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FIXING THE SKY

When nations made plans to save the ozone layer, they didn't factor in global warming. **Quirin Schiermeier** reports on how two environmental problems complicate each other.

Later this month, something sinister will start to take shape above Antarctica. As sunlight reappears in the polar skies after the long winter, chlorine and bromine compounds in the stratosphere will begin destroying part of the ozone layer that shelters Earth's surface from harmful ultraviolet radiation. Over the next few months, these pollutants will eliminate enough ozone to create a hole in the protective veil over the Antarctic continent.

That same phenomenon has occurred every spring since the late 1970s, although it took several years before scientists recognized and documented the emerging pattern. When, in 1985, a team of researchers from the British Antarctic Survey published a paper in *Nature* describing the ozone hole[1], the world was put on high alert. At about the same time, it was becoming clear that the ozone shield over much of the planet was vulnerable to pollutants emitted into the atmosphere. That concern propelled countries in 1987 to agree to phase out the production of ozone-destroying compounds — which stands out even today as the most ambitious action ever taken to tackle a global environmental problem.

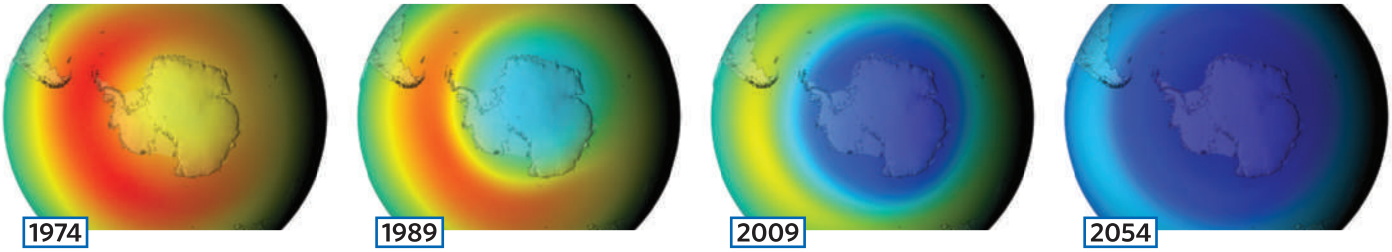
Thanks to that agreement, the Montreal Protocol, nations have made great strides towards repairing the planet's sunshield. Although the ozone hole that appears over Antarctica each year remains as bad as ever, the amount of chlorine in the atmosphere has started to decline and the rest of the ozone layer has started to show signs of recovery from a less dramatic, but still dangerous, thinning.

Amid the good news, however, lurk big questions about how long it will take to fix the sky. A decade ago, researchers projected that the ozone layer would fully recover by 2050, but now there is far more uncertainty in their estimates. One of the complicating factors is that greenhouse gases have altered atmospheric conditions in many ways since the Montreal Protocol was signed, some of which speed up ozone recovery and some of which delay it.

Scientists are only now gaining the necessary computing power to run long-term simulations that allow them to test which effects of climate warming might win out. These types of studies suggest that part of the global ozone layer will recover decades earlier than previously thought, whereas the Antarctic ozone hole may linger decades longer than was once hoped.

Complex interplay

Just as the climate influences ozone, changes to the ozone layer will, in turn, alter the climate. Ozone loss over Antarctica has already affected the climate there, for example, by helping to warm the Antarctic Peninsula and thereby contributing to the destruction of several ice shelves. And it may have tilted the odds towards more frequent droughts and fires in Australia.



In a NASA simulation, a world with no controls on chlorine and bromine pollution leads to extreme ozone loss (blue hues) over Antarctica.

NASA/GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO

"Stratospheric ozone and surface climate are coupled in many ways," says Susan Solomon, an atmospheric chemist at the National Oceanic and Atmospheric Administration in Boulder, Colorado. "It's a fascinating interplay of which we may not yet know the whole story."

Well before the ozone hole was recognized, scientists had started to worry about the effects that humans were having on the ozone layer. In 1974, Sherwood Rowland and Mario Molina, chemists at the University of California, Irvine, warned that chlorofluorocarbons (CFCs) could break down in the stratosphere and the chlorine released could destroy atmospheric ozone[2]. They later shared the 1995 Nobel Prize in Chemistry with Paul Crutzen of the Max Planck Institute for Chemistry in Mainz, Germany, for their pioneering work in understanding ozone chemistry.

