

15

Long-Term Effects on the Planet

I. GLOBAL CLIMATE CHANGE

Warming on the global scale is expected to occur as a result of the increase of carbon dioxide (CO₂) and other greenhouse gases (those that absorb and reradiate portions of the infrared radiation from the earth). What is debatable is the amount of warming that will occur by a particular point in time. The CO₂ concentration has increased by about 25% since 1850 [1]. This is due to both combustion of fossil fuels and deforestation, which decreases the surface area available for photosynthesis and the resulting breakdown of CO₂ to oxygen and water vapor.

The average temperature of the earth is difficult to measure, but most measurements show a very small overall change that would not be detectable to humans due to short-term and regional variations. Overall, however, a majority of scientific evidence appears to indicate that the temperature of the earth is increasing. There have been wide fluctuations in mean global temperatures, such as the ice ages, but on balance the mean temperature has remained constant, prompting some scientists to speculate some whimsical causes for such consistency. Charles Keeling, an atmospheric scientist, measured CO₂ concentrations in the atmosphere using an infrared gas analyzer. Since 1958, these data have provided the single most important piece of

information on global warming, and are now referred to as “Keeling curve” in honor of the scientist.

The Keeling curve shows that there has been more than 15% increase in CO_2 concentration, which is a substantial rise given that short time that the measurements have been taken. It is likely, if we extrapolate backward, that our present CO_2 levels are double what they were in pre-industrial revolution times, providing ample evidence that global warming is indeed occurring.¹

Another hypothesis for this rise in temperature is that the presence of certain gases in the atmosphere is not allowing the earth to reflect enough of the heat energy from the sun back into space. The earth acts as a reflector to the sun’s rays, receiving the radiation from the sun, reflecting some of it into space (called *albedo*) and adsorbing the rest, only to reradiate this into space as heat. In effect, the earth acts as a wave converter, receiving the high-energy, high-frequency radiation from the sun and converting most of it into low-energy, low-frequency heat to be radiated back into space. In this manner, the earth maintains a balance of temperature.

In order to better understand this balance, the light energy and the heat energy have to be defined in terms of their radiation patterns, as shown in Fig. 15.1. The incoming radiation (light) wavelength has a maximum at

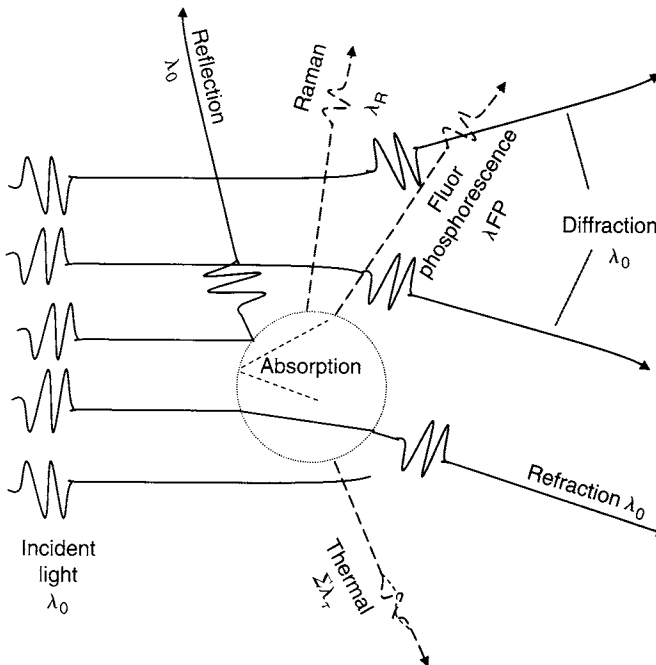


Fig. 15.1. Patterns for heat and light energy.

¹ The major source for this discussion is: Vallero, D.A., and Vesilind, P.A., *Socially Responsible Engineering: Justice in Risk Management*. John Wiley & Sons, Hoboken, NJ, 2006.

around 0.5 nm and almost all of it are lesser than 3 nm. The heat energy spectrum, or that energy reflected back into space, has the maximum at about 10 nm and almost all of it at a wavelength greater than 3 nm.

