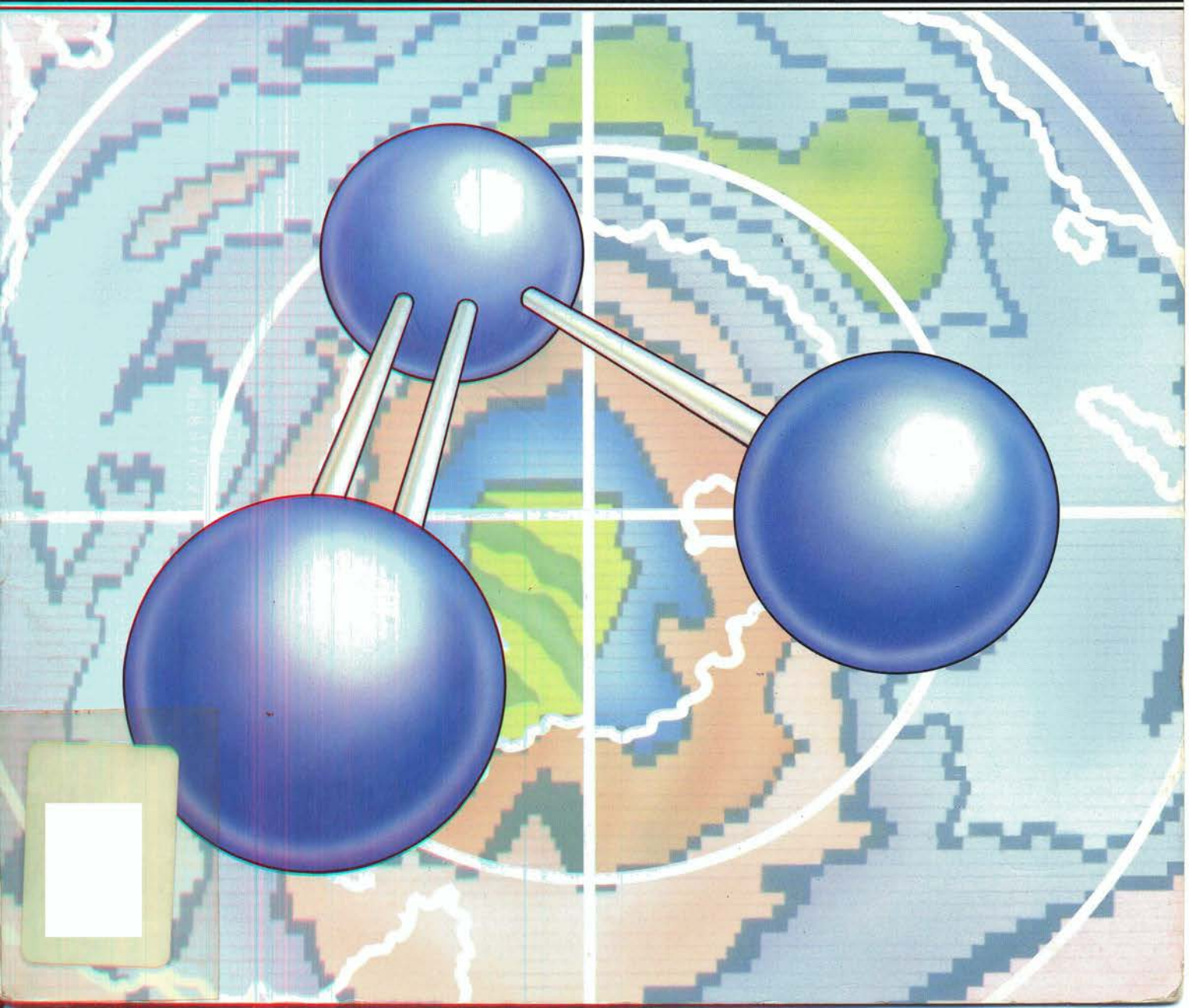




THE IMPACT OF OZONE-LAYER DEPLETION



United Nations Environment Programme
The Impact of Ozone-Layer Depletion
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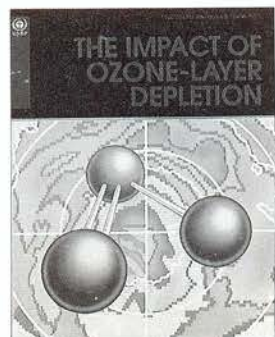
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are not necessarily those of the
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*Cover shows a
diagrammatic ozone
molecule
superimposed on a
map of ozone-layer
depletion in the
Antarctic.*



THE IMPACT OF OZONE-LAYER DEPLETION

The UNEP/GEMS Environment Library

Earthwatch was the name given in 1972 by the UN Conference on the Human Environment to the assessment activities included in its action plan. Under the plan, each UN agency monitors and assesses those aspects of the environment that fall within its mandate. This Global Environment Monitoring System (GEMS) was formally created two years later, in 1974, and the system is coordinated by the United Nations Environment Programme (UNEP) and its partner agencies through a Programme Activity Centre at UNEP's Nairobi headquarters.

GEMS now has more than a decade of solid achievement behind it. In that time, it has helped make major environmental assessments of such things as the impact of global warming, the pollution of urban air and freshwater resources, the rate of degradation of tropical forests and the numbers of threatened species—including the African elephant—in the world.

As is proper, the results of these assessments have been regularly published as technical documents. Many are now also published, in a form that

can be easily understood by those without technical qualifications, in the UNEP/GEMS Environment Library.

This is the seventh volume in the series, and one in which UNEP has a particular interest. Ten years ago few people had heard of the ozone layer, and even fewer had any suspicion that it was under threat from the release of man-made chemicals. Today—thanks in large part to UNEP initiatives—there is an international convention on protecting the ozone layer and a protocol, to which more than 70 of the world's nations are signatories, setting out how the consumption and production of the chemicals now known to cause the greatest damage to the ozone layer are to be reduced.

The second volume in this series covered the basic science of ozone depletion. This volume deals with the effects of ozone depletion on human health and the environment, and outlines ways of reducing damage to the ozone layer.

Michael D. Gwynne, Director
Global Environment Monitoring System



Michael D. Gwynne

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Foreword

The ozone layer that has shielded the Earth from damaging ultraviolet radiation since life began is diminishing. This is caused by the use we have made, over the past 60 years, of the ozone layer depleting substances, particularly CFCs and halons. Even if all such substances were banned tomorrow, we would still be committed to further ozone destruction throughout the next century because of the long-lived chemicals already released into the atmosphere. In fact, on the basis of phase-out dates laid down in the Montreal Protocol, it will take until about 2130 for these man-made compounds to disappear completely from the atmosphere.

Meanwhile, the effects of thinning ozone will be felt worldwide, mostly as a direct result of increased levels of ultraviolet radiation reaching the Earth's surface. These effects include health problems in the form of skin cancer, cataracts and depressed immunity to disease; damage to marine food chains, crops and materials such as plastics and paints used outside; the potential for increased global warming and air pollution; and even genetic mutations.

Fortunately, in the face of these grim consequences, action towards halting further ozone-layer depletion and repairing the damage already done has been remarkable. Since the ozone hole over Antarctica was first discovered in 1987, international scientific and political recognition of this most global of environmental problems has been encouraging in its speed and scope.

Through such panels and working groups as those responsible for the technical, environmental, scientific and economic assessments upon which this publication is based, the stringent terms of the Montreal Protocol for world-wide elimination of ozone-destructive CFCs and halons look certain to be met by the recommended dates—if not before.

Mostafa K. Tolba
Executive Director
United Nations Environment Programme



Mostafa K. Tolba

UNEP

Overview

... increasing amounts of damaging ultraviolet radiation could change genetic structure, alter immune systems, damage crops, disrupt the marine food web and enhance the scale of greenhouse warming ...

Ozone forms a layer in the stratosphere that absorbs dangerous solar ultraviolet radiation. Increasing amounts of man-made chemicals are accelerating the speed at which ozone molecules are destroyed.

These ozone-destroying chemicals come mainly from chlorofluorocarbons (CFCs) used in a range of products from refrigerators and air conditioners to soft foams and cleaning solvents; and from halons, used for fire-fighting. Their quantities in the atmosphere have been rising rapidly since the mid-1970s.

The ozone hole over Antarctica was discovered early in 1985. In 1989 it was confirmed that a similar potential for large-scale ozone destruction existed in the Arctic, and possibly above heavily populated areas as well.

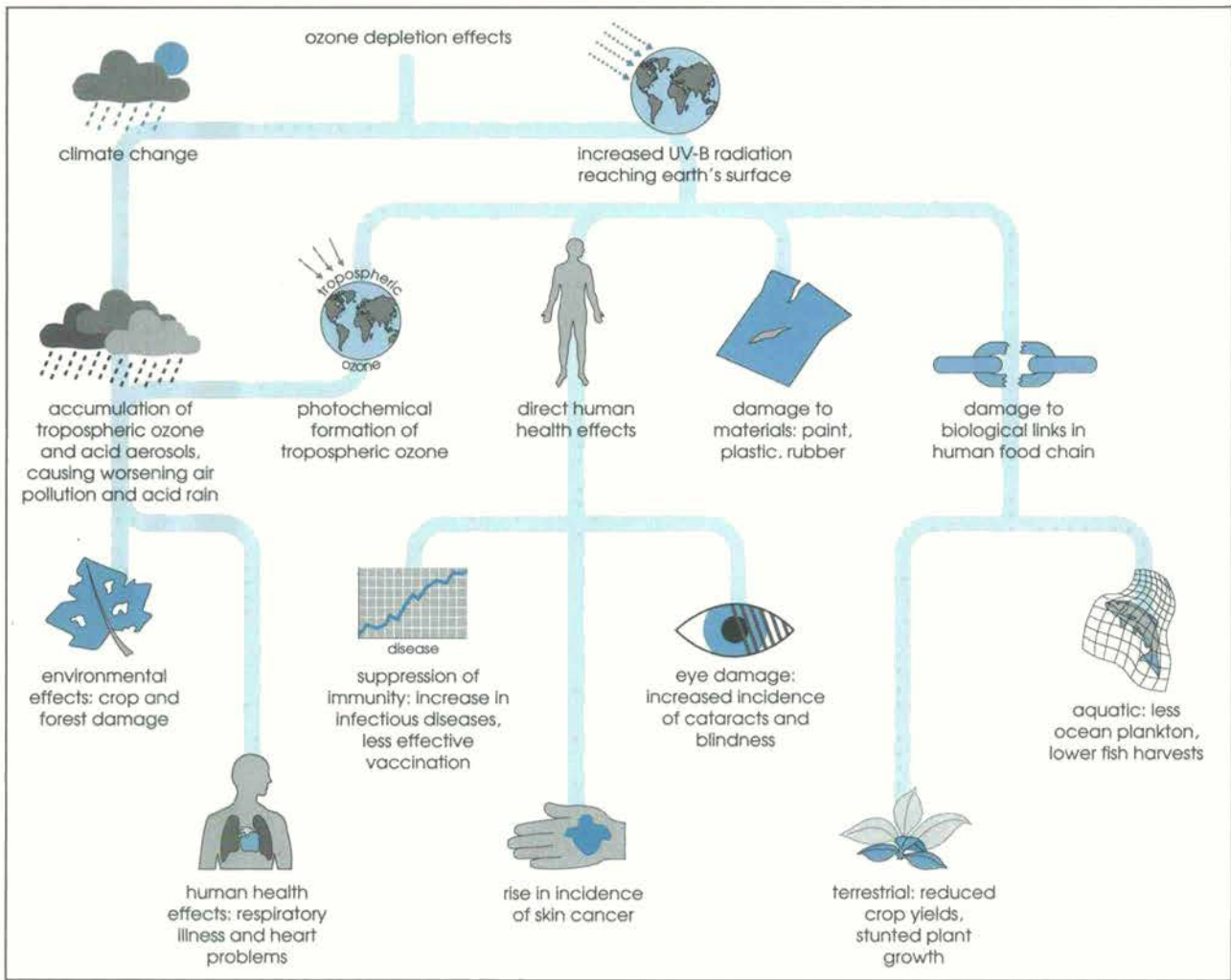
The panel assessing the science of ozone destruction (*see box*) has reported that man-made chlorine and bromine compounds are responsible for virtually all measured ozone losses. The panel warns that the world is already committed to worsening ozone destruction throughout the next century. The Antarctic ozone hole will form each southern spring until ozone-destroying chemicals are reduced to the extent that the atmosphere contains

The Vienna Convention and the Montreal Protocol

The first theory blaming CFCs for destroying stratospheric ozone was presented in 1974 by Sherwood Rowland, of the University of California and his collaborator Mario Molina. Their ideas were not taken up immediately; but by 1981, in accordance with a UNEP Governing Council decision, a working group of government, legal and technical experts drafted a 'Convention for the Protection of the Ozone Layer'. In 1985 this was adopted by 21 states and the European Community as the Vienna Convention.