Concern over that global thinning and the ozone hole led to the 1987 treaty known as the Montreal Protocol on Substances that Deplete the Ozone Layer. The treaty came into effect 20 years ago and was followed up by amendments that banned the worst ozone-destroying chemicals, such as CFCs (used in refrigeration, air-conditioning and foam production) and bromine-containing halons (used in fire extinguishers). The agreements yielded quick dividends: the effective concentration of ozone-destroying compounds in the stratosphere peaked in the late-1990s and has declined since then[3].

The Montreal provisions also came with a free gift for the climate because CFCs and their kin are much stronger greenhouse gases than carbon dioxide. By getting rid of those compounds, the ozone agreement has achieved five to six times greater reductions in warming effect than the Kyoto Protocol[4].

"The Montreal Protocol is just the most successful piece of international environmental legislation ever," says Solomon. "It also contains the unwritten memo to climate negotiators that we need to, and can, do much better in controlling greenhouse warming than we have been doing so far."

"If you have to have an ozone hole, the best place is Antarctica. In the tropics it would be very damaging to life."

— Susan Solomon

The 'world avoided'

A glance at a hypothetical future with no ozone protections illustrates what could have been. Paul Newman of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and his colleagues, used a model that simulates chemical reactions, atmospheric circulation and solar radiation to forecast a future in which production of ozone-depleting compounds is never regulated and grows at an annual rate of 3%. By 2065, two-thirds of the ozone would be destroyed — not just over the poles but everywhere[5]. CFCs would virtually eliminate the global ozone layer by the end of the century. People in New York, Buenos Aires and Tokyo, like everyone else living in mid-latitudes (the temperate regions between about 30° and 60° from the Equator), would be exposed to ultraviolet radiation so extreme that they would develop dangerous sunburn within 5 minutes, on average, one-third of the time it takes today. The level of DNA-mutating ultraviolet radiation would rise about six-fold, dramatically boosting skin cancer cases in humans (see 'Ozone and cancer').

But the ozone treaties will spare humans from living in a world unshielded from the might of the Sun. "The worst has been avoided," says Martin Dameris, an atmospheric and climate scientist at the German Aerospace Centre in Oberpfaffenhofen near Munich. "But it is also a reminder that we must not even think about watering down the protocol."

Continued pollutant use

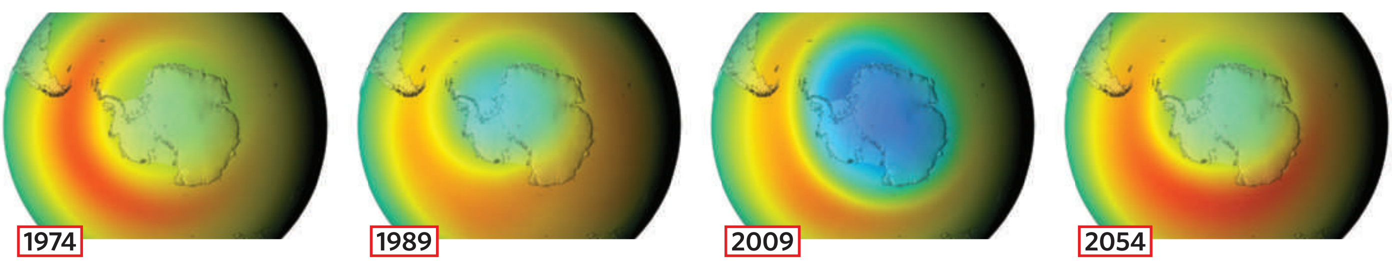
Environmental groups worry in particular about methyl bromide, which is used in agriculture to control pests. Under the provisions of the ozone-protection treaties, developed nations were supposed to stop using this compound by 2005, with developing nations following 10 years later. But lobbying by farming groups led to a stay of execution and the chemical is still in use in many developed countries. Another complicating factor is the large volume of chlorine and bromine stored in older air-conditioning and fire-fighting systems, much of which will eventually make its way into the atmosphere.

Once the chemicals get there, they linger for decades. So even though CFCs and several other ozone destroyers have been phased out, they will continue to eliminate ozone for many years. At present, stratospheric ozone concentrations around the globe are about 4% below the 1964–80 average, but the depletions differ substantially between hemispheres and latitudes. In tropical regions, there is relatively little ozone loss. Over the mid-latitudes, where the air mixes more readily with ozone-depleted air parcels from the poles, total ozone loss has reached 3% in the Northern Hemisphere, and around 6% in the Southern Hemisphere, since 1980 (ref. 3).

