11 Stratospheric Ozone and Global Warming

STRATOSPHERIC OZONE

The stratosphere contains approximately 97% of the ozone in the atmosphere, and most of it lies between 9–25 miles (15–40 km) above Earth's surface. Most ozone is formed over the tropics; however, slow circulation currents carry the majority of it to the poles. It also varies somewhat due to season, being somewhat thicker in the spring and thinner during the fall.

Ultraviolet Radiation

The sun emits a wide variety of electromagnetic radiation, including infrared, visible, and ultraviolet. Ultraviolet radiation can be subdivided into three forms: UVA, UVB, and UVC.

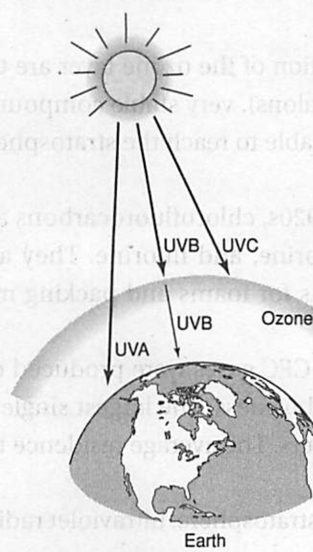


Figure 11.1 Ultraviolet radiation reaching Earth

UVA

UVA is closest to blue light in the visible spectrum and is the form of ultraviolet radiation that usually causes skin tanning. UVA radiation is 1,000 times less effective than UVB in producing skin redness, but more of it reaches Earth's surface than UVB. Birds, reptiles, and bees can see UVA since many fruits, flowers, and seeds stand out more strongly from the background in ultraviolet wavelengths. Many birds have patterns in their plumage (feathers) that are not visible in the normal spectrum (white light) but become visible in ultraviolet. The urine of some animals is also visible in the UVA spectrum.

UVB

UVB causes blistering sunburns and is associated with skin cancer.

UVC

UVC is found only in the stratosphere and is largely responsible for the formation of ozone.

OZONE DEPLETION

The ozone (O_3) layer is a belt of naturally occurring ozone gas that sits between 9–19 miles (15–30 km) above Earth and serves as a shield from the harmful ultraviolet B radiation emitted by the sun. Ozone is a highly reactive molecule and is constantly being formed and broken down in the stratosphere. There is widespread concern that the ozone layer is deteriorating due to the release of pollution that contains the chemicals chlorine and bromine.

Causes of Ozone Depletion

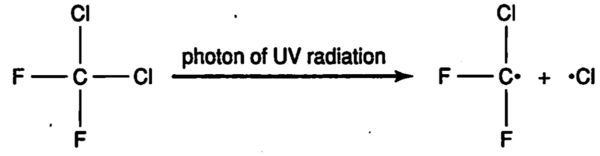
Thinning of the ozone layer was first discovered over Antarctica in 1986 due to the presence of extremely cold polar stratospheric clouds. Ozone depletion occurs seasonally (in the winter) and is due to the presence of both natural and human-made compounds that contain halogens (bromine, chlorine, fluorine, or iodine). Measurements indicate that the ozone over the Antarctic has decreased as much as 60% since the late 1970s, with an average net loss of about 3% per year worldwide.

The two main causes of degradation of the ozone layer are the presence of chlorofluorocarbons (CFCs) and halocarbons (halons), very stable compounds which, as a result of their chemical stability (persistence), are able to reach the stratosphere—there are no natural reservoirs of CFCs or halons in nature.

First manufactured during the 1920s, chlorofluorocarbons are nonflammable chemicals that contain atoms of carbon, chlorine, and fluorine. They are used in the manufacture of aerosol sprays, as blowing agents for foams and packing materials, as solvents, and as refrigerants.

By 1974, nearly 1 million tons of CFC gases were produced each year, and the chemicals were generating $8 billion worth of business. The largest single source of CFCs in the atmosphere is leakage from air conditioners. The average residence time for CFCs in the environment is 200 years.

When a CFC molecule enters the stratosphere, ultraviolet radiation causes it to decompose and produce atomic chlorine (Cl).



This atomic chlorine then reacts with the ozone in the stratosphere to produce chlorine monoxide (ClO):

$$Cl + O_3 \rightarrow ClO + O_2$$

The chlorine atom thus prevents the formation of ozone by sequestering oxygen atoms to form ClO. The chlorine monoxide then reacts with more ozone to produce even more chlorine in what essentially becomes a chain reaction:

$$ClO + O_3 \rightarrow Cl + 2O_2$$

Thus, one chlorine atom released from a CFC can ultimately destroy over 100,000 ozone molecules. Much of the destruction of the ozone layer that is occurring now is the result of CFCs that were produced many years ago since a CFC molecule takes about 8 years to reach the stratosphere, and the residence time in the stratosphere for a CFC molecule is over 100 years.

Halocarbons (halons) are organic chemical molecules that are composed of at least one carbon atom with one or more halogen atoms; the most common halogens in these molecules are fluorine, chlorine, bromine, and iodine, which are used as fire retardants (e.g., fire extinguishers), soil fumigants and pesticides (e.g., methyl bromide), solvents, and foam-blown insulation. The first synthesis of halocarbons was achieved in the early 1800s. However, production began accelerating when their useful properties as solvents and anesthetics, and their uses in plastics and pharmaceuticals, were discovered.

A large amount of the naturally occurring halocarbons are created by forest fires and other forms of biomass burning, volcanic activities, and marine algae, which produce millions of tons of methyl bromide annually. Bromine, which is found in much smaller quantities than chlorine, is about 50 times more effective than chlorine in its effect on stratospheric ozone depletion and is responsible for about 20% of the problem.

Effects of Ozone Depletion

During the onset of the 1998 Antarctic spring, a hole three times the size of Australia (over 3,500 miles [5,600 km] in diameter) developed in the ozone layer over the South Pole.

Harmful effects of increased UV radiation include:

- Increases in skin cancer
- Increases in sunburns and damage to the skin (premature aging)
- Increases in cataracts
- A reduction in crop production
- Deleterious effects on animals (since they don't wear sunglasses or sunscreen)
- A reduction in the growth of phytoplankton and the cumulative effect on food webs
- Increases in mutations, since UV radiation causes changes in the DNA structure
- Cooling of the stratosphere
- A reduction in the human body's immune system
- Climatic changes

Strategies for Reducing Ozone Depletion

Two of the most popular and current substitutes for CFCs are HCFCs (hydrochlorofluorocarbons) (e.g., Puron® is used as a refrigerant for air conditioners) and HFCs (hydrofluorocarbons). The main advantage that HCFCs and HFCs have over CFCs is that they are much less stable and more reactive with their additional hydrogen atom(s) (i.e., they can usually break down in the troposphere before reaching the stratosphere and destroying ozone). However, the disadvantage is that they have global warming greenhouse gas potentials up to 1,725 times greater than that of carbon dioxide.

Research is underway to find alternatives to the current use of HCFCs and HFCs. For example, Opteon®, the next-generation refrigerant and replacement for Puron®, has a greenhouse warming potential of 4, with virtually no effect on the ozone layer.

RELEVANT PROTOCOL

MONTREAL PROTOCOL: The Montreal Protocol is an international agreement designed to protect the stratospheric ozone layer. The treaty was originally signed in 1987 and stipulates that the production and consumption of compounds that deplete ozone in the stratosphere—carbon tetrachloride, chlorofluorocarbons (CFCs), halons, and methyl chloroform—were to be phased out by 2000. Nearly 97% of ozone-depleting chemicals have been phased out.

GLOBAL WARMING

When sunlight strikes Earth's surface, some of it is reflected back toward space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap the heat in the atmosphere.

