16.7: Global Warming

Learning Objectives

- Define global warming, climate change, the greenhouse effect, and greenhouse gases.
- Identify the gases present in the troposphere and stratosphere and their effects on life on Earth.
- Identify sources of greenhouse gases in the atmosphere and their levels over time.
- Discuss how the temperature of the Earth has varied over time and since 1900.

We hear a lot in the news about climate change and global warming. However, the terminology can sometimes be a bit confusing. How often have you heard someone ask why we are experiencing something like a polar vortex if global warming is happening? In order to make sense of what is happening to our planet, it is important to understand the two terms and the factors that influence them. It is only then that one can make informed decisions on the severity of the issue and how best to mitigate the effects. **Global warming** refers to the increase in the average temperature of the Earth's atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. **Climate change** includes both global warming, driven by human-induced emissions of greenhouse gases, and the resulting large-scale shifts in weather patterns. Though there have been previous periods of climatic change, since the mid-20th century humans have had an unprecedented impact on Earth's climate system and caused change on a global scale.

The Atmosphere and the Greenhouse Effect

The atmosphere is the air around and above us. We know we must have air to breathe. A human deprived of air's life-giving oxygen for just a brief time will lose consciousness, and within a few minutes will die. But air is far more than just a source of oxygen. That is because it protects Earth's organisms in ways that are absolutely essential for their existence. One major protective function is to act as a blanket to keep us warm. It does that by reabsorbing some of the infrared radiation which Earth receives from the sun and radiates back to space. By delaying the exit of this energy into outer space, the average temperature of Earth's surface remains at about 15° C (59° F) at sea level, though it can be much colder at certain times and places and significantly warmer at others. Without this warming effect, plants could not grow and most other known organisms could not exist. The second protective function of the atmosphere is absorption of very short wavelength ultraviolet solar radiation. Were this radiation to reach our level, it would tear apart biomolecules, making it impossible for most life forms to exist.

Although one might get the impression that the atmosphere is very thick, it is "tissue thin" compared to Earth's diameter. The altitude at which high-flying jet aircraft cruise marks the upper limit of the lowest of several layers of the atmosphere, the **troposphere**, which extends from sea level to about 11 km (Figure 16.7.1). As anyone who has driven to the top of Pike's Peak or some other mountain knows, the troposphere gets cooler with increasing altitude, from an average temperature of 15° C at sea level to an average of -56° C (-69° F) at 11 km. Above the layer of the troposphere, however, atmospheric temperature *increases* to an average of -2° C (35.6° F) at 50 km altitude. The layer above the troposphere is the **stratosphere**, which is heated by the absorption of intense ultraviolet radiation from the sun (Figure 16.7.2). There is virtually no water vapor in the stratosphere, and it contains ozone (O_3) and O atoms as the result of ultraviolet radiation acting upon stratospheric O_2. Beyond the stratosphere are layers called the mesosphere and thermosphere, but they are relatively less important in our discussion of the atmosphere.

