Global Change

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Summary

We all grumble about the weather - but - nothing is done about it.
Mark Twain

Nowadays, everybody is doing something about the weather but nobody is talking about it.
Stephen Schneider
Introduction

- Although the formation of the ozone hole and the development of the greenhouse effect share some similarities, the two are unrelated.
- The global response to these issues has been very different.

Welcome to the great climate experiment. Do you feel lucky? Over the past two centuries mankind has embarked on a global experiment in climate modification that may adversely affect natural systems all over the planet. Or it may not. The scale of the experiment is so large and the time involved so long that the basic parameters of the experiment are still being determined. Questions such as, Will increased cloud cover exaggerate or diminish global warming? Can technology provide us with a solution? Can nature correct this on its own or must we participate in the fix? have no easy answers. Meanwhile, we record the highest global temperatures on record and wonder if this is an omen of things to come or a random act of nature, part of the natural variation that is the climate cycle.

Although there had been long been speculation that our actions could alter global climate, it wasn't until the 1980s that the general public and national governments became fully aware of the close linkage between our actions and the state of this good Earth. In 1985, the British Antarctic Survey reported a marked thinning of the stratospheric ozone layer over the South Pole (Fig. 1). The same year, a conference of international scientists noted that future global warming was inevitable and would require international action.

Although ozone depletion and the global warming are separate environmental issues they share some common elements.

- Both are global in scale.
- Both are related to specific gases in the atmosphere, ozone in the stratosphere and carbon dioxide (and some other gases) in the troposphere.
- Both of the principal gases involved make up just a fraction of the atmosphere. The atmospheric concentration of carbon dioxide is approximately 370 parts per million; the concentration of ozone is measured in parts per billion.

Curiously, one of these large-scale environmental issues (ozone) received immediate attention and despite a host of
unknowns the international community forged an agreement (the Montreal Protocol on Substances that Deplete the Ozone Layer) and took concrete steps to address the problem. In contrast, the facts about the other issue (global warming) are still intensely debated by scientists, government agencies, industry and environmental groups. Most people in North America place their concerns with other environmental issues far ahead of global warming (Fig. 2). We have few firm commitments from nations for specific steps to mitigate potential warming. A contentious agreement, the Kyoto Protocol, is currently under debate and likely to be substantially overhauled before it is ratified by key governments. A lot of uncertainty exists in the minds of citizens of most nations over the potential future threat of global warming (Fig. 3).

The chapter begins with a description of the natural processes that are associated with ozone and the stratosphere. This section examines how ozone is concentrated in Earth's atmosphere and the constant breakdown and generation of ozone molecules that result from interaction with ultraviolet radiation. We discuss the natural variations in the thickness of the ozone layer with time and latitude to provide background for reviewing information on thinning of the ozone layer that follows. In both sections we also discuss how a manufactured gas (CFCs) was responsible for destruction of the ozone layer and why ozone depletion was concentrated over Antarctica. Finally, we examine the impact of the Montreal Protocol on CFC production and consider what the future holds for the global ozone layer.

Greenhouse gases and global change begins our analysis of global warming with some basic facts about the concentrations and role of carbon dioxide (and other greenhouse gases) in the atmosphere. We describe how recorded global temperatures have changed over the last century and discuss the apparent disparity between land- and satellite-based data on temperature change. Understanding of the impact of human activity on the planet's climate requires that we first comprehend how the natural system functions so we review human carbon emissions in the context of the global carbon cycle.

Any future adjustment of human activity to diminish greenhouse gas emissions will depend upon specific nations taking responsibility for a large share of existing and future emissions. The second section on global warming considers the
activities that result in the generation of greenhouse gases and their national sources. Greenhouse gases involve more than just carbon dioxide. Other gases that are present in smaller concentrations will remain in the atmosphere longer than carbon dioxide exaggerating their potential for warming.

It is increasingly clear that we can't turn the clock back to a time prior to the increase in carbon dioxide and other greenhouse gases. Global temperature records for the past century reveal an average rise of 1°F that obscures greater increases in some parts of the globe and little change elsewhere. Increasing temperatures are coupled with other examples of global climate change, including variations in global precipitation patterns and rising sea level. We can expect more of the same in the future but determination of the rate at which these changes may occur remains a research goal. A greenhouse world examines how the world might look if the predicted temperature changes of 2 to 4°C occur over the next century. Few of the changes are positive.
Ozone and the Stratosphere

- The ozone layer is located in the stratosphere.
- Reactions involving ozone, oxygen, and ultraviolet radiation continually destroy and create ozone in the stratosphere.
- The thickness of the ozone layer varies annually and seasonally.
- Ozone protects us from ultraviolet radiation that can cause skin cancer.
- Manufactured chlorofluorocarbons (CFCs) are responsible for the destruction of ozone.
- Ultraviolet radiation separates chlorine atoms from CFCs and the chlorine reacts with ozone to convert it to atmospheric oxygen.

Ozone and Ultraviolet Radiation

Earth's atmosphere is divided into four layers based upon their thermal characteristics (Fig. 4). The ground-level troposphere is overlain by the stratosphere, between ~10-50 km altitude. The stratosphere is enriched in ozone, a molecule made up of three oxygen atoms (O₃). In comparison, the more common atmospheric oxygen molecule (O₂) is made up of two oxygen atoms (O).

