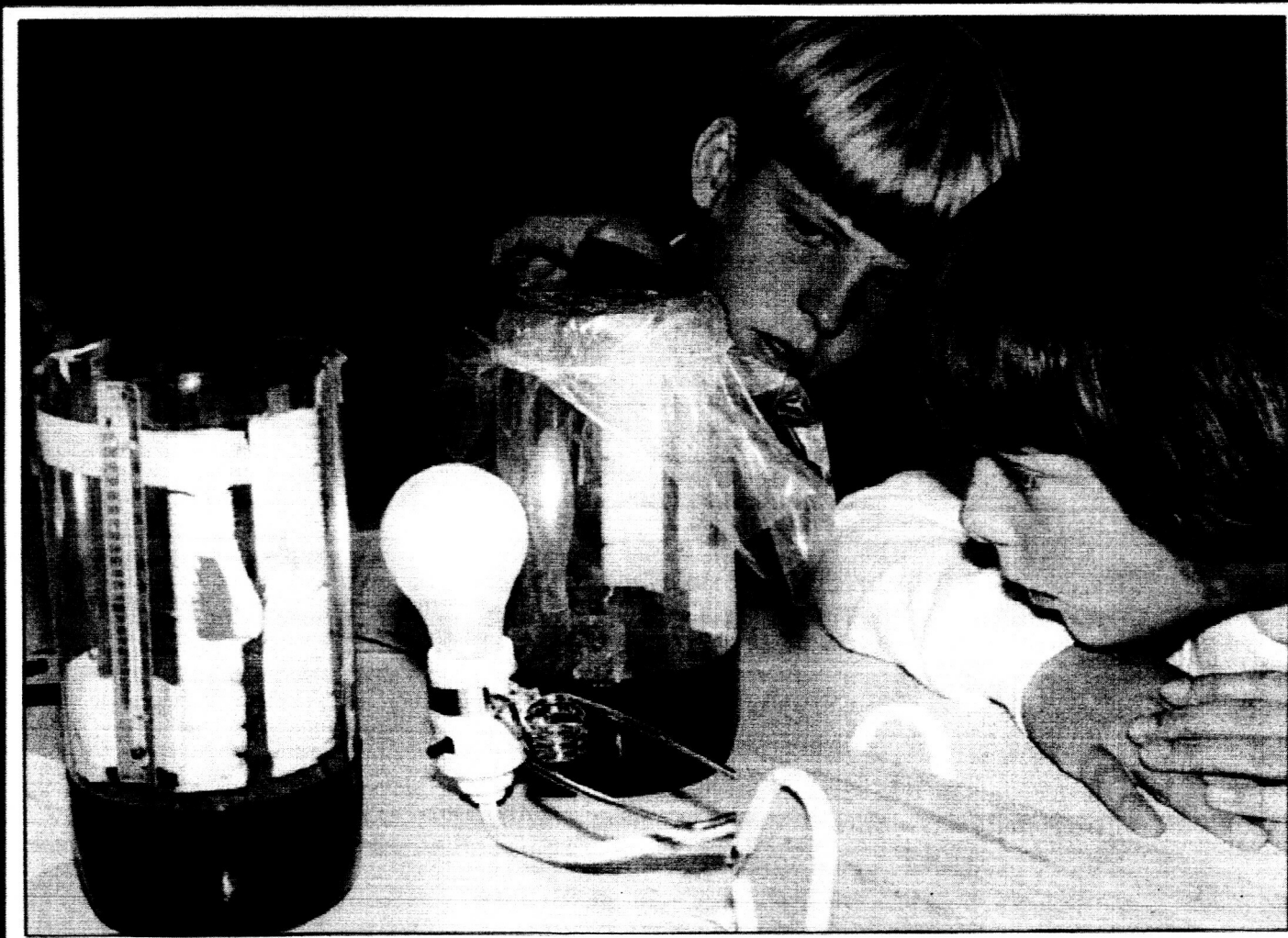


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Classroom Global Warming

Teaching Students about Earth's Atmosphere

Ozone, Climate, and Global Atmospheric Change

Joel S. Levine

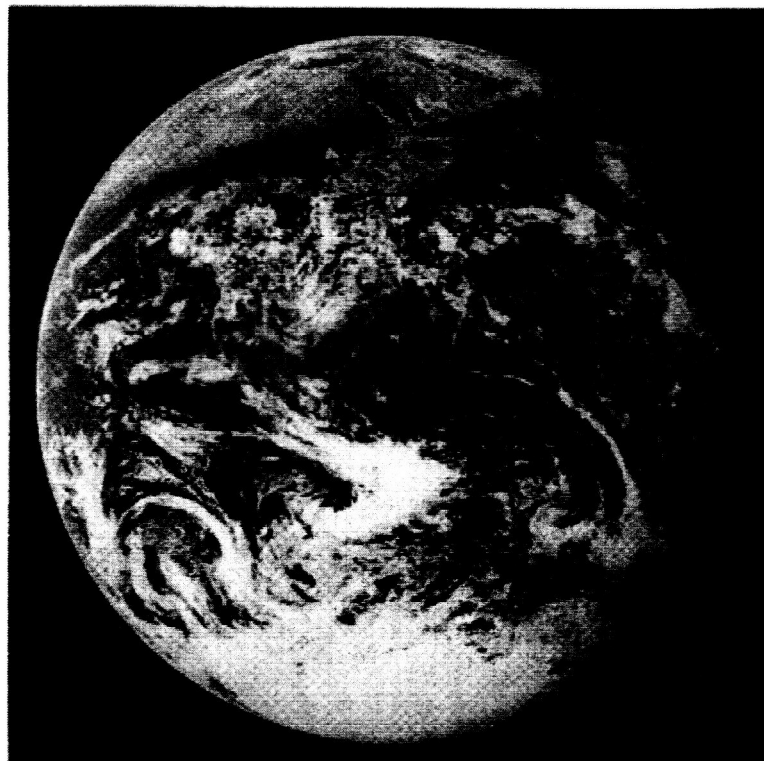
The delicate balance of the gases that make up our atmosphere allows life to exist on Earth. Ozone depletion and global warming are related to changes in the concentrations of these gases. To solve global atmospheric problems, we need to understand the composition and chemistry of the Earth's atmosphere and the impact of human activities on them.

The Composition of the Earth's Atmosphere

The atmosphere of our planet contains several hundred different gases of diverse origins. However, about 99.96 percent of the total mass of the atmosphere is due to the presence of three major permanent constituents: nitrogen (N_2), 78.08 percent by volume; oxygen (O_2), 20.95 percent by volume; and argon (Ar), 0.93 percent by volume. Water vapor (H_2O), an atmospheric gas with a variable concentration, ranges by volume from a small fraction of a percent up to 1 or 2 percent.

The remaining constituents of the atmosphere are trace gases whose atmospheric abundances are too low to be measured by percent (a unit of measure that

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The Earth photographed by the Apollo 17 astronauts in December 1972 during the final manned mission to the moon. The Antarctic ice cap is brightly illuminated. Two of the key elements that control the climate appear in the photograph: clouds and the oceans.

is the same as parts per hundred by volume). Instead, the concentrations of the trace gases are measured in terms of mixing ratio-the number of molecules of the trace gas divided by the number of total atmospheric molecules (nitrogen, oxygen, argon, and all the others) in one cubic centimeter of air. Trace gases such as ozone (O_3), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and halons (brominated CFCs) are measured in parts per million by volume (ppmv), parts per billion by volume (ppbv), or parts per trillion by volume (pptv). The concentrations of the major and