As both the light and heat energy pass through the earth's atmosphere, they encounter the aerosols and gases surrounding the earth. These can either allow the energy to pass through, or they can interrupt it by scattering or absorption. If the atoms in the gas molecules vibrate at the same frequency as the light energy, they will absorb the energy and not allow it to pass through. Aerosols will scatter the light and provide a "shade" for the earth.

The absorptive potential of several important gases is shown in Fig. 15.2, along with the spectra for the incoming light (short wavelength) radiation and the outgoing heat (long wavelength) radiation. The incoming radiation is impeded by water vapor and molecular oxygen and ozone. Most of the light energy comes through unimpeded.

The heat energy, however, encounters several potential impediments. As it is trying to reach outer space, it finds that water vapor, CO₂, CH₄, O₃, and N₂O all have absorptive wavelengths right in the middle of the heat spectrum. Quite obviously, an increase in the concentration of any of these will greatly limit the amount of heat transmitted into space. These gases are appropriately called *greenhouse gases* because their presence will limit the

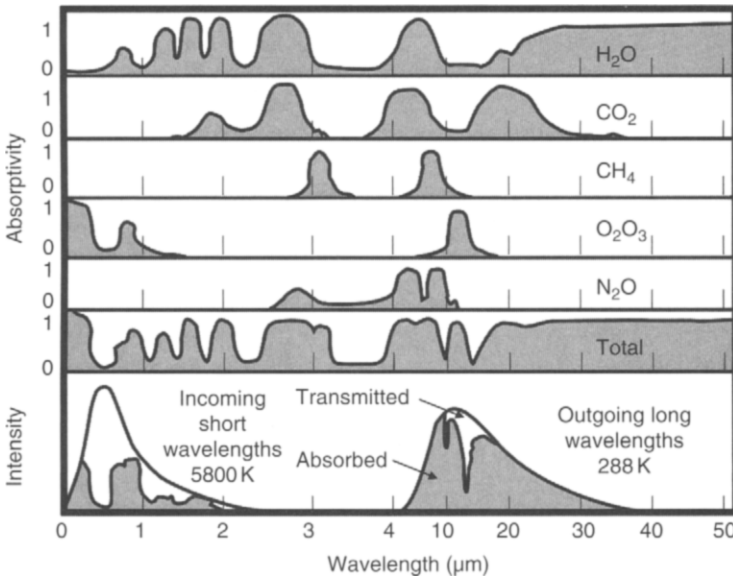


Fig. 15.2. Adsorptive potential of several important gases in the atmosphere. Also shown are the spectra for the incoming solar energy and the outgoing thermal energy from the earth. Note that the wavelength scale changes at 4 μm. Courtesy of Masters, G. M., *Introduction to Environmental Engineering and Science*. Prentice Hall, Englewood Cliffs, NJ, 1998.

heat escaping into space, much like the glass of a greenhouse or even the glass in a car limits the amount of heat that can escape, thus building up the temperature under the glass cover.

The effectiveness of a particular gas to promote global warming (or cooling, as is the case with aerosols) is known as *forcing*. The gases of most importance in forcing are listed in Table 15.1. Climate change results from natural internal processes and from external forcings. Both are affected by persistent changes in the composition of the atmosphere brought about by changes in land use, release of contaminants, and other human activities. Radiative forcing is the change in the net vertical irradiance within the atmosphere. Radiative forcing is often calculated after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding all tropospheric properties fixed at their unperturbed values. Commonly, radiative forcing is considered to be the extent to which injecting a unit of a greenhouse gas into the atmosphere changes global average temperature, but other factors can affect forcing, as shown in Figs. 15.3 and 15.4.

There is much uncertainty about the effects of the presence of these radiant gases (see Table 15.2), but the overall effect of the composite of gases is well understood. The effectiveness of CO₂ as a global warming gas has been known for over 100 years. However, the first useful measurements of atmospheric CO₂ were not taken until 1957. The data from Mauna Loa (Fig. 15.5) show that even in the 1950s the CO₂ concentration had increased from the baseline 280 to 315 ppm; and this has continued to climb over the last 50 years at a nearly constant rate of about 1.6 ppm year⁻¹. The most serious problem with CO₂ is that the effects on global temperature due to its greenhouse effect are delayed. Even in the completely impossible scenario of not emitting any new CO₂ into the atmosphere, CO₂ concentrations will continue to increase from our present 370 ppm to possibly higher than 600 ppm.

