

Polar Stratospheric Clouds and Ozone Depletion

Clouds rarely form in the dry, Antarctic stratosphere, but when they do, they chemically conspire with chlorofluorocarbons to create the "ozone hole" that opens up every spring

by Owen B. Toon and Richard P. Turco

More than two dozen scientists boarded a National Aeronautics and Space Administration's DC-8 based at Punta Arenas, Chile. The aircraft headed south, climbing through the sunrise sky high above the Antarctic peninsula into the stratosphere, that part of the atmosphere between 10 and 50 kilometers in altitude. As the plane entered the now well-known ozone hole in that September of 1987, it was greeted by a large cloud in the shape of an eye, with a bright red iris surrounding a green pupil. Along with an ER-2, a companion high-altitude aircraft, the DC-8 carried instruments to measure the aerosols, gases and atmospheric dynamics in such clouds as well as in the surrounding stratosphere. The expedition would help scientists to understand what had been observed two years before: the correlation between the depletion of ozone and the formation of those curious clouds.

During the past century, observers on land had periodically recorded the appearance of stratospheric clouds over both poles, at an altitude of about 20 kilometers. The clouds extend 10 to

100 kilometers in length and several kilometers in thickness. They glow with a seashell iridescence. Hence they are sometimes called nacreous, or mother-of-pearl, clouds.

In addition to nacreous clouds, investigators have found two other types. The second kind of cloud consists of nitric acid instead of pure water. The third species is identical to nacreous clouds in chemical composition but forms in a process that results in a larger cloud with no iridescence. When these three kinds of clouds form over the poles, scientists broadly refer to them as polar stratospheric clouds—PSCs, for short.

The eerie beauty and exotic nature of PSCs belie their more ominous significance. Recent work, including our own research, strongly indicates that PSCs trigger ozone depletion in the Arctic stratosphere. In the Antarctic stratosphere they help to create the ozone hole.

The ozone hole is not actually a hole but a region that contains an unusually low concentration of ozone [see "The Antarctic Ozone Hole," by Richard S. Stolarski; *SCIENTIFIC AMERICAN*, January 1988]. At ground level this molecule, consisting of three oxygen atoms, is a health hazard. In the stratosphere ozone is crucial to survival on the earth. Although ozone constitutes less than one part per million of the gases in the atmosphere, it absorbs most of the ultraviolet radiation from the sun.

Such radiation can affect the growth and reproduction of phytoplankton, the base of the marine food chain. In humans, excessive ultraviolet exposure has been implicated as a cause in skin cancers, cataracts and immune deficiencies. Although remotely located, the ozone hole in the Antarctic is nonetheless cause for concern: shifting circulation patterns carry masses of ozone-de-

pleted air north. It may thus forebode widespread ozone depletion throughout the stratosphere.

In 1985 Joseph C. Farman and his co-workers at the British Antarctic Survey first reported that significant ozone depletion had been occurring over Antarctica since the late 1970s. Satellite measurements from *Nimbus 7*, managed by Arlin Krueger of the NASA Goddard Space Flight Center, showed that over the years the depletion from austral spring to austral spring has generally worsened. About 70 percent

OWEN B. TOON and RICHARD P. TURCO study atmospheric chemistry, radiation and microphysics, frequently applying information gained from planetary explorations. Toon received his Ph.D. from Cornell University and is currently an associate fellow at the National Aeronautics and Space Administration Ames Research Center. He was one of the leaders of the airborne missions to the polar regions. Turco received his Ph.D. from the University of Illinois at Urbana-Champaign and is professor of atmospheric sciences at the University of California, Los Angeles. The authors were members of the research team that first introduced the concept of nuclear winter.

STRATOSPHERIC CLOUDS can form over the polar regions if the air cools suffi-

of the ozone above Antarctica, which equals about 3 percent of the earth's ozone, is lost during September and October. Measurements by David Hofmann and his co-workers at the University of Wyoming revealed that most of the ozone loss occurred at altitudes between about 12 and 30 kilometers.

Scientists have advanced a number of theories to explain what causes the ozone hole. Several major expeditions have served to winnow out the wrong ones. One principal group of theories, for example, suggested that atmospheric motions alone caused the ozone hole. Proponents of these theories thought that the circulation pattern over the poles may have gradually changed, so that upward moving winds might now blow over Antarctica during the spring. These winds would replace ozone-rich stratospheric air with ozone-poor air from the troposphere, the atmosphere below 10 kilometers.

Max Loewenstein and his group from the NASA Ames Research Center, Leroy E. Heidt and his colleagues at the National Center for Atmospheric Research (NCAR) and others showed such hypotheses to be incorrect. According to the dynamic models used by advocates of the circulation theories, high concentrations of trace gases originat-