Table 1. Major and Selected Trace Gases in the Atmosphere

Gases	Concentration
Nitrogen (N ₂)	78.08 percent by volume
Oxygen (O ₂)	20.95 percent by volume
Argon (Ar)	0.93 percent by volume
Water vapor (H ₂ O)	0 to 1 or 2 percent by volume
Carbon dioxide (CO ₂)	350 ppmv
Ozone (O ₃)	
In troposphere	0.02 to 0.1 ppmv
In stratosphere	0.1 to 10 ppmv
Methane (CH ₄)	1.7 ppmv
Nitrous oxide (N ₂ O)	0.31 ppmv
CFC-12 (CF ₂ Cl ₂)	0.5 ppbv
CFC-11 (CFCl ₃)	0.3 ppbv
Halon-1301 (CBrF ₃)	2.0 pptv
Halon-1211 (CBrClF ₂)	1.7 pptv
Hydroxyl (OH)	
In troposphere	0.015 pptv
In stratosphere	0.02 pptv to 0.3 ppbv
Nitric Oxide (NO)	
In troposphere	0 to 1 ppbv
In stratosphere	Up to 0.02 ppmv

Note: The concentrations of atmospheric gases are given in either percentage by volume (which is the same as parts per hundred by volume), parts per million by volume (ppmv), parts per billion by volume (ppbv), or parts per trillion by volume (pptv).

selected trace gases in the atmosphere are summarized in table 1.

It is an interesting and somewhat ironic fact that the chemistry of the atmosphere and the temperature of our planet are not controlled by the major gases, but rather by the trace gases. There is growing evidence that the trace-gas composition of the atmosphere is changing. The environmentally significant trace gases are affected by both natural and human-produced gases. Among these gases are the chlorofluorocarbons, human-made gases such as CFC-11 and CFC-12 that are used as propellents in aerosol spray cans; halons used in fire extinguishers; and carbon dioxide, nitrous oxide, and methane, which are produced by the burning of fossil fuels and living and dead biomass and by the metabolic processes of microorganisms in the soil, wetlands, and oceans of our planet.