Although relatively minor compared with the extreme ozone loss over Antarctica each spring, the mid-latitude changes have a notable effect because so much of the population lives there. The additional ultraviolet light may cause hundreds of thousands of extra cases of skin cancer each year worldwide, with the full effects still decades away[3].

But there is good news for the mid-latitudes, because ozone concentrations there have started to show signs of rebounding. "It seems as if mid-latitude ozone is going up," says Richard Stolarsky, an atmospheric chemist at Goddard. The upward trend is still not clear enough to be able to firmly establish its cause, he says, "but we're pretty confident that reduced chlorine load [in the atmosphere] is contributing to the rebound".

Although researchers once estimated that it would take



Controls on pollution are projected to prompt a recovery of the ozone hole later this century.

until 2050 for the mid-latitude ozone layer to recover fully, model simulations now suggest that point will come perhaps 20 years earlier, especially in the Northern Hemisphere, which is not greatly affected by the Antarctic ozone hole[6]. The faster recovery can be considered a benefit of global warming. As greenhouse gases trap heat in the lower atmosphere, they cool the stratosphere above, which slows down the ozone-destroying chemical reactions. Moreover, models that simulate climate and atmospheric chemistry suggest that global warming will speed up the circulation pattern that carries ozone-rich air from the tropics to the mid-latitudes, thereby boosting ozone amounts there.

Quick reactions

Closer to the poles, however, the influence of global warming becomes less clear, especially for the Antarctic ozone hole. Cooling in the stratosphere there would, by itself, lead to more ozone destruction by stimulating the growth of polar stratospheric clouds. In the extremely dry stratosphere above Antarctica, such clouds form when temperatures drop below −78 °C, and they provide a surface for the chemical reactions that rapidly strip an oxygen atom from the three-oxygen ozone molecule.

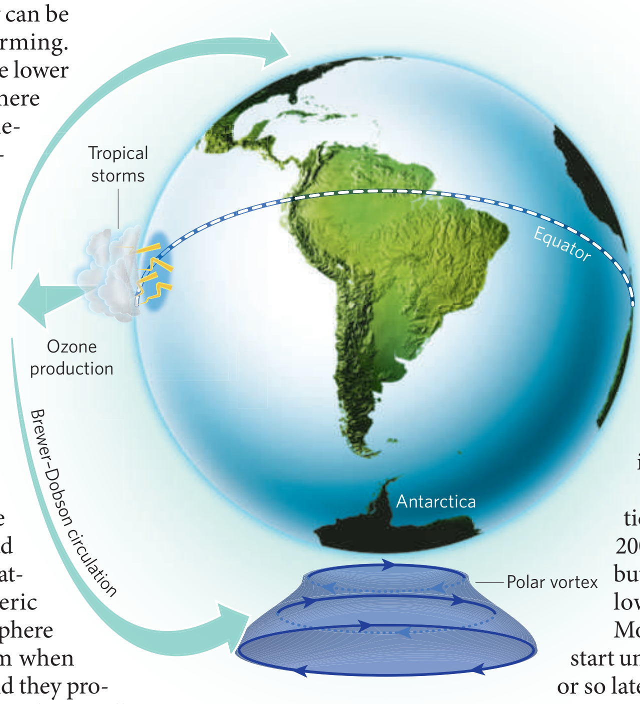
The ice particles play a powerful part. Outside the polar regions, a chlorine atom in the stratosphere can eliminate only a few hundred ozone molecules before it reacts with other gases such as nitrous oxide, breaking the cycle. But on the surface of polar ice particles, it can catalytically convert tens of thousands of ozone molecules. And it happens quickly. In the heart of the Antarctic ozone hole, between 14 and 21 kilometres above the surface, the loss rate can reach up to 3% per day[3]. By the beginning of October, the cloud-mediated reactions destroy nearly every ozone molecule in that altitude band.

In 1992, researchers predicted that greenhouse warming would speed up the destruction so strongly that it would cause ozone holes to open above the Arctic as well[7]. But that analysis left out an important effect, says John Austin, an author of the study and a modeller at the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. Normal atmospheric flow, called the Brewer–Dobson circulation, causes air to rise into the stratosphere over the tropics, and then travel towards the higher latitudes, where it sinks back into the lower atmosphere (and heats up as it gets compressed). If climate change accelerates that cycle, it will speed up the downward flow above the polar regions, which would enhance the compression of the sinking air and raise atmospheric temperatures there. Especially in the Arctic, that heating effect in the polar stratosphere will impede ozone loss, says Austin.