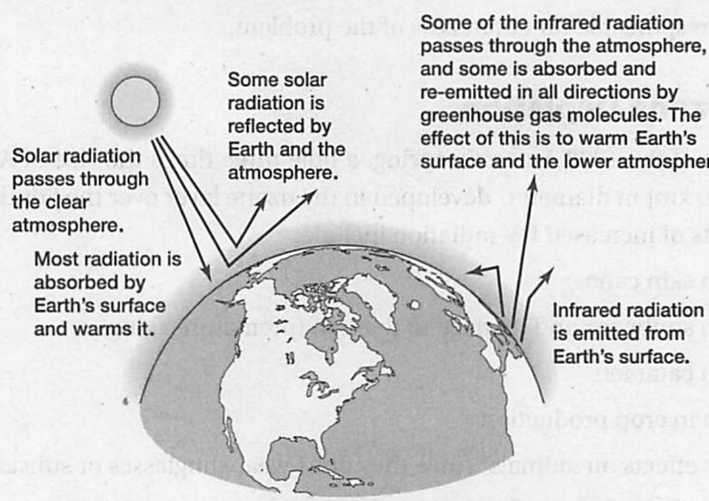
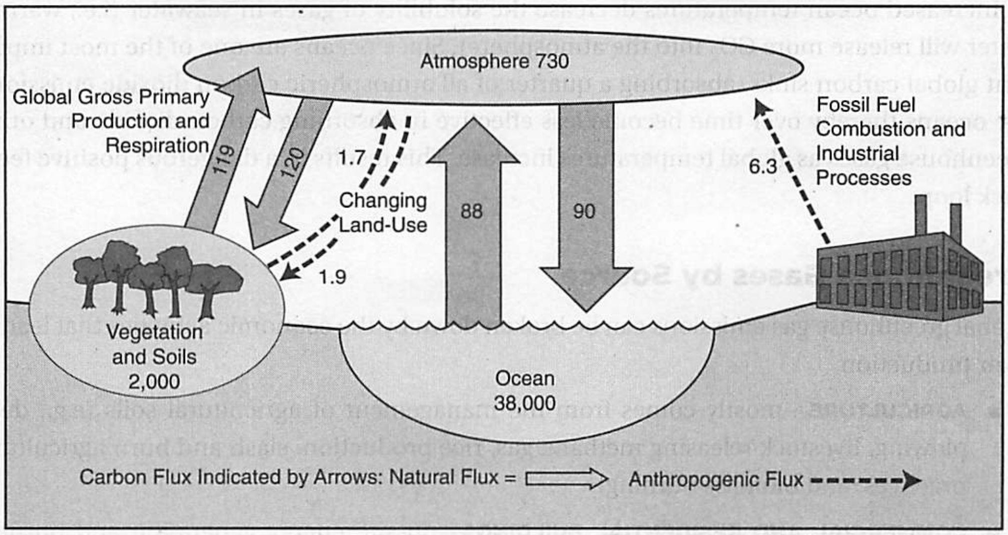


Figure 11.2 The greenhouse effect

Trends in Global Greenhouse Gas Emissions

The concentration of carbon dioxide in the atmosphere is naturally regulated by numerous processes that occur in the carbon cycle. The movement (flux) of carbon between the atmosphere and the land and oceans is naturally and primarily regulated by: (1) the intake of CO_2 during photosynthesis; and (2) being absorbed by seawater. However, these natural processes can absorb only about half of the net 6 billion metric tons of anthropogenic carbon dioxide emissions produced each year.



Source: Intergovernmental Panel on Climate Change

Figure 11.3 Global carbon cycle (billion metric tons carbon)

Figure 11.4 shows that for the past 2,000 years, the atmospheric concentrations of CO_2, CH_4, and N_2O—three important, long-lived greenhouse gases—have increased substantially since around the time of the beginning of the Industrial Revolution (approximately 1750), and the rates of increase in the levels of these gases has been dramatic. By analyzing gas bubbles in ice core samples, scientists discovered that CO_2, for instance, never increased more than 30 ppm during any previous 1,000-year period, but has already risen by 30 ppm in the past 20 years.

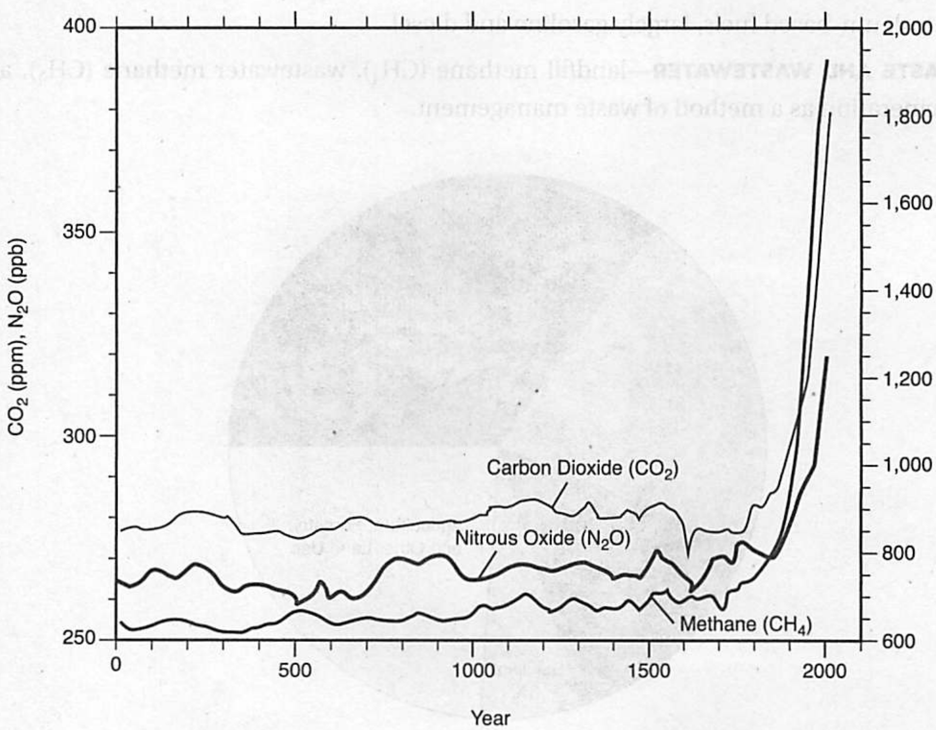


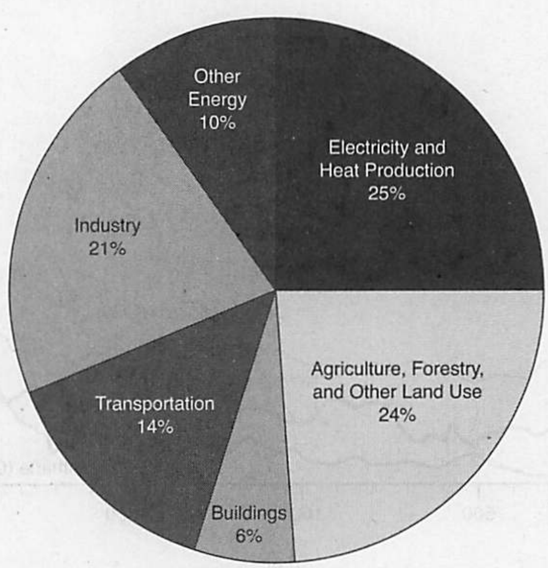
Figure 11.4 Atmospheric CO_2, CH_4, and N_2O concentrations over the last 2,000 years

Increased ocean temperatures decrease the solubility of gases in seawater (i.e., warmer water will release more CO_2 into the atmosphere). Since oceans are one of the most important global carbon sinks, absorbing a quarter of all atmospheric carbon dioxide emissions, the oceans thereby over time become less effective in absorbing carbon dioxide and other greenhouse gases as global temperatures increase. This results in a dangerous positive feedback loop.

Greenhouse Gases by Source

Global greenhouse gas emissions can be broken down by the economic activities that lead to their production.

- **AGRICULTURE**—mostly comes from the management of agricultural soils (e.g., deep plowing, livestock releasing methane gas, rice production, slash and burn agricultural practices, and biomass burning).
- **COMMERCIAL AND RESIDENTIAL BUILDINGS**—on-site energy generation and burning fuels for heat in buildings or cooking in homes.
- **ENERGY SUPPLY**—the burning of coal, natural gas, and oil for electricity and heat is the largest single source of global greenhouse gas emissions.
- **INDUSTRY**—primarily involves fossil fuels burned on-site at facilities for energy; cement manufacturing also contributes significant amounts of CO_2 gas.
- **LAND USE, LAND USE CHANGE, AND FORESTRY**—includes deforestation of old-growth forests (carbon sinks), land clearing for agriculture, strip mining, fires, and the decay of peat soils.
- **TRANSPORTATION**—involves fossil fuels that are burned for road, rail, air, and marine transportation; almost all (95%) of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel.
- **WASTE AND WASTEWATER**—landfill methane (CH_4), wastewater methane (CH_4), and incineration as a method of waste management.