The Origin of Atmospheric Ozone

The development of the atmospheric ozone layer had a very significant impact on the evolution of life on our planet. Throughout most of its 4.6 billion-year history,

in the atmosphere to shield the Earth's surface from the biologically lethal ultraviolet radiation (electromagnetic radiation between 200 and 300 nanometers) emitted by the Sun. Before the development of the atmospheric ozone layer, life was restricted to the ocean depths where several meters of seawater absorbed the solar ultraviolet radiation and offered protection to the earliest forms of life on our planet.

About 600 million years ago, oxygen built up in the atmosphere to about 10 percent of its present atmospheric level as a result of photosynthetic activity. At this point, ozone, which is chemically formed from oxygen, reached sufficient levels in the atmosphere to effectively absorb incoming solar ultraviolet radiation, and, for the first time, living organisms could leave the safety of the ocean and live on land.

Ozone (O₃), composed of three oxygen atoms via atmospheric photochemical and chemical reactions, is a trace atmospheric gas. About 90 percent of the total atmospheric content of ozone is located in a layer between about 15 and 50 kilometers above the Earth's surface in the atmospheric region known as the stratosphere (see figure 1).

Changes in the Ozone Layer

The Antarctic Ozone Hole

Recent ground-based, aircraft, and satellite measurements have indicated an alarming trend in the level of ozone in the stratosphere over the Antarctic. These measurements indicate that, for more

there was an insufficient level of ozone

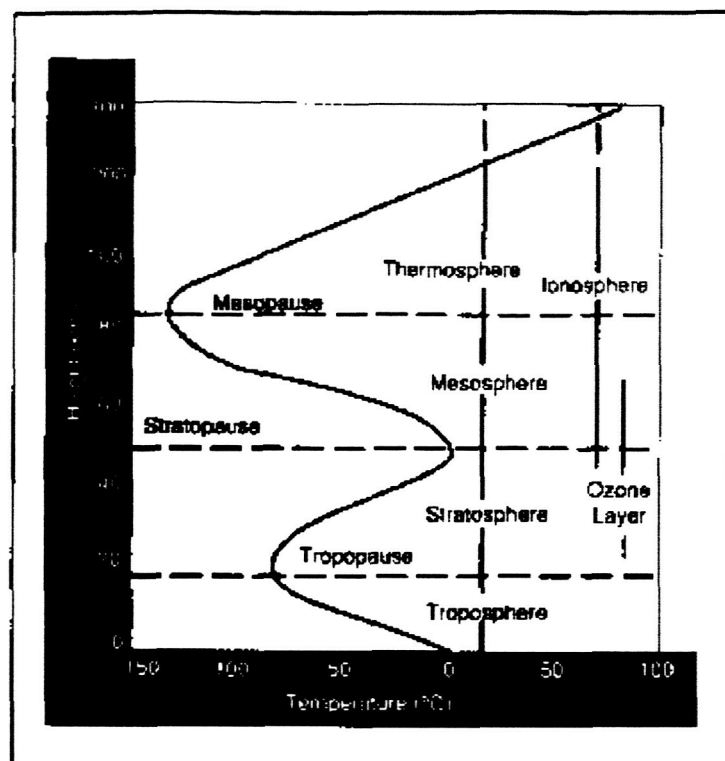


Figure 1. The structure of the Earth's atmosphere illustrating the various regions. Each region is defined by its temperature gradient. (Earth Systems Sciences Committee, NASA, 1988)

than a decade, during a specific period each year, the levels of ozone in the stratosphere have decreased by more than 50 percent. The so-called "hole" in the ozone layer is produced each year during a 4- to 6-week period, beginning in late September, which is the start of spring in the Southern Hemisphere. The area of the Antarctic ozone hole, about the size of the continental United States, has grown larger each year during this period.

Four to six weeks after the first appearance of the Antarctic ozone hole, ozone from the Southern Hemisphere mid-latitudes is transported to the South Pole by the general circulation patterns of the atmosphere and replenishes the missing gas. Then the following spring the hole reappears.

Global Changes in stratospheric Ozone

Is there evidence for stratospheric ozone depletion outside of the Antarctic region? The Ozone Trends Panel, formed by NASA in October 1986, in collaboration with the National Oceanic and Atmospheric Administration, the Federal Aviation Administration, the World Meteorological Organization, and the United Nations Environment Program has reanalyzed and reassessed the data on ozone abundances collected by the 30-year-old network of ground-based Dobson spectrophotometers concentrated in the Northern Hemisphere and by satellite instruments operating since the

percentage points between 1969 and 1986. The panel concluded that between 30°N latitude and 64°N latitude, from 1969 to 1986, stratospheric ozone decreased between 1.7 and 3.0 percent. The larger decreases occurred at the high latitudes in winter; the smaller drops occurred in summer.