Methane is the product of anaerobic decomposition and human food production. One of the highest producers of methane in the world is New Zealand which boasts 80 million sheep. Methane is also emitted during the combustion of fossil fuels and cutting and clearing of forests. The concentration

TABLE 15.1

Relative Forcing of Increased Global Temperature

Gas	Percent of relative radiative forcing
Carbon dioxide, (CO ₂)	64
Methane (CH ₄)	19
Halocarbons (mostly CFCs)	11
Nitrous oxide (N ₂ O)	6

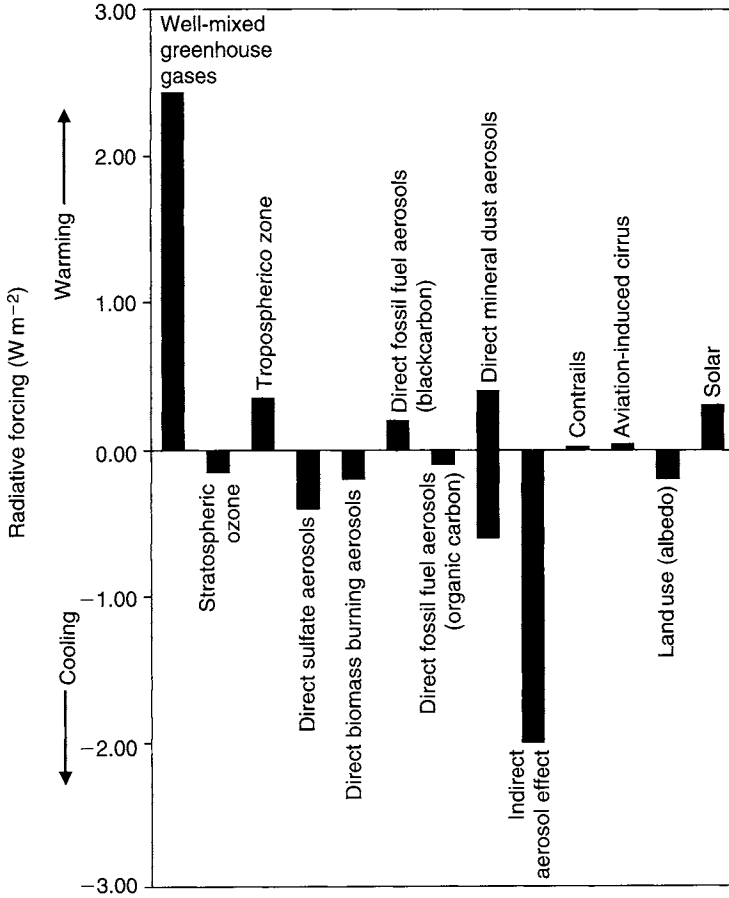
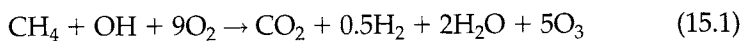


Fig. 15.3. The global mean radiative forcing ($W m^{-2}$) of the climate system for the year 2000, relative to 1750. The Intergovernmental Panel on Climate Change (IPCC) has applied a level of scientific understanding (LOSU) index in accorded to each forcing (see Table 15.2). This represents the Panel’s subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The relative contribution of the principal well-mixed greenhouse gases is shown in Fig. 15.4. *Data from: IPCC, Climate Change 2001: The Scientific Basis, Chapter 6—Radiative Forcing of Climate Change, 2001.*

of CH_4 in the atmosphere has been steady at about 0.75 ppm for over a thousand years, and then increased to 0.85 ppm in 1900. Since then, in the space of only a hundred years, it has skyrocketed to 1.7 ppm. Methane is removed from the atmosphere by reaction with the hydroxyl radical (OH) as:



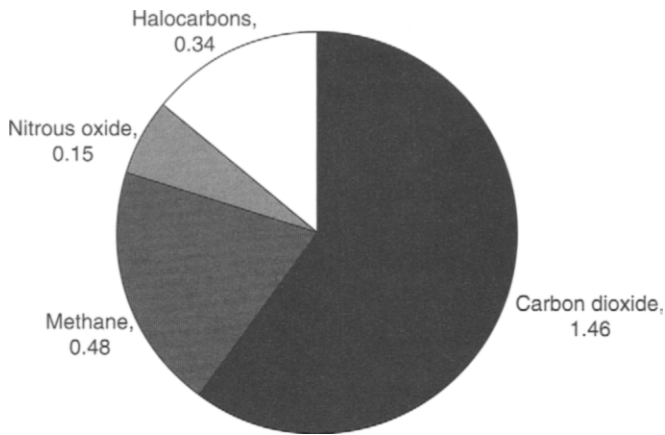


Fig. 15.4. Relative contribution of well-mixed greenhouse gases to the $+2.43 \text{ W m}^{-2}$ radiative forcing shown in Fig. 15.3. Data from: IPCC, *Climate Change 2001: The Scientific Basis*, Chapter 6—Radiative Forcing of Climate Change, 2001.

TABLE 15.2

Level of Scientific Understanding (LOSU) of Radiative Forcings

Forcing phenomenon	LOSU
Well-mixed greenhouse gases	High
Stratospheric O ₃	Medium
Tropospheric O ₃	Medium
Direct sulfate aerosols	Low
Direct biomass burning aerosols	Very low
Direct fossil fuel aerosols (black carbon)	Very low
Direct fossil fuel aerosols (organic carbon)	Very low
Direct mineral dust aerosols	Very low
Indirect aerosol effect	Very low
Contrails	Very low
Aviation-induced cirrus	Very low
Land use (albedo)	Very low
Solar	Very low

Source: IPCC, *Climate Change 2001: The Scientific Basis*, Chapter 6—Radiative Forcing of Climate Change, 2001.

This indicates that the reaction creates carbon dioxide, water vapor, and ozone, all of which are greenhouse gases, so the effect of one molecule of methane is devastating to the production of the greenhouse effect.

Halocarbons, or the same chemical class linked to the destruction of stratospheric ozone, are also radiant gases. The most effective global warming gases are CFC-11 and CFC-12, both of which are no longer manufactured, and the banning of these substances has shown a leveling off in the stratosphere. Nitrous oxide is also in the atmosphere mostly as a result of

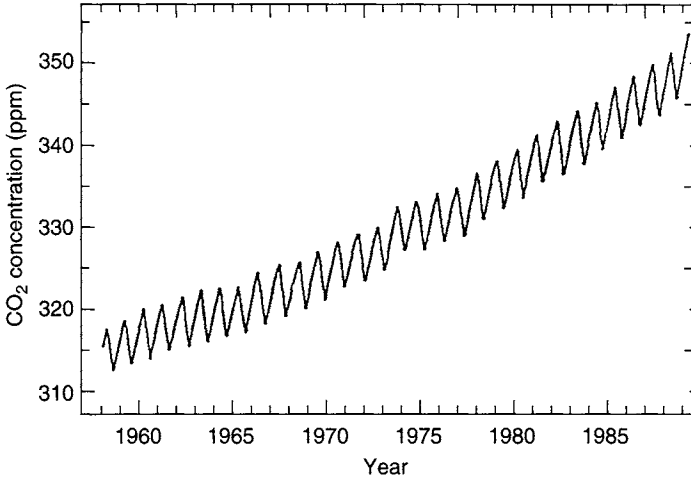


Fig. 15.5. Mean monthly concentrations of atmospheric CO₂ at Mauna Loa. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the Northern Hemisphere. *Source:* Lindzen [2].

human activities, especially the cutting and clearing of tropical forests. The greatest problem with nitrous oxide is that there appears to be no natural removal processes for this gas and so its residence time in the stratosphere is quite long.