With climate change acting both to warm and to cool the polar stratosphere, researchers do not yet know which effect will win out. The results are not consistent from one model to the next and there is still considerable uncertainty on this topic, says Darryn Waugh, an atmospheric scientist at Johns Hopkins University in Baltimore, Maryland.

OZONE'S LONG JOURNEY

Ozone molecules are produced in the stratosphere over the tropics and are then transported towards the poles where they sink into the lower stratosphere. Over Antarctica, a vortex of winds isolates the polar stratosphere during winter and spring, which bottles up the cold air there and fosters the formation of springtime ozone holes.



One factor holding back progress in this area is the time it takes to conduct the research. There are still relatively few groups with the computing power to run long simulations with sufficiently complex models that mimic both atmospheric chemistry and climate. In the case of the Princeton lab, it takes 3 months of continuous computing with a 100-processor system to conduct a 100-year simulation, says Austin. "I have to watch it every day," he says, to make sure that the experiment does not get stuck. "Otherwise three months turns into four or five."

For now, the ozone hole above Antarctica shows no sign of getting any better. In 2002 and 2004 the ozone loss was less severe, but in 2006 ozone levels fell to a new record low and have since remained depressed. Most scientists don't expect the recovery to start until at least 20 years from now — a decade or so later than was projected just five years ago.

That is because models that simulate the movement of chemicals suggest that the stratosphere over Antarctica will remain saturated with ozone-destroying substances for another 10–20 years. And according to many models, it will take until 2060 or 2065 for nearly complete recovery, when polar concentrations of ozone-destroying compounds drop below their 1980s values.

The latest modelling results have raised an additional complicating factor: the influence of bromine compounds. Concentrations of bromine in the stratosphere are higher than models suggest they should be, perhaps because more bromine is making its way into the stratosphere than had been predicted. If that trend continues, a small ozone hole — about one-tenth its current size — would continue to form for decades beyond 2065, according to work done by the Princeton lab. "Even by the end of the century, you don't see complete recovery," says Austin, who cautions that this result is still preliminary.

> **"Ozone chemistry and atmospheric dynamics influence each other. It's difficult to keep apart what's pushing from what's pulling."**
> — Martin Dameris

For humans, and for most animals and plants, the extra ultraviolet light let in by the ozone hole may not present a significant problem. The peak ozone loss occurs early in the spring, when the Sun is still low over the horizon, which limits the amount of ultraviolet radiation reaching the surface.

"If you have to have an ozone hole, the best place is Antarctica," says Solomon. "If it occurred in the tropics it would be very damaging to life."

But aside from letting in slightly more radiation, the ozone hole has the indirect effect of altering the local climate, which causes atmospheric changes that can be felt throughout much of the Southern Hemisphere. Ozone is normally an enormous source of heat for the stratosphere because it absorbs solar ultraviolet radiation. The absence of ozone throughout much of the polar stratosphere leads to a 6 °C or so cooling there. Solomon has found that this cooling effect has helped to seal off the Antarctic continent by strengthening the vortex of westerly winds that flow around the polar cap[8].

This discovery serves as an explanation for several puzzling features of Antarctica's climate. The strong vortex locks very cold air on the high plateaus in the continent's interior and thus shelters the coldest regions on Earth from the effects of greenhouse warming. Large parts of Antarctica have experienced a cooling trend over the past 30 years — a fact often raised by those who deny any reality to global warming. But Solomon's work shows that ozone loss helps to explain the lack of warming in the interior parts of Antarctica.

Message in a bottle

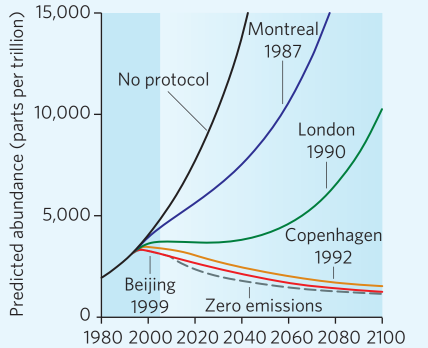
With the colder air bottled up over Antarctica, it does not flow out as frequently over the edges of the continent. That helps to explain why the Antarctic Peninsula, exposed to relatively mild oceanic air, has become one of the fastest-warming places on Earth. In the past couple of years, two large ice shelves have disintegrated along the peninsula, whereas six others show signs of retreat, sending gargantuan icebergs floating off into the Southern Ocean.