There is other evidence to suggest that concentrations of ozone in the troposphere (the lowest atmospheric layer that extends from the surface to the beginning of the stratosphere and contains the remaining 10 percent of atmospheric ozone) have been increasing by about 1 percent per year over the past 20 years. This means that the decreases in stratospheric ozone probably exceed those for the total column content, which is the sum of tropospheric and stratospheric ozone.

What Is Destroying the Ozone?

The Ozone Trends Panel attributed the observed decreases in stratospheric ozone to increasing atmospheric levels of chlorofluorocarbons (see figure 2). The chlorofluorocarbons, Freon-11 (CFC1_3) and Freon-12 (CF_2Cl_2), are usually referred to as CFC-11 and CFC-12, respectively.

The major source of atmospheric CFC-11 and CFC-12

late 1970s.

In March 1988, the panel reported their findings: global levels of stratospheric ozone had fallen several

is the aerosol spray can, which uses these chemically inert gases as propellents. CFCs are also used as refrigerants in home and automobile air conditioners and in the manufacturing of closed-cell and open-cell foams.

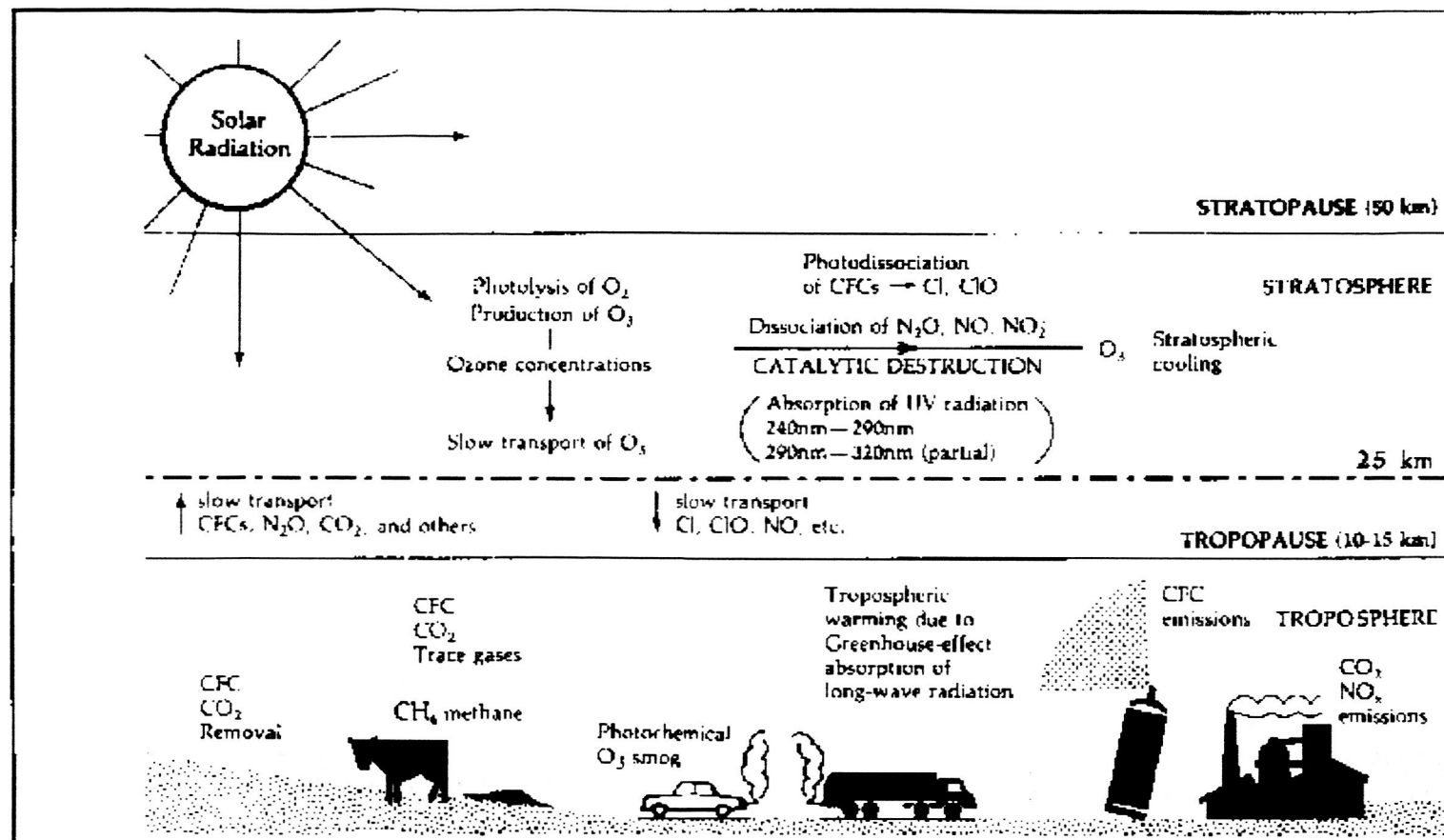


Figure 2. A schematic illustrating some sources and sinks for greenhouse gases and the chemical transformation of these gases in the troposphere and stratosphere. (International Geosphere-Biosphere Programme, 1990)

Additional trace gases that destroy ozone in the stratosphere by chemical reactions include bromine (Br), nitric oxide (NO) and the hydroxyl radical (OH). Methane reactions produce the water vapor that releases the hydroxyl radical in the stratosphere.

