

science applied

Were We Successful in Halting the Growth of the Ozone Hole?

We rely on refrigeration to keep our foods safe and edible, and on air conditioning to keep us comfortable in hot weather. For many years, the same chemicals that made refrigeration and air conditioning possible were also used in a host of other consumer items, including aerosol spray cans and products such as Styrofoam. These chemicals, called chlorofluorocarbons, or CFCs, were considered essential to modern life, and producing them was a multibillion-dollar industry. CFCs were considered “safe” because they are both nontoxic and nonflammable.

Why do we need an ozone layer?

In the 1970s, scientists learned that CFCs might be responsible for destroying ozone in the upper atmosphere. This discovery led to great concern because a layer of ozone in the upper atmosphere protects us from high-energy ultraviolet (UV) radiation, which causes sunburns, skin cancer, and cataracts as well as environmental damage. In the 1980s, scientists reported an ozone “hole,” or depletion of ozone, over Antarctica and documented dangerous thinning of the ozone layer elsewhere.

The nations of the world faced a critical choice: should they continue to produce and use CFCs, and risk further damage to the ozone layer and the resulting effects on people and natural systems, or should they reduce ozone depletion by discontinuing use of this important class of chemicals? In 1987, the majority of nations chose the latter course. As of this writing, most of the world has stopped using CFCs. But the choice at the time was a difficult one. What were the scientific findings that convinced nations to phase out CFCs, the economic consequences of this important decision, and

finally, the impact of the CFC ban on the environment? Have we, indeed, protected the ozone layer?

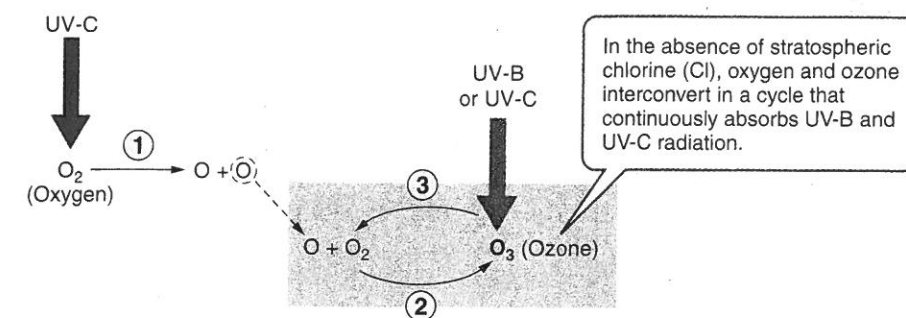
How do chlorofluorocarbons damage the ozone layer?

As we saw in Chapter 2, the Sun radiates energy at many different wavelengths, including the ultraviolet range. The ultraviolet wavelengths are further classified into three groups: UV-A, or low-energy ultraviolet radiation, and the shorter, higher-energy UV-B and UV-C wavelengths. UV radiation of all types can damage the tissues and DNA of living organisms. Exposure to UV-B radiation increases the risks of skin cancer and cataracts and suppresses the immune system. Exposure to UV-B is also harmful to the cells of plants and reduces their ability to convert sunlight into usable energy. UV-B exposure can therefore lead to crop losses and effects on entire biological communities. For example, losses of phytoplankton—the microscopic algae that form the base of many marine food chains—can harm fisheries.