Parallel plans for a protocol containing specific regulatory measures were laid down in the Convention, but then in 1985, the British Antarctic Survey published irrefutable evidence of the ozone hole over Antarctica. The Montreal Protocol was finalized and approved on 16 September 1987 and came into force in January 1989. The Protocol, ratified by 36 countries accounting for about 80 percent of global CFC consumption, called for reducing

the production and use of the five most widely used CFCs and the three major halons. The aim was to achieve the 1986 level of CFC use by July 1989; 80 percent of that level by July 1993; and 50 percent of the 1986 level of consumption by July 1998. Special provisions were made for developing countries with low per capita consumption. Parties to the protocol agreed to limit halon use to 1986 levels after 1992. Importantly they agreed to list products containing controlled substances by January 1992, and ban their import from non-parties the following year. Parties have also been urged to consider import control measures for goods produced with (but not themselves containing) controlled substances. Finding substitutes seemed an impossible task in 1987; but the progress made and further research on ozone loss persuaded the second conference of Protocol parties, held in London in July 1990, to agree to phase out the most potent CFCs and halons by the year 2000.



less than 2 parts per billion by volume (ppbv) of chlorine. Before industrialization, natural atmospheric chlorine levels were only 0.6 ppbv. Before the Antarctic ozone hole began to form, concentrations of chlorine compounds in the stratosphere above Antarctica had risen to 1.5–2.0 ppbv. Today they make up 3.0–3.5 ppbv and are rising rapidly. CFCs and halons remain in the atmosphere for decades—in some cases for more than 100 years. Even if we immediately stopped all emissions and destroyed all remaining CFCs and halons, it would be towards the end of the 21st century before atmospheric levels of chlorine compounds had dropped to levels that no longer permitted the formation of the Antarctic ozone hole. The panel emphasized that future ozone destruction is likely to be greater than predicted by computer models so far because some of the processes causing the Antarctic depletion are still too complex to be incorporated in the computer programs.

The Montreal Protocol, which was amended in 1990, aims to phase out the production of CFCs, halons, carbon tetrachloride and methyl chloroform completely by the year 2005. If this is achieved, levels of chlorine compounds in the atmosphere by 2050 would be slightly below today's levels. This would still not

Figure 1 This flowchart shows how the increased UV-B radiation and change in climate caused by depleted ozone will affect life on Earth.

CFCs and halons remain in the atmosphere for decades—in some cases for up to 100 years.

be low enough to stop the ozone hole forming each southern spring. But it would mean that from about the end of the next century ozone destruction would start to slow down, and by around 2130, many of the man-made chlorine compounds would have disappeared from the atmosphere.

Accelerating ozone-layer depletion will have serious impacts on most of the planet's life forms. For every 10 percent depletion of the ozone layer, we can expect a 20 percent increase in ultraviolet radiation arriving at the ground in life-damaging wavelengths. This radiation could change genetic structure, alter immune systems, damage crops, disrupt the marine food web, and enhance greenhouse warming by affecting the carbon dioxide-absorbing capacity of plankton in the oceans. The incidence of human skin cancers could increase, and the sight of millions could be affected as more intense ultraviolet radiation damages eyes and causes cataracts. Immune responses may be depressed in people exposed to increased radiation levels; vaccination programmes may thus become less effective; and infectious diseases may become more common and more severe. Plant growth may be inhibited by the extra ultraviolet radiation and crop yields may be reduced.

The Montreal Protocol assessments

'Beginning in 1990, and at least every four years thereafter, the Parties shall assess the control measures provided for in Article 2 on the basis of available scientific, environmental, technical and economic information. At least one year before each assessment, the Parties shall convene appropriate panels of experts qualified in the fields mentioned and determine the composition and terms of reference of any such panels. Within one year of being convened, the panels shall report their conclusions, through the Secretariat, to the Parties.'

Article 6, Montreal Protocol

In October 1988, a working group of the Montreal Protocol on Substances that Deplete

the Ozone Layer established four review panels to implement Article 6 of the Protocol. They covered the scientific, environmental, technical and economic aspects of ozone-layer depletion. The main conclusions reached by the panels were published and distributed in 1990 by the United Nations Environment Programme, which acts as the Secretariat to the Protocol.

The conclusions represent the collective judgement of several hundred experts in the field from 21 developed and 9 developing countries. The World Meteorological Organization helped prepare the scientific assessment.

This publication is based largely on information included in the first four assessment reports.

Adverse effects on nitrogen-fixing bacteria in rice paddies may result in drastic drops in production.

Air pollution is expected to worsen as increasing amounts of ultraviolet radiation spark more of the chemical reactions that produce smog and acid rain, and a range of materials, from plastics to wood and rubber, will degrade more rapidly.

Ozone destruction and its impacts cause grave concern, but there is room for optimism as well. More than three years ago, alarm at the scale of the threat sparked rare cooperation and action among the world's scientists and governments. Global efforts of scientists and industrial experts since 1985 have resulted in further understanding of the processes of ozone destruction, and in technological discoveries that now suggest that ozone-destroying chemicals can largely be eliminated by 2000. When the Montreal Protocol was signed in 1987, there was no actual proof that CFCs were destroying the ozone layer, and little prospect of finding usable ozone-safe substitute chemicals.

By 1990, when the Protocol was stringently tightened, there was proof of accelerating ozone layer depletion, and clear evidence that man-made chlorine and bromine compounds were responsible. There were also encouraging developments on the technological front. Substitutes for several uses of CFCs are now at the stage of commercial production, and technical experts claim that although they do not know exactly how the technologies will develop, we can reasonably expect a virtually complete halt to CFC emissions by 2000. Politically, there has also been surprisingly rapid international action. The Protocol was negotiated over only 2 years, when accepted wisdom held that about 10 years were needed to gain international consensus on something as difficult as urgent reductions in CFC use.

The industrialized world caused the problem of ozone layer depletion, through its development of CFCs and other chemicals. It therefore agrees that it has a responsibility to provide financial and technological help to developing countries, to allow them to continue to improve living standards for their people without using the older, polluting technologies that destroy ozone. The situation is urgent. Much has already been achieved in the field of cooperation, and in developing alternatives to the chemicals that destroy ozone. Much more is needed in terms of scientific research, technological developments, and rapid and practical transfer to the developing world of the necessary technologies and knowledge that will allow a global elimination of CFCs and other chemicals, and the eventual repair of the ozone layer.

Politically, there has also been surprisingly rapid international action. The Protocol itself was negotiated over only 2 years, when accepted wisdom held that about 10 years were needed ...

The scientific background

The ozone layer lies mostly in the stratosphere, from 12 to 50 km above the earth's surface. Together with ozone in lower parts of the atmosphere, it acts like a giant sunshade, protecting plants and animals from much of the sun's harmful ultraviolet radiation. Without ozone, the life forms that have developed on earth could not flourish.

Atmospheric ozone not only prevents lethal wavelengths of ultraviolet from reaching the earth's surface, but it also filters out 70–90 percent of the less damaging portions of ultraviolet radiation. Radiation at these wavelengths is responsible for sunburn, skin cancers and cataracts, and can weaken the immune systems that protect us from infection. It can also retard plant growth and damage the genetic structure of some plants and animals.

Ozone is a simple molecule of three oxygen atoms. Although its presence

allows life here to flourish, it is a toxic gas which is dangerously irritating to the respiratory system. Ozone is only a minor constituent of the atmosphere. If all the ozone in the atmosphere from ground level to a height of some 60 km could be assembled at the earth's surface, it would comprise a layer of gas only about 3 mm thick, weighing some 3000 million tonnes.

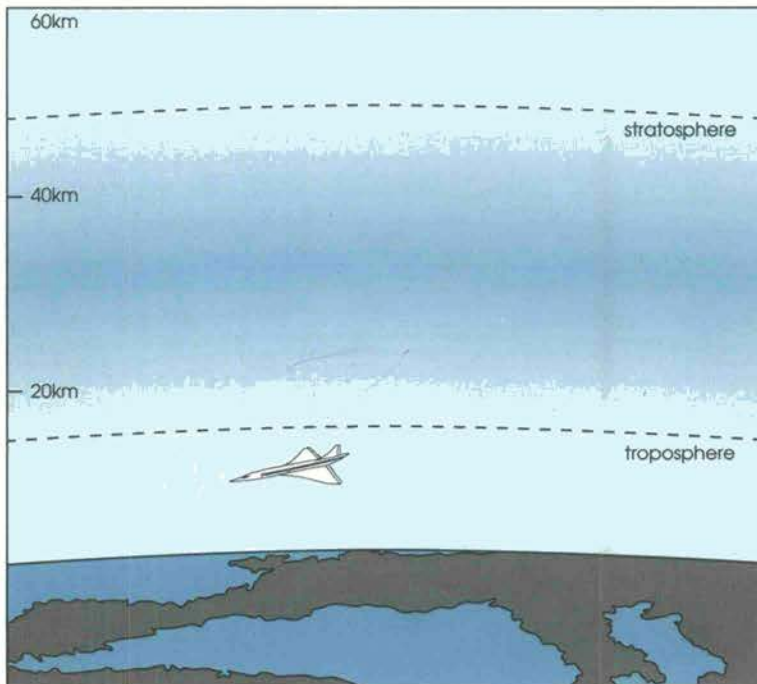
Nearly all the atmosphere's ozone is contained in its two lowest layers: the troposphere, which extends from the surface up to about 12 km, and the stratosphere, which extends up to about 50 km. About 90 percent of all the ozone in the atmosphere is in the stratosphere.

Ozone acts as a greenhouse gas in the upper troposphere and lower stratosphere. Changes in the concentration of ozone in these regions will modify the scale of greenhouse warming.

Man-made chemicals are destroying the ozone in the stratosphere. Over the past 10 years, the ozone layer has been unaffected in the tropics, but has lost up to 8 percent in winter in mid- and high northern and southern latitudes, and up to 60 percent in Antarctica during the southern spring.

Because of the long lag times involved in ozone atmospheric chemistry, ozone-layer depletion is now bound to continue throughout most of the next century. Moreover, future ozone losses are likely to be greater than those so far predicted, as the predicted losses underestimate the observed loss. This is presumably because the models do not take into account the effects of clouds that form in the stratosphere in high latitudes or aerosol particles in mid-latitudes.

Figure 2 Most atmospheric ozone is found in the stratosphere, about 12–50 km above the earth.



The Antarctic ozone hole

Over the past 10–15 years, there has been a large, rapid and unexpected loss of ozone in the stratosphere each spring above Antarctica. Every spring up to 95 percent of stratospheric ozone is destroyed at a height of 12–24 km above the earth's surface—the heart of the polar ozone layer. Satellite observations show that the ozone hole is sometimes larger than the area of the United States.

The latest measurements show that throughout the entire stratosphere, from 12 to 50 km above the surface, half the ozone layer above Antarctica is destroyed each spring. Scientific theory did not predict this scale of destruction. The rate at which ozone in the stratosphere above mid- to high latitudes is now disappearing is much faster than was predicted.

There is strong scientific evidence that man-made chlorine and bromine compounds are to blame for these losses. In

the stratosphere above Antarctica during the spring, when the ozone hole is at its largest, amounts of reactive chlorine compounds, which cause rapid and large-scale destruction of ozone, are 50–100 times higher than at other times of the year.

The seeds of ozone destruction above Antarctica are sown in the winter, when a vortex of extremely cold air blows around the pole. No sunlight enters the vortex in the Antarctic winter night, and no air from warmer latitudes moves into the vortex. The extreme cold primes the vortex for ozone destruction by allowing clouds of nitric acid and water ice to form in the lower polar stratosphere.

Reactions between particles in these polar stratospheric clouds and stable chlorine and bromine compounds play a major role in large-scale ozone depletion above Antarctica. Under certain conditions, for example, one molecule of chlorine

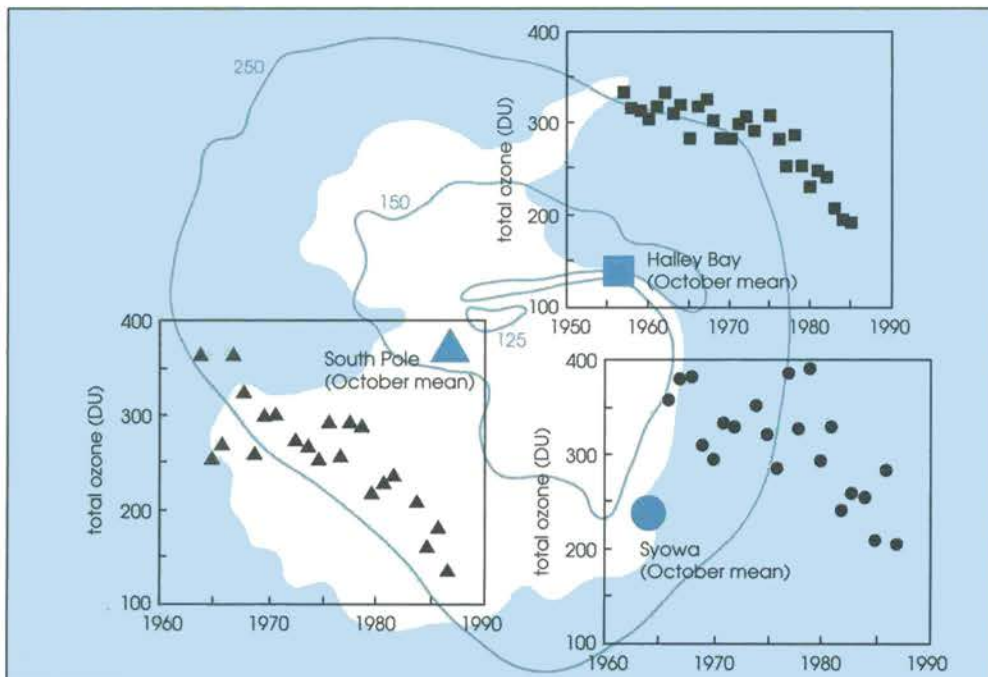


Figure 3 The long-term trends in total ozone, as observed from 3 ground based Antarctic stations, have decreased substantially over the past 20 years.

monoxide can destroy 10 000 to 100 000 ozone molecules.