Figure 4. Four layers of the atmosphere are identified by their thermal characteristics. Orange line plots temperature vs. altitude.
Ozone is formed when ultraviolet (UV) radiation causes oxygen molecules to dissociate (break) into two oxygen atoms.

\[(i) \quad O_2 + UV \rightarrow O + O\]

Temperature increases upward in the stratosphere as ozone molecules concentrated in the upper two-thirds of the layer absorb ultraviolet radiation. The individual atoms combine with other oxygen molecules to form ozone molecules.

\[(ii) \quad O_2 + O \rightarrow O_3\]

Ozone molecules absorb harmful UV radiation and are themselves dissociated into an oxygen molecule and atom. Ultraviolet B radiation has the potential to cause health problems such as skin cancer. There are over half a million cases of UV-related skin cancers in the U.S. each year.

\[(iii) \quad O_3 + UV \rightarrow O_2 + O\]

The oxygen atom soon recombines with another oxygen molecule to form an ozone molecule [see equation (ii)]. The UV radiation is converted from light to heat, causing temperatures to rise with increasing altitude in the stratosphere. There is no long-term change in the volume of ozone as a new ozone molecule is formed at the end of this reaction series. (For more on the four layers of the atmosphere, see The Structure of the Atmosphere section in the chapter, the Atmosphere.)

Natural Variations in Ozone Thickness

The thickness of the ozone layer is measured in Dobson units (DU). A layer of ozone 1 Dobson unit thick would be equivalent to a thickness of 0.01 mm at 0°C at air pressures typical of Earth’s surface (~1,000 millibars or 1 atmosphere). The average thickness of the ozone layer over the U.S. is ~300 DU.

To accurately evaluate the significance of changes in the thickness of the ozone layer we must understand annual and seasonal variations in layer thickness. Natural variations in the thickness of the ozone layer are linked to variations in solar radiation reaching Earth.
The longest record of ozone measurements is from Arosa, Switzerland, where measurements began in the 1920s (Fig. 5). Yearly averages at this site have fluctuated between 300 and 360 DU but have declined since the 1970s. The highest ozone values are recorded in the spring, the lowest in the fall. Seasonal variations in ozone thickness at Arosa range from 280 to 375 DU. The ozone layer has nearly constant thickness (~260 DU) at the tropics but becomes thicker and subject to larger seasonal variations at higher latitudes (Fig. 6).

CFCs and Ozone Depletion

In June 1974, scientists F. Sherwood Rowland and Mario Jose Molina, published an article in the journal *Nature* that suggested that the use of manufactured group of gases known as **chlorofluorocarbons** (CFCs) was resulting in depletion of the ozone layer. Rowland and Molina (with Paul Crutzen) received the Nobel Prize in chemistry (1995) for their work. CFCs are volatile organic compounds (e.g., Freon) that were first discovered by Du Pont in 1928 and were subsequently

Figure 5. Graph of thickness of ozone layer above Arosa, Switzerland from 1926 to 1992. Graph courtesy of U.S. EPA’s Science of Ozone depletion website.

Figure 6. Variations in ozone thickness with latitude for three U.S. locations, 1998. Measurements taken at the midpoint of each month. Ozone thickness increases with latitude but all locations show some seasonal variations.
widely adopted as aerosol propellants and refrigerants in the
1950s. The U.S. banned aerosol sprays with CFCs in 1978 and
phased out the production of CFCs (replacing them with less-
destructive HFCs and HCFCs) by January 1, 1996.

There are several different types of CFCs but all are inert, that
is, they do not react with other gases in the atmosphere.
Consequently, they remain in the atmosphere for periods of 20
to 200 years, depending on the type of CFC. CFCs can be
broken down into their constituent parts by UV radiation (a
process known as photolysis). Individual chlorine atoms, freed
by photolysis, remain in the stratosphere to destroy thousands
of ozone molecules by the following steps.

1. UV radiation separates chlorine atoms from CFCs in
   Earth’s atmosphere.

2. The chlorine (Cl) atom reacts with ozone to form chlorine
   monoxide (ClO) and oxygen.

   (i) \( \text{Cl} + \text{O}_3 \rightarrow \text{ClO} + \text{O}_2 \)

3. Free oxygen atoms strip the oxygen from the chlorine
   monoxide to form another oxygen molecule and chlorine.

   (ii) \( \text{ClO} + \text{O} \rightarrow \text{O}_2 + \text{Cl} \)

4. The free chlorine atom repeats step 2. This sequence is
   repeated approximately 100,000 times for each chlorine
   atom.

Approximately 80% of the chlorine in the atmosphere comes
from manufactured compounds (CFCs) and 20% comes from
natural sources (volcanic eruptions, wildfires, seawater). The
total volume of stratospheric chlorine has increased by
approximately 4 times since the 1950s.

Think about it . . .

Draw a concept map that illustrates the relationship among
ozone, oxygen, CFCs, chlorine, and ultraviolet radiation.
Thinning of the Ozone Layer

- The ozone "hole" is actually an area over Antarctica where the ozone layer is significantly thinner than normal.
- Thinning is greatest over Antarctica because of unique weather conditions.
- Thinning occurs elsewhere but is much less than that observed at the South Pole.
- The Montreal Protocol represents an international agreement to phase out the use of CFCs worldwide.
- The rate of increase of CFC-11 in the atmosphere has recently been halted.
- Chlorine levels in the atmosphere are beginning to decrease in some locations.
- Ozone levels over Antarctica will not return to normal for another ~50 years.

There is no actual "hole" in the ozone layer, there is no location where ozone is completely absent in the stratosphere. However there are several locations where there has been a substantial reduction in the thickness of the layer.