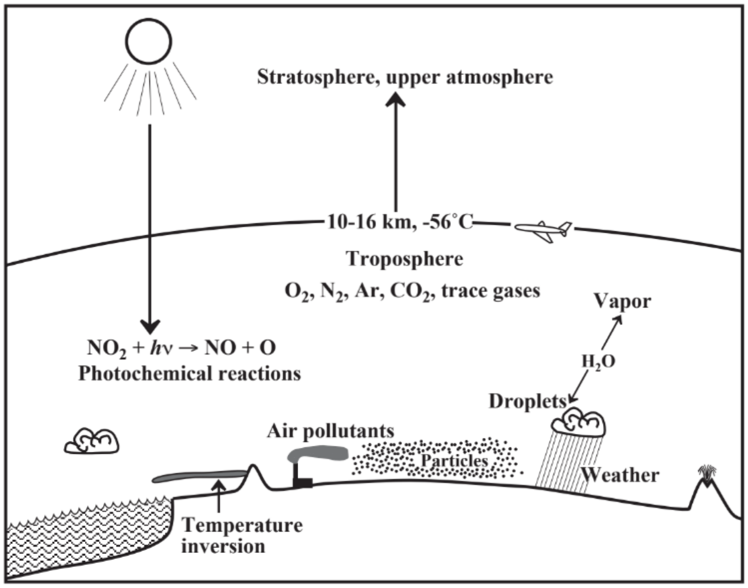


Figure 16.7.1. The troposphere is the very thin layer of the atmosphere closest to Earth, containing most of the atmosphere's air and water vapor. It is the source of oxygen, carbon dioxide, nitrogen, and water used by living organisms and as raw materials for manufacturing. With the important exception of stratospheric ozone destruction, it is where most air pollution phenomena occur.

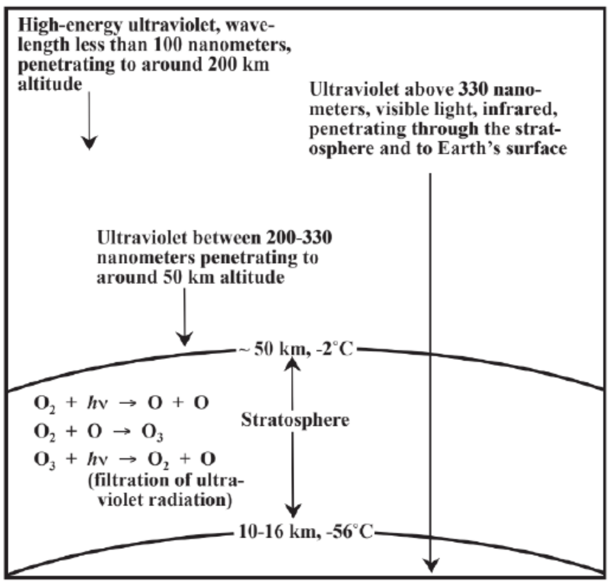


Figure 16.7.2. The upper atmosphere, including the stratosphere and regions beyond, is particularly important in the absorption of radiation that would make life impossible if it reached Earth's surface. The layer of ozone, O_3, in the stratosphere is of the utmost importance and one that is subject to damage from anthropogenic species released into the atmosphere.

There is an enormous amount of energy reaching Earth's atmosphere from the sun as sunlight. As shown in Figure 16.7.3, some of the incoming energy reaches Earth's surface, some is absorbed in the atmosphere, warming it, and some is scattered back to space. The energy that reaches the Earth's surface, primarily as light at a maximum intensity of 500 nanometers in the visible region, must be released back into the atmosphere, which it does as infrared radiation (with maximum intensity at about 10 micrometers (μm), primarily between 2 μm and 40 μm). Water molecules, carbon dioxide, methane, and other minor species in the atmosphere absorb some of the outbound infrared radiation, which eventually is all radiated to space. This temporary absorption of infrared radiation warms the atmosphere — a **greenhouse effect**. The term greenhouse effect is a slight misnomer in the sense that physical greenhouses warm via a different mechanism. The greenhouse effect as an atmospheric mechanism functions through radiative heat loss while a traditional greenhouse as a built structure blocks convective heat loss. The result, however, is an increase in temperature in both cases.