Once the stable compounds of chlorine and possibly bromine have been changed into highly reactive forms, they need only sunlight to begin tearing apart ozone molecules, destroying them far more rapidly than earlier theory predicted. The quantities of reactive chlorine and bromine that have been observed above Antarctica are sufficient to destroy the ozone layer at rates of up to a few percent a day—the scale of destruction observed during the Antarctic spring.

The chemicals that break down ozone are present in the stratosphere in relatively tiny amounts. The large quantities of chlorine monoxide measured above Antarctica by aircraft and ground-based instruments in 1987, which allowed scientists to conclude that reactive chlorine compounds were responsible for much of the Antarctic ozone losses that spring, represented one part of

chlorine monoxide per billion molecules of other gases in the stratosphere. Such apparently insignificant amounts of reactive chlorine compounds were in fact 100 times more concentrated than in other parts of the stratosphere, where little or no ozone destruction was observed.

Observations and laboratory research on stratospheric chlorine compounds have now confirmed that chlorine chemistry accounts for most, if not all, the ozone destruction that occurred in the Antarctic spring of 1987.

Establishing how ozone is destroyed above the poles required a reexamination of the chemical reactions known to occur in the stratosphere. The process begins with the formation of polar stratospheric clouds. These then trigger the breakdown of stable chlorine molecules into highly reactive forms of chlorine.

Chemical reactions at the surface of polar stratospheric clouds prevent nitrogen

Quasi-biennial oscillation, solar cycles and ozone depletion

Two other factors thought to affect the atmospheric abundance of ozone are the quasi-biennial oscillation and the 11-year solar cycle.

The quasi-biennial oscillation in winds in the stratosphere above the tropics is linked with changes at higher latitudes as well. In the tropics, winds in the stratosphere blow either easterly or westerly, shifting direction roughly every two years.

The quasi-biennial oscillation was easterly in 1988, when the Antarctic ozone hole was significantly smaller than in the previous year. In 1989 the quasi-biennial oscillation was still easterly and, accordingly, a smaller ozone hole was expected. But the 1989 Antarctic ozone hole was almost identical to the 1987 hole—the worst ozone destruction recorded.

Solar cycles also contribute to variations in the amounts of total ozone. During high solar activity, when the sun's ultraviolet emissions are greater, increased amounts of ozone are expected at low and mid-latitudes in the upper stratosphere. A three percent variation in total ozone has been observed over the 11-year solar cycle. There seems to be a correlation between the solar cycle and the quasi-biennial oscillation, but this has not been definitively established.

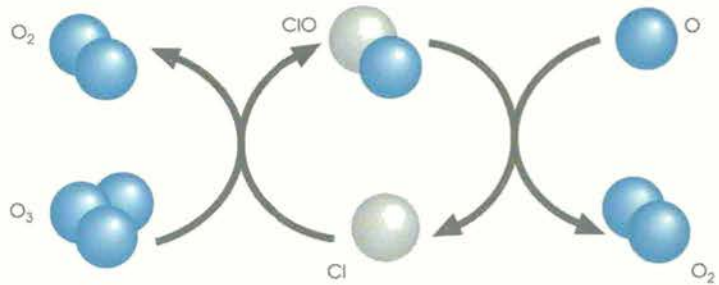
However, even though these two phenomena could reduce the rate of ozone destruction, the reductions would not compensate for the large-scale destruction being triggered by emissions of man-made chemicals.

oxides from slowing down the rate of ozone destruction—as they normally do when they capture reactive forms of chlorine and change them back into more stable molecules. In polar stratospheric clouds, by contrast, nitrogen oxides are tied up in the long-lived species HNO_3 (nitric acid), and so cannot convert chlorine monoxide into reservoirs of more stable chlorine compounds. As a result, highly reactive chlorine compounds stay in the stratosphere in greater quantities and for longer than normal, increasing rates of ozone destruction.

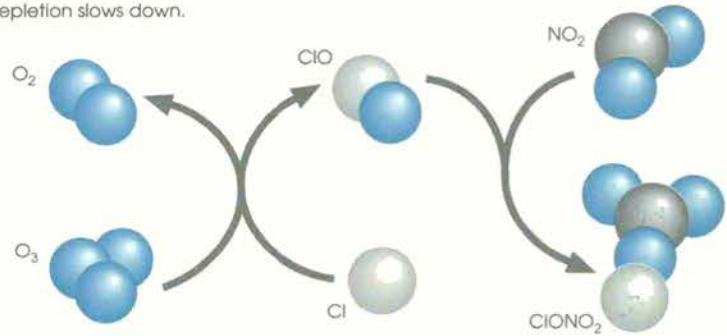
Further evidence that reactions at the surface of polar stratospheric clouds are responsible for most of the ozone destruction observed above Antarctica in the spring came in September 1987, when substantial denitrification of the Antarctic lower stratosphere, at heights of 18–20 km, was observed, reinforcing the theory that the clouds tie up the nitrogen oxides and prevent them creating reservoirs of less destructive forms of chlorine.



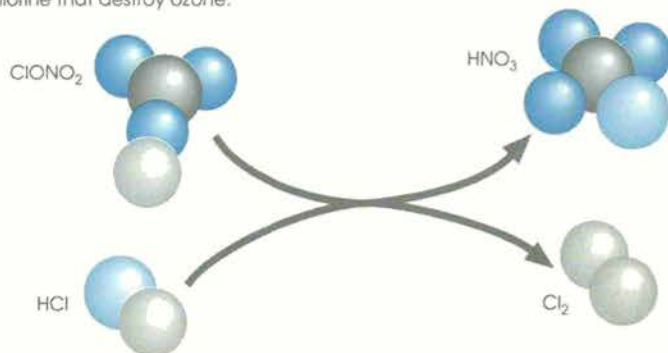
Chlorine reacts with ozone, breaking it down to form oxygen and chlorine monoxide: the latter reacts with free oxygen to reform chlorine and the cycle starts again.



When nitrogen oxide is present the cycle is disrupted, long-lived chlorine compounds are formed, and the rate of ozone depletion slows down.



However, on polar stratospheric clouds, long-lived chlorine compounds are converted to highly reactive forms of chlorine that destroy ozone.



Mid-latitude ozone-layer depletion

The ozone layer is not only diminishing above Antarctica. In mid-December 1987, following what was, until 1991, the deepest Antarctic ozone hole ever, ground-based observations showed a sudden drop of about 10 percent in stratospheric ozone above southern Australia and New Zealand, which lasted for the rest of the month.

Reduced ozone levels have now been measured year-round at latitudes much nearer the Equator, in both hemispheres, and the evidence suggests that these decreases are largely due to chlorine and bromine. Decreases in winter in the northern hemisphere have been recorded since the 1970s but there is now evidence of significant decreases in the spring and summer in both hemispheres at both middle and high latitudes (as much as 3.5 percent at 45°N in summer over the period 1979–91).

The rate of loss appears to be accelerating. The loss per decade was about 2 percentage

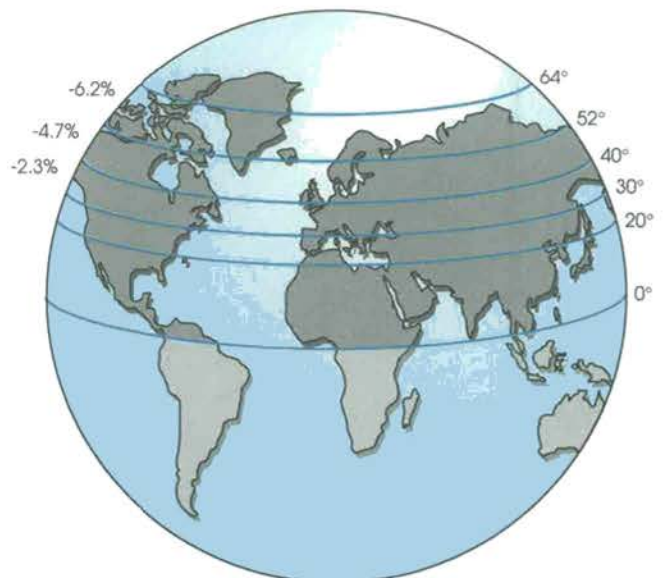
points higher during the 1980s than during the 1970s.

As levels of chlorine and bromine continue to increase—as they inevitably will—it is expected that mid-latitude ozone depletions will be as large during the 1990s as they were during the 1980s—reaching 6 percent in summer and about 10 percent in winter by the year 2000.

Ozone depletion in lower latitudes is partly due to the spread of ozone-poor air when the polar vortex breaks up in late spring. The vortex may also process a larger volume of air, changing stable chlorine into more reactive forms and priming this air to destroy ozone as it moves to lower latitudes.

Sulphuric acid particles may also trigger reactions, causing rapid destruction of stratospheric ozone. This could be particularly important after a volcanic eruption. It could also allow a greater rate of ozone destruction above heavily polluted areas.

Figure 4 shows the average winter changes in atmospheric ozone depletion over the period 1970–86 in northern latitudes. The average annual change for the same bands was –2.3 percent, and for summer was –1.3 percent. Long-term trends cannot be explained by known natural variations.





Arctic ozone-layer depletion

Ozone-layer depletion has also occurred in the northern hemisphere. In northern mid-latitudes, the ozone layer in the 38–43 km slice of the stratosphere thinned by 5–13 percent between 1979 and 1986. Ozone continues to thin during the winter at altitudes of 25 km and below. It is now thought inevitable that an Arctic ozone hole will form, though it is unlikely to be as deep or long-lived as its Antarctic counterpart.

Polar stratospheric clouds have been sighted in the Arctic, although there are 10–100 times more of them above Antarctica. The Arctic also has a vortex that blows round the pole in winter, which can create the extremely cold conditions needed for ozone destruction; again, this differs from the Antarctic vortex. Above the Arctic, the vortex wanders over lower latitudes as well, allowing warmer air to raise temperatures within the vortex.

Theoretically, warmer temperatures within the vortex make polar stratospheric clouds less likely to form and process inert chlorine molecules into highly reactive compounds. However, reactive chlorine compounds destroy ozone only in the presence of sunlight. As the Arctic vortex moves towards lower latitudes, it is more likely to be struck by sunlight. If air in the vortex has already been primed for ozone destruction, this sunlight could initiate large-scale ozone destruction.

Observations of Arctic stratosphere chemistry show changes similar to those observed in Antarctica, and indicate greater efficiency at destroying ozone than previously realized. During the winter of 1987–8, concentrations of chlorine monoxide, formed after reactive chlorine compounds have destroyed ozone molecules, were found to be three to six times greater than photochemical models predicted for that latitude and time of year. Mini-holes—which have already been observed above the Antarctic Peninsula, where several nations maintain

observing stations—are also found in the northern hemisphere. A particularly intense mini-hole was observed during the 1989 Airborne Arctic Stratospheric Expedition. Satellite measurements showed that levels of ozone depletion were similar to the worst experienced over Antarctica.

It is now thought that the northern hemisphere was lucky to escape an Arctic ozone hole in 1989. In January and February of that year, concentrations of reactive chlorine species in the Arctic stratosphere were 50–100 percent higher than expected, and reached levels similar to those observed in the Antarctic ozone hole. Minimum temperatures in the high northern latitudes that year were unusually low in late January and early February, and polar stratospheric clouds were observed as far south as 50°N. Associated with the record low temperatures was a strong westerly vortex over the polar cap. Conditions were almost perfect for an Arctic ozone hole to develop.

But in mid-February, the Arctic warmed dramatically. Two anticyclones developed, over the Pacific and then over the Atlantic, and the disturbances from these systems split the Arctic vortex. Temperatures rose above the threshold required for the formation of polar stratospheric clouds, and it is thought that air rich in ozone and nitrogen oxides probably moved polewards. This warming of the Arctic vortex and infusion of ozone and nitrogen oxides probably played an important role in limiting ozone loss in the Arctic during 1989. However, another very cold winter and spring in the northern hemisphere could produce severe Arctic ozone loss.

While ozone depletion over Antarctica happens over largely unpopulated regions, a depleted ozone layer above the Arctic could seriously affect the populations of northern Europe, Canada, Greenland and Siberia.