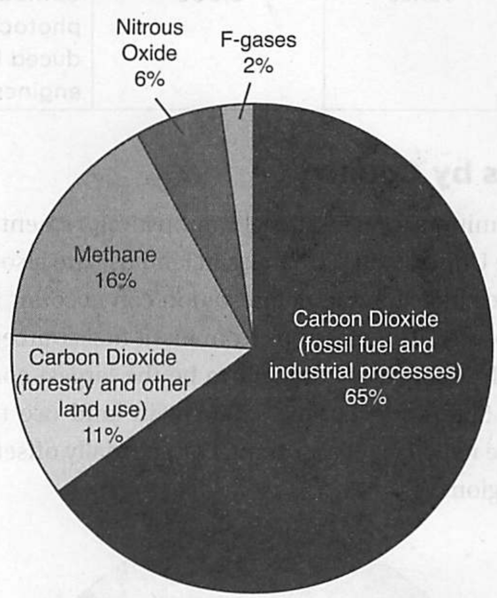
Source: U.S. Environmental Protection Agency (EPA)

Figure 11.5 Greenhouse gases by source

Greenhouse Gas Emissions by Gas

At the global scale, the key greenhouse gases emitted by human activities are:

- **CARBON DIOXIDE (CO_2)**—Fossil fuel use is the primary source of CO_2. The way in which people use land is also an important source of CO_2, especially when it involves deforestation. Land can also remove CO_2 from the atmosphere through reforestation and the improvement of soils.
- **METHANE (CH_4)**—Agricultural activities, waste management, and energy use all contribute to CH_4 emissions.
- **NITROUS OXIDE (N_2O)**—Agricultural activities, such as fertilizer use, are the primary sources of N_2O emissions.
- **FLUORINATED GASES (F-GASES)**—Industrial processes, refrigeration, and the use of a variety of consumer products all contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).
- **BLACK CARBON PM_X**—Black carbon is a solid particle or aerosol, not a gas, but it also contributes to the warming of the atmosphere.



Source: U.S. Environmental Protection Agency (EPA)

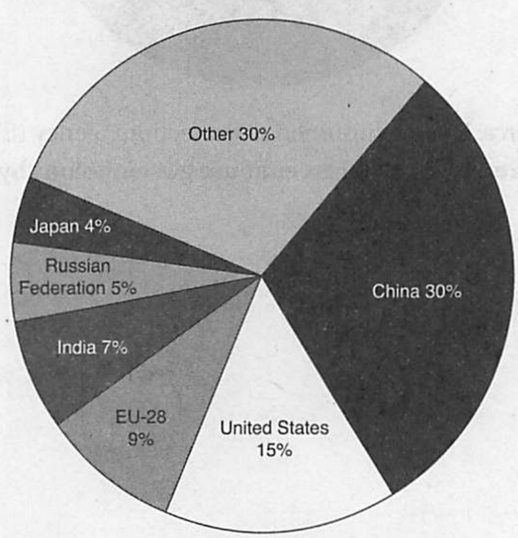
Figure 11.6 Annual greenhouse gas emissions by gas

Warming Potential of Various Greenhouse Gases

Greenhouse Gas	Average Time in Troposphere (Years)	Relative Warming Potential (CO_2 = 1)	Source
Carbon Dioxide (CO_2)	100	1	Burning oil, coal, deforestation, cellular respiration
Chlorofluorocarbons (CFCs)	15 (100 in stratosphere)	1,000–8,000	Air conditioners, refrigerators, foam products, insulation
Halons	65	6,000	Fire extinguishers
Methane (CH_4)	15	25	Rice cultivation, cattle/sheep raising, landfills, natural gas leaks, coal production
Nitrous Oxide (N_2O)	115	300	Burning fossil fuels, fertilizers, livestock wastes, plastic manufacturing
Sulfur Hexafluoride (SF_6)	3,200	24,000	Electrical industry as a replacement for PCBs
Tropospheric Ozone (O_3)	Varies	3,000	Combustion of fossil fuels, photochemical smog produced by internal-combustion engines

Greenhouse Gases by Country

The top carbon dioxide emitters from fossil fuel combustion, cement manufacturing, and gas flaring are China and the United States. Changes in land use are also significant contributors of CO_2 as global estimates indicate that deforestation can account for 5 billion metric tons of CO_2 emissions, or about 16% of emissions from fossil fuel sources. Tropical deforestation in Africa, Asia, and South America are thought to be the largest contributors to emissions. However, in the United States and Europe, changes in land use that are associated with human activities have the net effect of absorbing CO_2, partially offsetting the emissions from deforestation in other regions.

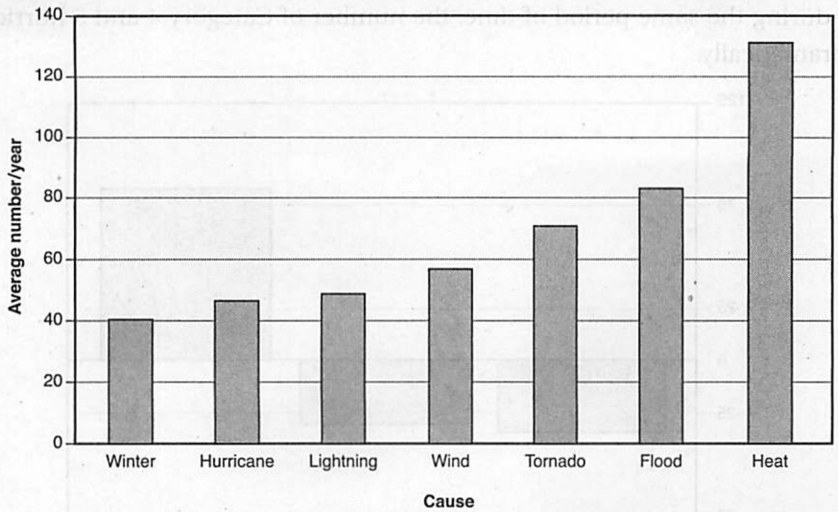


Source: U.S. Environmental Protection Agency (EPA)

Figure 11.7 Greenhouse gas emissions by country

IMPACTS AND CONSEQUENCES OF GLOBAL WARMING

Global warming affects the weather, the economy, and numerous other aspects of life.

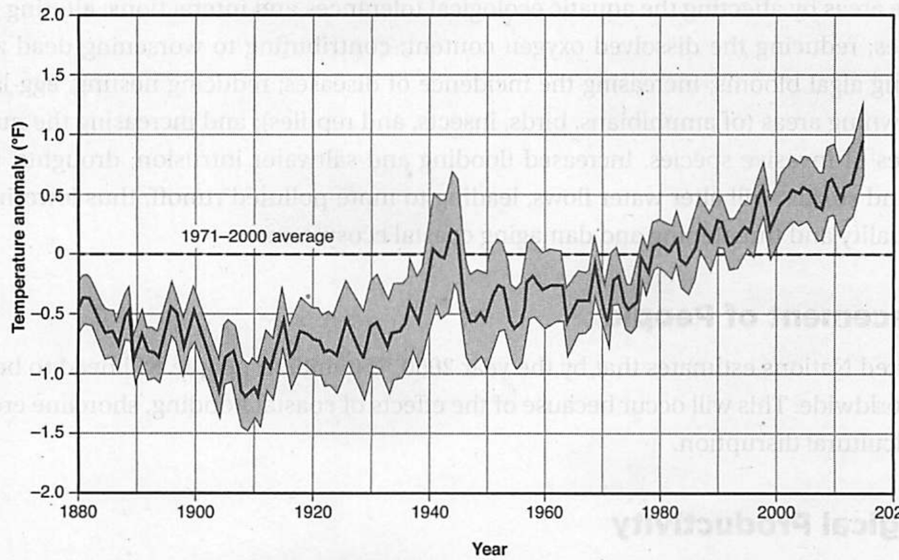


Source: U.S. National Weather Service

Figure 11.8 U.S. Weather Fatalities (average per year for 1986–2015)