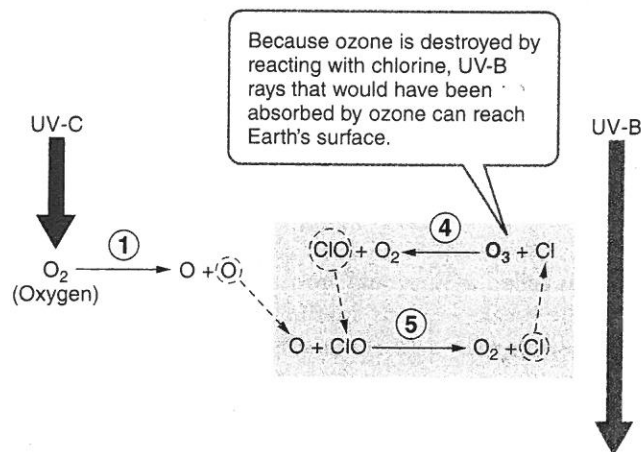
Next we examine the chemistry of ozone production and how the introduction of chlorine atoms disturbs ozone’s steady state in the stratosphere. Oxygen molecules (O_2) are common throughout Earth’s atmosphere. When solar radiation hits O_2 in the stratosphere, 16 to 50 km (10–31 miles) above Earth’s surface, a series of chemical reactions begins that produces a new molecule: ozone (O_3).

In the first step, UV-C radiation breaks the molecular bond holding an oxygen molecule together:





(a) Ozone production and cycling



(b) Effect of chlorine on ozone

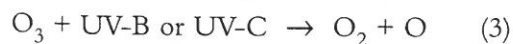
FIGURE SA1.1 Oxygen-ozone cycles in the stratosphere. Circled numbers refer to the numbered chemical reactions in the text.

This happens to only a few oxygen molecules at any given time. The vast majority of the oxygen in the atmosphere remains in the form O_2 .

In the second step, a free oxygen atom (O) produced in reaction 1 encounters an oxygen molecule, and they form ozone. The simplified form of this reaction is written as follows:



Both UV-B and UV-C radiation can break a bond in this new ozone molecule, forming molecular oxygen and a free oxygen atom once again:



Thus the formation of ozone in the presence of sunlight and its subsequent breakdown is a cycle (FIGURE SA1.1) that can occur indefinitely as long as there is UV energy entering the atmosphere. Under normal conditions, the amount of ozone in the stratosphere remains at steady state.

However, certain chemicals can promote the breakdown of ozone, disrupting this steady state. Free chlorine (Cl) is one such chemical. The concern over CFCs began when atmospheric scientists realized that CFCs were introducing chlorine into the stratosphere. When chlorine is present, it can attach to an oxygen atom in an ozone molecule, thereby breaking the bond between that atom and the molecule and forming chlorine monoxide (ClO) and O_2 :



Subsequently, the chlorine monoxide molecule reacts with a free oxygen atom, which pulls the oxygen from the ClO to produce free chlorine again:



Looking at reactions 4 and 5 together, we see that chlorine starts out and ends up as a free Cl atom. In contrast, an ozone molecule and a free oxygen atom are converted into two oxygen molecules. A substance that

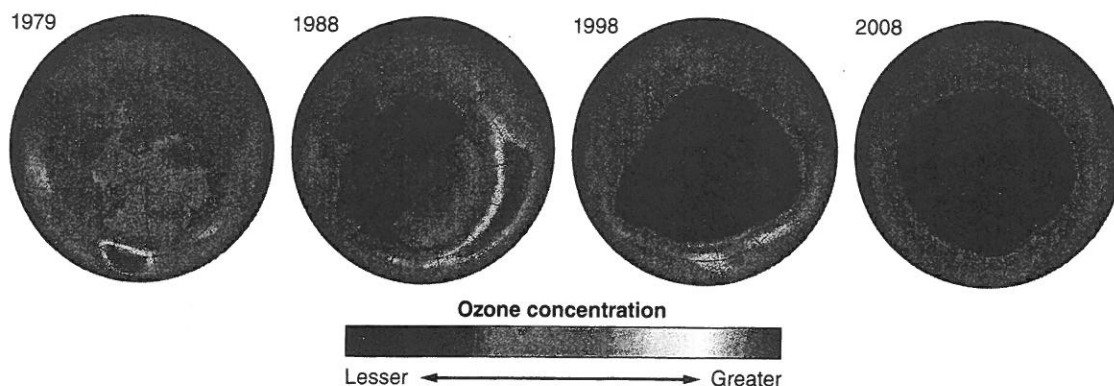


FIGURE SA1.2 The ozone hole over time. An area of decreased atmospheric ozone concentration has been forming during the Antarctic spring (September–December) every year since 1979. There has been a decrease in ozone to about one-third of its 1979 concentration.