Figure 5 This map of the Arctic Circle, northern Europe, Siberia, Scandinavia, Canada, Greenland and Iceland shows the area that could be affected by a serious Arctic ozone hole.

Effects on society

Ozone-layer depletion poses many serious threats to human health and planetary life. As the stratospheric ozone layer thins, relatively more of the harmful wavelengths of ultraviolet radiation will reach the Earth's surface. Ultraviolet radiation has many—mostly damaging—effects on people, animals, plants and materials.

These effects will worsen as ozone depletion continues. As the ozone layer is reduced, the Earth's surface is exposed to more of the shorter wavelengths that damage living things. For each 10 percent depletion of the ozone layer, we can expect 20 percent more radiation in these damaging wavelengths.

This radiation may result in widespread eye damage and outbreaks of infectious diseases, as well as an increase in the incidence of skin cancers. Vaccination against some diseases may become less effective; and more shorter-wave

ultraviolet radiation will trigger chemical reactions in the lower atmosphere, increasing smog and acid rain and leading to a rise in respiratory problems.

Many plants will grow more slowly and some could be stunted; yields from some crops may fall and forests may be damaged. In the oceans, the extra radiation will damage or kill juvenile forms of fish, crabs and shrimp. Populations of plankton—the base of the marine food web—may also be seriously affected, causing flow-on effects throughout the marine food web. By also reducing the capacity of these organisms to absorb carbon dioxide, one of the major greenhouse gases, more radiation is likely to enhance greenhouse warming.

Although more research is needed to understand these effects fully, ultraviolet radiation reaching Earth will continue to increase throughout the next century, with possibly serious consequences.

Ozone-layer depletion and global warming

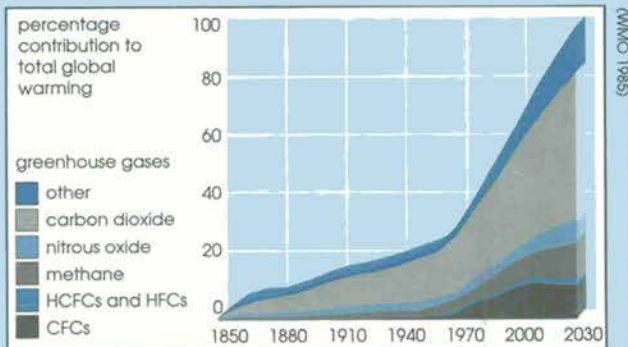
Ozone-layer depletion seems likely to increase the rate and scale of greenhouse warming, by reducing the effectiveness of the carbon dioxide sink in the oceans.

At present, phytoplankton in the oceans absorb up to half the atmospheric carbon dioxide. However, it is known that this activity drops significantly when these tiny organisms are exposed to even small increases in ultraviolet radiation. The Montreal Protocol's Environmental Effects Panel has warned that any reduction in the carbon-fixing activity of phytoplankton will undoubtedly affect global climate by allowing large amounts of carbon dioxide to remain in the atmosphere, adding to the extent of global warming. A 10 percent decrease in carbon dioxide uptake by the oceans would leave about the same amount of carbon dioxide in the atmosphere as is produced by fossil fuel burning.

Moreover, the oceans will not step up their absorption of carbon dioxide to the same degree as the expected

emission increases on land. If atmospheric carbon dioxide increases by 10 percent, the oceans will only absorb an extra 1 percent.

On the other hand, depletion of ozone in the lower stratosphere in middle and high latitudes results in a decrease in radiative forcing. Warming trends are also offset by the cooling effects of volcanic sulphur emissions.



Ultraviolet radiation

Ultraviolet radiation is divided into three types, according to wavelength. UV-A radiation, emitted at wavelengths of 315–400 nm (1 nanometre is a millionth of a millimetre, or 10^{-9} m) is unaffected by ozone reduction, and is relatively harmless. UV-B radiation, emitted at 280–315 nm, is affected by decreases in atmospheric ozone. It is UV-B that causes most of the damage to plants and animals. UV-C—which is lethal—is emitted at wavelengths of 200–280 nm. Fortunately, UV-C is completely absorbed by atmospheric ozone and oxygen. Even with severe ozone reduction, UV-C radiation would still be absorbed by the remaining ozone.

As stratospheric ozone diminishes, proportionately more of the ultraviolet radiation reaching the Earth's surface will arrive in the shorter UV-B wavelengths.

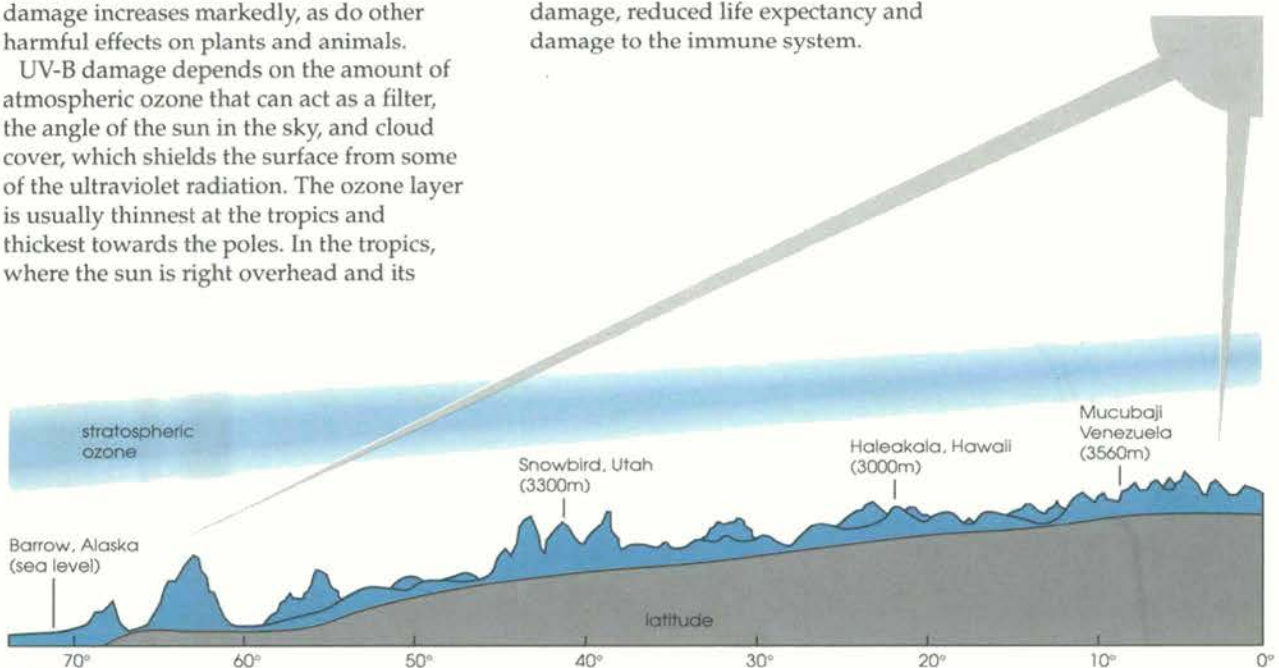
This change in ultraviolet wavelengths will seriously affect all the planet's life forms. As ultraviolet radiation shifts more towards the 280-nm wavelength, DNA damage increases markedly, as do other harmful effects on plants and animals.

UV-B damage depends on the amount of atmospheric ozone that can act as a filter, the angle of the sun in the sky, and cloud cover, which shields the surface from some of the ultraviolet radiation. The ozone layer is usually thinnest at the tropics and thickest towards the poles. In the tropics, where the sun is right overhead and its

rays take the most direct route through the atmosphere to the Earth's surface, ultraviolet radiation is less filtered.

Higher latitudes, which have the advantage of a thicker ozone layer, also receive their sunlight at a more oblique angle. This means that the ultraviolet radiation has a longer path to take through the earth's atmosphere, and is more affected by the filtering processes of ozone before it reaches the surface. Predicted levels of ozone depletion over the tropics will be considerably lower than at the high latitudes. However, the shorter path of ultraviolet radiation to the earth's surface over the tropics (see diagram below), and particularly UV-B, would have serious implications. While rising rates of skin cancer from increased UV-B radiation may be the main concern of developed nations, it seems likely that ozone-layer depletion could have additional more serious health effects in tropical countries. These effects include more viral infections and eye damage, reduced life expectancy and damage to the immune system.

Figure 6 shows how UV-B radiation is more intense at near the tropics where the sun's rays are more direct and have less of the stratospheric ozone filter to pass through before reaching the Earth's surface.



Immune systems and vaccination

Ultraviolet radiation suppresses allergic reactions of the skin and profoundly affects the immune system—particularly in skin cells, where it is often the body's first line of defence against infection.

Normally, a vaccine injected into the skin triggers an immune response as the injected antigens stimulate the production of lymphocytes in the skin. In UV-treated skin, however, the activity of these antibody-producing cells is suppressed, and there is an increase in numbers of another type of cell (called an effector T-cell), which normally prevents the body from rejecting essential substances such as its own proteins.

When skin has been over-exposed to ultraviolet radiation, these T-cells prevent the body from recognizing the vaccine being injected as foreign tissue; consequently the body fails to produce the antigens required for defence.

This has important implications not only for the development of skin cancers, but also for many infectious diseases. If the body cannot recognize when it should develop immunity to a diluted disease being introduced as a vaccine, the vaccination itself could help establish the disease. Consequences could be serious, particularly in less developed countries where the control of infections such as measles depends on effective immunization.

Many diseases could be affected by the suppression of immune responses caused by increased UV-B. At the very least, these include all diseases that have a stage involving the skin: measles and other viral diseases that cause a rash to develop, such as chicken pox and herpes; parasitic diseases introduced through the skin, such as malaria and leishmaniasis; bacterial diseases, such as tuberculosis and leprosy; and fungal infections, such as candidiasis.

Global warming will add to the problems of infectious diseases. As the climate

warms, disease-carrying insects, such as malarial mosquitoes, will be able to survive in higher latitudes and altitudes, allowing diseases previously restricted to the tropics into what were temperate regions.

The combination of a rise in infectious diseases as the climate warms and the capacity of UV-B to suppress immune responses may significantly increase the future spread and severity of infectious diseases.

Vaccination programmes designed to deal with insect-borne diseases could be compromised if vaccines were given to people who had been exposed to high amounts of UV-B. Also, in the more northern countries, where global warming may encourage people to get out in the sun earlier in the season, they may be exposed to increased UV-B as the ozone layer diminishes.

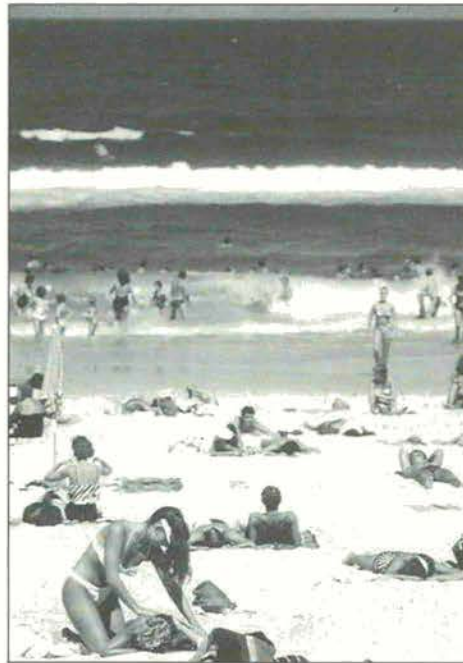
Skin cancer

The combination of increased exposure to UV-B radiation, and the capacity of UV-B to suppress the skin's immune defences, will mean much higher rates of skin cancer.

A convincing and clear-cut relationship has been established between UV-B radiation and potentially fatal non-melanoma skin cancer. Excessive exposure to UV-B is known to cause skin cancer. In addition, because UV-B suppresses the skin's immune responses, the body's immune system is less likely to reject a growing tumour.

To a certain extent, the skin will adapt to more UV-B by becoming thicker and browner. The growth of extra skin cells, however, may mean greater susceptibility to skin cancer. It has been calculated that a 5 percent decrease in ozone would mean a 14 percent increase in basal cell carcinoma—the most common type of non-melanoma skin cancer—and a 25 percent increase in squamous cell carcinoma—the type of non-melanoma skin cancer that is most frequently fatal. In the United States, a 5 percent decrease in ozone could mean an additional 56 000 people developing basal cell carcinomas, and an extra 25 000 developing squamous cell carcinomas each year. Conservative estimates suggest an extra 240 000 people per year world-wide developing non-melanoma skin cancers, with fair-skinned individuals more at risk.

For cutaneous malignant melanoma (another type of skin cancer) the US Environmental Protection Agency concluded that every 1 percent decrease in stratospheric ozone could mean an extra 2 percent of the world's population developing this type of cancer (106 million people at 1990 figures), and an extra 0.2–3 percent (10.6–15.9 million people) dying as a result.



Australian Tourist Commission

The days of people sunbathing for hours on end in quest for the supposed healthy glow of a suntan are surely numbered as the true health risks of such exposure become more obvious.



Figure 7 shows how death rates from one form of skin cancer—melanoma—vary with latitude. Death rates among white people are much higher nearer the Equator.