Changes in Tropospheric Weather Patterns

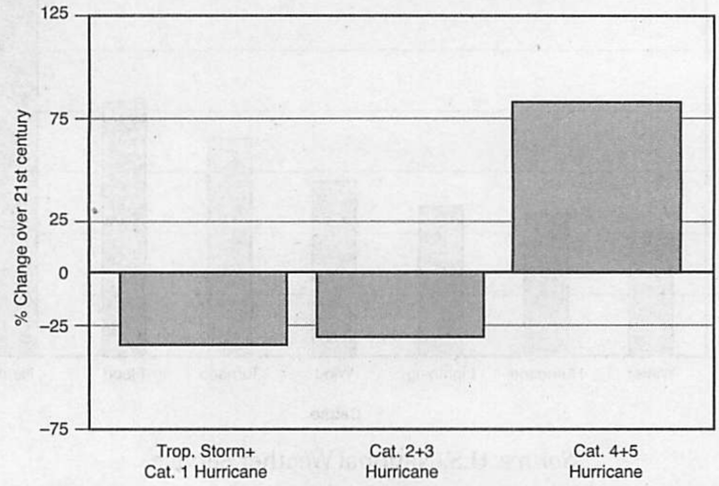
Air temperatures today average 5°F to 9°F (3°C to 5°C) warmer than they were before the Industrial Revolution. Higher average air temperatures may result in higher amounts of rainfall in many areas because of higher rates of evaporation and may also be accompanied by an increase in the frequency or severity of storms, increases in surface water and/or groundwater inputs, increases in sedimentation in bodies of water, increases in flooding and associated water runoff, and increases in the rate of aquifer recharge—all of which have a direct impact on the biodiversity of the biota in an area.



Source: U.S. Environmental Protection Agency (EPA)

Figure 11.9 Average global sea surface temperature

Worldwide, Category 4 or 5 hurricanes have risen from 20% of all hurricanes in the 1970s to 35% of all hurricanes in the 1990s. Computer simulations and projections for the 21st century show that the number of Category 1, 2, and 3 hurricanes in the Atlantic will diminish while, during the same period of time, the number of Category 4 and 5 hurricanes will increase dramatically.



Source: U.S. National Oceanographic and Atmospheric Administration (NOAA)

Figure 11.10 Projected changes in Atlantic hurricane frequency (2000–2100)

Coastal Ecosystems

Global warming has the potential to completely alter the structure and function of estuaries and coastal wetlands. Sea-level rise threatens to inundate many coastal wetlands, seriously affecting the biota, with little room to move inland because of coastal development. In the next 100 years, taking into account the ongoing sinking of land in some coastal areas, net sea-level rise could exceed six feet. Warmer water with potentially higher dissolved carbon dioxide levels, accompanied by a lower pH, will alter the species composition in these extremely sensitive areas by affecting the aquatic ecological tolerances and interactions; altering nutrient cycles; reducing the dissolved oxygen content; contributing to worsening dead zones; increasing algal blooms; increasing the incidence of diseases; reducing nesting, egg-laying, and spawning areas (of amphibians, birds, insects, and reptiles); and increasing the number and types of invasive species. Increased flooding and saltwater intrusion, droughts, hurricanes, and storms will alter water flows, leading to more polluted runoff, thus lowering the water quality and threatening and damaging coastal ecosystems.

Displacement of People

The United Nations estimates that by the year 2050, 150 million people will need to be relocated worldwide. This will occur because of the effects of coastal flooding, shoreline erosion, and agricultural disruption.

Ecological Productivity

Satellite photos have shown that ecological productivity in the Northern Hemisphere has increased since 1982. In the tropics, plants increase productivity more so than older trees (which are carbon sinks).

Forest Fires

Boreal forest fires in North America used to average 2.5 million acres (10,000 sq km). They now average 7 million acres (28,000 sq km). Current forest management practices may also be contributing to the increase.

Glacier Melting

The total surface area of glaciers worldwide has decreased 50% since the end of the 19th century. Glacier melting causes:

- Landslides
- Flash floods
- Glacial lake overflow
- Increased variation in the water flows into rivers
- The displacement of people (e.g., the Hindu Kush and Himalayan glacier melts are reliable water sources for people living in China, India, and much of Asia—without glacier melt, water for agriculture and hydroelectric production in these areas would be seriously impacted)

The main ice-covered landmass is Antarctica at the South Pole, with about 90% of the world's ice and 70% of its freshwater. Antarctica is covered with ice that is an average of about 7,000 feet (2,000 m) thick. If all of the Antarctic ice melted, sea levels around the world would rise about 200 feet (60 m).

At the North Pole, the ice is not nearly as thick as it is at the South Pole, and it floats on the Arctic Ocean. If it melted, sea levels would not be affected—remember, melting ice only raises the level of seawater if it does not float in the water. There is a significant amount of ice covering Greenland, which would add another 20 feet (7 m) to the oceans if it melted. Since Greenland is closer to the equator than Antarctica is, the temperatures are higher, so that ice is more likely to melt.

Compounding the problem of melting ice from land raising sea levels is the phenomenon of thermal expansion of water (as water get warmer, water molecules move further apart, increasing the ocean's volume).

Increase in Disease

In areas that experience wetter conditions due to global warming (i.e., an increase in evaporation and atmospheric water content), there are more areas that are suitable for mosquitoes to breed, which will increase the rates of malaria, dengue fever, Zika virus, and yellow fever. Warmer temperatures also allow many insects to:

- Have a longer breeding season
- Have access to more reliable food resources for a longer time period
- Not be subject to winter freezes that naturally tend to thin insect populations

Warmer water also promotes and increases bacterial activity in water supplies and may promote the spread of amoebic dysentery, cholera, and giardia.

In areas that experience drier conditions, due to changes in tropospheric weather patterns as a result of global warming, water stagnation becomes more common in riparian areas and results in higher water temperatures and associated bacterial counts. These conditions are conducive to an increase in mosquito and other disease-carrying vector populations.

Increase in Health and Behavioral Effects

Higher air temperatures have been proven to result in higher incidences of heat-related deaths caused by cardiovascular disease, heat exhaustion, heat stroke, hyperthermia, and diabetes. Furthermore, stress and the resulting rage brought on as by-products of increased air temperatures can dramatically affect human behavior. For example, projections show that an increase of just 2°F (1°C) would result in a dramatic increase in homicides and other serious crimes.

Increase in Property Loss

Weather-related disasters have increased threefold since the 1960s. Insurance payouts have increased fifteenfold (adjusted for inflation) during this same time period. Much of this can be attributed to people moving to vulnerable coastal areas.

Loss of Biodiversity

Arctic fauna will be most affected. The food webs of polar bears that depend on ice flows, birds, and marine mammals will be drastically affected. Many species have shifted their ranges toward the poles, averaging 4 miles (6 km) per decade, and bird migrations are averaging over 2 days earlier per decade. Grasses have become established in Antarctica for the first time. Many species of fish and krill that require cooler waters will be negatively affected, with major repercussions occurring within food webs. Decreased glacier melt, caused by dwindling glaciers, will also negatively affect migratory fish, such as salmon, that need sufficient river flow.

Loss in Economic Development

Money that was earmarked for education, improving health care, reducing hunger, and improving sanitation and freshwater supplies will instead be spent on mitigating the effects of global warming.

Ocean Acidification

Fossil fuel combustion and industrial processes release over 7 billion tons (6.5 billion m.t.) of carbon into the atmosphere each year. Ocean acidification occurs when CO_2 in the atmosphere reacts with water to form carbonic acid. The atmospheric concentration of CO_2 prior to the Industrial Revolution was 280 parts per million (ppm); in 2005, it had climbed to 379 ppm, about a 33% increase. Depending on the extent of future CO_2 emissions and other factors, the Intergovernmental Panel on Climate Change (IPCC) predicts that ocean acidity could increase by 150% by 2100.

Certain marine organisms (e.g., crustaceans, mollusks, reef-forming corals, and some species of algae and phytoplankton) are particularly vulnerable to small changes in the concentration of hydrogen ions (H^+) whose concentration is measured on the pH scale. These species, known as "marine calcifiers," all create skeletons or shells out of calcium carbonate ($CaCO_3$). When carbonate ions (CO_3^{2-}) combine with the hydrogen ions released by carbonic acid, they are rendered useless for shell-building organisms. The concentration of carbonate ions is expected to decline by half during this century due to increased atmospheric carbon dioxide levels.

