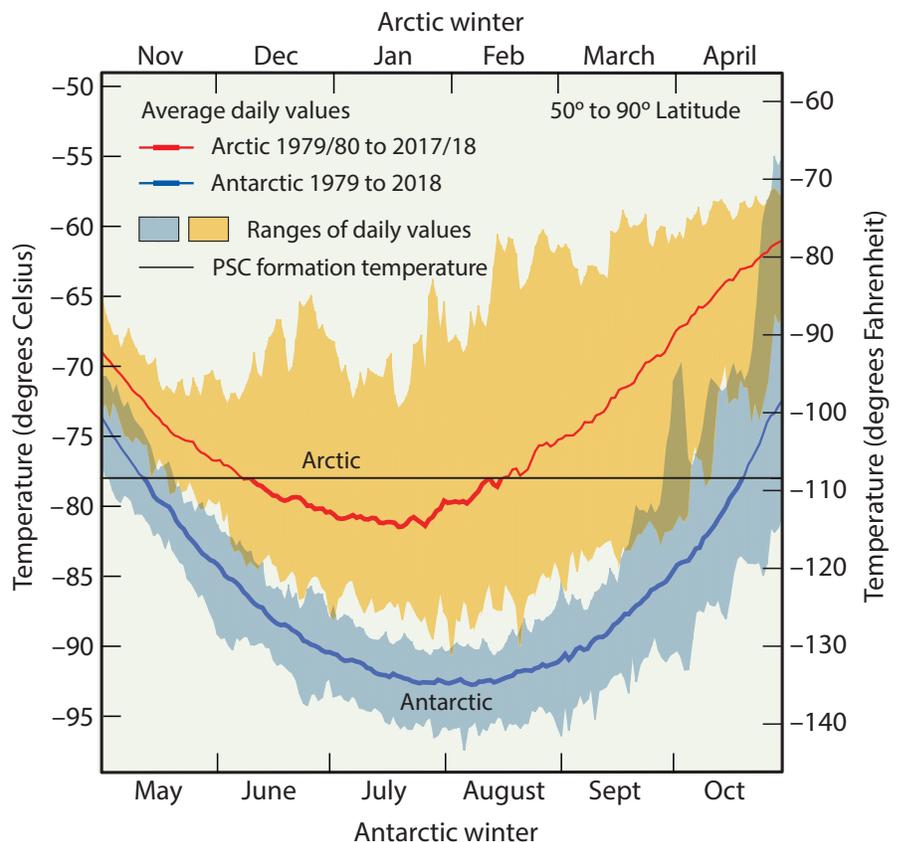
Ozone-depleting substances are present throughout the stratospheric ozone layer because they are transported great distances by atmospheric air motions. The severe depletion of the Antarctic ozone layer known as the “ozone hole” occurs because of the special meteorological and chemical conditions that 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  $-92^{\circ}\text{C}$  in July and August in a typical year. Over the Arctic, average minimum values are near  $-80^{\circ}\text{C}$  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  $-78^{\circ}\text{C}$ . 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  $\text{ClO}$  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<sub>2</sub>) 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  $-78^{\circ}\text{C}$  ( $-108^{\circ}\text{F}$ ) 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 ( $67^{\circ}\text{N}$ ), 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 ( $\text{HNO}_3$ ), and sulfuric acid ( $\text{H}_2\text{SO}_4$ ). 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 ( $\text{HNO}_3$ ) and water condensing on pre-existing liquid sulfuric acid-containing particles. Some of these particles freeze to form solid particles. At even lower temperatures ( $-85^\circ\text{C}$  or  $-121^\circ\text{F}$ ), 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  $\text{HNO}_3$ .

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,  $\text{ClONO}_2$  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  $\text{HNO}_3$ , their descent removes  $\text{HNO}_3$  from regions of the ozone layer. This process is called *denitrification* of the stratosphere. Because  $\text{HNO}_3$  is a source for nitrogen oxides ( $\text{NO}_x$ ) in the stratosphere, denitrification removes the  $\text{NO}_x$  available for converting the highly reactive chlorine gas ClO back into

the reservoir gas  $\text{ClONO}_2$ . 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  $\text{HNO}_3$ . 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).