The net effect of these global pollutants is still being debated. Various atmospheric models used to predict temperature change over the next 100 years vary widely. They nevertheless agree that some positive change will occur, even if we do something drastic today (which does not seem likely). By the year 2100, even if we do not increase our production of greenhouse gases and if the United States signs the Kyoto Accord that encourages the reduction in greenhouse gas production, the global temperature is likely to be between 0.5°C and 1.5°C warmer.

Firm evidence for the amount of warming taking place in terms of actual temperature measurements has been complicated primarily by the magnitudes of natural climatic variations that occur. A summary of the available measurements shown by Kellogg [3] is given in Fig. 15.6. Other factors contributing to warming trends are the length of temperature records; the lack of representative measurements over large portions of the earth, primarily the oceans and polar regions; and the urban sprawl toward locations at which temperature measurements are made, such as airports.

Although there has been a warming trend over the past 100 years, it is not necessarily due to the greenhouse effect. The concern of the scientific community about accelerating changes in the next 40–50 years is based not only on the recent observations of temperature compared with past observations, but also on the physical principles related to the greenhouse effect.

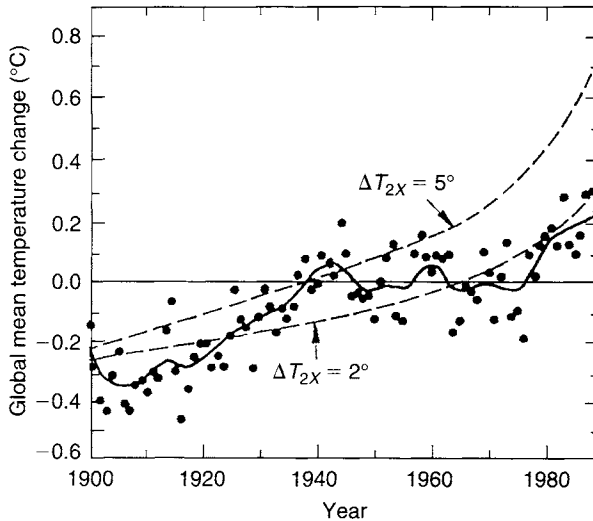


Fig. 15.6. Combined land–air and sea surface temperatures from 1900, relative to 1951–1980 average (solid line and dots), adapted from Folland *et al.* [4]. The land–air temperatures were derived by Jones [5] and the sea surface temperatures by the UK Meteorological Office and Farmer *et al.* [6]. The smoothed curve was obtained by a low-pass binomial filter operating on the annual data (shown by dots), passing fluctuations having a period of 290 years or more almost unattenuated. The dashed lines are calculated global temperature changes from the mean of the period 1861–1900, using the climate model of Wigley and Raper [7], and observed concentrations of greenhouse gases, adapted from Wigley and Barnett [8]. The upper curve assumes an equilibrium temperature increase for a doubling of greenhouse gases of 5 K, and the lower one assumes it to be 2 K; both curves are based on an ocean vertical diffusion coefficient (K) of $0.63 \text{ cm}^2 \text{ s}^{-1}$ and temperature of the water in sinking regions (π), the same as the global mean. *Source:* Kellogg [3].

Global climate models have been used to estimate the effects in terms of temperature changes. Considerable difficulties are encountered in at least two areas. One is the difficulty in accounting properly for moisture changes including cloud formation. An important mechanism of heat transfer is through water vapor and water droplets. Of course, cloud cover alters the radiational heating at any given time. The second difficulty is accounting for solar radiation variability and the occasional injection of fine particulate matter into the atmosphere by volcanic activity, both of which alter the amount of solar radiation reaching the ground. Results from most model attempts suggest that global average surface temperatures will increase on the order of 1.5–4.5°C over the next century.

The greatest concern about global warming is the regional and seasonal effects that will result. Of considerable significance could be changes in the patterns of precipitation in the agricultural and forested regions during the growing seasons, in particular.

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and United

Nations Environment Program (UNEP). This panel gave its official report in Geneva in November 1990 at the Second World Climate Conference. This group predicted that if no significant actions are taken to curtail consumption of fossil fuel worldwide, the global mean temperature will increase at a rate of 0.2–0.5°K per decade over the next century [9]. This is at a rate faster than seen over the past 10 000 years or longer.