Increasing eye damage

Cataracts and blindness are also expected to increase with further ozone layer depletion. Unlike the skin, which can partially adapt to ultraviolet radiation by becoming thicker and browner, the eye has no such tolerance. Instead, research shows that eyes become more sensitive with repeated exposure to excessive radiation. UV-B radiation can damage the cornea, the lens and—to a lesser extent—the retina.

The eye first responds to damaging UV-B radiation by developing photokeratitis (or snow blindness) in which the front of the eye, the eyelids and the skin surrounding the eyes redden. Further exposure can cause cataracts.

A recent study has directly linked cortical cataracts to UV-B exposure. Cataracts are already the largest cause of blindness in the world. In 1985, the World Health

Organization estimated that cataracts were responsible for 17 million cases of blindness: more than half the global total.

The Environmental Effects Panel, after revising an original US Environmental Protection Agency estimate, concluded that had there been a 1 percent reduction of the ozone layer in 1985, there would have been an extra 100 000–150 000 cases of cataract-induced blindness.

In addition, exposure to sunlight has recently been established as a factor in the development of intraocular melanoma—a cancer affecting the eyes. People living in lower latitudes are about three times more likely to develop this type of tumour, with blue-eyed individuals at greatest risk.

Queues for daily dressing change after mass cataract operations in India. The number of operations necessary to prevent blindness is certain to increase as the ozone layer thins.



Tom Aston/Panos Pictures

Impacts on the oceans

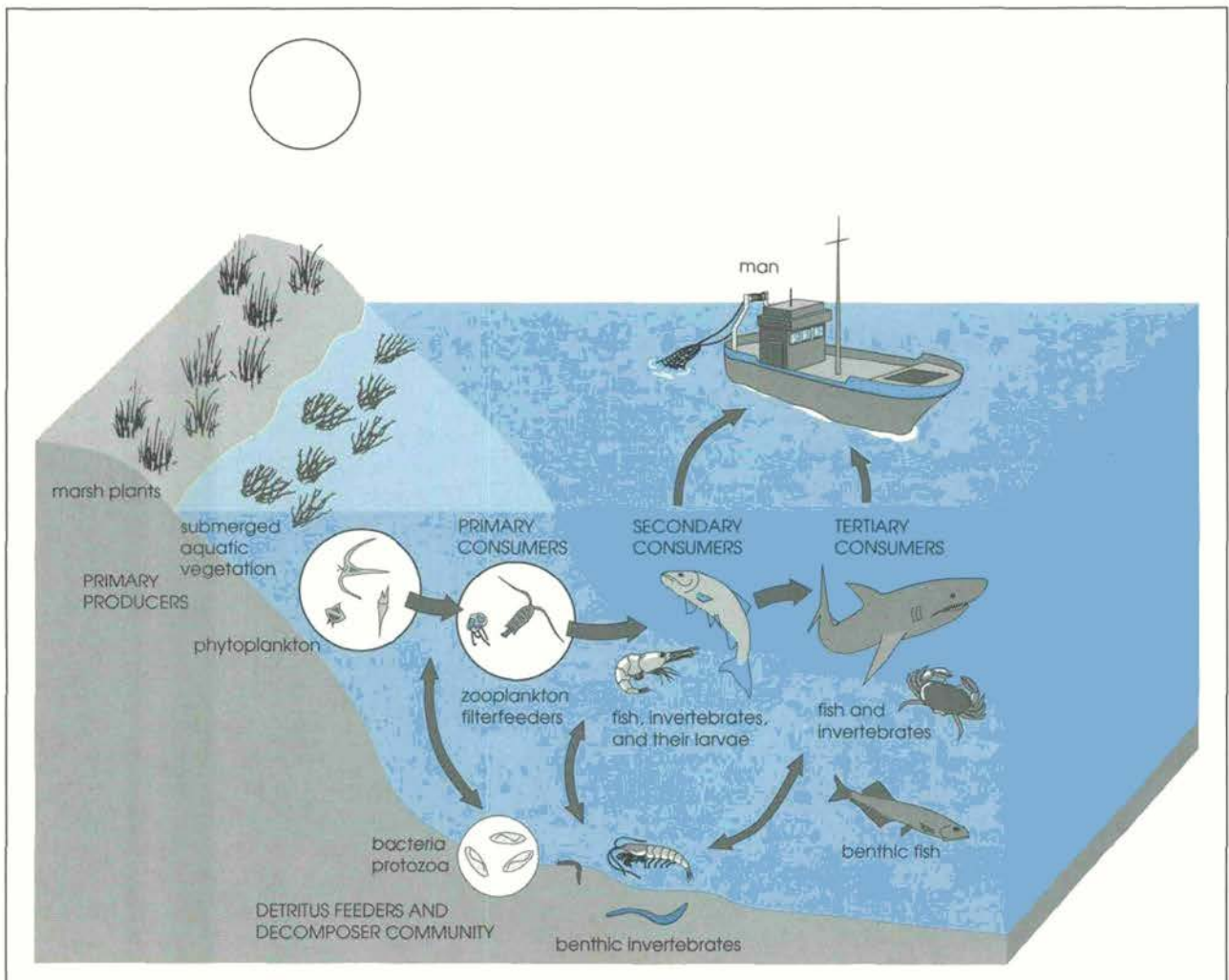
Ozone-layer depletion seems likely to disrupt ocean life and seriously affect the marine food web. Of major concern is the impact that increasing amounts of ultraviolet radiation will have on plankton and other tiny marine organisms at the base of the marine food web.

These creatures, which provide the original food source for every other living thing in the oceans, are highly sensitive to current UV-B radiation because they lack

the protective UV-B-absorbing outer layers of higher forms of plants and animals. As ozone levels diminish, growth and survival of the primary producers are likely to be threatened by the resulting increases in UV-B, with wide-ranging consequences.

Phytoplankton are the plant varieties of plankton. Each year, they produce more than one-half of the Earth's biomass. Their annual biomass production has been calculated as 6×10^{14} kg—a mass equivalent

Figure 8 Because the primary producers are sensitive to increased levels of UV-B, ozone-layer depletion potentially threatens the whole marine food chain.



to that of a coal train longer than the distance from Earth to the Moon and back.

Even slightly increased doses of UV-B radiation reduce the amount of food phytoplankton create through photosynthesis, and that even a small loss in production would dramatically affect the intricate marine ecosystem, with serious knock-on effects for global food supply.

Zooplankton, which feed off phytoplankton and form the second stage of the marine food web, are also affected by increased UV-B radiation. If ozone-layer depletion reached 15 percent over temperate waters, it would take less than five days in summer for half the zooplankton in the top metre of these waters to die from the increased radiation.

UV-B also damages juvenile fish, shrimp and crab larvae and other small animals in the oceans. These damaging effects closely parallel the effects on zooplankton. The ability of food fish larvae to reproduce, grow and survive diminishes as ultraviolet radiation increases. On the North American Pacific coastal shelf at the height of summer, a 16 percent reduction in ozone

would kill 50 percent, 82 percent and 100 percent of anchovy larvae aged 2, 4 and 12 days, respectively.

If, as seems likely, plankton numbers and production drop, and smaller amounts of fish, shrimp and crabs survive to adulthood, less food will be available for adult fish and other higher forms of marine life—and so for human consumption.

It has been estimated that a 16 percent ozone depletion would cause a 5 percent decrease in plankton numbers, and a 6–9 percent drop in fish yield, with severe consequences for global food supply. A 7 percent drop in fish yield represents the loss of 6 million tonnes of fish each year.

More than 30 percent of the world's animal protein for human consumption comes from the sea, and in many countries, particularly developing ones, this percentage is significantly higher.

Enhanced UV-B radiation could also dramatically change species composition among the oceans' plant communities. This could further disrupt the marine food web by removing yet another source of food for marine creatures.

Increased levels of damaging UV-B may cause fish catches to dwindle, resulting in hardship to those whose livelihoods depend on what they harvest from the oceans.



FAO

Impacts on land plants

Increased ultraviolet radiation will disrupt many ecosystems on land. Rice production may be drastically reduced by the effects of UV-B on the nitrogen-assimilating activities of micro-organisms. Tiny organisms, such as cyanobacteria, play an essential role in providing nitrogenous material for ecosystems by fixing atmospheric nitrogen dissolved in water—something that higher plants cannot do.

This group of organisms is adversely affected even by current levels of ultraviolet radiation. As the ozone layer diminishes, it is likely that the supply of natural nitrogen to ecosystems, such as tropical rice paddies, will be significantly reduced, with drastic consequences.

Developing nations with little money available for artificial fertilizers will be hit particularly hard. Cyanobacteria supply rice paddies with large amounts of essential nitrogen at no cost. It has been estimated that the annual nitrogen assimilation by this type of organism amounts to 35 million tonnes—compared with the 30 million tonnes of artificial nitrogen produced each year.

Yields of many other crops will also drop as UV-B increases, with some species and varieties worse affected than others. Only a few studies have been made under realistic ultraviolet radiation conditions, but results from these studies suggest that global agricultural yield is potentially at risk as ozone depletion continues.

Of the plant species studied so far, about half have been found to be sensitive to enhanced levels of ultraviolet radiation. Most plants tend to grow at a slower rate, and to be smaller and more stunted as adult plants when they have been exposed to large amounts of UV-B. Photosynthetic activity, transpiration rates and flowering are also affected.

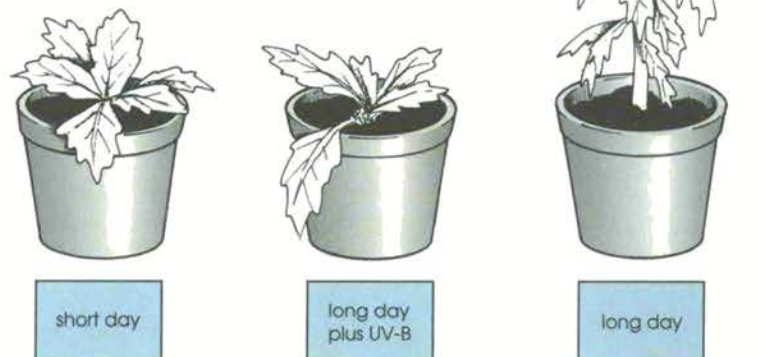
Significant reductions in yield—of up to 25 percent for a 25 percent ozone depletion—have been found in several soybean

cultivars. These trials also showed a possible lessening of food quality, enhanced by reductions in the protein and oil content of the seeds. In a trial of 10 crop species, half the species showed yield reductions of between 5 percent and 90 percent. Wheat yields dropped by 5 percent, potato yields by 21 percent and squash by 90 percent. Rice, peanuts and corn were not affected.

Although considerably more research is needed, experiments already suggest that for some plants, increased UV-B inhibits pollen germination. Germination rates of *Petunia hybrida* and *Vicia collosa* were inhibited by 65 percent under moderate UV-B radiation. It also appears possible that increases in UV-B radiation may alter the timing of flowering. This could have far-reaching effects if insect-pollinated plants start flowering earlier or later than the appearance of their natural insect pollinators.

Increased ultraviolet radiation may also threaten the health and survival of forests. The seedlings of 3 out of 10 conifer species—lodgepole pine, red pine and loblolly pine—were smaller and more stunted when exposed to such radiation in experiments.

Figure 9 illustrates how exposure of some plants to continuous daylight and UV-B radiation can inhibit flowering, resulting in the similar stunted growth shown by those exposed only to limited light.



Increased air pollution

Ozone is a toxic gas, and its presence in the lower atmosphere contributes to air pollution. If stratospheric ozone diminishes, the extra UV-B reaching the troposphere will cause increased chemical reactivity—and therefore greater pollution—in both urban and rural areas where nitrogen oxide levels are high enough to contribute to ozone production. Remote areas with very low nitrogen oxide levels will probably enjoy even cleaner air than they do now, however, because without the nitrogen oxides from man-made emissions to sustain ozone production, increased ultraviolet radiation will destroy ozone more rapidly. Worse pollution will pose problems for human health and welfare, necessitating costly control policies.

That more UV-B radiation is likely to enhance the chemical reactivity, or oxidizing potential, of the troposphere has already been demonstrated in smog chamber experiments. UV-B stimulates the formation of very reactive radicals—molecules that react rapidly with other chemicals, forming new substances. The hydroxyl radical (OH^\cdot), for example, initiates the reactions that produce virtually every trace gas found near the Earth's surface.

Hydroxyl radicals stimulate the creation of tropospheric ozone and other potentially harmful pollutants, including hydrogen peroxide, sulphuric acid and other acids. Most of these pollutants are formed from the chemicals emitted from factories, vehicles and other sources.

Smog formation creates other oxidized organic chemicals, such as formaldehydes. These molecules can also produce reactive hydrogen radicals when they absorb UV-B. Consequently, as UV-B increases, there will be more reactive hydrogen radicals in the air, allowing the production of yet more smog and acid rain.

In urban areas, a 10 percent depletion of the ozone layer is likely to result in a 10–25

percent increase in tropospheric ozone. The problem will be worst in heavily polluted urban areas with few emission controls, but even urban areas with extensive emission controls will be affected because the increased atmospheric chemical activity will lessen the effectiveness of control programmes.