Dramatic thinning of the ozone layer over the South Pole has been dubbed the ozone "hole" by the media. A reduction in thickness of the ozone layer beyond expected natural variations was first reported above Antarctica in 1985 and the thinning has become more pronounced. Examination of atmospheric records suggests that the "hole" began to grow in the late 1970s.

The size of the "hole" has gradually increased in size (Fig. 7). The present area of dramatic thinning covers all of Antarctica and parts of adjoining oceans. Recent research has shown that...
during October, when it is spring in the Southern Hemisphere, the ozone layer thickness declines to a minimum thickness of \(~100\) DU above Antarctica (Fig. 8), down from \(~320\) DU in the late 1950s. Such dramatic thinning is too great to be accounted for by annual or seasonal variations.

Why Is the Ozone "Hole" over the South Pole?

The bulk of CFCs are produced and used in the Northern Hemisphere so it might be unexpected that the greatest thinning of the ozone is over the unpopulated ice-covered South Pole. The reasons for the location of the "hole" are related to the unique weather patterns that are associated with Antarctica.

- The ozone hole occupies the polar vortex, a near-circular high-pressure system that isolates the atmosphere over Antarctica.
- Temperatures in the vortex are below \(\sim -80^\circ C\) and lead to the formation of polar stratospheric clouds composed of nitric acid and water.
- Chlorine compounds in the stratosphere react with cloud particles to release the chlorine needed to destroy ozone molecules.
- The absence of polar stratospheric clouds elsewhere results in much less ozone loss.

Declines in ozone thickness are also recognized above North America and Europe (Fig. 9). However the magnitude of thinning is substantially less than over Antarctica (less than 10% vs \(~70\%)\).

Figure 8. Graph of average ozone thickness measured near the South Pole. Note that these values will be higher than the absolute minimum value measured on a given day. Despite the annual fluctuations, there is a clear decline in thickness with time. Image from the NOAA Climate Modeling and Diagnostics Laboratory's (CMDL) South Pole Ozone Program website.
Our Ozone Future

Production of the more common types of CFCs (e.g., CFC-11) has decreased in recent years and this has been reflected in stabilization of CFC levels in the atmosphere (Fig. 10). CFC production in the developed world was halted by an international agreement known as the Montreal Protocol that required phasing out the manufacture of CFCs by 1996. Developing nations were given more time to stop production because their efforts represented a small proportion of global production and they had less access to alternatives. The decline in CFC production began approximately a decade ago and has been mirrored by a decrease in the concentrations of atmospheric chlorine and various CFCs.

It will take a few more years for the lower concentrations of chlorine to reach the stratosphere where they will cause less ozone destruction than occurs presently. Global CFC production has already dropped by more than 50% from its
peak of over a million tons in 1988 and ozone levels over Antarctica are expected to return to normal levels around the middle of the next century.

Several new coolants (hydrochlorofluorocarbons, HCFCs; hydrofluorocarbons, HFCs) have replaced CFCs. HFCs have no impact on the ozone layer and HCFCs have only limited ability to deplete ozone because they have a much shorter residence time in the atmosphere than CFCs. For example, HCFC-141b remains active for seven years, in contrast to the 60-year life span of CFC-11.

Think about it . . .
Use the URL below to visit NASA's Total Ozone Mapping Spectrometer's site (URL below) and determine the thickness of the ozone layer over your house using maps or latitude and longitude values.
(http://jwocky.gsfc.nasa.gov/teacher/ozone_overhead.html)

Greenhouse Gases and Global Change

- The volume of greenhouse gases has increased since the industrial revolution.
- Increasing volumes of greenhouse gases promotes warming of Earth.
- Global temperatures have increased by 1°F over the last century.
- Carbon is present in the atmosphere, biosphere, oceans, and rocks.
- Approximately half of the anthropogenic carbon dioxide is added to the atmosphere.
- Forests represent "sinks" that have the potential to absorb excess greenhouse gases.

Although there is some debate on the rate and severity of global warming, the basic science behind the warming hypothesis is solid and reveals two clear facts:
The concentration of a number of greenhouse gases, principally carbon dioxide, has steadily and measurably increased in the atmosphere over the last two centuries. Carbon dioxide levels have increased by about a third since the Industrial Revolution (Fig. 11) and are now higher than at any other time in the almost the last half million years.

- Greenhouse gases (water vapor, carbon dioxide, methane, nitrous oxide, CFCs) in the lower atmosphere trap heat reflected from Earth's surface, the greenhouse effect, warming the planet. (For more on the relationship between solar radiation and the greenhouse effect, go to the Solar Radiation and the Atmosphere section of the chapter, The Atmosphere.)

Average global temperatures, measured at hundreds of sites on Earth's surface over the last century show an increase of 1°F over the last century (Fig. 12). These readings were taken at ground level, at a range of latitudes, and over land and water. Some regions show increases of more than average, others are less. Greater increases are found in high-latitude regions, other areas near the equator show little change.

Scientists have collected evidence that shows that the 20th century was the warmest in the last millennium, the 1990s were the warmest decade, and 1998 was the warmest year in the last thousand years. An international agency, the Intergovernmental Panel on Climate Change (IPCC), has reviewed reams of climate data and has concluded that human activity has had a "discernable" influence on global climate over the last century. (For more on past climates see Climate History, and for more on how scientists determine how
Satellite measurements of temperatures in the atmosphere have been collected since 1979 and show no clear trend in changing temperatures (Fig. 12). The apparent contradiction between surface and atmospheric temperature data has provided ammunition for those who seek to cast doubt on the legitimacy of the science behind global warming. However, interpretation of the satellite data is complicated by ozone depletion which is thought to yield a cooling effect, and calibration problems with the satellites themselves as they slowly fall from orbit. Both surface and satellite data show a slight warming trend when corrections for the changes in satellite orbits are taken into account.