Most recently, in *Climate Change 2007: The Physical Science Basis—Summary for Policymakers*, the IPCC has stated that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.” They also assert:

- Average Arctic temperatures increased at almost twice the global average rate in the past 100 years. Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7% (2.1–3.3%) per decade, with larger decreases in summer of 7.4% (5.0–9.8%) per decade.
- Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%.
- Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa, and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions. Long-term trends have not been observed for the other large regions assessed.

Among the groups using advanced climate system models are the following five: National Center for Atmospheric Research (NCAR), NOAA Geophysical Fluid Dynamics Laboratory (GFDL), NASA Goddard Institute for Space Studies (GISS), United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU). Proper simulation of cloudiness is difficult with the models. As part of a study of sensitivity to the inclusion of cloudiness, each of 14 models was run with clear skies and then with their simulation of cloudiness [10]. A climate sensitivity parameter (CSP) was determined for each model. If the ratio of the CSP with clouds included to the CSP with clear skies was 1.0, the clouds had no feedback effect on temperature, but if the ratio was greater than 1, the cloud feedback was positive (to increase temperature). For the foregoing five models the range of ratios was from unity (no feedback) to 1.55 (a fairly strong positive feedback). All of these models consider two cloud types, stratiform and convective, but there are differences in the way these are calculated. It can be concluded that considerable work will be needed before the treatment of clouds can be considered satisfactory [3]. Some arguments have been made that cloudiness may provide a negative

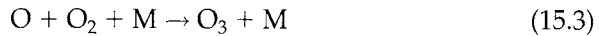
feedback to temperature increases [2], i.e., cause a decrease in temperature. These results indicate that this is not likely.

Penner [11] has pointed out that short-lifetime constituents of the atmosphere such as nitric oxide, nitrogen dioxide, carbon monoxide, and non-methane hydrocarbons may also play roles related to global warming because of their chemical relations to the longer-lived greenhouse gases. Also, SO_2 with a very short life interacts with ozone and other constituents to be converted to particulate sulfate, which has effects on cloud droplet formation.

II. OZONE HOLES

During each September of the mid-1980s, scientists began to observe a decrease in ozone in the stratosphere over Antarctica. These observations are referred to as "ozone holes." To understand ozone holes, one needs to know how and why ozone is present in the earth's stratosphere.

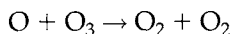
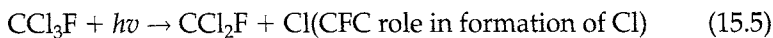
Stratospheric ozone is in a dynamic equilibrium with a balance between the chemical processes of formation and destruction. The primary components in this balance are ultraviolet (UV) solar radiation, oxygen molecules (O_2), and oxygen atoms (O) and may be represented by the following reactions:



where hv represents a photon with energy dependent on the frequency of light, v , and M is a molecule of oxygen or nitrogen. The cycle starts with the photodissociation of O_2 to form atomic oxygen O (Eq. 15.2). O atoms react with O_2 in the presence of a third molecule (O_2 or N_2) to form O_3 (Eq. 15.3). Ozone absorbs UV radiation and can undergo photodissociation to complete the cycle of formation and destruction (Eq. 15.4). At a given altitude and latitude a dynamic equilibrium exists with a corresponding steady-state ozone concentration. This interaction of UV radiation with oxygen and ozone prevents the penetration of shortwave UV to the earth's surface. Stratospheric ozone thus provides a UV shield for human life and biological processes on the earth's surface.