Rural areas will also suffer more from smog and acid rain because many of them have enough atmospheric nitrogen oxides and hydrocarbon compounds to provide the building blocks used by reactive chemicals to form new polluting chemicals. In rural areas in the mid-latitudes, a 20 percent reduction in stratospheric ozone is likely to cause a 10 percent increase in tropospheric ozone.

Acid rain is expected to increase for another reason. More UV-B radiation seems likely to cause global increases in atmospheric hydrogen peroxide. This is the principal chemical that oxidizes sulphur dioxide to form sulphuric acid in cloud water, making it an important part of acid rain formation. In rural regions with higher concentrations of 0.2–1.4 ppbv of nitrogen oxides, hydrogen peroxide concentrations can be expected to rise by about 30 percent.

Even in remote areas, increased UV-B is expected to cause slightly higher levels of hydrogen peroxide.

It now also seems possible that the rate and number of chemical reactions caused by increased UV-B radiation could generate higher concentrations of solid particles in the atmosphere (aerosols). As these particles reach the lower stratosphere, they could provide a surface for the kind of large-scale destruction of ozone presently observed only above Antarctica and the Arctic. Consequently, heavily polluted areas could suffer substantial increases in ultraviolet radiation as the polluting particles initiate even greater ozone destruction in the stratosphere above them.

Damage to materials

Ozone depletion and its resulting increases in ultraviolet radiation will cause many materials to degrade more rapidly. Plastics used outdoors will have much shorter lifetimes with even marginal increases in short-wavelength ultraviolet radiation.

The effects will be widespread. Polyvinyl chloride (PVC) sidings, window and door frames, pipes, gutters and trims used in building are likely to degrade faster, along with cable coverings, polycarbonate and acrylic glazing and coatings, and unsaturated reinforced polyester outdoor panels, water tanks and pipes.

Polyurethane and polypropylene car bumpers and coatings will not last as long; nor will the high-performance composites used in aircraft construction. Nylon, polyethylene and polypropylene fishing nets, ropes and sacks used at sea will deteriorate faster, as will vessel hulls made of unsaturated reinforced polyester.

Faster degradation will also affect the mulch film and plastics used in greenhouses. In addition, outdoor plastics, such as stadium seats, tyres and hoses, polymer-based coatings and industrial packaging will be adversely affected.

Developing countries will suffer the most from this because plastics are a cheap—and therefore popular—form of building material. Damage to plastics will be more severe in regions near the Equator because of higher temperatures and more sunshine.

There is virtually no quantitative information on other materials that might be affected by higher levels of UV-B radiation. These materials include rubber products, paints and coatings, wood, paper and textiles. All will degrade faster as ozone layer depletion continues.



F. Mathiou/FAO

Many plastics, such as those used to cover these cultivation tunnels in Bahrain, will degrade more quickly with exposure to higher levels of UV-B radiation.

Ozone-friendly technology

CFCs and related chemicals have been used in a wide variety of products since the 1930s, when CFC 12 began replacing ammonia and sulphur dioxide as the primary refrigeration coolant. From 1931 to 1945, CFC 12 production increased 35-fold. By 1974, following the introduction in the 1940s and 1950s of CFC-blown foams and aerosols, the total annual CFC 11 and 12 market had reached 445 000 tonnes.

CFCs are used in refrigerators and, till now, have been a crucial ingredient in large air-conditioning units and vehicle air-conditioning systems. They are used to make soft and rigid foams for products such as furniture cushions, mattresses, packaging, building insulation material, computer cabinets, tennis rackets, steering wheels, car bumpers and life jackets.

Other CFCs are used as solvents; the propellant in aerosols; for sterilization procedures in hospitals; and for instant freezing of foods such as corn-on-the-cob, raspberries and raw shrimp.

Halons are used to extinguish fires, and come in three forms. Two of these, Halons 1211 and 2402, are sprayed onto a fire, while Halon 1301 is used to flood a room or section of a building with extinguishing gas. The latter is particularly valuable for fighting fires in computer installations, museums and other locations, such as aircraft engines, where specialized, irreplaceable or very expensive equipment would be damaged by water spray or

carbon dioxide extinguishers. One particularly attractive feature is that, unlike other substances such as carbon dioxide, Halon 1301 extinguishes the fire without immediate harm to people in the area.

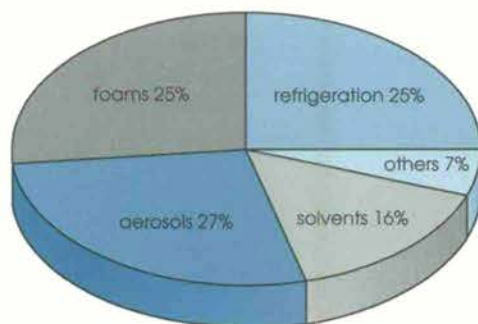
Two other chemicals that significantly damage the ozone layer are carbon tetrachloride and methyl chloroform, both of which have recently (1990) been added to the Montreal Protocol. Carbon tetrachloride has an ozone-destroying potential as high as that of some CFCs. It is used as a feedstock in the production of CFC 11 and CFC 12 and many pesticides; as a solvent in the manufacture of synthetic rubber and dyes; as a metal degreaser; as a dry-cleaning agent; as a fire extinguisher; and as a grain fumigant.

Methyl chloroform is used mainly as an all-purpose industrial solvent for vapour degreasing operations and the cold cleaning of fabricated metal parts and other materials. It is also used for dry cleaning clothes; for dirt-repellent textile finishes; as an adhesive solvent; in aerosols; for cleaning semiconductors; in manufacturing fluorocarbons and related chemicals; in steel manufacture; and in producing coatings, inks, textiles and other goods.

Searching for substitutes for these seemingly indispensable chemicals began in 1987, with the signing of the Montreal Protocol. Under the auspices of UNEP, a technology review panel was established, drawing on the knowledge of 110 experts from 22 countries. Five international subcommittees examined and reported on substitutes for refrigeration, air conditioning and heat pumps; rigid and flexible foams; electronic, degreasing and dry-cleaning solvents; aerosols and sterilants; and halon fire extinguishers.

CFC substitutes must fulfil certain criteria. Apart from performing like CFCs, they must not be toxic. Equally important, a substitute must not contribute to global warming, either directly, by absorbing the

Figure 10 shows the relative contributions of different technologies to controlled CFC use in 1986. Foam, aerosol, and refrigeration manufacture used these substances in roughly equal proportions.



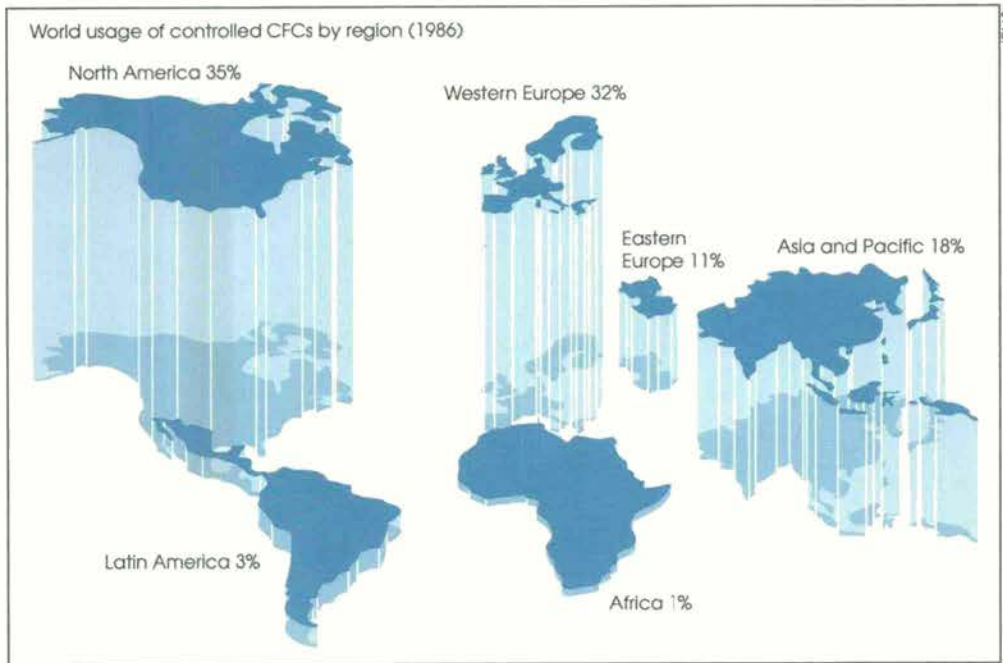


Figure 11 illustrates how North America and Western Europe led world use of controlled CFCs in 1986.

sun's heat once it is emitted, or indirectly, through lowering the energy efficiency of the process or appliance in which it is used. Generating power through fossil-fuel burning contributes one-third of all carbon dioxide emissions—the major cause of global warming. If a CFC substitute caused lower energy efficiency, more power would have to be generated and hence more pollutants would be emitted, enhancing global warming. For example, the stock of existing refrigerators consume an estimated 30 000 megawatts of electricity. If a substitute for the CFC 12 used as a cooling liquid was 5 percent less energy efficient, 1500 megawatts would be added to the world demand for electricity as new appliances replaced the old.

The short-term phase-out of CFCs depends on continuing to use hydrochlorofluorocarbons (HCFCs)—which themselves destroy ozone, although to a much lesser extent. HCFCs survive intact in the

atmosphere for far less time than CFCs, and a significant proportion of them are destroyed in the lower atmosphere, before reaching the stratosphere.

Only completely eliminating emissions of CFCs, halons, HCFC 22, methyl chloroform and carbon tetrachloride will bring atmospheric chlorine below the threshold at which the Antarctic ozone hole appears. But the technology review panel claims that if we stop using HCFC substitutes by 2050, their use will not significantly affect the timescale for restoring the ozone layer.

Although CFC substitutes not containing chlorine will eventually be developed, short-term restrictions on using HCFCs would considerably delay phasing out CFCs, raise costs and reduce energy efficiency, thereby adding to global warming. The refrigeration industry considers unrestricted availability of HCFC 22, for example, a prerequisite for developing CFC substitutes before the year 2000.

Refrigeration and air conditioning

CFCs used as cooling fluids in freezers, refrigerators, air conditioners and heat pumps make up 25 percent of global CFC consumption—most of which can be attributed to industrial uses and to vehicle air conditioning. World-wide, the cooling fluids in domestic refrigerators account for one percent of global CFC consumption, while the CFCs used to insulate domestic refrigerators constitute another 4 percent. While developing countries are expected to make 30 percent more domestic refrigerators each year, this rate of growth is still relatively insignificant in terms of total global CFC consumption.

Although emission reductions of about 45 percent by 1994 and 50–60 percent by 1997–8 appear feasible, completely replacing the CFCs in refrigerators with ozone-friendly substitutes is expected to take 15–20 years. Alternative refrigerants that use HCFCs, hydrofluorocarbons (HFCs) or blends of these chemicals are available now but existing equipment will have to be upgraded and replaced slowly. CFCs will still be needed after the year 2000 for servicing older refrigeration and vehicle air-conditioning systems that cannot use substitute chemicals, but it will probably no longer be necessary to manufacture new CFCs: by then, recycling existing chemicals will probably meet much of the demand.

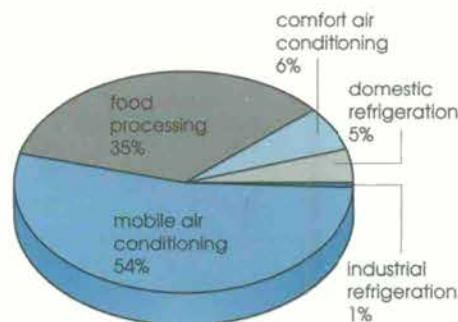
Some industrial refrigeration systems can switch over to alternative cooling fluids, but in most cases CFCs will be reduced by conserving and recycling existing stocks. Plants built after 1998 will probably not use CFCs, but small quantities of CFCs will have to be available till approximately 2015 to repair older units that cannot use alternative chemicals. The technology review panel believes that using alternatives, and conserving and reclaiming refrigerants, will mean using 92 percent less CFCs for industrial refrigeration by 1998.

Virtually all refrigerated containers use CFC 12 refrigerant—there is currently no alternative. If CFC 12 is to be phased out by the year 2000, as planned, equipment valued at about \$US2000 million might have to be scrapped to save using 245 tonnes of CFC 12 per year. If it were necessary and possible to change to a new HCFC refrigerant, the conversion cost for a single large refrigerated ship could be about \$US1.8 million, with a cost for the world fleet of roughly \$US700 million.

Air conditioning in cars and trucks is another problem. Mobile air-conditioning units currently use CFC 12 exclusively, and it is estimated that 28 percent of global CFC 12 production is used this way. There is no direct substitute for the CFC 12 used in mobile air conditioners; consequently, conversion to another refrigerant remains a major undertaking. Conservation and recycling seem to be the best short-term ways to reduce CFC use.