Ozone Depletion Caused by Chlorine and Bromine

The cause of the Antarctic ozone hole is now believed to be the chlorine and bromine originally released from the CFCs and halons, or brominated CFCs. These two elements are released into the atmosphere through a series of reactions.

Chlorine atoms are liberated in the stratosphere by the action of solar radiation on CFC-11 and CFC-12

Most halons are used as fire-extinguishing agents. The atmospheric concentrations of Halon-1301 and 1211 are only 2 pptv and 1.7 pptv, respectively. However, their atmospheric levels are increasing at rates of 15 percent and 12 percent per year, respectively. The atmospheric lifetime of Halon-1301 is about 110 years; that of Halon-1211, about 25 years.

Ozone Depletion Caused by Nitric Oxide

Molecules of nitric oxide also destroy stratospheric ozone. These molecules are produced by the chemical transformation of nitrous oxide in the stratosphere. Most nitrous oxide is produced by bacteria in natural and fertilized soils during the processes of nitrification and denitrification.

The surface concentration of nitrous oxide is about 0.31 ppmv. Measurements indicate that nitrous oxide is increasing about 0.2 to 0.3 percent per year. The atmospheric lifetime of nitrous

molecules, the only significant source of chlorine atoms in the stratosphere. The ice clouds that form in the dry, frigid, isolated Antarctic stratosphere greatly facilitate the chemical reactions that free chlorine atoms from the reservoir compounds, where they reside after being released from the CFCs. Then the chlorine is readily available to chemically destroy ozone in the Antarctic stratosphere after the long, cold Antarctic winter.

Atmospheric levels of CFC-11 and CFC-12 are about 0.3 ppbv and 0.5 ppbv, respectively. The levels of each of these gases is increasing at a rate of about 5 percent per year. The atmospheric lifetimes (the time before the gas is destroyed or lost to the atmosphere) of CFC-11 and CFC-12 are about 65 and 130 years, respectively.

After warnings about stratospheric ozone depletion caused by CFCs, the United States banned the use of these gases in aerosol spray cans in 1978. Unfortunately, the rest of the world did not. However, in September 1987, representatives from more than thirty nations signed the Montreal Protocol, which froze CFC production rates at 1986 levels after 1989 and will cut them in half by 1999. In 1990, in London, the provisions of the original 1987 Montreal Protocol were strengthened by the participating countries. This will lead to a more rapid phaseout of aerosol spray CFCs and halons. Nevertheless, because of their very long atmospheric lifetimes, the impact of the CFCs and halons already released will still be felt for many years following their phaseout.

Also implicated in the springtime chemical destruction of ozone over the Antarctic is bromine (Br). Human-produced sources of bromine include the halons, or brominated CFCs, such as bromotrifluoromethane (Halon-1301: CBrF_3) and bromochlorodifluoromethane (Halon-1211: CBrClF_2). Bromine monoxide (BrO), produced from Halon-1301 and Halon-1211, reacts with chlorine monoxide (ClO), produced from CFCs, to release bromine (Br) and chlorine (Cl), both of which destroy ozone in the stratosphere.

oxide is about 150 years.

Effects of Ozone Depletion

Calculations indicate that for each one percent decrease in atmospheric ozone, the amount of solar ultraviolet radiation reaching the ground will increase by 2 percent. It is estimated that a 2 percent increase in solar ultraviolet radiation could increase future skin cancer cases by 3 to 6 percent each year. There are presently about 500,000 cases of skin cancer diagnosed each year in the United States.

It has also been suggested that solar ultraviolet radiation can damage the human immune system, cause billion of dollars worth of crop damage, and adversely affect plankton in the ocean, the base of the marine food chain.

What Is the Greenhouse Effect?

