

**Q10: Why has an “ozone hole” appeared over Antarctica when ozone-depleting gases are present throughout the stratosphere?**

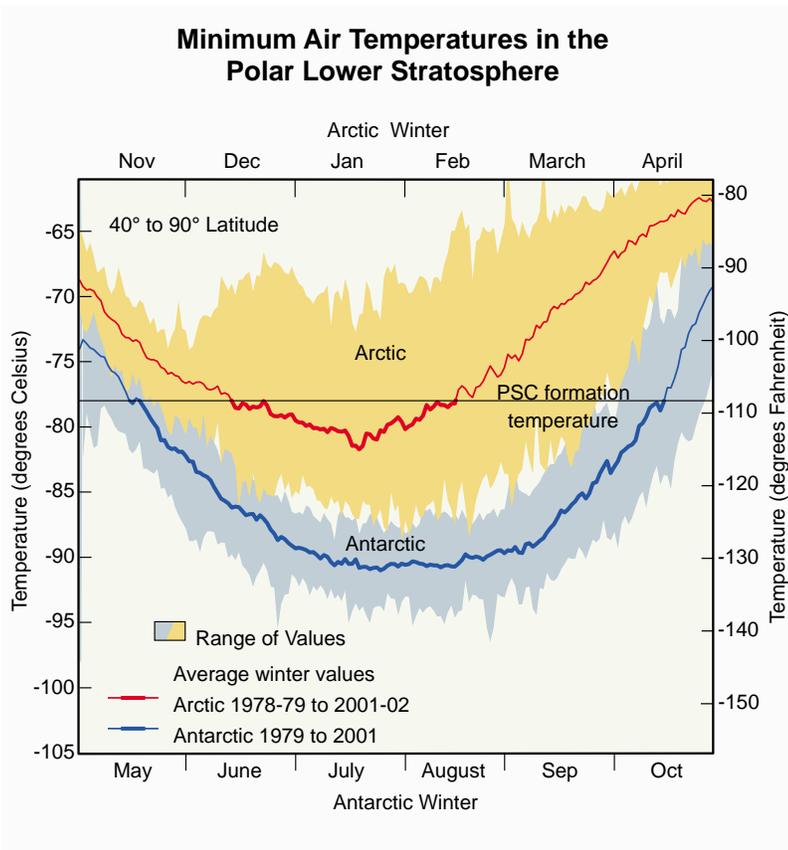
*Ozone-depleting gases are present throughout the stratospheric ozone layer because they are transported great distances by atmospheric air motions. The severe depletion of the Antarctic ozone layer known as the “ozone hole” forms because of the special weather conditions that exist there and nowhere else on the globe. The very cold temperatures of the Antarctic stratosphere create ice clouds called polar stratospheric clouds (PSCs). Special reactions that occur on PSCs and the relative isolation of polar stratospheric air allow chlorine and bromine reactions to produce the ozone hole in Antarctic springtime.*

The severe depletion of stratospheric ozone in Antarctic winter is known as the “ozone hole” (see Q11). Severe depletion first appeared over Antarctica because atmospheric conditions there increase the effectiveness of ozone destruction by reactive halogen gases (see Q8). The formation of the Antarctic ozone hole requires abundant reactive halogen gases, temperatures low enough to form polar stratospheric clouds (PSCs), isolation of air from other stratospheric regions, and sunlight.

**Distributing halogen gases.** Halogen source gases emitted at Earth’s surface 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 source gases have no important natural removal processes in the lower atmosphere and because winds and warm-air convection redistribute and mix air efficiently throughout the troposphere. Halogen gases (in the form of source gases and some reactive products) enter the stratosphere primarily from the tropical troposphere. Atmospheric air motions then transport them upward and toward the poles in both hemispheres.

**Low temperatures.** The severe ozone destruction represented by the ozone hole requires that low temperatures be present over a range of stratospheric altitudes, over large geographical regions, and for extended time periods. Low temperatures are important because they allow polar stratospheric clouds (PSCs) to form.



**Figure Q10-1. Arctic and Antarctic temperatures.** Stratospheric air temperatures in both polar regions reach minimum values in the lower stratosphere in the winter season. Minimum values over Antarctica reach  $-90^{\circ}\text{C}$  in July and August in an average year. Over the Arctic, minimum average values are near  $-80^{\circ}\text{C}$  in January and February. Polar stratospheric clouds (PSCs) are formed when winter temperatures fall below the formation temperature (about  $-78^{\circ}\text{C}$ ). This occurs on average for weeks to months over both poles (see heavy red and blue lines). Reactions on PSCs cause the highly reactive chlorine gas  $\text{ClO}$  to be formed, which increases the destruction of ozone. The range of minimum temperatures found in the Arctic is much greater than in the Antarctic. In some years, PSC formation temperatures are not reached in the Arctic, and significant ozone depletion does not occur. In the Antarctic, PSCs are formed over many months, and severe ozone depletion now occurs in each winter season.