The most viable candidate to replace CFC 12 is HFC 134a which, while not depleting ozone, does contribute to global warming. It is thought that HFC-134a could be introduced into new vehicles by 1994. A combination of converting to HFC 134a and phasing out the CFC 12 fleet could mean all mobile air-conditioning units using an ozone-acceptable refrigerant by 2010.

Figure 12 The breakdown of CFCs used for refrigeration shows that air-conditioning systems in cars are the major culprits, followed by commercial food uses.



Other uses

Foam production

Foam production accounts for a further 25–30 percent of global CFC consumption. It is technically feasible to reduce its use by 60–70 percent by 1993, with virtual elimination by 1995, provided HCFCs are commercially available at a reasonable price by 1993. Given current technology, many foam manufacturers have few other options without HCFCs. Non-CFC substitutes already compete in all sectors of the foam market, with the possible exception of appliance insulation, and without CFCs or HCFCs, foam products could not challenge these alternatives.

Solvents

CFC 113, which is used as a solvent for cleaning electronic circuit boards, precision instruments (such as gyroscopes and computer disk drives), metals, and clothing, represents about 16 percent of global CFC use, of which the electronics industry accounts for about 80 percent.

Although there is no single substitute for all CFC 113's uses, several possible alternatives mean it could be phased out by the year 2000. Phasing out CFC 113 depends only partly on HCFCs because many other options are available, including product and process substitutes, water cleaning, hydrocarbons and solvent-free cleaning processes. In the meantime, simply conserving and recycling CFC 113 could reduce its use by 50 percent.

Aerosols, sterilization and other uses

In 1986, CFCs used in aerosols accounted for 27 percent of global CFC use. With the exception of some medical products, such as asthma inhalers and other minor uses, virtually all consumption can be eliminated by switching to the wide variety of existing alternatives. The most common substitutes are the highly flammable hydrocarbons propane, butane and pentane. Non-flammable HCFCs (particularly HCFC 22,

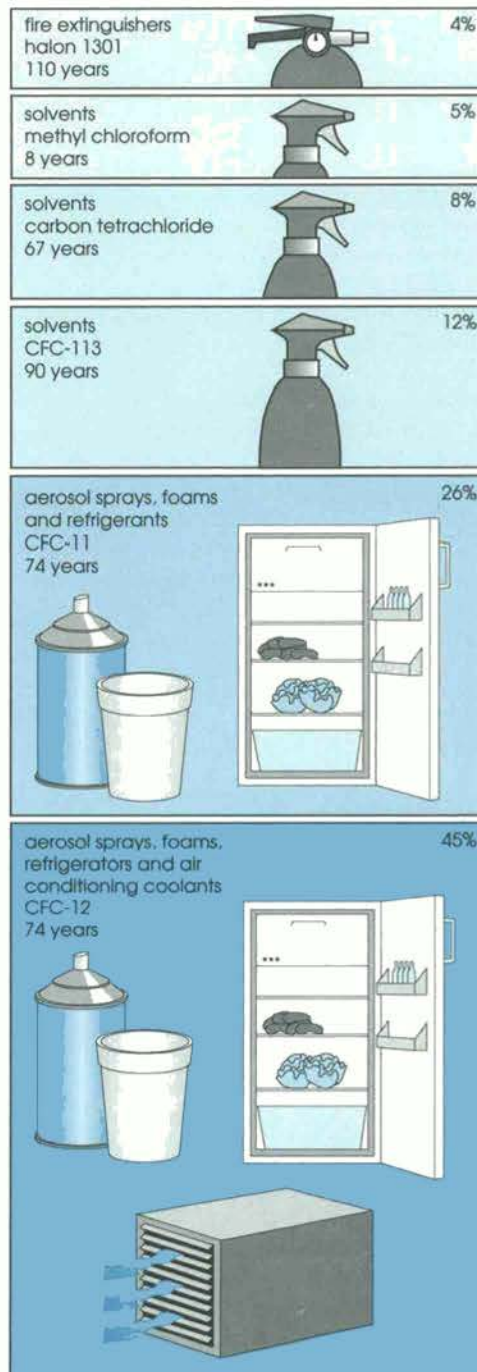


Figure 13 Percentage contributions to ozone depletion of the currently used chemicals; their applications; and their average lifetimes in the atmosphere.

which could work well in about 30 percent of CFC products) are also possibilities but they are still very expensive. Switching from CFCs will take time, allowing for reformulation, retrofitting and perhaps plant relocation because of the increased risk of explosion or fire associated with hydrocarbons.

An estimated 10–12 000 tonnes of controlled CFCs were used in medical products in 1986—including 3–4000 tonnes in inhalant drugs, such as asthma medication. It will be hard to eliminate such uses before the end of the century.

The use of approximately 20–25 000 tonnes of CFC 12 in sterilants could be substantially curtailed by substituting existing alternatives—such as steam sterilization and formaldehyde. It could be phased out by 1995 in developed countries and somewhat later in developing countries.

Liquid nitrogen, along with several commercially viable techniques, is an available alternative to using CFC 12 for fast-freezing delicate foods.

There are already substitutes available for 90–95 percent of the uses of methyl chloroform, and for most uses of carbon tetrachloride. The latter chemical is still needed as a feedstock for producing many of the substitute chemicals, but this use does not cause any harmful emissions: creating substitute chemicals absorbs all ozone-damaging parts of carbon tetrachloride.

Fire-fighting

Halons are hydrocarbons that contain bromine and sometimes chlorine, both of which damage the ozone layer. Despite accounting for less than three percent of controlled substances, their ozone depletion potential is great enough to make

Financial benefits of finding substitutes

The financial benefits of reducing CFC and halon use undoubtedly outweigh the costs of these reductions. Clearly there will also be significant health, agricultural and environmental advantages, but it is difficult—if not impossible—to put a price on the number of cases of cancer avoided, or the ecosystems left untouched by damaging UV-B radiation, for example.

Although most technical options for phasing out CFCs require initial capital investment, some are ultimately less expensive to use or may improve product quality. The first 50 percent reduction in global CFC use will require modest new capital investment, will incur little or no net cost, will result in some business disruption and will require very little abandonment of capital. Estimates for the remaining reductions vary widely and depend on future availability of CFC substitutes; their price, safety and energy efficiency; and the costs of re-engineering equipment and products. Substitution will lead to some savings. The hydrocarbons replacing CFCs

in aerosols are cheaper to produce. Many CFC solvents in electronics can be eliminated simply through better, less wasteful housekeeping procedures. Some blends of refrigerant substitute make refrigeration systems more energy efficient, which would benefit any country planning increased refrigerator use, especially if this use had to be supported by expanding the electrical power supply infrastructure. However, the Economic Assessment Panels established under the Montreal Protocol has warned that a rapid phase-out of some CFCs over a period of much less than 10 years will substantially increase costs due to abandonment of capital investment in CFC-producing and -using technologies. Such a schedule may not allow time for developing more energy-efficient domestic refrigerators, which could increase product cost without offsetting decreases in electricity costs and would enhance global warming through the increased carbon dioxide emissions from power stations.

reducing emissions a priority.

Unfortunately, there is not, nor does it seem probable that there will be, one single substitute for the halons used in fire-fighting. These halocarbons, while damaging ozone at 10 times the rate of CFCs, are exceptionally effective for fire-fighting because they do not conduct electricity, dissipate quickly, leave no residue, and do not harm humans. It is more likely that a range of alternative chemicals for specific applications will be developed.

A combination of reducing emissions during training and testing, adopting other fire protection measures and accepting a higher risk of fire will probably allow a phase-out of halons by 2005.

Unless new alternatives are developed, the world may have to choose between using halons for essential fire-fighting purposes, with the associated adverse impacts on the ozone layer, or accepting the possibility of an increased fire risk.

Halon 1301, with its capacity to flood an enclosed area and extinguish a fire without harming people or property, poses a particular dilemma. Experts believe that politicians may have to decide that no applications of Halon 1301 are important enough to tolerate its use.

Some insurance companies are already addressing this issue. In the United States, many insurance companies have cancelled all recommendations requiring halogenated fire-extinguishing agents, and its loss prevention management will consider alternatives to halons even in the case of potential catastrophic loss. Insurers of Northern Telecom have agreed to cover fire risk in electronic installations valued at up to \$US10 million without requirements for halon extinguishers.

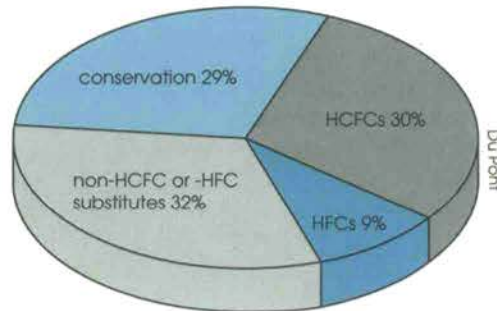
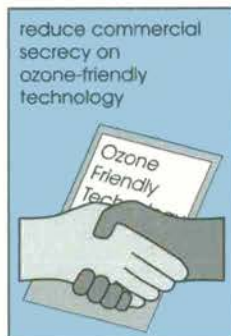
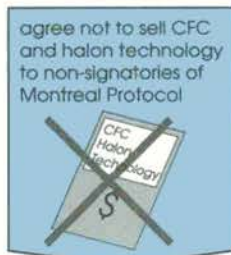


Figure 14 shows how today's use of CFCs could be displaced by the year 2000 with a combination of conservation, using HCFCs and HFCs, and, finally, by developing non-halocarbon substitutes.

The importance of global cooperation

ozone-friendly cooperation



Progress in finding substitutes for the ozone-destructive chemicals has been rapid since the Montreal Protocol was signed in 1987. It has been characterized by unprecedented cooperation between countries and within industry.

There were few potential substitutes in 1987 for the chlorofluorocarbons (CFCs) used in refrigeration and for cleaning electronic equipment. Finding alternatives for the halons used for fire-fighting was then considered such an intractable problem that the Protocol demanded only a freeze on the production and consumption of these chemicals, even though on a molecule-for-molecule basis they destroy 3 to 10 times as much ozone as CFCs.

Two years later, it was possible for the technical assessment panels investigating substitutes to report that use of the five CFCs controlled under the Protocol could be reduced by at least 95 percent by the year 2000 and that, given the rate of technological development, additional technical options would probably make it possible to eliminate CFCs completely before that. Although there are still no chemicals to match halons for fire protection, conservation practices and using other fire protection measures will allow halons to be phased out completely by 2005.

Many cooperative ventures have accelerated the development of ozone-friendly technologies. International chemical companies have formed consortia to test the toxicity of new alternative chemicals, successfully speeding up the process of finding commercially viable substitutes. Another consortium is examining the environmental acceptability of alternative chemicals, studying their ozone-depletion potential, global-warming potential, atmospheric decay times and the products formed as they decompose.

Research consortia have also been formed to develop new products. In the United

States, manufacturers of almost every brand of refrigerator and freezer sold there have joined the government in seeking compounds to replace CFCs.

The US Environmental Protection Agency and the Defense Department have organized a government-industry project to develop new ozone-safe fire-extinguishing alternatives to halons. Another consortium is evaluating CFC substitutes that can be used as building insulation materials.

In Japan, CFC manufacturers and users have conducted a campaign promoting reduced CFC use, while in the European Community, chemical producers have declared a joint commitment not to sell or license CFC or halon chemical-manufacturing technology to countries that are not signatories to the Protocol. This commitment has now also been taken up by the US company Du Pont, and by Australian manufacturers. These companies represent a large portion of world CFC production.

Clearly, the more that large, multinational CFC users announce corporate policies to reduce or eradicate the consumption of ozone-destructive products, the more quickly the Protocol's goals will be met. Siemens, the large German electronics company, replaced some of the CFC 113 it used with an alcohol solvent. This decision, which meant that all its circuit board components then had to be alcohol compatible, forced Siemens' suppliers to make them so or risk losing a substantial amount of business. This, in turn, allowed smaller manufacturers to take advantage of Siemens' environmentally aware initiative.

The European chemical industry intends to make alternatives equally available to all countries as the technology becomes established. Many companies are also ignoring the normal rules of commercial secrecy where new products are concerned and are making new ozone-safe technology available world-wide.

Recycling and destroying CFCs and halons

Government intervention will probably be necessary—in developing and developed nations alike—if existing CFCs and halons are to be recovered and recycled. Although major projects are under way in the public and private sectors of many countries, these programmes will probably not be globally implemented until the recycling infrastructure becomes cost effective.

Economic or regulatory incentives are inadequate; the market has not yet accepted recycled products; purity and standards specifications still demand the use of new CFCs and halons; and government regulations restrict the collection and transportation of used CFCs.