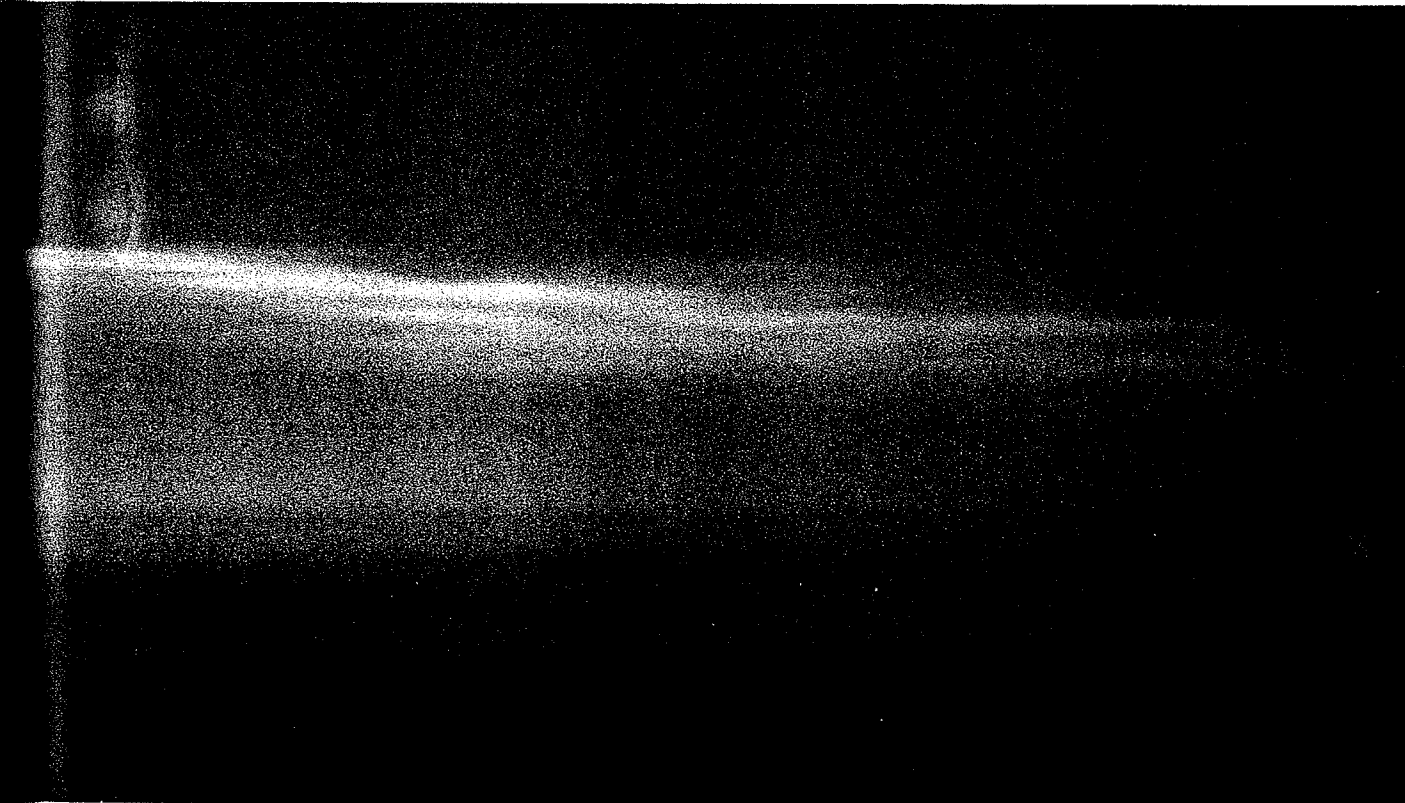
ing from the ground should be present at the altitude of the ozone hole. Measurements by the investigators revealed only low levels of the trace gases, however, indicating that ozone-hole air in fact comes from high altitudes, where ozone is normally abundant.

A second class of theories proposed that chemical reactions deplete ozone. One early hypothesis suggested that reactive nitrogen compounds, normally the most important agents for destroying ozone in the lower stratosphere, might exist at elevated concentrations near the ozone hole. The enhancement was presumed to result from the combined effects of increased solar activity and atmospheric circulation.

The theory proposed that the enhanced solar activity produced reactive forms of nitrogen over the South Pole at high altitudes. The downward motion of air then carried the reactive nitrogen into the lower stratosphere, where investigators observed the ozone loss. But Crofton B. Farmer and his colleagues from the NASA Jet Propulsion Laboratory, George H. Mount and his co-workers at the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory and others found that the reactive forms of nitrogen were also depleted in the ozone hole, hence disproving the theory.