aids a reaction but does not get used up itself is called a **catalyst**. A single chlorine atom can catalyze the breakdown of as many as 100,000 ozone molecules, until finally one chlorine atom finds another and the process is stopped. The ozone molecules are no longer available to absorb incoming UV-B radiation. As a result, the UV-B radiation can reach Earth's surface and cause biological harm.

How did nations address the ozone crisis?

In response to the findings described above, the U.S. Environmental Protection Agency banned the use of CFCs in most aerosol sprays in 1978. Policy makers deemed further actions to reduce CFC use too expensive.

By 1986, however, the political climate had changed dramatically. British scientists announced the discovery of a vast ozone “hole” forming seasonally over Antarctica (FIGURE SA1.2). This region of unusually low ozone concentrations had not been predicted by scientific models, and the idea of an unexpected hole in the ozone layer captured public attention. Moreover, two important reports appeared in 1985 and 1986, from the World Meteorological Organization and the EPA, that demonstrated an emerging scientific consensus on the magnitude of the ozone depletion problem. Finally, DuPont, the world's leading producer of CFCs, stated that CFC alternatives could be available within 5 years, given the right market conditions.

The issue remained contentious, however. In order to convert to CFC alternatives, many industries would need to be retrofitted with new equipment, and those industries were strongly opposed to the change. In 1987, a trade group called the CFC Alliance estimated that just stopping the *growth* of new CFC production

would cost more than \$1 billion and affect 700,000 jobs in the United States. In addition, because chlorine remains in the stratosphere for tens to hundreds of years, some argued that a reduction in CFCs would have minimal short-term benefits for the environment and would result in an improvement only after several decades, not justifying expensive changes now.

In spite of these objections, in 1987, 24 nations signed an agreement called the Montreal Protocol on Substances That Deplete the Ozone Layer. Those nations committed to taking concrete steps to cut the production of CFCs in half by the year 2000. As the scientific case against CFCs strengthened and the economic costs turned out to be less than had been projected, more nations joined the Montreal Protocol, and amendments added in 1990 and 1992 strengthened the treaty by calling for a complete phaseout of CFCs in developed countries by 1996.

Small amounts of CFCs continue to be used in developing countries, and certain agricultural chemicals and CFC replacements can also destroy ozone, although to a lesser degree than CFCs. However, because of the Montreal Protocol, CFC production worldwide had fallen to 2 percent of its peak value by 2004, and chlorine concentrations in the stratosphere are slowly decreasing. Scientists believe that stratospheric ozone depletion will decrease in subsequent decades as chlorine concentrations stabilize. New cases of skin cancer should eventually decrease as well, again after a significant time lapse due to the fact that some cancers take many years to appear.

The Montreal Protocol demonstrated that the manufacturers of products and the nations that used them were willing to make changes in manufacturing

processes, and incur economic hardship, in order to protect the environment. Even more importantly, the agreement protects both human health and nonhuman organisms. A 1997 study by the Canadian government estimated that the Montreal Protocol would cost the global economy \$235 billion (Canadian dollars) between 1987 and 2060, but would result in benefits worth twice that amount, even before considering the benefits to human health. For example, the study's economists estimated a global savings of almost \$200 billion in agriculture because without the Montreal Protocol, the increased UV-B radiation would have damaged crop productivity. They also found that protection of the ozone layer avoided \$238 billion in losses

to global fisheries that depend on UV-B-sensitive phytoplankton as a food source. Because of its success, policy makers and environmental scientists view the Montreal Protocol as a model for future action on other international environmental problems such as climate change.

References

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- Seinfeld, J. H., and S. N. Pandis. 2006. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*. 2nd ed. Wiley.