Shells also dissolve in environments that are too acidic. In fact, some deep, cold ocean waters are naturally too acidic for marine calcifiers to survive, with these organisms only existing above a certain depth known as the "saturation horizon." As a result of ocean acidification, the saturation horizon is expected to move closer to the surface by 150–700 feet (50–200 m) than it was during the 1800s. The Southern and Arctic oceans, which are colder and therefore naturally more acidic, may become entirely inhospitable for these organisms. The bottom line is that many species will suffer from the loss of marine calcifiers, which provide essential food and habitat (including coral reefs) for countless marine organisms.

Range Shifts

As temperatures increase, the habitat ranges of many North American species are moving north and to higher elevations. In recent decades, in both land and aquatic environments, plants and animals are being found at higher elevations at a median rate of 36 feet (11 m) per decade and at higher latitudes at a median rate of 11 miles (18 km) per decade. While this means a range expansion for some species, for others it means movement into a less hospitable habitat, increased competition, or range reduction, with some species having nowhere to go because they are already at or near the top of a mountain or at the limit of land suitable for their habitat.

As rivers and streams warm, warm-water fish are expanding into areas previously inhabited by cold-water species. As waters warm, cold-water fish, including many highly valued trout and salmon species, are losing their habitat, with projections of 47% habitat loss by 2080. Range shifts disturb the current state of the ecosystem and can limit opportunities for fishing and hunting.

Collectively, the ranges of vegetative biomes are projected to change across 5%–20% of the land in the United States by 2100.

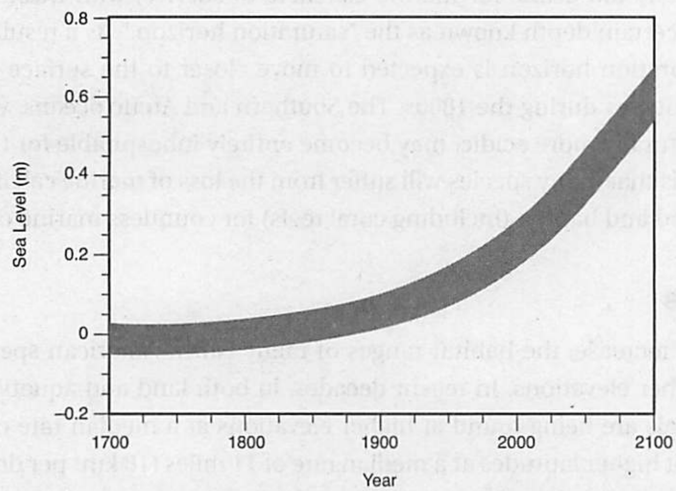
Releases of Methane from Hydrates in Coastal Sediments and Thawing Permafrost

Methane is a potent greenhouse gas that is about 20 times more effective per molecule than carbon dioxide is. The Arctic region is one of the many natural sources of methane. Arctic methane release is the release of methane from the seas and soils in permafrost regions of the Arctic, because of melting glaciers and global warming. This results in a positive feedback loop, as methane is itself a powerful greenhouse gas. Global warming accelerates its release, due to both the release of methane from existing stores and from rotting biomass. Large quantities of methane are stored in the Arctic in natural gas deposits, in permafrost, and as methane clathrates found on the seafloor. Permafrost and clathrates degrade upon warming. Thus, large releases of methane from these sources may arise as a result of global warming.

Rise In Sea Level

Sea levels have risen 400 feet (120 m) since the peak of the last ice age, 18,000 years ago. From 3,000 years ago to the start of the Industrial Revolution, the rate of sea level rise averaged

0.1 to 0.2 mm per year. However, from 1900 to today, the sea level has risen about 3 mm per year, over a tenfold increase. The IPCC predicts a global rise in sea levels by 20–40 inches (50–100 cm) by the year 2100, which would threaten the survival of coastal cities and entire island nations.



Source: International Panel on Climate Change—Geneva, Switzerland

Figure 11.11 Sea level rise (1700–projected 2100)

A significant rise in the sea level results in:

- Flooding in wetlands and estuaries, changing the salinity content of the water, the water depth, temperature, and light availability, which can seriously impact various life-forms that are unable to adapt
- Increased coastal erosion, which causes increased nutrient loads in the water
- Losses in fish and shellfish catches
- Waterlogging, which causes a loss of various plant species
- An increase in the number of storm surges, which causes personal property and infrastructure damage—this results in higher insurance premiums, a decrease in property values, and the cost of repair or relocation
- Oil spills that occur at sea, spreading further inland with serious repercussions to the biota and the economy
- The loss of cultural, recreational, and tourism resources, which causes a loss of livelihood and income
- Saltwater intrusion, which causes decreased aqua and agricultural production as well as the contamination of local water supplies

Slowing or Shutdown of Thermohaline Circulation

Glacial melting in Greenland would shift the saltwater-freshwater balance in the North Atlantic and would result in a decrease of heavier saline waters sinking than in traditional ocean circulation patterns. This would have significant effects on the fishing industry. Localized cooling in the North Atlantic, brought about through the reduction of thermohaline circulation currents (North Atlantic drift), could result in much colder temperatures in Britain and Scandinavia.

REDUCING CLIMATE CHANGE

Stabilizing the current global warming crisis would require:

- A decrease in methane emissions by 8%
- A decrease in nitrous oxide emissions by 50%
- A decrease in carbon dioxide emissions by up to 80%

The following table lists some examples of steps that can be adopted to mitigate the effects of global climate change in various sectors.

Steps That Can be Taken to Mitigate the Effects of Global Climate Change

Sector	Steps That Can Be Taken
Agriculture	- Introduce financial incentives (reduced taxes) for large agricultural corporations that institute standardized "good land management policies," such as increasing soil quality levels, utilizing conservation tillage techniques, reducing the use of water, and reducing the amount of inorganic, nitrogen-based fertilizers.
Buildings	- Require all public and private buildings to be insulated to a universal standard. - Institute a tax on all buildings found not to be in compliance with a universal, standardized level of insulation. - Require all appliances to be Energy Star® certified. - Give subsidies to homeowners and businesses who install photovoltaic solar systems.
Energy supply	- Reduce or eliminate government fossil fuel subsidies. - Introduce a "carbon tax" on nonrenewable energy sources.
Government	- Support treaties and protocols that require reductions in greenhouse gas emissions.
Industry	- Introduce federal tariffs on all imported products that do not meet energy-standard guidelines. - Institute sliding scale penalties based on carbon emissions.
Transport	- Increase vehicle miles per gallon regulations for both private cars and trucks with government penalties for miles driven using nonrenewable fuels. - Increase subsidies for public transportation. - Tax each parking space.
Waste management	- Require methane capture at all landfills.

PROTOCOLS AND AGREEMENTS

KYOTO PROTOCOL: The Kyoto Protocol is a plan created by the United Nations that tries to reduce the effects of climate change (i.e., global warming). The plan says that the 192 countries that have agreed to follow the Kyoto Protocol have to try to meet agreed-upon goals for reducing how much carbon dioxide and other greenhouse gases they release into the air. Countries with targets under the Kyoto Protocol have successively reduced their greenhouse gas emissions by over 20%, well in excess of the 5% target. The following countries have not ratified the Kyoto Protocol: Afghanistan, Andorra, Southern Sudan, Vatican City, Taiwan, and the United States.

PARIS AGREEMENT (2015): The Paris Agreement set out a global action plan to put the world on track to avoid dangerous climate changes. Traditionally, such pacts have required developed economies like the United States to take action to lower greenhouse gas emissions, but they have exempted developing countries like China and India from such obligations. The accord, which United Nations diplomats have been working toward for many years, changes that dynamic by requiring action in some form from every country, regardless of their current economic standing. Signing partners agreed to:

- A long-term goal of keeping the increase in the global average temperature to below 2°C above pre-industrial levels
- The need for global emissions to peak as soon as possible, recognizing that this will take longer for developing countries
- Undertake rapid reductions thereafter in accordance with the best available science

On June 1, 2017, U.S. President Donald Trump announced that the United States would cease all participation in the Paris Agreement, stating that a withdrawal would help American businesses and workers, especially those in the fossil fuel industry. The earliest withdrawal date for the United States cannot occur before November 4, 2020.

LOSS OF BIODIVERSITY

Information on habitat destruction needs to be compared with past habitat conditions. A long-term history of habitat conditions can be obtained from fossil records, ice core samples, tree ring analysis, and the analysis of pollen trapped in amber.