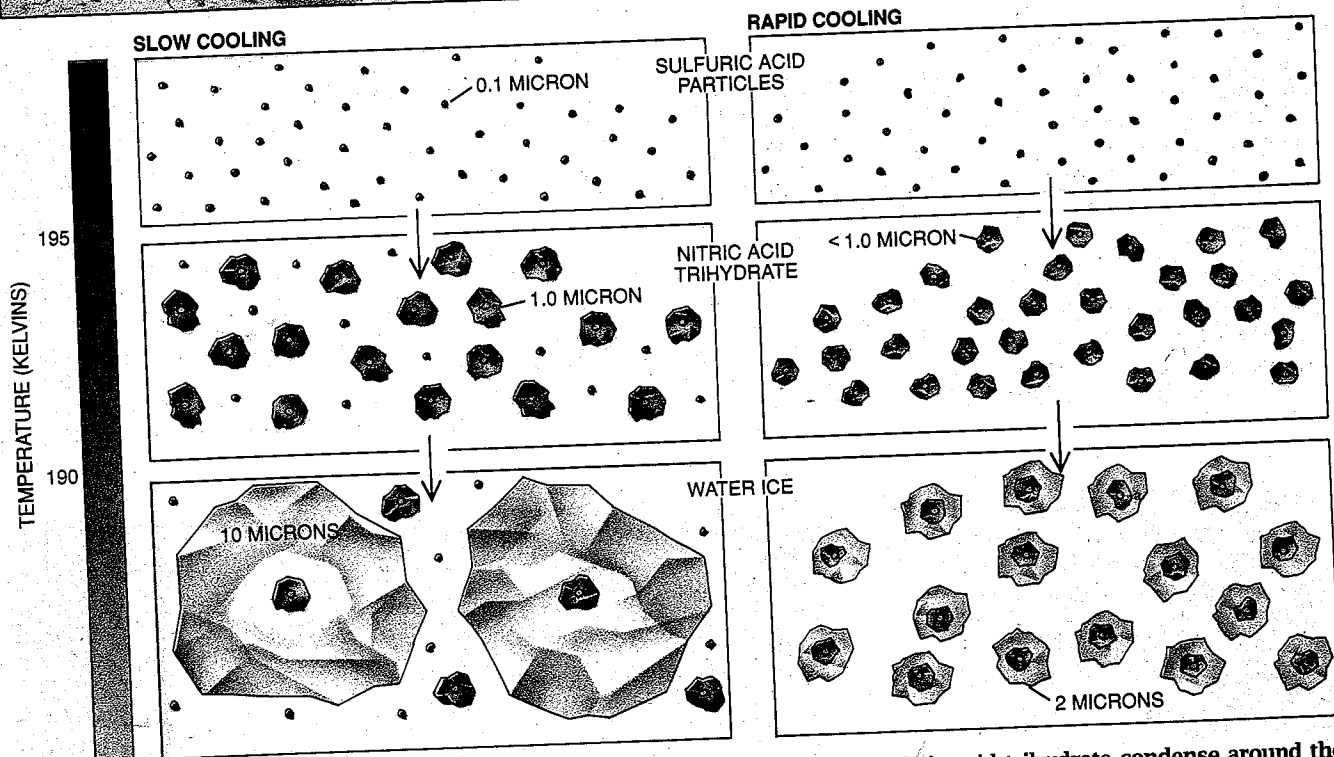
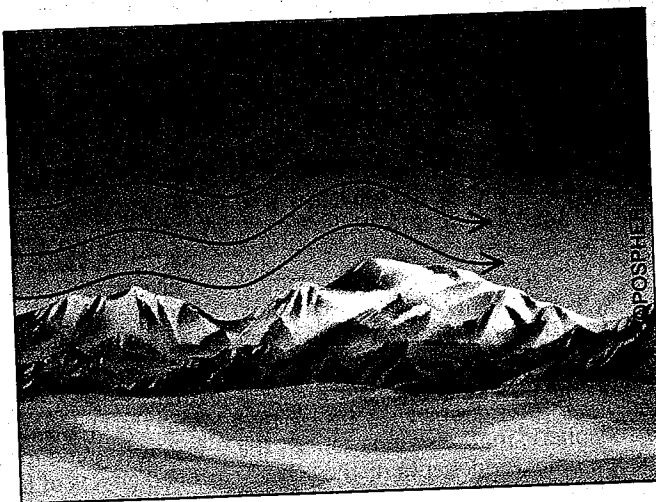
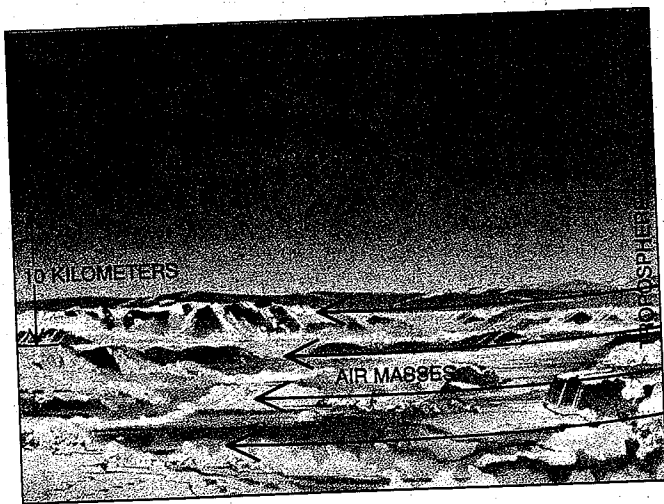
Farman and his colleagues proposed an alternative chemical interpretation, one that has now gained wide acceptance. Based on the mid-1970s work by Mario J. Molina, now at the Massachusetts Institute of Technology, and F. Sherwood Rowland of the University of California at Irvine, the theory suggests that chlorine compounds might be responsible for the ozone hole. Chlorine primarily enters the atmosphere as a component of chlorofluorocarbons (CFCs) produced by humans. These inert compounds, used in such diverse applications as coolants for air conditioners and refrigerators, as solvents for cleaning circuit boards and as agents for producing insulating foams, may survive 50 to 100 years in the atmosphere. In only a few years, winds throughout the troposphere uniformly distribute CFC molecules released from a single point. Over the decades, the molecules eventually reach the middle stratosphere, about 30 kilometers or higher. There, ultraviolet light from the sun tears them apart.

The chlorine released from the CFC molecules initially either exists as free chlorine or reacts with ozone to form chlorine monoxide (ClO). These two forms of chlorine then react further to form stable compounds that are the so-called reservoirs of chlorine. The reser-



ciently during the winter. Nitric acid trihydrate clouds are visible as thin, dark orange layers. The water-ice clouds appear

whitish. The clouds, such as these over Stavanger, Norway, help to initiate the chemical reactions that destroy ozone.