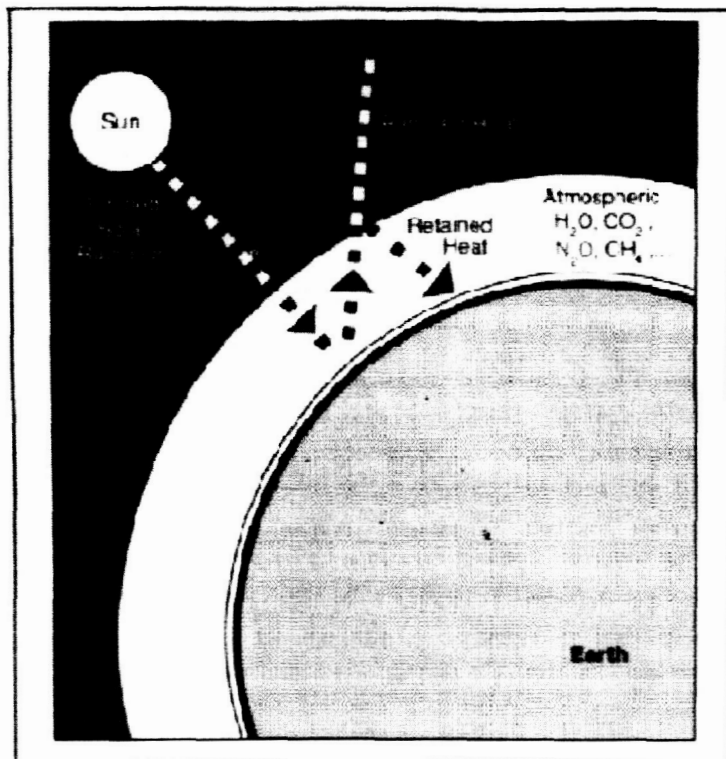
Another change in the atmosphere that is affecting our climate is the increasing concentrations of greenhouse gases. This buildup of greenhouse gases results in a greater warming of the Earth's surface.

Greenhouse gases have the ability to absorb, or trap, upward-moving infrared radiation, heat energy, emitted by the Earth's surface (see figure 3). The greenhouse gases quickly reemit, or release, the absorbed heat energy with approximately 50 percent of the reemitted energy directed back toward the Earth's surface. This heat energy would have been lost to space if it had not been trapped by greenhouse gases.

Ozone, Methane, Nitrous Oxide, and the CFCs as Greenhouse Gases

While ozone in the stratosphere is decreasing, measurements indicate that ozone, as well as other trace gases, is increasing in the troposphere. It is ironic that, while ozone in the stratosphere is beneficial

Carbon dioxide is chemically inert in the atmosphere. Hence, there are no significant atmospheric reactions that form sinks, or repositories, for carbon dioxide. The sinks for carbon dioxide include uptake and incorporation in the living biosphere during photosynthetic activity, dissolution in the ocean with the subsequent formation of carbonate



rocks (limestone, calcite, dolomite, etc.) and the build-up of the gas in the atmosphere.

Carbon dioxide is produced by biological respiration on land and in the ocean and by the burning of fossil fuels and living and dead biomass. It is interesting to note that the bulk of the burning of fossil fuels occurs in the industrialized or developed countries, while almost all of the biomass burning takes place in the Third World developing countries of South America, Africa, and Asia.

The Double Whammy of Deforestation

Deforestation by burning, a widespread practice in the world's tropical rain forests, adversely impacts the trace-gas composition of the atmosphere in two different ways. First, the burning of the tropical forests produces large amounts of carbon dioxide, carbon monoxide (CO), methane, and other trace gases that are the combustion products of biomass burning. Second, the tropical forest is an important sink, or repository, for carbon dioxide. Atmospheric carbon dioxide is incorporated into the living biomass via the process of photosynthesis, which in turn produces atmospheric oxygen.

Figure 3. The greenhouse effect results from the fact that the atmosphere is transparent to incoming solar radiation, but absorbs and reemits infrared radiation emitted at the surface. This effect is made stronger by increasing concentrations of water vapor, carbon dioxide, nitrous oxide, and methane. (Earth Systems Sciences Committee, NASA, 1988)

to human health and survival, tropospheric ozone in high concentrations is a pollutant that is harmful to human, animal, and plant life.

In the troposphere, ozone is chemically formed from the combustion products of fossil fuel burning, including automobile exhaust gases, and the combustion products of biomass burning. Increasing trace gases in the troposphere, in addition to ozone, include carbon dioxide, methane, nitrous oxide, and the chlorofluorocarbons CFC-11 and CFC-12 (see figure 4). All six of these gases are greenhouse gases.

Water Vapor as a Greenhouse Gas

Water vapor is the most important atmospheric greenhouse gas. The water vapor concentration of the troposphere, where almost all of the water vapor in the atmosphere is located, is controlled by atmospheric temperature and the evaporation and condensation cycle. At present, atmospheric water vapor concentrations do not appear to be changing as a result of human activities.