Plants are initially more susceptible to habitat loss than animals. This occurs for several reasons:

- Plants cannot migrate.
- The dispersal rates of seeds are slow events (e.g., spruce trees can increase their range about 1 mile [1.6 km] every 100 years).
- Plants cannot seek nutrients or water.
- Seedlings must survive, and they are grown in degraded conditions.

Animals can cope with habitat destruction by migration, adaptation, and/or acclimatization. Migration depends upon:

- The magnitude and rate of degradation
- The organism's ability to migrate
- Access routes or corridors
- The proximity and availability of suitable new habitats

Adaptation is the ability to survive in changing environmental conditions. Adaptation depends upon:

- The magnitude and rate of degradation
- Birth rate
- The length of generation
- Population size
- Genetic variability
- Gene flow between populations as a function of variation

Acclimatization is the process in which an individual organism adjusts to a gradual change in its environment (e.g., a change in temperature, humidity, photoperiod, or pH), allowing it to maintain performance across a range of environmental conditions. Acclimatization depends upon:

- The magnitude and rate of degradation
- Physiological and behavioral limitations of the species

Introduced Species

Invasive or exotic species are animals and plants that are transported to any area where they do not naturally live. The spread of nonnative species has emerged in recent years as one of the most serious threats to biodiversity. It has undermined the ecological integrity of many native habitats and pushed some rare species to the edge of extinction. Some introduced species simply out-compete native plants and animals for space, food, or water. Other negative impacts include predation of nontargeted species and the disruption of food webs and/or biogeochemical cycles.

About 15% of the estimated 6,000 nonnative plant and animals species in the United States cause severe economic or ecological impacts and have been implicated in the decline of about 40% of the species listed for protection under the federal Endangered Species Act. Examples of introduced species include:

- **DUTCH ELM DISEASE** (caused by a fungus) is transmitted to elm trees by elm bark beetles. Since 1930, the disease has spread from Ohio through most of the country, killing over half of the elm trees in the northern United States.
- **EUROPEAN GREEN CRABS** found their way into the San Francisco Bay area in 1989. They out-compete native species for food and habitat, and they eat huge quantities of native shellfish, threatening commercial fisheries.

- **WATER HYACINTH** is an aquatic plant, introduced to the United States from South America. It forms dense mats, reducing sunlight for submerged plants and aquatic organisms, crowding out native aquatic plants, and clogging waterways and intake pipes.
- **ZEBRA MUSSELS** first came to the U.S. from Eurasia in ship ballast water released into the Great Lakes. Since 1988, they have spread dramatically, out-competing native species for food and habitat. Zebra mussels can attach to almost any hard surface—they clog water intake and discharge pipes, attach themselves to boat hulls and docks, and even attach to native mussels and crayfish.

Endangered and Extinct Species

Since 1500 C.E., approximately 816 species that we know about have become extinct, 103 of them since 1800—a rate 50 times greater than the natural background rate. In the next 25 years, extinction rates are expected to rise as high as 25%. According to the Nature Conservancy, about one-third of all U.S. plant and animal species are at risk of becoming extinct.

Mammals that are listed as "endangered" rose from 484 in 1996 to 520 in 2000, with primates increasing from 13 to 19 different species. Endangered birds increased from 403 species to 503 species. Endangered freshwater fish more than doubled from 10 species to 24 species in four years. One-fourth of all mammals and reptiles, one-fifth of all amphibians, one-eighth of all birds, and one-sixth of all conifers are in some manner endangered to the point of extinction.

Arguments for protecting endangered species include:

- Maintaining genetic diversity
- Maintaining keystone species
- Maintaining indicator species
- Preserving the endangered species' aesthetic, ecological, educational, historical, recreational, and scientific value
- Preserving the endangered species' yet to be discovered value (e.g., more than a quarter of all prescriptions written annually in the United States contain chemicals discovered in plants and animals)

The following table provides examples of some characteristics that have contributed to the endangerment or extinction of various species of animals.

Characteristics That Have Contributed to Endangerment or Extinction

Characteristic	Example
Compete for food with humans	African penguins
High infant mortality	Leatherback turtles
Highly sensitive to changes in environmental conditions	Cotton-top tamarinds
Hunting for sport	Passenger pigeons, blue whale, Bengal tiger
Introduction of nonnative invasive species	Bandicoots threatened by cats that were introduced by Europeans
Limited environmental tolerance ranges	Frogs whose eggs are sensitive to water pollution, temperature changes, and the destruction of wetlands
Limited geographic range	Pandas
Long or fixed migration routes	Salmon in the Pacific Northwest that have been driven to extinction because of dam construction, logging, and water diversion
Loss of habitat	Red wolf, whooping crane
Low reproductive rates or specialized reproductive behavior	Whales, elephants, and orangutans (female orangutans have a maximum of three offspring during their lifetime)
Move slowly	Desert tortoise
No natural predators, which makes them vulnerable as they lack natural defensive behaviors and mechanisms	Dodo birds, Steller sea cows, sea otters
Not able to adapt quickly	Polar bears
Possess characteristics sought after for commercial purposes	Sharks (fins), elephants (ivory), rhinoceros horns (perceived aphrodisiac quality), gorillas (meat)
Require large amounts of territory	Tigers
Small numbers of the species, which limits genetic diversity	Tigers
Specialized feeding behaviors and/or diet	Pandas
Spread of disease by humans or livestock	African wild dog (susceptible to the spread of disease by livestock)
Superstitions	Aye ayes—people native to Madagascar believe that aye ayes bring bad luck, therefore resulting in killing aye ayes

Maintaining Biodiversity

Biodiversity can be protected by:

- Properly designing and updating laws that legally protect endangered and threatened species (e.g., Endangered Species Act)
- Protecting the habitats of endangered species through private and/or governmental land trusts
- Reintroducing species into suitable habitats
- Managing habitats and monitoring land use
- Establishing breeding programs for endangered or threatened species
- Creating and expanding wildlife sanctuaries
- Restoring compromised ecosystems
- Reducing nonnative and invasive species

RELEVANT LAWS AND TREATIES

MULTIPLE-USE ACT (1960): Directed that the national forests be managed for timber, watershed, range, outdoor recreation, wildlife, and fish purposes.

THE CONVENTION ON INTERNATIONAL TRADE IN ENDANGERED SPECIES OF WILD FAUNA AND FLORA (CITES) (1963): An international agreement between governments to ensure that international trade in wild animals and plants does not threaten their survival.

MARINE MAMMAL PROTECTION ACT (1972): Established federal responsibility to conserve marine mammals.

ENDANGERED SPECIES ACT (1973): Provided a program for the conservation of threatened and endangered plants and animals and the habitats in which they are found.

MULTIPLE-CHOICE QUESTIONS

1. Which of the following represents the greatest contribution of methane emission to the atmosphere?

   (A) Enteric fermentation or flatulence from animals
   (B) Coal mining
   (C) Landfills
   (D) Rice cultivation
   (E) Burning of biomass

2. Ozone depletion reactions that occur in the stratosphere are facilitated by

   (A) NO_2^-
   (B) NH_3
   (C) NH_4^+
   (D) N_2O
   (E) NO_3^-

3. In addition to absorbing harmful solar rays, how do ozone molecules help to stabilize the upper atmosphere?

   (A) They release heat to the surroundings.
   (B) They create a buoyant lid on the atmosphere.
   (C) They create a warm layer of atmosphere that keeps the lower atmosphere from mixing with space.
   (D) All of the above are correct.
   (E) None of the above are correct.

4. As a molecule, bromine is about 40 times more damaging to the ozone layer than chlorine. Under the Montreal Protocol, methyl bromide in developing countries was phased out in 2005. What was methyl bromide used for?

   (A) Sterilizing soil in fields and greenhouses
   (B) Killing pests on fruits, vegetables, and grain before export
   (C) Fumigating soils
   (D) Killing termites in buildings
   (E) All of the above

5. Rising sea levels due to global warming would be responsible for

   (A) the destruction of coastal wetlands
   (B) beach erosion
   (C) increased damage due to storms and floods
   (D) increased salinity of estuaries and aquifers
   (E) All of the above

6. True statements about global warming include which of the following?

   I. Average carbon dioxide levels in the atmosphere today are the highest they have ever been in Earth's history.
   II. Average global air temperatures today are the highest they have ever been in Earth's history.
   III. The increases in average global air temperatures are equally distributed across Earth's surface.