Reactions on the surfaces of the cloud particles initiate a remarkable increase in the most reactive halogen gases (see below and Q8). Temperatures are lowest in the stratosphere over both polar regions in winter. In the Antarctic winter, minimum temperatures are generally lower and less variable than in the Arctic winter (see *Figure Q10-1*). Antarctic temperatures also remain below the PSC formation temperature for much longer periods during winter. This occurs, in part, because there are significant differences between the hemispheres in the distributions of land, ocean, and mountains at middle and high latitudes. The winter temperatures are low enough for PSCs to form for nearly the entire Antarctic winter but usually only for part of every Arctic winter.

**Isolated conditions.** Air in the polar stratospheric regions is relatively isolated from other stratospheric regions for long periods in the winter months. The isolation comes about because of strong winds that encircle the poles, preventing substantial motion of air in or out of the polar stratospheres. The isolation is much more effective in the Antarctic. Once chemical changes occur in the low-temperature air as a result of the presence of PSCs, the changes remain for many weeks to months.

**Polar stratospheric clouds (PSCs).** Polar stratospheric clouds cause changes in the abundances of reactive chlorine gases. Reactions occur on the surfaces of PSC particles that convert the reservoir forms of reactive chlorine gases,  $\text{ClONO}_2$  and  $\text{HCl}$ , to the most reactive form  $\text{ClO}$  (see *Figure Q8-1*).  $\text{ClO}$  increases from a small fraction of available reactive chlorine gases to nearly all that is available (see Q8). With increased  $\text{ClO}$ , additional catalytic cycles involving  $\text{ClO}$  and  $\text{BrO}$  become active in the chemical destruction of ozone when sunlight is available (see Q9).

PSCs form when stratospheric temperatures fall below about  $-78^\circ\text{C}$  ( $-108^\circ\text{F}$ ) in polar regions. As a result, PSCs are often found over vast areas of the winter polar regions and over a significant altitude range. At low polar temperatures, nitric acid ( $\text{HNO}_3$ ) and sulfur-containing gases condense with water vapor to form solid and liquid PSC particles. At even lower temperatures, ice particles also form. 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 Q10-2*). PSCs are often found near mountain ranges in polar regions because the motion of air over the mountains can cause local cooling of stratospheric air.

When temperatures warm in spring, PSCs no longer form and the production of  $\text{ClO}$  ends. Without continued  $\text{ClO}$  production,  $\text{ClO}$  amounts decrease as other chemical reactions reform  $\text{ClONO}_2$  and  $\text{HCl}$ . As a result, the intense period of ozone depletion ends.

**PSC removal.** Once formed, PSC particles move downward because of gravity. The largest particles move down several kilometers or more in the stratosphere during the low-temperature winter/spring period. Because most PSCs contain nitric acid, their downward motion removes nitric acid from regions of the ozone layer. That process is called *denitrification*. With less nitric acid, the highly reactive chlorine gas  $\text{ClO}$  remains chemically active for a longer period, thereby increasing chemical ozone destruction. Because PSC formation temperatures are required (see *Figure Q10-1*), denitrification occurs each winter in the Antarctic and in some, but not all, Arctic winters.

### Arctic Polar Stratospheric Clouds



**Figure Q10-2. Polar stratospheric clouds.** This photograph of an Arctic polar stratospheric cloud (PSC) was taken from the ground at Kiruna, Sweden ( $67^\circ\text{N}$ ), on 27 January 2000. PSCs form during winters in the Arctic and Antarctic stratospheres. The particles grow from the condensation of water along with nitrogen and sulfur gases. Because the particles are large and numerous, the clouds often can be seen with the human eye when the Sun is near the horizon. Reactions on PSCs cause the highly reactive chlorine gas  $\text{ClO}$  to be formed, which is very effective in the chemical destruction of ozone.

## TWENTY QUESTIONS

**Discovering the role of PSCs.** The formation of PSCs has been recognized for many years from ground-based observations. However, 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 PSCs 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 PSC role developed from laboratory studies of their surface reactivity, computer modeling studies of polar stratospheric chemistry, and direct sampling of PSC particles and reactive chlorine gases, such as ClO, in the polar stratospheric regions.

### **The Discovery of the Antarctic Ozone Hole**

The first decreases in Antarctic ozone were observed in the early 1980s over research stations located on the Antarctic continent. The observations showed unusually low total overhead 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 British Antarctic Survey and the Japan Meteorological Agency. The results became more widely known in the international community after they were published in the journal *Nature* in 1985 by three scientists from the British Antarctic Survey. Soon after, satellite measurements confirmed the spring ozone depletion and further showed that in each late winter/spring season starting in the early 1980s, the depletion extended over a large region centered near the South Pole. The term “ozone hole” came about from satellite images of total ozone that showed very low values encircling the Antarctic continent each spring (see Q11). 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.