In 1975, Rowland and Molina [12] postulated that chlorofluorocarbons (CFCs) could modify the steady-state concentrations of stratospheric ozone. CFCs are chemically very stable compounds and have been used for over 50 years as refrigerants, aerosol propellants, foam blowing agents, cleaning agents, and fire suppressants. The use has been curtailed since many of these compounds have been banned throughout the globe. The Montreal Protocol on Substances that Deplete the Ozone Layer is an international agreement designed to protect the stratospheric ozone layer. The treaty was originally signed in 1987 and substantially amended in 1990 and 1992 that stipulates

that the production and consumption of compounds that deplete ozone in the stratosphere be phased out. Chlorofluorocarbons (CFCs), halons, carbon tetrachloride, and methyl chloroform were to be phased out by 2000 and methyl chloroform by 2005. Revisions to the Clean Air Act in 1998 induced the United States to limit the production and import of methyl bromide to 75% of the 1991 baseline. In 2001, production and import were further reduced to 50% of the 1991 baseline. In 2003, allowable production and import were again reduced, to 30% of the baseline, leading to a complete phaseout of production and import in 1995. Beyond 2005, continued production and import of methyl bromide are restricted to critical, emergency, and quarantine and pre-shipment uses. Because of their stability in the troposphere, CFCs remain in the troposphere for long periods of time, providing the opportunity for a portion of these chemicals to diffuse into the stratosphere. Rowland and Molina suggested that CFCs in the stratosphere would upset the balance represented by Eqs. (15.3) and (15.4). In the stratosphere, CFCs would be exposed to shortwave UV radiation with wavelengths $\lambda < 220$ nm and undergo photodissociation, releasing chlorine atoms (Cl), and Cl would interfere with the ozone balance in the following manner:



The chlorine atoms would provide another destruction pathway for ozone in addition to Eq. (15.4), shifting the steady-state ozone to a lower value. Because of the catalytic nature of Eqs. (15.6) and (15.7), one chlorine atom destroys many ozone molecules.

The discovery of ozone holes over Antarctica in the mid-1980s was strong observational evidence to support the Rowland and Molina hypothesis. The atmosphere over the South Pole is complex because of the long periods of total darkness and sunlight and the presence of a polar vortex and polar stratospheric clouds. However, researchers have found evidence to support the role of ClO in the rapid depletion of stratospheric ozone over the South Pole. Figure 15.7 shows the profile of ozone and ClO measured at an altitude of 18 km on an aircraft flight from southern Chile toward the South Pole on September 21, 1987. One month earlier the ozone levels were fairly uniform around 2 ppm (vol).

Ozone holes are considered by many as a harbinger of atmospheric modification. Investigators have found a similar but less intense annual decrease in ozone over the Arctic region of the globe. Additional studies are providing evidence for stratospheric ozone depletion over the northern temperate regions of the globe. These observations prompted a worldwide phaseout of

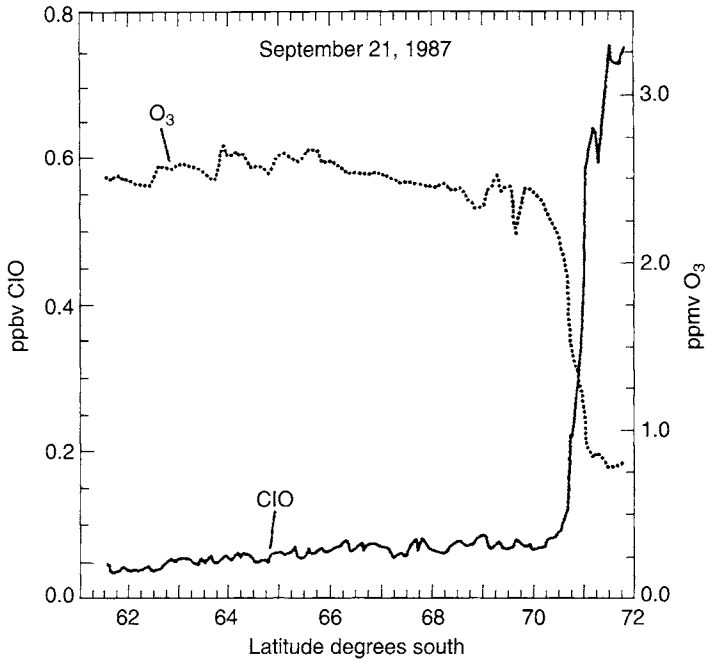


Fig. 15.7. Stratospheric ozone and CIO concentrations at an altitude of 18 km measured by aircraft flying south over Antarctica on September 27, 1987. The dramatic decrease in ozone at a latitude of 71° is attributed to the role of CIO in catalytic destruction of ozone. Adapted from Anderson *et al.* [13].

the manufacture and use of CFCs and halogens. These chemicals will be present at elevated levels for many years to come because of their stability.