Carbon Dioxide as a Greenhouse Gas

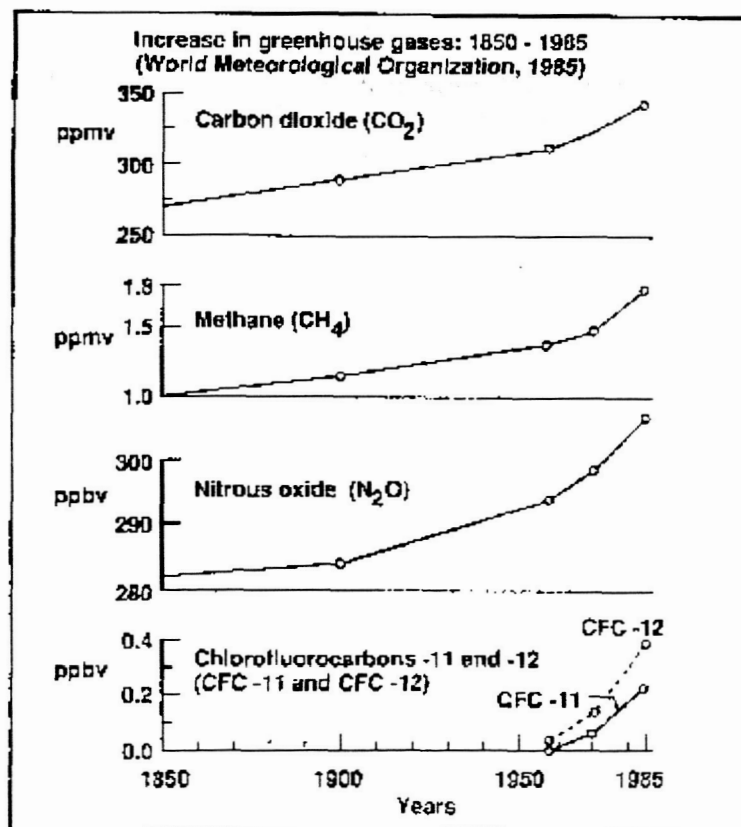


Figure 4. The increase in atmospheric concentrations of greenhouse gases from 1850 to 1985. (World Meteorological Organization, 1985)

After water vapor, carbon dioxide is the most important greenhouse gas. The surface concentration of carbon dioxide is about 350 ppmv. Measurements indicate that carbon dioxide is increasing by about 0.5 percent per year.

Ozone Update

In October 1991, the most recent assessment of stratospheric ozone, entitled the Scientific Assessment of Stratospheric Ozone—1991, was finalized. The study was coordinated by the United Nations Environmental Program (UNEP), the World Meteorological Organization (WMO), the United Kingdom Department of the Environment, the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA). The report of the results and implications of this study is just now coming out. Because of the timeliness of this new scientific assessment and its relevance to this article, I have excerpted the following major points from the executive summary.

EXCERPTS FROM THE EXECUTIVE SUMMARY

Latest Assessments

Global Ozone Decreases: Ground-based and satellite observations continue to show decreases of total column ozone in winter in the northern hemisphere. For the first time, there is evidence of significant decreases in spring and summer in both the northern and southern hemispheres at middle and high latitudes, as well as in the southern winter. No trends in ozone have been observed in the tropics. These downward trends were larger during the 1980s than in the 1970s. The observed ozone decreases have occurred predominantly in the lower stratosphere.

Polar Ozone: Strong Antarctic ozone holes have continued to occur and, in four of the past five years, have been deep and extensive in area. This contrasts to the situation in the mid-1980s, where the depth and area of the ozone hole exhibited a quasi-biennial modulation. Large increases in surface ultraviolet radiation have been observed in Antarctica during periods of low ozone. While no extensive ozone losses have occurred in the Arctic comparable to those observed in the Antarctic, localized Arctic ozone losses have been observed in winter concurrent with observations of elevated levels of reactive chlorine.

Ozone and Industrial Halocarbons: Recent laboratory research and re-interpretation of field measurements have strengthened the evidence that the Antarctic ozone hole is primarily due to chlorine- and bromine-containing chemicals. In addition, the weight of evidence suggests that the observed middle- and high-latitude ozone losses are largely due to

chlorine and bromine. Therefore, as the atmospheric abundances of chlorine and bromine increase in the future, significant additional losses of ozone are expected at middle latitudes and in the Arctic.

Implications for Policy Formulations

The findings and conclusions of the research of the past few years may have several major implications on policy decisions regarding human-influenced substances that lead to stratospheric ozone depletions and to changes in the radiative forcing of the climate system.

Continued Global Ozone Losses: Even if the control measures of the amended Montreal Protocol (London, 1990) were to be implemented by all nations, the current abundance of stratospheric chlorine (3.3–3.5 ppbv) is estimated to increase during the next several years, reaching a peak of about 4.1 ppbv around the turn of the century. With these increases, the additional middle-latitude ozone losses during the 1990s are expected to be comparable to those observed during the 1980s, and there is the possibility of incurring wide-spread losses in the Arctic. Reducing these expected ozone losses requires further limitations on the emissions of chlorine- and bromine-containing compounds.