It is clear that greenhouse gases trap heat in the atmosphere and that the concentration of greenhouse gases has increased over the last century and that global temperatures have also increased during this time. However, before we can attempt to deal with the issue of controlling greenhouse gas emissions we must first understand how these gases (especially carbon dioxide) fluctuate naturally. If we can recognize how carbon dioxide and other gases are absorbed by natural systems we may be able to enhance those systems or at least prevent their destruction.

Figure 12. Changing average global temperature, 1850 to 1996, for surface readings and for atmosphere (satellite) measurements (1979-1996). Graph from U.S. EPA Global Warming website.
Global Carbon Cycle

Carbon is one of the most basic components in Earth’s climate system. It is present in a variety of forms in four reservoirs:

- **Atmosphere - as the gas carbon dioxide.** Carbon dioxide enters the atmosphere by breathing of animals (respiration) and weathering of rocks; CO₂ is removed because of photosynthesis by plants. Atmospheric carbon dioxide levels fluctuate annually. CO₂ levels are lower during the growing season when plants absorb the gas, and higher during the winter when plants are not growing (Fig. 13). The difference between seasons is most significant at high latitudes and is least obvious near the equator. Consequently, the degree of fluctuation in CO₂ levels varies with latitude.

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**Figure 13.** Seasonal fluctuations and annual trends in carbon dioxide concentrations in air samples collected from Barrow, Alaska (top, latitude 71 N), and Ascension Island, Atlantic Ocean (below, latitude 8 S). Seasonal fluctuations are greater (~10 ppm) in Barrow than on Ascension Island (~1-2 ppm). Both sites show a steady increase in carbon dioxide over the several decades. From Conway, T.J. and others, 1994. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.
• **Biosphere** – in organisms (plants, animals). Plants extract carbon dioxide from the atmosphere (photosynthesis) and animals eat the plants (and consume the carbon). Carbon is returned to the atmosphere when the organisms die or may be withheld from the cycle for millions of years if it is trapped in fossil fuel deposits (coal, oil).

• **Oceans** – as dissolved carbon dioxide. Marine organisms (e.g., plankton) extract carbon dioxide from ocean waters to form skeletons. The more productive the ocean, the more carbon will be accumulated. The accumulated skeletons eventually form sedimentary rocks (limestone) that trap the carbon within the rock layers.

• **Rocks** – as an element of calcium carbonate (limestone) and fossil fuel deposits. Limestone releases carbon dioxide to the atmosphere when it undergoes chemical weathering at Earth’s surface.

The volume of carbon in these reservoirs fluctuates in time and space but remained essentially constant on a global scale until the Industrial Revolution. With the addition of **anthropogenic** greenhouse gases - gases produced by human activity - these natural carbon dioxide reservoirs were required to absorb increased volumes of carbon dioxide. The principal sources of anthropogenic gases are fossil fuel consumption (transportation, electric utilities) and deforestation (Fig. 14). Anthropogenic greenhouse gases are absorbed in natural sinks with approximately half of the gases added to the atmosphere (the rest goes to the biosphere and oceans).

Just to maintain greenhouse gases at their present atmospheric concentrations would require that we either reduce greenhouse gas emissions by half or substantially increase the uptake of greenhouse gases in natural or artificial sinks. A 50% cut in global fossil fuel use (or deforestation) is unrealistic because it

![Figure 14. Sources and sinks of anthropogenic carbon dioxide emissions (billions of tons). Approximately half of the emissions are added to the atmosphere.](image-url)
would require substantial reductions in our use of electricity and personal transportation. Increases in atmospheric greenhouse gas concentrations are therefore inevitable, at least in the short term, but may be partially mitigated by expanding the role of natural sinks.

**Increased biological activity** in the oceans or on land could absorb some of the excess gases. Unfortunately, many of the world's most productive biological communities are the tropical rainforests that are in decline. An estimated 15 million hectares of tropical forests are lost each year worldwide. The creation of new forest areas is complicated by the competition for land from development and agriculture. Recent research suggests that increased carbon dioxide may promote plant growth that will in turn absorb more greenhouse gases. However, for increased growth rates to be sustained, plants will also require additional supplies of water and nutrients that may not be readily available. Additionally, the increased temperatures associated with global warming may act to hinder the growth of plants suited to cooler environments. Some scientists have suggested adding iron to the oceans to spur growth in marine planktonic organisms that extract carbon dioxide from marine environments. However, the idea of altering one part of the Earth system in an attempt to fix human-induced modifications in another part has received relatively little support and new research suggests that the story is more complex than it first appears.

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**Think about it . . .**

Draw and label a diagram that illustrates the components of the global carbon cycle. Show the links between sinks and sources for carbon in the different parts of the Earth system.
Greenhouse Gas Emissions

- The main greenhouse gases are water vapor, carbon dioxide, methane, halocarbons, and nitrous oxide.
- Global warming potential is a relative measure of the amount of heat a gas can trap.
- Anthropogenic greenhouse gases are produced by human activity.
- Most greenhouse gases are generated in the Northern Hemisphere.
- The U.S. produces nearly a quarter of global greenhouse gas emissions.