FORMATION OF POLAR STRATOSPHERIC CLOUDS occurs when the air cools sufficiently for vapor to condense. The cooling may take place slowly, as when the stratosphere radiates heat into space or is uplifted by air masses sliding below it (top left). Rapid cooling occurs when air flows over mountains, creating a standing-wave pattern that reaches the stratosphere (top right). As the temperatures drop below 195 kel-

vins, particles of nitric acid trihydrate condense around the sulfuric acid particles in the stratosphere, forming nitric acid trihydrate clouds. Water-ice clouds form if the temperature drops below 190 kelvins; the water vapor condenses on the nitric acid trihydrate particles and on any remaining sulfuric acid particles. Under rapidly cooling conditions, a greater fraction of such particles become condensation nuclei.

voirs consist primarily of the gaseous forms of hydrochloric acid (HCl), produced in a reaction of free chlorine with such common atmospheric constituents as methane, and chlorine nitrate (ClONO₂), formed in a reaction between ClO and nitrogen dioxide (NO₂).

Chlorine reservoirs themselves do not destroy the ozone layer. In these compounds, chlorine remains inert and cannot react with ozone. Early computer models concluded that CFCs should not have a major effect on the ozone layer. They indicated that only small

amounts of ozone would be destroyed by some of the chlorine in the reservoirs that does manage to escape and become active.

Evidently some mechanism in the Antarctic stratosphere was freeing more of the chlorine from these inert reservoirs. Susan Solomon and her co-workers at the NOAA Aeronomy Laboratory and Michael B. McElroy and his co-workers at Harvard University provided the first hints of what this mechanism might be. In 1986 they suggested that the observed correlation between

the cycle of ozone depletion and the presence of polar stratospheric clouds implied that chemical reactions taking place on the ice particles in the clouds freed chlorine from the reservoirs.

At first glance, the cloud theory encountered an apparent problem: clouds in the stratosphere were thought to be uncommon. The relative humidity there averages about 1 percent. Moreover, water vapor constitutes only a few parts per million of the air, a factor of 1,000 less than the

amount in the troposphere, where most clouds form.

Until recently, the only kind of stratospheric cloud thought to exist was the nacreous cloud. These clouds form at altitudes of about 15 to 30 kilometers and are the stratospheric versions of the lenticular (lens-shaped) clouds familiar to inhabitants of windy, mountainous regions. Lenticular clouds form as air rushes over mountains. The air creates a standing pattern of so-called lee waves downwind from the mountains. In the ascending portion of the lee waves, the air rapidly expands and cools. If there is sufficient moisture, it will condense on the many particles in the air. The waves thus become visible as clouds.

If the air is stably stratified and the wind does not change speed or direction at higher altitudes, the standing-wave pattern created by the mountains can propagate into the stratosphere. Nacreous clouds then tend to form on the crests of the standing waves. They do so through condensation on any aerosols present.

Sudden cooling and condensation of water vapor form the nacreous clouds. Because the mountains create standing waves, the clouds remain stationary, even though air constantly rushes through them. The ice crystals collect water as air currents push them through the clouds, so they grow to about two microns in size before all the water has been collected. When the crystals reach the descending portion of the lee waves, the air compresses and thus heats, evaporating the ice. A single cloud may extend from 10 to 100 kilometers in length. The energy of the standing wave may be sufficiently high so that a succession of such clouds may exist.

The distribution of sizes across the cloud gives nacreous clouds their iridescence. The smallest ice particles occur at the leading and trailing edges because the particles there have just begun to grow or have nearly evaporated; the largest form at the center. Particles at all positions in the cloud diffract passing sunlight. The intensity of the diffracted light depends on the wavelength of the light and size of the particle. As a result, when the clouds are viewed at moderate angles from the direction of the sun, they appear brightly colored. The colors follow the contour of the clouds, mimicking the distribution of particle sizes.

Nacreous clouds indicated to meteorologists that the stratosphere was indeed cold enough to enable water ice to form, at least near the polar regions.

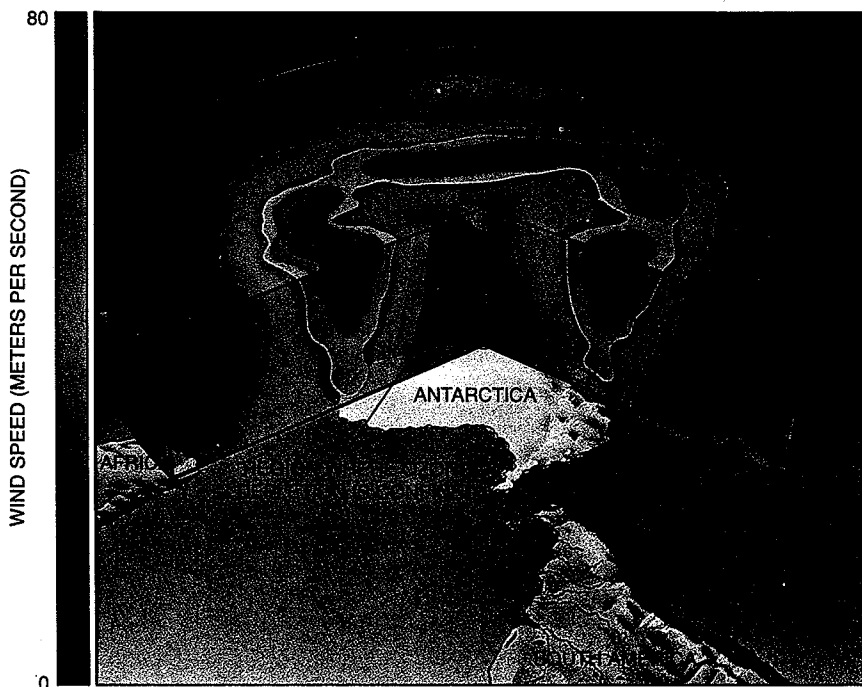
But because of the extreme dryness, the temperature must fall below 190 kelvins (-83 degrees Celsius). Only during the Antarctic winter are such temperatures maintained for any length of time. (Clouds also exist in the Arctic stratosphere, but they form less frequently because the average winter temperatures there are higher than in the Antarctic.)