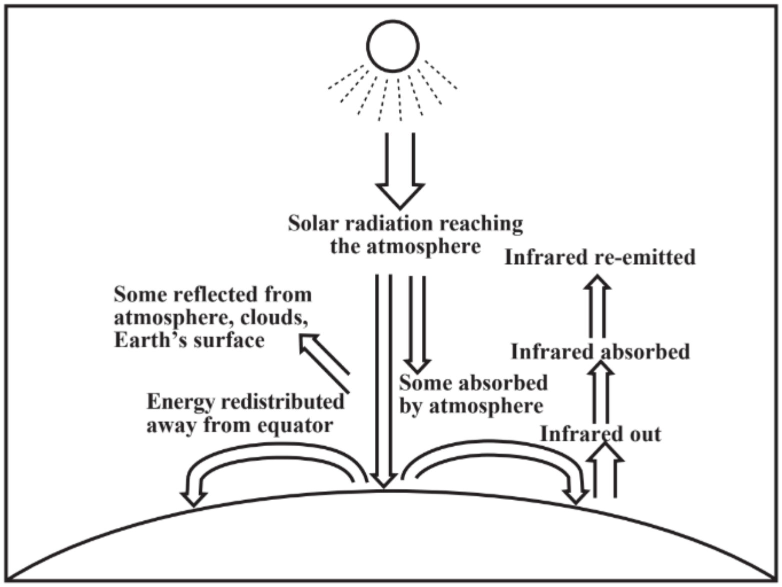


Figure 16.7.3. Some of the solar energy reaching the top of the atmosphere penetrates to Earth's surface, some is absorbed in the atmosphere, which warms it, and some is scattered by the atmosphere and from Earth's surface. Outgoing energy is in the infrared region. Some of it is temporarily absorbed by the atmosphere before being radiated to space, causing a warming (greenhouse effect). The equatorial regions receive the most energy, part of which is redistributed by warm air masses and latent heat in water vapor away from the equator.

The fraction of electromagnetic radiation from the sun that is reflected by Earth's surface varies with the nature of the surface. The percentage reflected is very important because it determines how effective incoming radiation is in warming the surface and it is expressed as **albedo**. Freshly plowed black topsoil has a very low albedo of only about 2.5%. This means that only 2.5% of the radiation is reflected and the rest is absorbed. In contrast, the albedo of a covering of fresh snow is about 90%. The anthrosphere affects albedo. One example of this is in cultivating land, turning over relatively high albedo grass and covering it with exposed black soil that absorbs light energy very strongly. Another is covering of large areas of Earth's surface with asphalt paving which reflects sunlight poorly.

Earth's natural greenhouse effect is critical to supporting life and initially was a precursor to life moving out of the ocean onto land. Human activities, mainly the burning of fossil fuels and clear cutting of forests, have increased the greenhouse effect and caused global warming.

Greenhouse Gases and Global Warming

The maintenance of Earth's heat balance to keep temperatures within limits conducive to life is very complex and not well understood. Geological records show that in times past, Earth was sometimes relatively warm and that at other times there were ice ages in which much of Earth's surface was covered by ice a kilometer or two thick. The differences in average Earth temperature between these extremes and the relatively temperate climate conditions that we now enjoy were only a matter of a few degrees. It is also known that massive volcanic eruptions and almost certainly hits by large asteroids have caused cooling of the atmosphere that lasted for a year or more. There is now concern that anthropogenic gas emissions, particularly of carbon dioxide from fossil fuel combustion, may be having a warming effect upon the atmosphere.

A **greenhouse gas** (sometimes abbreviated **GHG**) is a gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect. It's important to realize that water vapor (H_2O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, it is still an essential component of the natural greenhouse effect that occurs in our atmosphere. The four major categories of greenhouse gases that have been impacted by humans the most are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and synthetic fluorinated gases including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). These will be discussed below and a numeric comparison is provided in Table 16.7.1.

Carbon dioxide (CO_2) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we'll discuss here. Remember that CO_2 is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO_2 is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry. To get an idea of how CO_2 concentration has changed over time, watch Video 16.7.1. This video contains atmospheric CO_2 concentrations measured directly, dating back to 1958, as well as atmospheric CO_2 concentrations measured indirectly from ice core data, dating back to 800,000 BCE. Ice core data shows us that the atmospheric CO_2 concentration never exceeded 300 ppm before the industrial revolution. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. As of early 2022, the current atmospheric CO_2 concentration is over 400 ppm. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases lead to an increase in the surface temperature of the Earth.