The principal greenhouse gases are water vapor, carbon dioxide (CO₂), methane, halocarbons (HFCs, including CFCs), and nitrous oxide. With the exception of water vapor, all are produced by human activities. Water vapor accounts for most of the natural greenhouse effect. The bulk (86%) of U.S. greenhouse gas emissions are from fossil fuel (oil, natural gas, coal) energy sources with the remainder supplied by industry, agriculture, and landfill gases such as methane (Fig. 15).

Global warming potential (GWP), the ability of gases to trap heat in the atmosphere, vary for different greenhouse gases. Individual molecules of methane, nitrous oxide, and HFCs trap more heat than a molecule of carbon dioxide but CO₂ is much more common in the atmosphere.

The amount of heat a gas can trap depends on the type of gas and the length of time it remains in the atmosphere. The atmospheric lifetimes for key greenhouse gases vary from 1 to 300 years. The GWP compares the amount of heat trapped by a greenhouse gas to the heat trapped by an equivalent volume of carbon dioxide over a specific period of time (100 years). Rapidly increasing nitrous oxide and HFC gases may represent a more significant component of greenhouse gases in the future (Fig. 16).
Greenhouse gas emissions vary with location. Gases are associated with human activities and are therefore concentrated where most people live. Global carbon emissions are equivalent to approximately 7 billion tons of carbon dioxide each year. The principal sources for this carbon are the developed nations that account for 73% of all carbon emissions, 22% coming from the U.S. alone (Fig. 17). The majority of carbon emissions for the last five decades occurred in the Northern Hemisphere between 30 to 60 degrees latitude and increased each decade. Global carbon dioxide emissions more than tripled from 1950 to 1990.
Early signs suggest that international goals of reductions in greenhouse gas emissions will be difficult to achieve. Many of the developed nations signed the Climate Change Convention at the "Earth Summit" in Rio de Janeiro in 1992. The nations pledged to try to return carbon emissions to 1990 levels by the year 2000.

Reductions only occurred where nations were making sweeping industrial reforms (e.g., shifting from coal to natural gas in electric utilities, U.K.) or shutting down underperforming energy-intensive government-run industries (e.g., Russia). Meanwhile, the developing nations are pushing hard to raise their economies by expanding their use of the same fossil fuels that got us into this mess in the first place. By the year 2035 it is estimated that China will have surpassed the U.S. as the world’s greatest producer of greenhouse gases.

Current trends suggest that atmospheric carbon dioxide levels will double by 2030 and may triple by 2100. Doubling of CO₂ concentrations would be delayed to 2100 if global emissions were frozen at current levels.

Global Climate Change

- Global data on temperature, precipitation, and sea level suggest Earth has been warming over the last century.
- Temperatures have increased by an average of 1°F.
- Precipitation has increased by 1% worldwide (5% in U.S.).
- Sea level has risen by 15 to 20 centimeters (6-8 inches) on average.
- Past climate records indicate that global temperatures can change rapidly, raising the possibility of catastrophic climate change.
- The impact of global change on society will largely depend on the rate of climate change.
Trends over the Last 100 Years

Several basic observations suggest that Earth is in the midst of a warming cycle, probably related to an increase in greenhouse gas concentrations in the atmosphere.

**Temperature**

The 10 hottest years on record have occurred since 1983, 7 in the last decade. Global average temperatures have increased by 1°F in the last century. Temperature increases are greater in higher latitudes than around the equator (Fig. 18). Temperatures have also risen faster at night than during the day.

A short-term cooling trend is apparent in the record of global temperatures for the early 1990s (Fig. 12). The cooling occurred when Mt. Pinatubo volcano erupted in the Philippines in 1991. **Sulfate particles** and other fine debris from the eruption were carried high into the atmosphere, blocking incoming solar radiation and producing a cooling trend that lasted until the debris fell to Earth.

Similar tiny sulfate particles (approximately 0.1 microns across) known as **aerosols** are produced by the combustion of fossil fuels in industrialized nations. Aerosols are a form of air pollution that contributes to acid rain. The pollutants have the same effect as the volcanic eruption; they diminish the warming effect for some industrialized nations, even producing a cooling effect in areas of heaviest air pollution (e.g., China), often associated with coal-burning power plants. Efforts to reduce air pollution will inevitably reduce these localized cooling effects. (For more on the role of fossil fuels in

![Figure 18. Map of global warming trends for the second half of the last century. Areas that have warmed are represented by red dots and cooled areas show blue dots. The size of the dots increases with temperature changes. Some of the areas that have cooled are located downwind from industrial centers. Map from U.S. EPA Global Warming website.](image-url)
generating air pollution see the Air Pollution section of the chapter, Energy and Air Pollution.)

Precipitation
Global precipitation has increased by an average 1% over land during the last century. Greatest increases are in the higher latitudes. U.S. precipitation has increased by 5% (Fig. 19) and precipitation in southern Canada has risen by 10 to 15%. Higher rainfall is associated with increased temperatures that result in greater evaporation from the oceans and supply more moisture for precipitation over continents.

Sea Level
The average sea level has increased by 15 to 20 cm worldwide in the last century. Much of this is related to the thermal expansion of surface ocean waters because of higher temperatures. The remainder is the result of melting glaciers and the transfer of groundwater to surface runoff following use.