CFCs represent only one class of chemicals being released to the atmosphere which have long-term effects. Replacement chemicals will be reviewed for potential adverse effects on the atmosphere. In addition, other radiant (greenhouse) gases will be subject to investigation and questioning of their role in global warming scenarios.

REFERENCES

1. Schneider, S. H., *Bull. Am. Meteorol. Soc.* **71**, 1292–1304 (1990).
2. Lindzen, R., *Bull. Am. Meteorol. Soc.* **71**, 288–299 (1990).
3. Kellogg, W. W., *Bull. Am. Meteorol. Soc.* **72**, 499–511 (1991).
4. Folland, C. K., Karl, T., and Vinnikov, K. Ya., Observed climate variations and change, in *Climate Change: The IPCC Scientific Assessment*, Working Group 1 Report (Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., eds.), pp. 195–238. Cambridge University Press, Cambridge, 1990.
5. Jones, P. D., *J. Climatol.* **1**, 654–660 (1988).

6. Farmer, G., Wigley, T. M. L., Jones, P. D., and Salmon, M., *Documenting and Explaining Recent Global-Mean Temperature Changes*. Climatic Research Unit, Norwich, Final Report to NERC, UK, Contract No. GR3/6565, 1989.
7. Wigley, T. M. L., and Raper, S. C. B., *Nature* **330**, 127–131 (1987).
8. Wigley, T. M. L., and Barnett, T. P., Detection of the greenhouse effect in observations, in *Climate Change: The IPCC Scientific Assessment*, Working Group 1 Report (Houghton, J. T., Jenkins, G. J., and Ephraums, J. J., eds.), pp. 239–256. Cambridge University Press, Cambridge, 1990.
9. World Meteorological Organization, *WMO and Global Warming*, WMO No. 741, Geneva, Switzerland, 1990.
10. Cess, R. D., Potter, G. L., Blanchet, J. P., Boer, G. J., Ghan, S. J., Kiehl, J. T., Le Treut, H., Li, Z.-X., Liang, X.-Z., Mitchell, J. F. B., Morcrette, J.-J., Randall, D. A., Riches, M. R., Roeckner, E., Schlese, U., Slingo, A., Taylor, K. E., Washington, W. M., Wetherald, R. T., and Yagai, I., *Science* **245**, 513–516 (1989).
11. Penner, J. E., *J. Air Waste Manage. Assoc.* **40**, 456–461 (1990).
12. Rowland, F. S., and Molina, M. J., *Rev. Geophys. Space Phys.* **13**, 1–35 (1975).
13. Anderson, J. G., Brune, W. H., and Proffitt, M. H., *J. Geophys. Res.* **94**, 465–479 (1989).

SUGGESTED READING

- American Meteorological Society, *Bull. Am. Meteorol. Soc.* **72**, 57–59 (1991).
- Congressional Research Service, *Global Climate Change*. CRS Issue Brief IB89005, 2001.
- Congressional Research Service, *Global Climate Change: US Greenhouse Gas Emissions—Status, Trends, and Projections*. Report No. 98-235 ENR, Updated March 12, 2002.
- US Environmental Protection Agency, *Protection of Stratospheric Ozone: Incorporation of Montreal Protocol Adjustment for a 1999 Interim Reduction in Class I, Group VI Controlled Substances*. 40 CFR Part 82, 1999.

QUESTIONS

1. What are the difficulties in the use of climate models to estimate effects of increased CO₂?
2. What is the primary reason for the increase of CO₂ in the atmosphere?
3. What is the importance of having ozone in the stratosphere?
4. What is the effect of CFCs entering the stratosphere?
5. Why is there such strong disagreement over the models used to predict global climate change? What are the major sources of uncertainty?
6. Why do you think that the phaseout of methyl chloroform took longer than the other phased compounds in the Montreal Protocol?