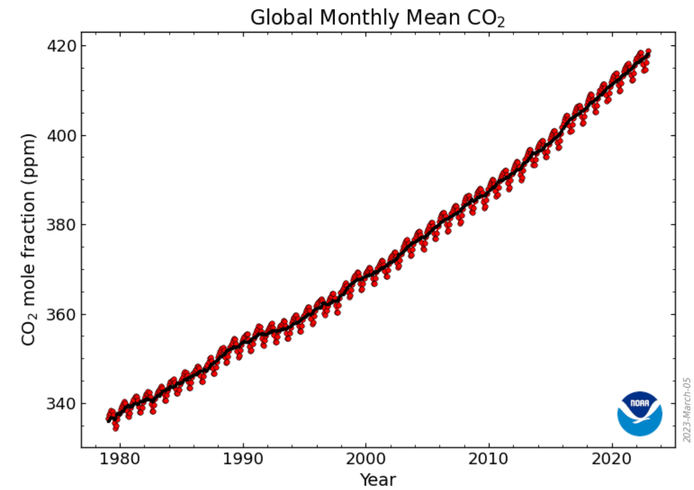
Video 16.7.1: History of atmospheric CO_2, from 800,00 years ago to January 2022. (National Oceanic and Atmospheric Administration)

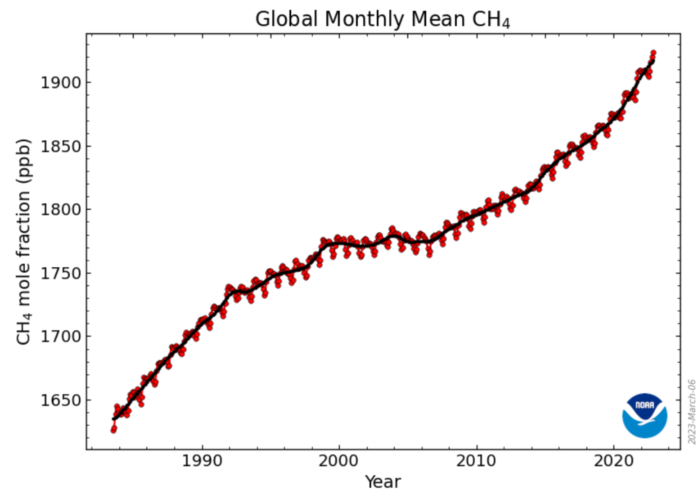
While CO_2 is produced by aerobic cellular respiration, gases such as **methane** (CH_4) and **nitrous oxide** (N_2O) are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH_4 emissions. In addition to anaerobic bacteria, methane is also a significant component of natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. Finally, landfills contribute significantly to CH_4 emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH_4 include swamps, wetlands, and volcanoes.

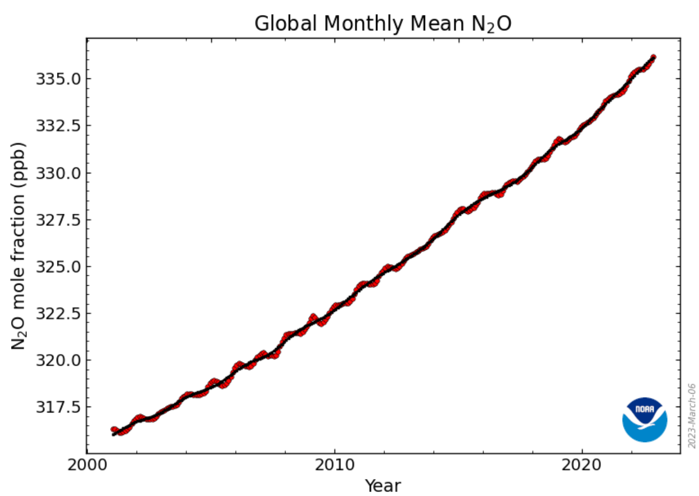
The vast majority of N_2O production by humans comes from agricultural land management. While some N_2O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N_2O emissions. Some N_2O is also emitted from transportation and industry.