The magnitude of sea level rise has been above average for some areas of the U.S. coastline (Fig. 20). Sea level has risen faster than average along the Gulf Coast (~50 cm) where land is subsiding as sea level rises. In contrast, sea level has actually fallen (relative to the land) along northern coastlines as the land is still rebounding upward following the removal of massive ice sheets at the end of the last Ice Age. Rising sea levels will have the greatest impact on the low-lying lands along the Atlantic and Gulf Coasts and least impact on the more rugged shorelines of the Pacific Coast.

Figure 19. U.S. precipitation trends since 1900. Red dots correspond to an increase in precipitation, larger dots represent larger increases. Blue dots indicate that precipitation decreased. Map from U.S. EPA Global Warming website.
Earth's history is one of cyclical fluctuations in climate over short and long time intervals. The switch between warm and cool periods of climate was thought to be a gradual one lasting at least for centuries but recent investigations of ice cores from Greenland and Antarctica have forced scientists to change that view. Temperatures surged at a rate of 7°C over a decade highlighting the dramatic end to a thousand-year cold snap (called the Younger Dryas) that marked the close of the last major Ice Age approximately 11,000 years ago.

One concern of climate scientists today is, Can we trigger such a rapid climate change through human activity? Is there a natural threshold that we may surpass, after which climate change becomes non-linear and catastrophic? (For more on how Earth's climate has changed through time, see Climate History in the chapter, Earth's Climate System.)

Think about it . . .
Use the Venn diagram found at the end of the chapter to compare and contrast the science of ozone depletion and global warming.
A Greenhouse World

- Current climate models predict an average increase in global temperatures by 3 to 4°F.
- Temperatures could increase by up to 20°F in some locations and decrease elsewhere.
- Climate models can recreate past climates with reasonable accuracy.
- Changing climate will cause changes in how society interacts with Earth, including changing water use patterns and modifications in land use.
- Developed nations failed to meet goals set at the Earth Summit to reduce greenhouse gases.
- New goals were agreed to in the Kyoto Protocol that will reduce greenhouse emissions by 6 to 8% below 1990 levels within the next 20 years.

It is unlikely that we will be able to substantially reduce anthropogenic greenhouse gas emissions in the near future. We must be prepared to adjust to environmental changes associated with a greenhouse world if we are unable to prevent increases in emissions. Therefore, it becomes important that we try to understand the potential changes that may occur.

Current climate models predict ~3 to 4°F average global temperature increase if the atmospheric carbon dioxide concentration doubles. However, this average value hides much greater increases in northern latitudes 10 to 20°F and potential cooling in high latitudes of the Southern Hemisphere.

Figure 21. Changes in global temperatures expected when carbon dioxide concentrations reach double their pre-industrial level. Map from former White House Climate Change website.
(Fig. 21). The tropics will exhibit the smallest change in temperatures.

How accurate are the most recent climate models? (Or how good are these predictions?) One way to evaluate their accuracy is to compare model predictions to the record of recent climates (1850-present) for which we have reliable observations. Such comparisons reveal first-order similarities between predictions and observations (Fig. 22). Differences between these values are substantially less than changes in temperature observed over the last century.

The consequences of rising temperatures vary considerably around the world and the exact details are difficult to determine for specific locations such as individual states. Furthermore, the impact will vary with the rate of warming and the resources a nation can make available to offset any negative consequences. However, some general patterns have been consistently identified by different models and these are briefly described below.

- Rising temperatures will increase evaporation and precipitation but the distribution of the extra rainfall will not be even around the globe. Middle latitudes are expected to become drier (e.g., much of the U.S.).
• Changing climate is expected to increase the severity and/or frequency of **storms and heat waves**, increasing structural damages and heat-related mortality rates.

• Consequences of a drier climate could alter the balance of water resources, including **lower river discharges** leading to less barge traffic and decreasing potential for generating hydroelectric power, and less water for agricultural and municipal users could result in changing land use patterns (e.g., less irrigation) and water rationing.

• Changing climate will result in **shifting ecosystems**. Vegetation would migrate northward with climate belts. Typical migration rates for trees such as oaks are measured in hundreds of feet per year. In contrast the average rate of temperature change is 3 km (2 miles) per year for a warming of 2°C per century. **Species extinction** rates will climb if ecosystems have insufficient time to adapt to the migration of climate belts.

• **Agricultural production** will increase in some regions and decrease in others, but is currently expected to show little change at a national scale. There would be reduced potential for grazing on some grasslands and **severe droughts** similar to the Dust Bowl may substantially reduce crop yields.

• Nations that rely on marginal agriculture to feed a large proportion of their population may be faced with famine and the exodus of refugees because of drought conditions. In contrast, nations at higher latitudes will enjoy **longer growing seasons**.

• Warmer conditions may impact human health by allowing **tropical diseases** (e.g., malaria) to become prevalent at higher latitudes.

• **Global sea levels will rise** by at least 20 centimeters (8 inches) over the next century causing coastal flooding, especially in association with more frequent hurricanes.

**What Can Be Done?**

Less than 20 years ago, governments forged an international agreement, the Montreal Protocol, to combat the threat of global-scale climate changes resulting from the destruction of Earth's ozone layer. Today we are again faced with a potential threat to global climates but the source is not a relatively minor group of chemicals such as CFCs but is the lifeblood of the
world's major economies, fossil fuels. Any solutions to this problem will require more dramatic action than the relatively limited steps of the Montreal Protocol.