Satellite data, however, revealed what land-based observers could not see. The Stratospheric Aerosol Measurement (SAM) II instrument, launched on board the *Nimbus 7* satellite in 1978 and managed by M. Patrick McCormick of the NASA Langley Research Center, detected particles in the air by examining sunlight as it grazes the limb of the earth. SAM II showed that stratospheric clouds existed over Antarctica even when the temperature dropped to only 195 kelvins (-78 degrees C). Such temperatures are too warm for nacreous clouds to form. Therefore, the clouds can be supposed to be created by some other process. Buttressing that conclusion was the fact that these newly discovered PSCs were too extensive to have formed from air currents flowing over mountains.

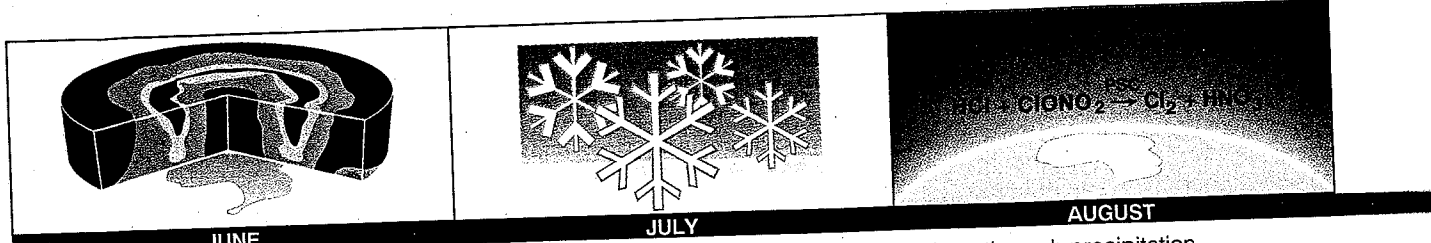
Along with Paul J. Crutzen of the Max Planck Institute for Chemistry in Mainz and Frank Arnold of the Max Planck Institute for Nuclear Physics in Heidelberg, we and our co-workers proposed

in 1986 that these clouds must differ in composition from nacreous clouds, which consist of pure water condensed on suspended particles. Chemical theories for ozone destruction require the removal of reactive nitrogen, which would otherwise trap chlorine as chlorine nitrate, one of the primary chlorine reservoirs. We deduced that the clouds might serve as a nitrogen sink. If so, they would consist of a frozen form of nitric acid (HNO_3) with three water molecules for each nitric acid molecule. Such a compound, called nitric acid trihydrate ($\text{HNO}_3 \cdot 3\text{H}_2\text{O}$), not only accounts for the nitrogen removal but also condenses at temperatures higher than does pure water.

In a series of independent observations, groups led by David W. Fahey of the NOAA Aeronomy Laboratory, Bruce W. Gandrud of NCAR and Rudolf F. Pueschel and Stefan A. Kinne of the NASA Ames Research Center confirmed our theories. Along with other researchers, we also determined that these clouds do not commonly form by the sudden cooling of air uplifted by mountains. A slowly cooling process usually produces these clouds. The winter polar stratosphere radiates energy away to space through the long polar night, and eventually vast regions reach temperatures at which cloud particles will form. In addition, weather systems in the lower atmosphere slide beneath



ANTARCTIC POLAR VORTEX confines the ozone depletion within a ring of rapidly circulating air. Wind speeds are represented by colors within the disk. The geography is not to scale. The diagram is based on a computer-generated image made by Mark R. Schoeberl and Leslie R. Lait of the National Aeronautics and Space Administration Goddard Space Flight Center.



- Antarctic winter begins.
- Vortex develops, and temperature becomes cold enough for clouds to form.

- PSCs denitrify and dehydrate the stratosphere through precipitation.
- Hydrochloric acid and chlorine nitrate react on cloud surfaces to free chlorine.
- Winter temperatures drop to their lowest point

the polar stratosphere, lifting and cooling the air. During the winter, when these processes cause the temperature to drop below about 195 kelvins, clouds of nitric acid trihydrate form. The sulfuric acid particles in the air serve as seeds. Such seed particles come from sulfur gases produced by natural biological processes and anthropogenic sources. Circulation patterns transport the sulfur released in the lower atmosphere to the stratosphere. Also, explosive volcanic eruptions can spew sulfur gases directly into the stratosphere. The particles, about 0.1 micron in size, may be especially abundant for a few years thereafter. In 1982 El Chichón in Mexico, near Pichucalco, expelled about five million tons of sulfur into the stratosphere.

to map individual clouds. They found that the clouds often occur as multiple, kilometer-thick layers stretching out over distances sometimes exceeding several thousand kilometers. Compared with nacreous clouds, nitric acid trihydrate clouds are less massive and more tenuous, making them difficult to see with the naked eye.