Approaches to Lowering Global Risks: Lowering the peak and hastening the subsequent decline of chlorine and bromine levels can be accomplished in a variety of ways, including an accelerated phase-out of controlled substances and limitations on currently uncontrolled halocarbons.

Elimination of the Antarctic Ozone Hole: If all nations were to fully comply with the phase-out schedule of the amended Montreal Protocol, and if all uses of hydrochlorofluorocarbons (HCFCs) [hydrogen-containing CFCs that are more chemically active and hence shorter-lived than other CFCs] were discontinued, then it is estimated that stratospheric chlorine abundances would return to 2 ppbv sometime between the middle and the end of the next century. This is the level at which the Antarctic ozone hole appeared in the late 1970s and hence, is the level that is considered necessary (assuming other conditions are constant, including bromine loading) to eliminate the ozone hole. Such levels could never have been reached under the provisions of the original Protocol (Montreal, 1987).

The statistics on the loss of the world's tropical rain forests are staggering. Less than 60 percent of the originally forested land in the tropics remains. Most of the destruction of the tropical forests by burning has taken place in the last 30 years. Deforestation rates are about 28 million acres a year, or about 50 acres a minute. At that rate, what remains

not precisely known. For one thing, there is very little information available on the type and concentration of gases produced by biomass burning in the rest of the world's very diverse ecosystems, such as midlatitude and northern latitude forests and wetlands. A recent report by the National Academy of Sciences indicates

of the world's tropical rain forests could be reduced by half in less than 50 years and be totally gone within 100 years.

The amount of carbon dioxide and other trace gases produced during biomass burning on a global scale is

about 1.7 ppmv. Atmospheric measurements indicate that methane is increasing about 1.0 percent per year. Most methane is produced by microorganisms in anaerobic, oxygen-deficient, environments. The major global sources of methane are wetlands, swamps, and rice paddies (all strongly anaerobic environments). Other major sources of methane are enteric fermentation in cattle, natural gas and mining losses, and biomass burning.

Unlike carbon dioxide, methane is chemically active in both the troposphere and stratosphere. In the troposphere, the reaction between methane and the hydroxyl radical (OH) leads to the chemical production of ozone, which is a greenhouse gas.

In the stratosphere, methane is an important source of water vapor. The hydroxyl radical formed from the chemical transformation of water vapor leads to the destruction of stratospheric ozone. On the other hand, methane reactions also decrease the effectiveness of chlorine and nitric oxide in the destruction of stratospheric ozone.

Possible Effects of Greenhouse Gases

Theoretical calculations of climate change are often made by using computer models that project the effect of the increasing concentrations of greenhouse gases. It should be emphasized that the climate is a very complex and not completely understood system that is controlled and regulated by incoming solar radiation, outgoing Earth-emitted radiation, clouds, the oceans, and the evaporation and precipitation cycle, as well as by atmospheric greenhouse gases.

Temperature Increases Caused by Greenhouse Gases

Theoretical climate calculations indicate that a doubling of atmospheric carbon dioxide could increase the global average equilibrium surface temperature of our planet between 1.5°C and 4.5°C and that a doubling of atmospheric methane could increase the equilibrium

that biomass burning may cover as much as 5 percent of the total land area of our planet each year.

Methane as a Greenhouse Gas and Ozone Depleter

Another carbon-containing greenhouse gas is methane. The surface concentration of methane is

Polar Warming and Rising Sea Levels

According to these theoretical calculations, a surface temperature increase of only 1°C or 2°C at midlatitudes could result in a heating of the polar regions several times greater. This would happen because the melting of polar ice and snow would expose the underlying land or ocean, which do not reflect the Sun's rays as well as highly reflective ice and snow. The greater absorption of solar radiation would amplify the temperature increase in these ice- and snow-covered regions.

Because heating results in both the thermal expansion of seawater and the melting of polar ice and snow, a temperature increase could result in a rise of the world's oceans by a foot or more by the year 2050. Such a rise in sea level would threaten the homes of tens of millions of people worldwide.

Further Information

This is a general presentation that can be used as a background to prepare units for all levels of students. If you need a more detailed description of the chemical reactions involved in ozone destruction, write to Science Activities for a photocopy of "The Chemistry of Ozone Destruction," an unpublished appendix to this article.

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surface temperature of the Earth between 0.2°C and 0.4°C. Similar calculations indicate that a doubling of atmospheric nitrous oxide could increase the equilibrium surface temperature between 0.3°C and 0.4°C and an increase of CFC-11 and CFC-12 to 2 ppbv each could increase the equilibrium surface temperature by about 0.3°C for each gas. A 50-percent increase of ozone in the troposphere could lead to an increase in surface temperature of about 0.3°C.

These calculations indicate that as a result of the increasing atmospheric levels of the greenhouse gases, the mean global temperature of our planet will increase by at least 1°C per decade.

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