International policy makers met in Kyoto, Japan, in December 1997 to attempt to take some tentative steps toward a global agreement to battle the threat of global warming. The resulting **Kyoto Protocol** included an agreement among the developed nations to reduce greenhouse emissions to 1990 levels by 2008-2012, and 6 to 8% below those levels in the five years that followed (6% for Japan, 7% for U.S., 8% for nations of the European Union). For the Protocol to go into effect it had to be ratified by countries that account for 55% or more of global carbon dioxide emissions (for 1990) of developed countries. U.S. ratification of the treaty would have required the acceptance of the Senate.

The Bush administration made it clear early in its tenure that it would not support the Kyoto Protocol nor would it make any effort to regulate carbon dioxide emissions from power plants. A revised, weaker version of the protocol was supported by delegates from 180 nations in Bonn, Germany, in July 2001. The U.S. opted out of the new version of the treaty.

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**Think about it . . .**

What are some of the potential actions that could be taken to diminish the impact of global warming? Consider how you would answer the questions below if you were a member of each of the groups on the list that follows:

1. Consider how global warming might impact your group or how your group might impact global warming.
2. Identify steps that your group could take to diminish its impact on global warming or cite reasons that would encourage others to change their habits to reduce harm to your group.

- A major oil company
- A utility that burns coal to generate electricity
- A large car manufacturing company
- A national insurance company
- A small island nation with an average elevation of 1 meter
- A heavily populated developing nation (e.g., India)
- A developed nation with a high standard of living (e.g., U.S., Japan)
- A family of four with two vehicles.
Summary

1. Compare and contrast the ozone "hole" and the greenhouse effect.
Both are tied to global climate patterns, both are related to specific gases in the atmosphere (ozone is tied to chlorofluorocarbons; the greenhouse effect is tied to carbon dioxide). Concerns over ozone depletion resulted in the rapid phaseout of chlorofluorocarbons but there has been little action to curtail the use of fossil fuels, the primary source of carbon dioxide.

2. Where is the ozone layer located?
The stratosphere, lies between ~10 to 50 km altitude and is enriched in ozone, a molecule made up of three oxygen atoms.

3. How is ozone formed?
Ozone is formed when ultraviolet radiation causes oxygen molecules to break into individual oxygen atoms. The atoms combine with other oxygen molecules to form ozone molecules.

4. How is the thickness of the ozone layer measured?
The thickness of the ozone layer is measured in Dobson units (DU). A layer of ozone 1 Dobson unit thick is equivalent to a thickness of 0.01 mm at 0°C and air pressures typical of Earth’s surface.

5. How does ozone thickness vary naturally?
The longest record of ozone measurements is from Arosa, Switzerland, where yearly averages have fluctuated between 300 and 360 DU. The highest ozone values are recorded in the spring, the lowest in the fall. Seasonal variations in ozone thickness at Arosa range from 280 to 375 DU. The ozone layer has nearly constant thickness (~260 DU) at the tropics but becomes thicker and subject to larger seasonal variations at higher latitudes.

6. Why is destruction of ozone bad for people on Earth?
Ozone absorbs harmful ultraviolet B rays that would otherwise reach the Earth's surface causing health effects such as an increased frequency of skin cancer and perhaps decreasing crop yields.

7. What is the name of the chemical compound that destroys ozone?
Ozone is destroyed by chlorofluorocarbons (CFCs) volatile organic compounds (e.g., Freon) that have been used as refrigerants, aerosol propellants, and solvents.

8. How do these compounds destroy ozone?
UV radiation separates chlorine atoms from CFCs in Earth’s atmosphere. The chlorine (Cl) atom reacts with ozone to form chlorine monoxide (ClO) and oxygen. Free oxygen atoms strip the oxygen from the chlorine monoxide to form another oxygen molecule and chlorine.

9. Is there a hole in the ozone layer?
There is no location where ozone is completely absent in the stratosphere. Dramatic thinning of the ozone layer over the South Pole has been dubbed the ozone "hole" by the media. A reduction in thickness of the ozone layer beyond expected natural variations was first reported above Antarctica in 1985 and the thinning has since become more pronounced.

10. Where is thinning of the ozone layer greatest? Why?
The greatest thinning of the ozone is over the unpopulated ice-covered South Pole. The location of the "hole" is related to the unique weather patterns that are associated with Antarctica. The ozone hole occupies the polar vortex, a near-circular high-pressure system that isolates the atmosphere over Antarctica. Temperatures in the vortex are below –80°C and lead to the formation of polar stratospheric clouds composed of nitric acid and water. Chlorine compounds in the stratosphere react with cloud particles to release the chlorine needed to destroy ozone molecules.

11. Has the ozone layer above North America changed thickness?
Yes. Declines in ozone thickness are also recognized above North America and Europe. However, these are substantially smaller than the thinning over Antarctica.

12. What is the Montreal Protocol and what effect has it had on the ozone layer?
In 1987, many of the world's nations signed the Montreal Protocol, an agreement to reduce CFC production by half in the next 10 years. Later amendments to the agreement called for the total phaseout of CFC manufacturing in most developed nations by January 1, 1996.
13. How has the concentration of carbon dioxide in the atmosphere changed since the Industrial Revolution? The volume of carbon dioxide, methane, and other greenhouse gases in the atmosphere has increased since the Industrial Revolution. Concentrations of carbon dioxide have increased by 30%.

14. How has global temperature changed in the last century? Many of the world’s leading authorities on global warming are members of the Intergovernmental Panel on Climate Change which recently issued a report concluding that sufficient evidence now exists to prove that humans have had a "discernable" influence on climate. The report points to an increase in global temperatures by 1°F over the last century.