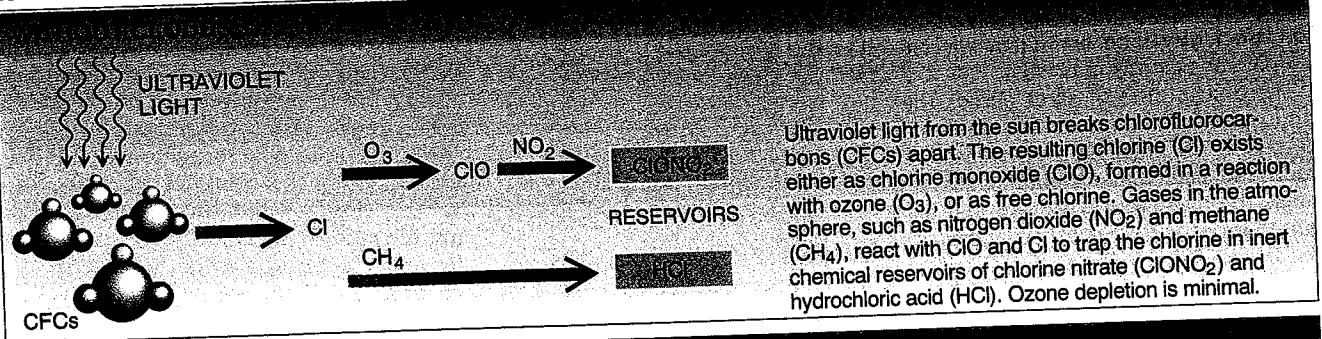
In addition to nacreous and nitric acid trihydrate clouds, another kind of PSC can form. The third type occurs if the Antarctic winter temperature slowly drops below 190 kelvins. As the air cools, water vapor condenses on some of the suspended particles, forming water-ice clouds. The seed particles are the nitric acid particles (which have themselves grown on sulfuric acid particles) that compose the nitric acid trihydrate clouds.

This type of PSC, like the nacreous clouds, contains water ice. Researchers commonly classify the two kinds of water-ice clouds together but distinguish them by their rate of formation (nacreous clouds form by rapid cooling).

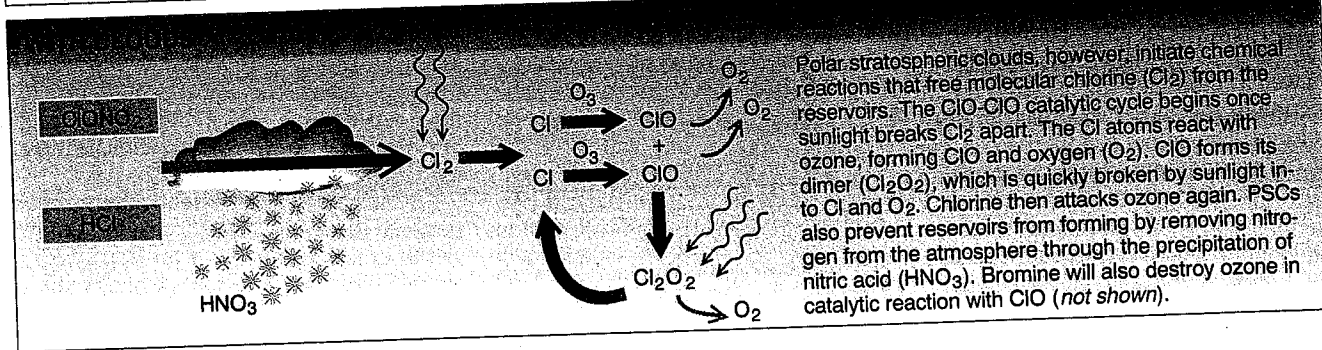
These water-ice clouds are not as common as nitric acid trihydrate clouds, especially in the Arctic, because of the extremely low temperature necessary for their formation.

Unlike the rapidly cooling water-ice clouds, the slowly cooling water-ice clouds are barely visible to ground observers. Although the mass of condensed water is nearly equal in both kinds of water-ice clouds, the particles in the slowly cooling clouds are larger than those of nacreous clouds. The rapid cooling that forms nacreous clouds transforms virtually all suspended aerosols into nuclei for condensation; slow cooling uses only a small fraction of the particles present. As a result, nacreous clouds contain a large number of small ice crystals, about two microns in size. Slowly cooling clouds have fewer, but larger, crystals that exceed a size of 10 microns. Because slowly cooling water-ice clouds contain fewer discrete particles per volume, they do not reflect light as well as their nacreous cousins do.

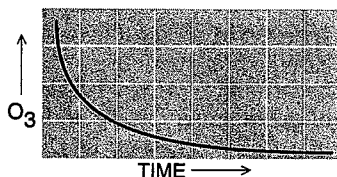
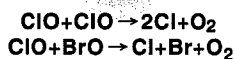
How Polar Stratospheric Clouds Help Chlorine Destroy Ozone



Ultraviolet light from the sun breaks chlorofluorocarbons (CFCs) apart. The resulting chlorine (Cl) exists either as chlorine monoxide (ClO), formed in a reaction with ozone (O₃), or as free chlorine. Gases in the atmosphere, such as nitrogen dioxide (NO₂) and methane (CH₄), react with ClO and Cl to trap the chlorine in inert chemical reservoirs of chlorine nitrate (ClONO₂) and hydrochloric acid (HCl). Ozone depletion is minimal.



Polar stratospheric clouds, however, initiate chemical reactions that free molecular chlorine (Cl₂) from the reservoirs. The ClO-ClO catalytic cycle begins once sunlight breaks Cl₂ apart. The Cl atoms react with ozone, forming ClO and oxygen (O₂). ClO forms its dimer (Cl₂O₂), which is quickly broken by sunlight into Cl and O₂. Chlorine then attacks ozone again. PSCs also prevent reservoirs from forming by removing nitrogen from the atmosphere through the precipitation of nitric acid (HNO₃). Bromine will also destroy ozone in catalytic reaction with ClO (not shown).