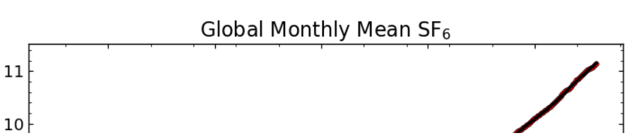
One class of greenhouse gas chemicals that has no natural sources is the **fluorinated gases**. These include HFCs, PFCs, and SF_6, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in Table 16.7.1. Some of these chemicals, as well as the older **chlorofluorocarbons** (CFCs), have been phased out by international environmental legislation under the Montreal Protocol. Due to their long lifespan, many of these now banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO_2, CH_4, and N_2O, are responsible for most of the human-caused global climate change over the past century. Figure 16.7.4 shows the increases in all four categories of gases for the past 20 years or longer.


Global Monthly Mean CO_2
CO_2 mole fraction (ppm)
420
400
380
360
340
1980
1990
2000
2010
2020
Year
2023-March-05


Global Monthly Mean CH_4
CH_4 mole fraction (ppb)
1900
1850
1800
1750
1700
1650
1990
2000
2010
2020
Year
2023-March-06


Global Monthly Mean N_2O
N_2O mole fraction (ppb)
335.0
332.5
330.0
327.5
325.0
322.5
320.0
317.5
2000
2010
2020
Year
2023-March-06


Global Monthly Mean SF_6
11
10

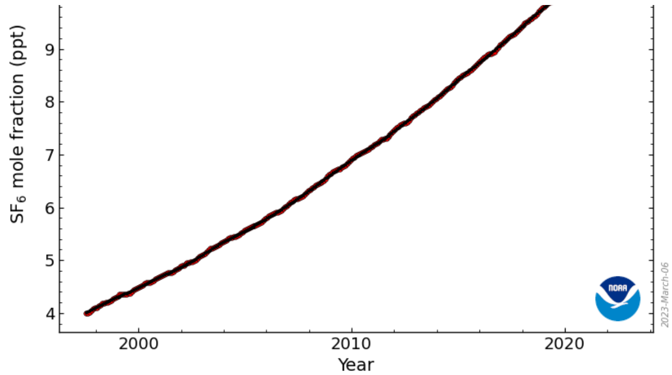


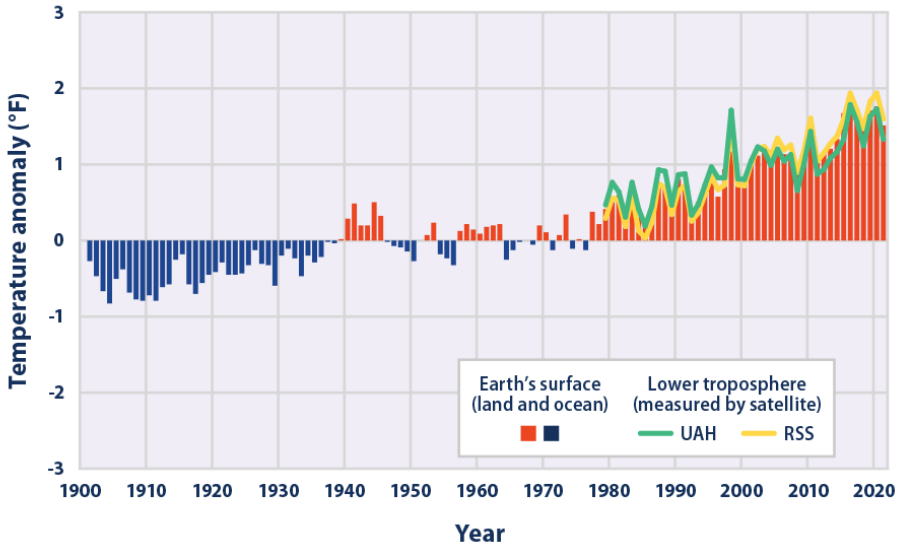
Figure 16.7.4: Global monthly averages for greenhouse gas concentrations expressed as ppm (parts per million), ppb (parts per billion), or ppt (parts per trillion). Samples were taken from a globally distributed network of air sampling sites. Red circles show the monthly average centered on the middle of each month. Black lines show the long term trend with seasonal cycles removed. (National Oceanic and Atmospheric Administration)

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the **global warming potential**, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO_2 is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO_2 always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in Table 16.7.1. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH_4 and N_2O compared to CO_2.