15. What are the principal elements of the global carbon cycle? Carbon dioxide enters the atmosphere by breathing of animals (respiration) and weathering of rocks. Plants extract carbon dioxide from the atmosphere (photosynthesis) and animals eat the plants (and consume the carbon). Carbon is returned to the atmosphere when the organisms die, or is trapped in fossil fuel deposits (coal, oil). Marine organisms extract carbon dioxide from ocean waters to form skeletons. The accumulated skeletons eventually form sedimentary rocks (limestone) that trap the carbon within Earth. Limestone releases carbon dioxide to the atmosphere when it undergoes chemical weathering at Earth’s surface.

16. Why does atmospheric carbon dioxide fluctuate seasonally? Carbon dioxide concentrations fall when plants absorb the gas during the growing season. Levels rise during winter when plants are not growing. The difference between seasons is most significant at high latitudes (except near poles where vegetation is rare) and is least obvious near the equator.

17. What are the common types of manufactured greenhouse gases? The principal greenhouse gases are water vapor, carbon dioxide, methane, halocarbons (HFCs, including CFCs), and nitrous oxide. With the exception of water vapor, all are produced by human activities.

18. What are the principal sources for greenhouse gases? The principal sources of global anthropogenic carbon dioxide emissions are fossil fuel use and deforestation. The bulk (86%) of U.S. greenhouse gas emissions are from energy sources with
the remainder supplied by industry, agriculture, and landfill gases (methane).

19. What is global warming potential?  
Global warming potential (GWP) represents the ability of gases to trap heat in the atmosphere. The GWP compares the amount of heat trapped by a greenhouse gas to the heat trapped by an equivalent volume of carbon dioxide over a specific period of time (100 years). The GWP for carbon dioxide is 1; for methane, 21; for nitrogen dioxide, 310; and for halocarbons it can be as high as 11,700.

20. How much of the world carbon emissions are generated by the U.S.?  
The principal sources for carbon dioxide are the developed nations which account for 73% of all carbon emissions, 22% from the U.S. alone.

21. What are anthropogenic greenhouse gases?  
Anthropogenic gas emissions are produced by human activity. The principal sources of anthropogenic carbon dioxide emissions are fossil fuel use and deforestation.

22. What happens to anthropogenic carbon dioxide?  
Greenhouse gases produced by human activity are absorbed by natural carbon dioxide reservoirs. The oceans and the terrestrial biosphere (mainly forests) soak up approximately half of the anthropogenic carbon dioxide, the remainder enters the atmosphere.

23. What is the evidence that global temperatures are increasing?  
The 10 hottest years on record have occurred since 1983. Global average temperatures have increased by 1°F in the last century.

24. How have aerosols affected global warming?  
Aerosols, tiny particles of sulfates generated primarily from industrial sources reflect incoming sunlight and therefore reduce solar radiation trapped by greenhouse gases.

25. How has precipitation changed during the last century?  
Global precipitation has increased by an average 1% over land during the last century. Higher rainfall is associated with increased temperatures that result in greater evaporation from the oceans.
26. How has sea level been affected by increasing temperatures?
The average sea level has increased worldwide. Much of this is attributed to the thermal expansion of surface ocean waters because of higher temperatures.

27. Why has sea level actually decreased in some parts of the U.S.?
Sea level has fallen (relative to the land) along northern coastlines because the land is still rebounding (rising) following the removal of massive ice sheets at the end of the last Ice Age.

28. How fast does climate change?
Recent data suggest that climate can change rapidly. Temperature change on Greenland approximately 500 years ago was about 1°C per 50 years, nearly four times as rapid as the rate of temperature increase over the last century. The North Atlantic Ocean temperature increased by more than 7°C over a decade at the end of the Younger Dryas cold interval at the close of the last ice age.

29. How will global temperatures change if carbon dioxide increases to double its preindustrial level?
Current climate models predict ~3 to 4°F average global temperature increase if atmospheric carbon dioxide concentration doubles. However, this average value hides much greater increases in northern latitudes 10 to 20°F and potential cooling in high latitudes of the Southern Hemisphere. The tropics will exhibit the smallest change in temperatures.

30. How accurate are current climate models in recreating past climate changes?
One way to evaluate their accuracy is to compare model predictions to the record of recent climates (1850-present) for which we have reliable observations. Such comparisons reveal first-order similarities between predictions and observations. Differences between these values are substantially less than changes in temperature observed over the last century.

31. What are some of the environmental consequences of global warming?
Rising temperatures will increase evaporation and precipitation. Some areas will have a drier climate because the effect of increased evaporation outweighs any increase in
rainfall. Middle latitudes are expected to become drier. Changing climate is also expected to increase the severity of storms. Changing climate will result in shifting ecosystems. Vegetation would migrate northward with climate belts. Species extinction rates will climb if ecosystems have insufficient time to adapt to the migration of climate belts. Nations that rely on marginal agriculture to feed large proportion of their population may be faced with famine and the exodus of refugees because of drought conditions.

32. What steps have been taken by world governments to try to reduce the impact of climate change?
The Kyoto Protocol (December 1997) represented an agreement among developed nations to reduce greenhouse emissions to 1990 levels by 2008-2012, and 6 to 8% below those levels in the five years that follow. The original agreement was altered to ensure broad international support in 2001 and it remains to be seen how effective it will be in reducing greenhouse gas emissions.
Venn Diagram: The Science of Ozone Depletion vs. Global Warming

Use the Venn diagram, below, to compare and contrast the similarities and differences between the science of ozone depletion and global warming.