So as the ozone hole shrinks during this century, it will uncork the air bottled up over the continent. "The polar vortex won't be as tight anymore, and cold interior air could make it to the peninsula more frequently," says Solomon. "That would help."

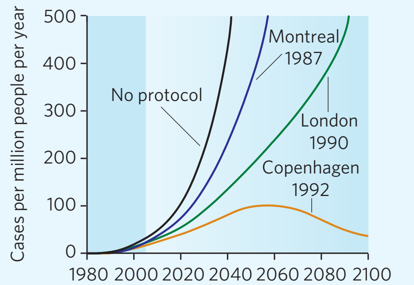
THE TREATY THAT WORKED

Without the Montreal Protocol and its amendments, the amount of ozone-destroying compounds would continue to rise, driving up skin-cancer rates.

OZONE-DESTROYING COMPOUNDS



EXTRA SKIN-CANCER CASES



SOURCE: REF. 3

Elsewhere around Antarctica, for instance in the Ross Sea, sea-ice coverage is growing. Solomon was among the first to suggest that stronger atmospheric circulation around Antarctica may be behind that seemingly puzzling trend as well. Indeed, model experiments have recently confirmed that the ozone hole alters circulation patterns in just such a way to explain the sea-ice expansion and the overall climate changes in the Antarctic[9].

Looking beyond Antarctica, James Risbey of the Center for Dynamical Meteorology and Oceanography at Monash University in Clayton, Australia, suggests that ozone loss is responsible for reduced rainfall and more frequent droughts over southern Australia. This happens, he says, because the cooling caused by ozone depletion over Antarctica has lowered atmospheric pressures there, speeding up the vortex of winds around the continent (see graphic, page 794). That pulls the rain-bearing westerly winds southwards, keeping them away from Australia. Risbey speculates that the ozone loss over Antarctica has caused a 20% reduction in rainfall in the dry season over Australia.

"Ozone chemistry and atmospheric dynamics influence each other. That's why it's difficult to keep apart what's pushing from what's pulling," says Dameris. "Much is speculation still, and there may be surprises."

His experiments with a model that simulates climate and atmospheric chemistry suggest that rising sea surface temperatures in the tropical oceans will strengthen the Brewer–Dobson circulation[10]. That could result in less ozone inside the tropics and more ozone outside, leading to abnormally high ozone concentrations in the mid-latitudes. That extra ozone would help protect people but it could have unwanted effects, perhaps by altering the chemistry of the stratosphere or by hindering the growth of plants, says Dameris.

Over the long term, as chlorine and bromine pollution are cleaned from the skies, climate change will take over and be the dominant human influence on ozone concentrations, he says. "Not many people have started thinking about what that might mean. It's getting about time." ■

Quirin Schiermeier is *Nature*'s Germany correspondent. Additional reporting by Richard Monastersky.

Ozone and cancer

With the thinning of global ozone layer in the past 30 years, a surge in skin-cancer rates would be expected. And at first glance, that seems to have happened. The incidence of melanoma in the United States has more than doubled since 1975, with almost 69,000 cases expected to be diagnosed this year. In some parts of Australia and New Zealand, which have the highest incidence and mortality of melanoma in the world, the numbers have jumped by more than 50% since 1994.

However, attributing that trend to ozone depletion is difficult because skin-cancer rates depend on other factors such as lifestyle, sunscreen use and how often tumours are diagnosed, all of which have changed over time. It also takes decades for skin cancer to appear after exposure. So the peak in cancer from the past thinning of the ozone layer has not yet hit.

Based on predicted increases in the amount of ultraviolet radiation, and assuming that factors other than ozone will remain unchanged, the World Meteorological Organization and United Nations Environment Programme predict that additional skin cancer cases will top out around mid-century at 100 or so cases per million per year above 1980 levels — which would translate to at least 700,000 extra cases worldwide. Those rates should eventually return to 1980 values.

Without the Montreal Protocol and its subsequent provisions on chlorofluorocarbons, skin cancer cases would have been expected to quadruple by 2050 and to sharply increase further thereafter[3] (see graphic, above). **Q.S.**

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