Table 16.7.1. Comparison of Greenhouse Gases.

Greenhouse gas	**Chemical formula or abbreviation**	**Lifetime in atmosphere**	**Global warming potential (100-year)**
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12 years	28-36
Nitrous oxide	N_2O	114 years	298
Hydrofluorocarbons	Abbreviation: HFCs	1-270 years	12-14,800
Perfluorocarbons	Abbreviation: PFCs	2,600-50,000 years	7,390
Sulfur hexafluoride	SF_6	3,200 years	22,800

The concern with increasing concentrations of greenhouse gases in the atmosphere is that it will lead to — indeed *is* leading to — an excess of a good thing, warming of the global atmosphere. Is Earth warming? Sophisticated computer models indicate that it is, backed by evidence from increasingly accurate temperature records over more than 100 years (Figure 16.7.5). These temperature records have been especially accurate over the last several decades because they have been read over all Earth's surface by satellite. Worldwide, 2016 was the warmest year on record and 2020 was the second-warmest. The decade from 2012 to 2021 was the warmest decade on record since measurements with thermometers began. While average surface temperature both globally and within the 48 contiguous states has risen at an average rate of 0.17° F per decade since 1901, the United States has warmed at a faster rate than the global rate since the late 1970s.



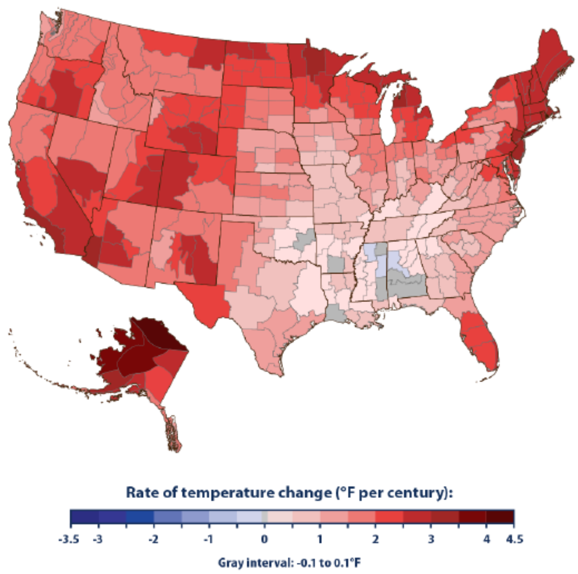


Figure 16.7.5: The first chart shows worldwide temperatures from 1901 to 2021 using the 1901-2000 average as a baseline for depicting change. Choosing a different baseline period would not change the shape of the data over time. "UAH" and "RSS" represent two different methods of analyzing the original satellite measurements. The second figure shows how average air temperatures have changed in different parts of the United States since 1901 for the contiguous 48 states and since 1925 for Alaska. (NOAA via epa.gov)

Summary

- The atmosphere is made up of different layers of gases, each of which has a unique function in making life on Earth possible. The stratosphere contains ozone which prevents damaging UV radiation from reaching the surface. The troposphere contains a variety of gases which keep the Earth at a moderate temperature to sustain life.
- Gases that trap heat in the atmosphere are called greenhouse gases.
- The greenhouse effect is the process by which radiation from a planet's atmosphere warms the planet's surface to a temperature above what it would be without this atmosphere.
- Global warming refers to the increase in the average temperature of the Earth's atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect.

- Greenhouse gases differ in their ability to produce the greenhouse effect as measured by the global warming potential, or GWP. A molecule of CH_4 is about 28 times more effective than one of CO_2 at absorbing infrared radiation, while N_2O is 298 times more effective . The synthetic fluorinated gases are even much higher (in the thousands). This is largely due to their very long residence time in the atmosphere.

Contributors and Attributions

- Marisa Alviar-Agnew (Sacramento City College)

- Libretext: Introduction to Environmental Science (Zendher et al.)
- US EPA
- National Oceanic and Atmospheric Administration
- Stanley E. Manahan (University of Missouri)
- Vicki MacMurdo (Anoka-Ramsey Community College)