   (A) I only
   (B) II only
   (C) I and II
   (D) III only
   (E) All of these choices are false.

7. One of the reasons why the vortex winds in the Antarctic are important in the formation of the hole in the ozone layer is

   (A) they prevent warm, ozone-rich air from mixing with cold, ozone-depleted air
   (B) they quickly mix ozone-depleted air with ozone-rich air
   (C) they harbor vast quantities of N_2O
   (D) they bring in moist, warm air, which accelerates the ozone-forming process
   (E) None of the above

8. Although the Montreal Protocol curtailed production of ozone-depleting substances, the peak concentration of chemicals in the stratosphere is only now being reached. When do scientists expect a recovery in the ozone levels in the stratosphere to occur?

   (A) Immediately
   (B) Within 5 years
   (C) Within 20 years
   (D) Within 50 years
   (E) In about 100 years

9. Over the past 1 million years of Earth's history, the average trend in Earth's temperature would best be described as

   (A) very large fluctuations, from periods of extreme heat to periods of extreme cold
   (B) very little change, if any, fairly uniform and constant temperature
   (C) a general cooling trend
   (D) a general warming trend
   (E) a number of fluctuations varying by a few degrees

10. The agency responsible for the identification and listing of endangered species is the

(A) Forest Service
(B) Agriculture Department
(C) National Park Service
(D) Fish and Wildlife Service
(E) Endangered Species Department of the Interior

11. A treaty that controls international trades in endangered species is known as (the)

(A) Endangered Species Act
(B) CITES
(C) International Treaty on Endangered Species
(D) Lacey Act
(E) Federal Preserve System

12. Managing game species for sustained yields would be consistent with what conservation approach?

(A) Wildlife management approach
(B) Species approach
(C) Ecosystem approach
(D) Sustainable yield approach
(E) Holistic approach

13. A certain insect was causing extensive damage to local crops. The farmers, who were environmentally conscious and did not want to use pesticides, decided to introduce another insect into their fields that studies have shown would prey on the pest insect. Before any action is taken, the farmers should consider (the)

(A) Principle of Natural Balance
(B) Principle of Unforeseen Events
(C) Murphy's Law
(D) Law of Supply and Demand
(E) Precautionary Principle

14. Which of the following is the biggest threat to wildlife preserves?

(A) Hunters
(B) Poachers
(C) Global warming
(D) Invasive species
(E) Tourists

15. A certain species of plant is placed on the threatened species list. Several years later it is placed on the endangered species list. This is an example of

(A) a negative-negative feedback loop
(B) a positive-negative feedback loop
(C) a negative-positive feedback loop
(D) a negative feedback loop
(E) a positive feedback loop

16. The specific form of radiation that is largely responsible for the formation of ozone in the stratosphere is

(A) UVA
(B) UVB
(C) UVC
(D) infrared
(E) gamma rays

17. Which of the following is NOT an effect caused by increased levels of ultraviolet radiation reaching Earth?

(A) Warming of the stratosphere
(B) Cooling of the stratosphere
(C) Increased genetic damage
(D) Reduction in immunity
(E) Reduction in plant productivity

18. Which of the following gases is NOT considered a greenhouse gas, responsible for global warming?

(A) SO_2
(B) N_2O
(C) H_2O
(D) SF_6
(E) CH_4

19. Which of the following effects would result from the shutdown or slowdown of the thermohaline circulation pattern?

(A) A warmer Scandinavia and Great Britain
(B) Freshwater fish moving into the open ocean
(C) A colder Scandinavia and Great Britain
(D) A saltier ocean
(E) A drier Scandinavia and Great Britain

20. The largest number of species are being exterminated per year in

(A) grasslands
(B) deserts
(C) forests
(D) tropical rainforests
(E) the tundra

FREE-RESPONSE QUESTION

By Brian Palm, Catholic Memorial School, West Roxbury, MA
A.B. Dartmouth College, Hanover, NH
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(a) An April 2015 article in *Nature* described the likelihood of the "methane time bomb" that would push our climate situation to a point of irreversible change. This example of a positive feedback loop is one of many that could occur in a "climate changed" world. Identify AND describe ONE other positive feedback mechanism in an ecological system.

(b) CCS stands for Carbon, Capture, and Storage, a process that utilizes a number of technologies to capture and then store (hopefully for a long time) the carbon dioxide produced through coal-fired electricity generation. One of the major concerns about CCS is its cost. In 2009, a Harvard University lab estimated that it would cost $150 to capture and sequester one ton of CO_2. If a single 500 MW coal-fired plant generates about 3 million tons of CO_2 each year, calculate the additional, annual cost burden for a single coal-fired plant of this size.

(c) List AND describe ONE economic consequence of climate change, ONE human health consequence of climate change, and ONE environmental consequence of climate change.

MULTIPLE-CHOICE ANSWERS AND EXPLANATIONS

1. **(C)** Since 1800, there has been a 150% increase in methane concentrations in the atmosphere compared with a 30% increase in carbon dioxide. Methane is about 30 times more effective in contributing to global warming than carbon dioxide.

2. **(D)** Nitrous oxide is responsible for about 7% of the anthropogenic greenhouse gases and stays in the atmosphere for about 120 years. The concentration of nitrous oxide in the atmosphere has increased about 15% since the Industrial Revolution. The main sources of nitrous oxide are inorganic fertilizers and industrial processes. Natural sources of nitrous oxide arise from biological processes within the soil and oceans.

3. **(D)** Solar energy that is absorbed by ozone molecules and is partly turned into heat creates a warm region in the stratosphere which creates a stable air mass that resists sinking and mixing with the lower atmosphere, effectively forming a barrier. In the ozone layer, temperature increases with height, creating a stable and buoyant air mass that keeps an effective lid on the lower atmosphere.

4. **(E)** Methyl bromide (CH_3Br), also known as bromomethane, originates from both natural and human sources. In the ocean, marine organisms are estimated to produce approximately 62,000 tons (approximately 56,000 m.t.) annually. Methyl bromide is banned by the Montreal Protocol, but it has continued to receive "critical use" exemptions from the U.S. Environmental Protection Agency to be used as a soil fumigant (primarily in strawberry fields) to prevent spoilage during storage. This exemption for U.S. agricultural use does not have a specified end date. The amount of methyl bromide allowed for critical uses in the United States has declined from approximately 8,000 tons (7,500 m.t.) in 2005 to approximately 400 tons (approximately 375 m.t.) in 2015.

   Both chemical and nonchemical alternatives to methyl bromide exist. For example, steam sterilization of soil is a viable alternative to using chemical fumigants for certain pests and soil types. Other nonchemical alternatives include integrated pest management techniques, pheromones, electrocution, and light traps.

5. **(E)** Sea level rise is caused primarily by two factors related to global warming: the added water from melting land ice and the expansion of seawater as it warms.

6. **(E)** Earth's primitive forests first appeared around 300 million years ago during the Carboniferous Period. Before then, the atmosphere held far more CO_2 but concentrations declined throughout the Carboniferous Period (359 to 299 million years ago during the late Paleozoic Era) as plants flourished and absorbed more and more CO_2 from the atmosphere through photosynthesis, creating carbon sinks (coal, oil, etc.). During the Carboniferous Period, the atmosphere became greatly depleted of CO_2 (declining from about 2,500 ppm to 350 ppm) so that by the end of the Carboniferous Period the atmosphere was less favorable to plant life and plant growth slowed. Today, CO_2 concentrations are approximately 380 ppm (0.038% of our atmosphere). The Arctic is feeling the effects of increases in average global air temperatures the most with average temperatures in Alaska, western Canada, and eastern Russia rising at twice the rate of the global average.

7. **(A)** Ozone depletion follows an annual cycle that corresponds to the amount of light that reaches the Antarctic. The cycle begins every year around June when vortex winds develop in the Antarctic. Cold temperatures produced by these winds create

polar stratospheric clouds that capture floating chlorofluorocarbons (CFCs) and other ozone-depleting compounds. For the next two months, a reaction occurs on the cloud surface that frees the chlorine in the CFCs but keeps it contained within the vortex. In September, sunlight returns to the Antarctic and triggers a chemical reaction, causing chlorine to convert ozone to oxygen gas. November brings a breakdown in the vortex and allows the ozone-rich air to combine with the thinning ozone. Wind currents carry this mixture over the Southern Hemisphere.