SEPTEMBER

OCTOBER

NOVEMBER

- Sunlight returns to the center of vortex as the austral spring begins, and PSCs disappear because of increasing temperatures.
- ClO-ClO and ClO-BrO catalytic cycles destroy ozone.

- Lowest levels of ozone are reached.

- Polar vortex breaks down.
- Ozone-rich air from mid-latitudes replenishes the Antarctic stratosphere.
- Ozone-poor air spreads over the Southern Hemisphere.

All three types of PSCs—nitric acid trihydrate, slowly cooling water-ice and rapidly cooling water-ice (nacreous) clouds—act as key components of the Antarctic ozone depletion. The PSCs can activate chlorine on their surfaces as well as use up reactive nitrogen, which would otherwise transfer chlorine to its reservoirs. Furthermore, slowly cooling water-ice and nitric acid trihydrate clouds can entirely deplete the stratosphere of nitrogen.

Laboratory studies by Molina and Ming-Taun Leu of J.P.L. and Margaret Tolbert of the Stanford Research Institute International and their co-workers showed that a reaction between hydrochloric acid and chlorine nitrate—the two compounds that hold chlorine in its inactive state—will indeed occur on water-ice and nitric acid trihydrate surfaces. That reaction, which produces molecular chlorine (Cl_2) and nitric acid, is negligibly slow without the presence of solid particles.

In the sunlight of the Antarctic spring, molecular chlorine quickly dissociates into highly reactive atomic chlorine, precipitating the ClO-ClO catalytic cycle. In this cycle the newly liberated chlorine atom breaks apart ozone to yield an oxygen molecule and chlorine monoxide. Molina discovered that the gas-phase chlorine monoxide reacts with itself, forming its dimer (Cl_2O_2). Sunlight readily dissociates the dimer into free chlorine atoms, leading to further ozone destruction. Chlorine thus maintains a catalytic role in ozone depletion [see illustration on opposite page].

Were nitrogen dioxide present, it would quickly combine with chlorine monoxide to trap the chlorine in the inert reservoir molecule, chlorine nitrate, thus halting the ClO-ClO catalytic cycle. But the PSCs prevent the reaction because they convert any nitrogen present into nitric acid.

James G. Anderson and his co-workers at Harvard University, as well as Robert L. deZafra and Philip Solomon of the State University of New York at Stony Brook, found astonishingly high levels of ClO in the Antarctic ozone

hole—about 500 times the amount found at mid-latitudes at the same altitude. Given such a high concentration, the ClO-ClO catalytic cycle can account for most of the observed losses in the ozone hole. A single chlorine atom may destroy thousands of ozone molecules before encountering reactive nitrogen or hydrogen compounds that eventually return chlorine to its reservoirs. Laboratory studies of these various reactions are continuing so that scientists can refine the pathways the chemistry takes and determine more precisely the reaction rates.

The active chlorine freed by the PSCs also plays a role in another significant catalytic process, one that involves bromine. Human activities contribute bromine, which is an important component of some types of fire-extinguishing compounds, to the atmosphere. The reaction may account for about 20 percent of the ozone destruction.

McElroy and his co-workers first suggested how the reaction proceeds. Bromine removes an oxygen atom from ozone, forming bromine monoxide (BrO). This compound will react with chlorine monoxide. The reaction forms molecular oxygen and frees the bromine and chlorine atoms, which then react with ozone again, repeating the process. Evidence for such a catalytic process comes from the 1987 observations by William H. Brune of Pennsylvania State University and Anderson of Harvard, who measured significant levels of bromine monoxide in the Antarctic ozone hole.

In addition to causing chemical reactions that convert the inert forms of chlorine to reactive forms (and the reactive forms of nitrogen into inert ones), PSCs also denitrify, or remove nitrogen from, the stratosphere. The slowly cooling water-ice clouds may be the primary agents that cause the denitrification. The cloud's water-ice particles not only form on nitric acid particles but also can absorb nitric acid in vapor form. The particles, which reach about 10 microns or larger, then fall from the Antarctic stratosphere as

snow. This process both denitrifies and dehydrates the stratosphere. Nacreous clouds do not seem capable of removing nitrogen from the atmosphere. The rapid air currents through the cloud tend to evaporate the water-ice particles before any precipitation occurs.

Like the slowly cooling water-ice clouds, nitric acid trihydrate clouds seem able to denitrify the air as well. Their particles typically reach only about one micron in diameter—small enough to remain suspended. The small size results from the fact that the stratosphere contains very little nitric acid. Some clouds do form so slowly that their particles grow over one micron and thus may fall out of the stratosphere. Evidence for such a process comes from observations of the Arctic stratosphere, which has been denitrified but not dehydrated. In addition, lidar measurements by Browell show that some nitric acid trihydrate clouds contain particles larger than one micron.

The current PSC-chlorofluorocarbon theory for the formation of the ozone hole explains many observations. The release of CFCs from human activities, mainly in the Northern Hemisphere, is responsible for depleting ozone in the Southern Hemisphere because the long atmospheric lifetime of CFCs causes them to be uniformly distributed throughout the atmosphere. The ozone hole occurs near Antarctica during spring because the formation of the hole requires the presence of stratospheric clouds, which form only during the coldest times of the year. The first rays of spring sunlight initiate the chemical reactions that deplete ozone.

The ozone loss is more obvious over Antarctica than over the Arctic because the Antarctic stratosphere is colder, enabling more clouds to form, particularly below 20 kilometers. More clouds produce additional reactive chlorine atoms and remove nitrogen compounds, leading to greater ozone loss.