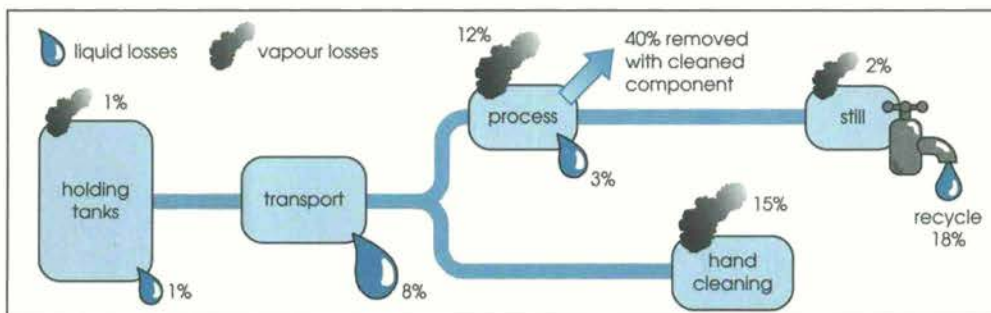
Recovering and recycling refrigerants, such as CFC 12, is difficult. Although proper methods could theoretically recycle 92–99 percent of used refrigerant, it would be impossible to achieve this in practice. Recovery equipment is little advertised and expensive, and minimum quantities quoted by CFC producers represent perhaps a whole year's use of refrigerant for a single dealer. Governments or specialized companies need to organize the collection and storage of small quantities of used refrigerant from households, as well as the larger amounts from industry. To develop a suitable national and international recycling service will almost certainly require economic incentives or legislative action. In the meantime, conserving refrigerant by avoiding unnecessary leaks

when manufacturing, repairing and testing equipment is essential—and has the added incentive of saving money.

Several promising technologies exist to destroy both CFCs and halons. What seems to be needed is a 'cradle-to-grave' management system for these chemicals which would keep a record of them and prescribe and check handling criteria from the moment they are produced to the time they are disposed. Such a system might be developed in conjunction with, or under the auspices of, UNEP.

In the case of halons, the existing global bank has been estimated at approximately 110 000 tonnes. Technical experts believe this bank should be managed at a national level, to recover the highest possible quantities for recycling and re-use in essential new systems; to eliminate emissions released during periodic maintenance or dismantling of installations; to allow precise evaluation of the quantities of halons emitted to the atmosphere; and to destroy quantities that cannot be recovered due to contamination.

There is also a strong need for systematic observation of all chlorine- and bromine-containing chemicals that can contribute to the chlorine and bromine loading of the atmosphere and hence to ozone depletion and global warming. This would allow the scientific community to evaluate the environmental impacts of these chemicals.



Northern Telecom

Figure 15 shows how 82 percent of a CFC 113 solvent is typically lost during use, leaving a mere 18 percent for recycling. Improved recovery could increase the recycling potential to as much as 50 percent.

Future policy options

The world has taken swift and practical steps to begin slowing down, and then repairing, damage to the ozone layer.

Many industrialized countries are already reducing production and use of the CFCs and halons that destroy stratospheric ozone. Some even plan to beat the phase-out dates laid down by the Montreal Protocol. Sweden, for example, wants to phase out controlled CFCs completely by 1994, six years ahead of schedule. At the same time, however, many developing nations are starting to use more of these chemicals, as they continue to raise living standards.

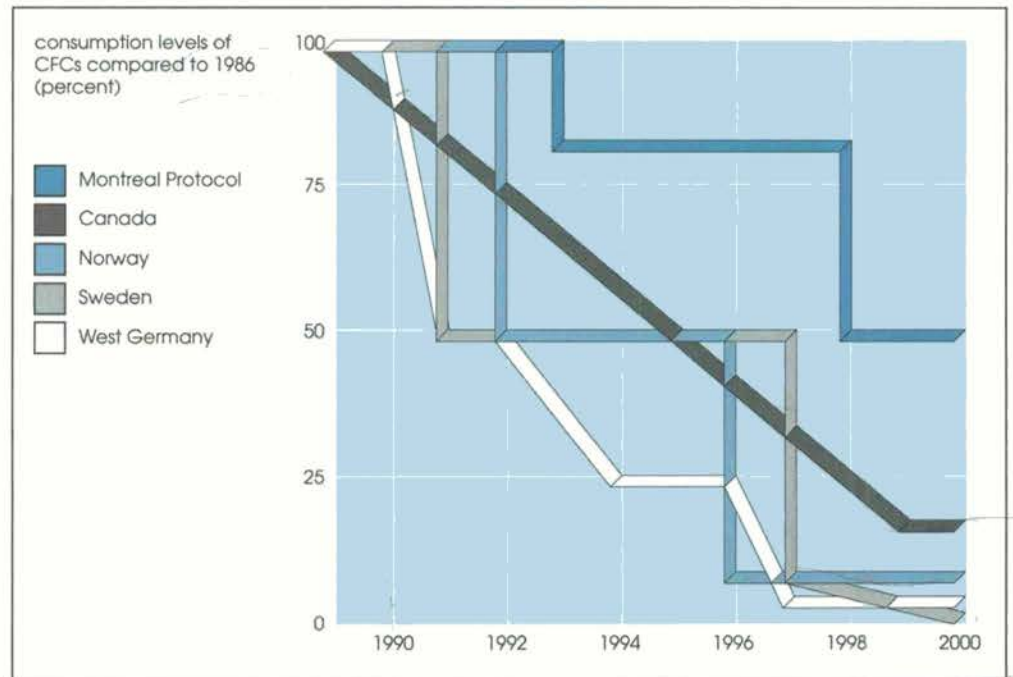
If the ozone layer is eventually to be repaired, a full partnership is needed between the developed countries that have largely caused the problem and the developing countries that wish to make products such as refrigerators and air conditioners (considered necessities by the developed world) available to their people.

Developing countries with over-strained economic resources cannot afford to install new technologies that do not use CFCs. Technical expertise is being developed mainly by the richer countries that up till now have been the main producers and consumers of CFCs.

The Montreal Protocol acknowledges that stopping the destruction of the ozone layer is a global problem requiring global solutions. For developing countries to leapfrog the older, polluting technologies and move directly to new, environmentally sound methods, a variety of international technology transfer mechanisms will be needed, including technical training, trade incentives, joint ventures and multi- and bilateral assistance.

An initial fund offering assistance to developing countries was established by signatories to the Montreal Protocol in June 1990. This fund allows developing nations to continue improving living standards by

Figure 16 Some industrialized countries have committed themselves to phasing out controlled CFCs ahead of the deadlines laid down in the Montreal Protocol.



providing such benefits as refrigeration and air conditioning without significantly increasing the rate of ozone destruction by using CFCs in appliances.

Other funding mechanisms have also been suggested. These vary from increasing overseas development aid to charging for CFC use or contributing a small percentage, perhaps 0.1 percent, of GNP. If this latter course were adopted, roughly \$US13 billion a year would be available.

Governments could also impose a transition fee on CFCs. If a fee of 25 US cents per kilogram, linked with ozone depletion potential, were applied to world output of CFCs, over \$US300 million could be raised in the first year. If the same fee were applied while CFCs and halons were being phased out, it could raise about \$US2 billion between now and the year 2000.

Multilateral development institutions, including the World Bank, the Inter-American Development Bank, the Asian

Development Bank and the African Development Bank, can play a crucial role in facilitating the transfer of technology needed during the period of transition from CFCs to ozone-friendly substitutes. A new pilot programme, the Global Environment Facility (GEF), exists to give grants and low-interest loans to help developing countries protect and manage the environment, ozone-layer protection being one of its specific goals.

International assistance could include the following measures.

- ❑ Multilateral lenders supporting the goals of the Protocol, for example by including the potential for CFC substitution as a criterion for project evaluation, or by making rapid technology transfer a requirement for funding. Loans for projects using CFCs could be restricted, while those for establishing alternative technologies could be encouraged.

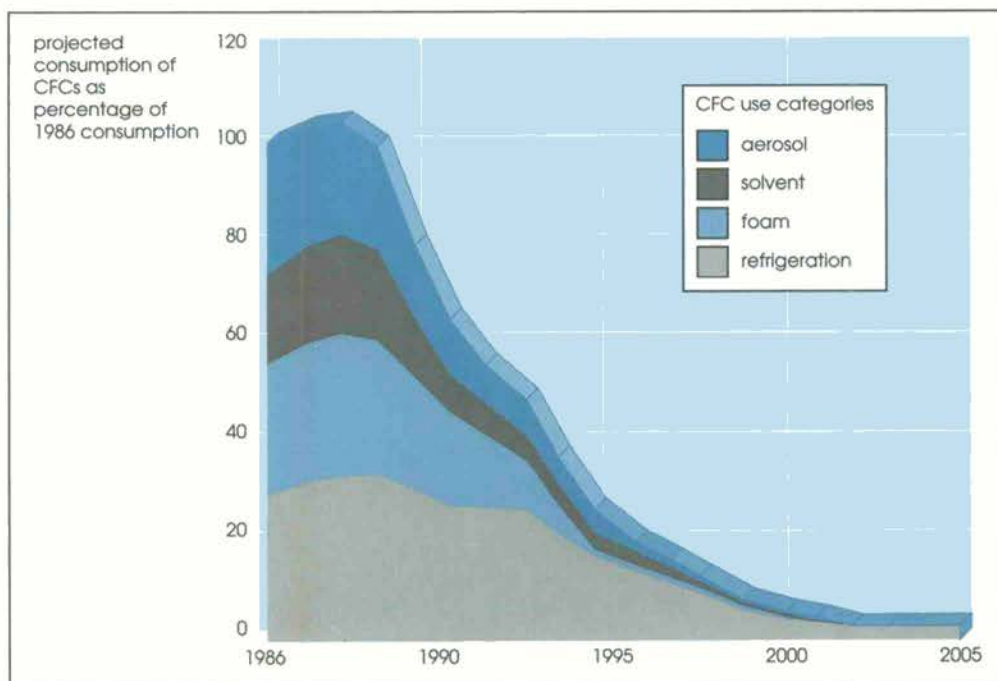
	sector	date
refrigeration		1989–2015
	domestic	1995–1999
	commercial/retail	1989–1999
	transport	1989–2010
	cold storage	1989–2005*
	comfort air conditioning	1991–2015
	industrial	1989–2010
	heat pumps	1989–2005*
	mobile air conditioning	1994–2010*
flexible foams		1989–1993
rigid foams		1989–1995
solvents		
	electronic	1995–1997
	metal cleaning	1993–1996
	dry cleaning	1993–1995
miscellaneous		
	aerosols (non-medical)	1990–1995
	aerosols (medical)	1995–2000
	sterilization	1990–1995

* these may be eliminated sooner if retrofitted to accept HFC/HCFC blends now being developed.

Table 1 shows estimated end-of-use dates world-wide for controlled CFCs. While some are encouraging, other time-scales do not appear to reflect the urgency of reducing CFC emissions before further damage is done to the fragile ozone layer.

- ❑ Protocol signatories could grant special access to their markets for CFC substitutes produced by developing countries, while restricting products containing or made with CFCs.
 - ❑ Developed countries could assist in licensing or transferring patents for substitute technologies, either by directly purchasing patents or rights in new products and processes and making them available to developing countries, or indirectly, by offering tax or regulatory relief to firms that privately transfer their CFC substitute technologies.
 - ❑ Developing countries could be helped to assess the technical and economic merits of various CFC replacement technologies, to establish which would best suit their needs. Such assistance might include providing an information clearinghouse, funding consultancy studies, and training personnel in non-CFC technology.
 - ❑ Direct subsidies could also be provided for CFC-free products, for example by providing grants for manufacturing the substitutes used in CFC-free refrigerators.
 - ❑ External debt relief could be linked with CFC controls. Compliance with the Protocol could be considered as either a necessary or a sufficient condition for writing off international debts.
- There is concern that obsolete CFC-using technologies could be dumped on developing countries. The projected phase-out of CFCs already agreed to or announced will mean many of the world's CFC-producing factories lying idle and a surplus of equipment that uses CFCs. By mid-1990, no company had pledged not to dump or sell CFC or halon products or production facilities to other countries.
- It is in the interests of industrialized nations to ensure that their efforts to

Figure 17 Recycling, conserving, and using CFC substitutes can theoretically reduce consumption dramatically, tapering off to about five percent of 1986 levels by 2005.



eliminate CFCs are not undermined by expanding CFC use in developing countries. Governments and industries in the industrialized countries therefore need to cooperate to forestall the sale of this excess equipment to developing countries.

There is a potential conflict between the global aims of the Protocol and the desire of manufacturers to recover development costs through licensing fees and royalties on CFC substitutes. Manufacturers must be able to recover these costs, yet seeking a rapid payback could drive up the price of CFC-free technologies, making it harder for developing nations to adopt them. Multi- and bilateral economic assistance could help diffuse CFC-free technology.

A further problem may arise from technology transfer not always being in the interest of all stakeholders. Manufacturers of CFC-free technologies will compete with one another, particularly in global markets such as

consumer appliances. National policies will probably be needed to stop the potential blocking of technology transfer, while at the same time preserving incentives for firms to develop and market substitutes for CFCs as rapidly as possible.

There is still great uncertainty about the likely extent of future ozone depletion. Depletion will worsen at least until the middle of next century; it is not known whether the present predictions will turn out to be underestimates of the eventual scale of depletion. Although scientific knowledge of ozone destruction has advanced considerably since the Montreal Protocol was originally signed, many aspects still need intensive investigation. It is important for national policies and industrial practices to remain flexible to enable them to benefit from increasing understanding, and to take action where necessary.

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