8. **(E)** Concentrations of ozone-depleting chlorofluorocarbons (CFCs) have leveled off in the stratosphere and have actually begun to decline in the lower atmosphere. A CFC molecule can take about 8 years after being released at ground level to reach the stratosphere. Decades may pass until it is converted by sunlight into a form that depletes ozone.

9. **(D)** Current climatic warming is occurring much more rapidly than past warming events. As Earth moved out of ice ages over the past million years, the global average temperature rose 4–7°C over the last 5,000 years. In the past 100 years, the temperature has risen 0.7°C, approximately ten times faster than the average rate with current models predicting that Earth will warm 2–6°C in the next century, a rate approximately 20 times faster than normal.

10. **(D)** The Fish and Wildlife Service, in the Department of the Interior, and the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce, share responsibility for the administration of the Endangered Species Act. An endangered species is one that is in danger of extinction throughout all or a significant portion of its range and is likely to become endangered in the foreseeable future.

11. **(B)** CITES (the Convention on International Trade in Endangered Species) is an international agreement between governments. Its aim is to ensure that international trade in specimens of wild animals and plants does not threaten their survival.

12. **(A)** The strength of the traditional wildlife management approach is that it explicitly uses and enhances natural processes to perpetuate populations.

13. **(E)** The Precautionary Principle states that if the consequences of an action are unknown but are judged to have some potential for major or irreversible negative consequences, that action should be avoided. The concept includes risk prevention, cost effectiveness, ethical responsibilities toward maintaining the integrity of natural biological systems, and risk assessment. It is not the risk that must be avoided but the potential risk that must be prevented.

14. **(C)** All choices but (C) can be dealt with on a local level through specific enforcement and management practices. Global warming is an issue that affects all ecosystems and must be solved on a global scale, requiring international cooperation.

15. **(E)** A positive feedback loop occurs in a situation in which a change in a certain direction (toward extinction in this case) causes the system to change in the same direction.

16. **(C)** Ozone is produced by oxygen and sunlight in the UVC wavelength range (<240 nm). In the atmosphere, this reaction works only at higher altitudes where there is

adequate high-energy UV penetration. The atomic oxygen so formed can combine with oxygen gas (O_2) to form ozone (O_3).

17. **(A)** The stratosphere has been cooling over the past three decades. The stratosphere contains the ozone layer, which absorbs sunlight and heats the stratosphere. This long-term cooling trend is generally accepted to result from the loss of the ozone layer as a result of human-made influences. However, the cooling trend is not uniform like ozone loss but, rather, broken into a series of jumps or discontinuities most likely associated with major volcanic eruptions that inject aerosols into the stratosphere. The aerosols also absorb sunlight and heat from the stratosphere, thus temporarily offsetting the cooling trend from ozone loss.
18. **(A)** Sulfur dioxide (SO_2) contributes to acid rain, not global warming.
19. **(C)** There is speculation that global warming could melt glaciers in Greenland, increasing the amount of freshwater in the North Sea. This disruption in balance between saltwater and freshwater could theoretically slow down or shut down thermohaline circulation that is responsible for the North Atlantic Drift (a section of the Gulf Stream) that currently stabilizes temperatures in Great Britain and Scandinavia.
20. **(D)** The tropics contain the highest biodiversity found anywhere on Earth. Deforestation in the tropics, in order to convert the land for agricultural purposes and cattle grazing, is occurring at unprecedented levels.

FREE-RESPONSE ANSWER

10 Total Points Possible

(a) *Maximum 2 points total: 1 point for identifying a viable positive feedback mechanism and 1 point for correctly describing the feedback loop. Note that the explanation must describe/correlate to the feedback loop that was identified.*

An April 2015 article in Nature *described the likelihood of the "methane time bomb" that would push our climate situation to a point of irreversible change. This example of a positive feedback loop is one of many that could occur in a "climate changed" world. Identify AND describe ONE other positive feedback mechanism in an ecological system.*

A positive feedback loop/mechanism refers to changes within a system where subsequent events are enhanced, amplified, or made larger. The result of such a mechanism is the movement of that system away from an equilibrium, or steady, state, making it less stable.

Students must link their identified positive feedback loop with an explanation that refers correctly to that mechanism. Examples of positive feedback loops AND their explanations are listed in the table on page 405.

Positive Feedback Loop Example	Associated Explanation of the Mechanism
Warmer temperatures = more evaporation = more water vapor = warmer temperatures	As the climate system warms, evaporation rates (oceans/lakes/soil/rivers) will increase. An increase in evaporation causes greater amounts of water vapor. Water vapor is a greenhouse gas that will then cause more warming. The output of more water vapor causes more warming, which causes more water vapor.
Warmer temperatures = loss of sea/land ice (Arctic and Antarctica) = lower albedo = less reflected light (greater conversion of light energy into infrared heat) = warmer temperatures	As the climate system warms, ice will melt (polar and other). As the ice melts, Earth's overall average albedo gets lower as the surface color is converted from areas that were once white (ice) to areas that are darker (soil/vegetation/water). These areas will absorb light energy, converting it into IR (infrared) instead of reflecting that light energy. The increase in IR will cause further warming which will melt more ice.
Warmer temperatures = melting of permafrost = release of methane trapped in permafrost = warming due to more methane (methane is a greenhouse gas)	As the climate system warms, permafrost melts in the higher latitudes (near the poles/Canada/Siberia/Alaska). When permafrost melts, the methane gas bubbles that were frozen in the permafrost will melt. The release of methane causes further warming because methane is a potent greenhouse gas.

(b) Maximum 2 points total: 1 point for the correct calculation setup and 1 point for the correct answer.

CCS stands for Carbon, Capture, and Storage, a process that utilizes a number of technologies to capture and then store (hopefully for a long time) the carbon dioxide produced through coal-fired electricity generation. One of the major concerns about CCS is its cost. In 2009, a Harvard University lab estimated that it would cost $150 to capture and sequester one ton of CO_2. If a single 500 MW coal-fired plant generates about 3 million tons of CO_2 each year, calculate the additional, annual cost burden for a single coal-fired plant of this size.

Responses must include a setup that is similar to the one below. While units are not required in this setup, the numbers should be consistent, and they should demonstrate the correct mathematical operation (in this case, the fact that $150 is multiplied by 3,000,000 [or 3×10^6]). The correct answer is $450,000,000. This can also be displayed as $$4.5 \times 10^8$ or as $450 million. Full credit is given for any variations, including 45×10^7 and 450×10^6, though one of the first two formats is preferred.

$$\frac{\$150.00}{\cancel{\text{tons of } CO_2}} \times \frac{3{,}000{,}000\ (3 \times 10^6)\ \cancel{\text{tons of } CO_2}}{\text{year}} = \$450{,}000{,}000/\text{year}$$

(c) *Maximum 6 points total: 2 points for listing and describing ONE economic consequence, 2 points for listing and describing ONE human health consequence, and 2 points for listing and describing ONE environmental consequence.*

List AND describe ONE economic consequence of climate change, ONE human health consequence of climate change, and ONE environmental consequence of climate change.

Examples and explanations will vary for each of these consequences. Students should recognize that consequences do not necessarily have to be positive or negative, but they must correctly describe the consequence category (i.e., the economic consequence must be related to relevant topics like jobs or money spent/earned, and the human health consequence must be related to humans, not other species or the loss of their habitat).

Examples of economic consequences:

- Due to the sea level rise that results from climate change and the loss of land ice/thermal expansion, coastal residents and businesses may need to redirect funds to pay for the construction of ocean defense mechanisms, including barriers, new roads, and other modifications to infrastructure.
- Due to increases in drought frequency, yields from agriculture will decrease, putting farmers at risk financially.

Examples of human health consequences:

- Due to increases in average annual temperatures, the risk of mosquito-borne illnesses will spread to higher latitudes and affect those populations.
- Due to increases in the frequency of heat waves, human populations will be exposed to prolonged periods of warmer-than-normal temperatures, which will place elderly segments of the population at an increased risk.

Examples of environmental consequences:

- Due to warmer temperatures, organisms that migrate risk missing important food sources due to earlier-than-normal or later-than-normal arrival of those events, placing these organisms at risk of starvation or death.
- As increased carbon dioxide levels saturate marine ecosystems, the more acidic waters will make it difficult for a range of species to build shells, causing potentially dramatic declines in important members of the marine food web.