Perhaps a more important difference between the two poles concerns the longevity of the Antarctic vortex, a ring of rapidly circulating air that confines the ozone depletion. The vortex remains

intact throughout the polar winter, well into midspring. Ozone destruction begins in September with the return of sunlight. Loss of ozone reaches its peak in October. In the Arctic, where circulation patterns differ significantly from those in the Antarctic, the vortex has long since disintegrated by the time the polar spring (March and April) arrives.

A feedback mechanism may further extend the lifetime of the Antarctic vortex. Ozone absorbs sunlight, thus heating the atmosphere; depleted ozone levels cause the air to remain cold longer. Such cold air encourages the formation of PSCs and stabilizes the vortex. Measurements have revealed that over the past decade, the temperature in the vortex has declined, and the time that the vortex remains intact has increased. Lamont R. Poole of the NASA Langley Research Center and his colleagues have shown that PSCs form more frequently as the temperature drops, completing the positive reinforcement of the system.

The early breakup of the Arctic vortex makes it difficult to assess the magnitude of the ozone loss in the Northern Hemisphere. But measurements made in 1989 by Brune and Anderson show that nearly equal quantities of reactive chlorine occur in each polar vortex at altitudes of about 18 kilometers. Apparently, conditions exist in the Arctic that encourage the formation of an ozone hole.

Browell and Michael H. Proffitt of the NOAA Aeronomy Laboratory found in 1989 that large regions in the Arctic stratosphere above 18 kilometers suffered ozone depletion equivalent to 6 percent of the total amount of ozone over the Arctic. For comparison, total ozone loss over Antarctica averages 50 percent or higher. Greater ozone destruction did not occur, because regions at altitudes below 18 kilometers were too warm for PSCs to form. In future years, loss of ozone will increase as atmospheric levels of chlorine continue to rise.

Unless the Arctic temperature drops significantly, ozone depletion in the Arctic should never rival the loss in the Antarctic. A lower average winter temperature would enable PSCs to form over a region of greater altitude and to persist longer. An international scientific campaign is planned for this winter to help develop models of future Arctic ozone loss.

Because the ozone hole requires the presence of polar stratospheric clouds and a stable vortex for its creation, it is necessarily trapped near the poles, where few people live. That does not

imply, however, the loss of ozone is restricted to the polar regions.

As the Antarctic vortex breaks up, pools of ozone-poor air spread over the Southern Hemisphere. In December of 1987 Rodger Atkinson of the Australian Bureau of Meteorology reported record-low ozone levels over Southern Australia and New Zealand after the breakup of the vortex. As those pools of low-ozone air spread out, they led to a small average ozone loss across the hemisphere. In addition, Adrian F. Tuck of the NOAA Aeronomy Laboratory has suggested that the Antarctic vortex may act as a chemical processor. Ozone-rich air may be entering the vortex, and ozone-poor air may be transported outward to the rest of the hemisphere. A high-altitude aircraft expedition being planned for 1993 will test this hypothesis and reveal more about the ozone depletion over Antarctica.

Not all ozone-destroying chemistry is confined to the polar regions. The sulfuric acid particles found throughout the stratosphere also trigger ozone reduction by freeing chlorine from its molecular reservoirs. Most significantly, those particles can also convert reactive nitrogen into inert forms, preventing the formation of chlorine reservoirs. The ozone loss caused by the sulfuric acid aerosols, however, is of a lesser magnitude than that caused by PSCs because of smaller mass and particle size.

Hofmann and Solomon have noted that the volcanic cloud created by the El Chichón eruption significantly reduced ozone levels. The amount of sulfate aerosols released rivaled the mass of nitric acid trihydrate PSCs. A large volcanic eruption early in the next century (when atmospheric chlorine levels will be higher) has the potential to induce significant global ozone loss.

Although many details remain unclear, investigators now understand quite well the fundamental link between stratospheric particulates and ozone destruction. Yet even the most thorough knowledge of stratospheric chemistry is unlikely to offer any quick technological means to stop the depletion. Replenishing the ozone lost annually—an amount comparable to the mass of the entire human population—would require at least 1 percent of the total U.S. energy output. This figure does not take into account the monumental task of transporting the ozone to the Antarctic vortex.

Instead the solution to ozone de-

pletion rests with international agreement among political leaders to restrict CFC production. In 1987 the U.S. and other industrial nations agreed to reduce the production of CFCs under the Montreal Protocol on Substances That Deplete the Ozone Layer. The protocol initially called for reducing emissions to 50 percent of 1986 levels before the year 2000. This reduction, however, would have allowed atmospheric levels of chlorine to increase to twice the current levels by the end of the next century.

As scientists became more certain of the chemistry of ozone depletion and the role that chlorine plays, the same nations recognized the need for swifter action. In the summer of 1990, they agreed to phase out chlorofluorocarbon production completely by the turn of the century.

Nevertheless, chlorine levels in the atmosphere will continue to increase over the coming decades. Large quantities of CFCs remain in refrigerators, air conditioners and foams, much of which will eventually be released into the atmosphere. Widespread use of safe replacements for CFCs seem to be at least a decade away.

Researchers predict that the amount of atmospheric chlorine will peak during the first decade of the next century. Because chlorofluorocarbons have such long lifetimes, chlorine may not return to levels that existed before the advent of the ozone hole until the middle of the next century, or even later.

Consequently, the destruction of ozone will be more severe every year for the next few decades, leading perhaps to a doubling in area of the Antarctic ozone hole. In effect, society has wagered that somewhat greater ozone loss is less likely to disrupt ecosystems and human activities than are rapid control and disposal of CFCs. No one yet knows the odds of winning this bet.

FURTHER READING

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