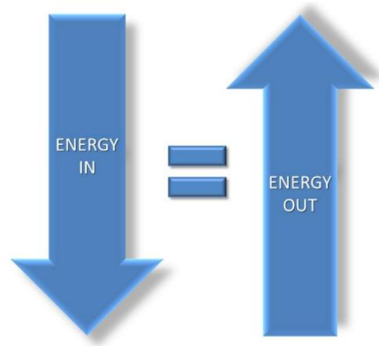
Energy: The Driver of Climate

Module Overview

The balance between incoming energy from the sun and outgoing energy from Earth ultimately drives our climate. This energy balance is governed by the first law of thermodynamics, also known as the law of conservation of energy. This law states that energy can be transferred from one system to another in many forms, but it cannot be created or destroyed. Therefore, any energy "lost" during one process will equal the same amount of energy "gained" during another.



First Law of Thermodynamics

When averaged over the course of a year, the incoming energy from the sun and outgoing energy from Earth are nearly in balance, keeping the average global temperature within the narrow range that supports and sustains life as we know it. In the following pages, you will learn about this balance between incoming and outgoing energy and how changes in this balance affect Earth's global average temperature.

In this module you will learn about energy, the ultimate driver of climate. You will learn about Earth's unique atmosphere and the role it plays in moderating our climate, along with the balance of incoming energy from the sun and outgoing energy from Earth.

When you complete this module, you should be able to:

- Compare the composition of Earth's early atmosphere to the present composition.
- Compare and contrast the layers of Earth's atmosphere.
- Explain the relationship between wavelength and frequency of electromagnetic waves.
- Analyze the sun's electromagnetic spectrum to explain why different percentages of wavelengths reach Earth.
- Use two fundamental laws (Stefan-Boltzmann law and Wien's law) to explain the correlation between temperature and radiation for the sun and Earth.
- Describe the three ways that heat energy is transferred within Earth's atmosphere and between its surfaces and the atmosphere.
- Calculate Earth's global radiation balance by analyzing the amount of incoming solar radiation and outgoing terrestrial radiation.
- Explain why some greenhouse gases are more effective absorbers of infrared radiation.
- Explain the relationship between Earth's energy budget and the global average temperature of Earth.
- Explain how the greenhouse effect works.
- Differentiate between the natural greenhouse effect and an amplified greenhouse effect.

The Atmosphere

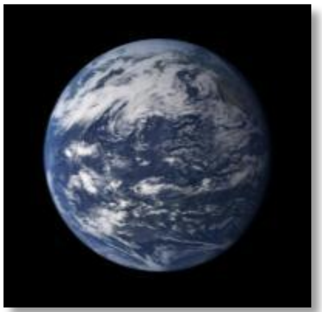


Image Credit: NASA

With 71% of its surface covered by a relatively thin layer of water (some of it frozen), Earth is the only planet in our solar system that appears capable of supporting higher forms of life. In addition to water, the other essential component for supporting life as we know it here on Earth is our unique atmosphere.

Image Credit: ***NASA***

The other planets in our solar system have compositions and conditions very different from Earth's. Venus, for example, has an average temperature of 450°C due to its relatively thick atmosphere consisting mostly of carbon dioxide. Mars has a thin atmosphere with a very small percentage of carbon dioxide, making it much colder than Earth.

Earth's History

What Was Earth's Ancient Atmosphere Like?

In Earth's early history, the atmosphere was much different, and Earth did not have liquid water. Scientists theorize that a lot of debris or meteorites from space bombarded Earth, which caused the outer layer of Earth to melt. After the bombardment stopped, Earth began to cool. As the molten surface became solid, gases were released into the atmosphere. These gases consisted mostly of carbon dioxide (CO_2), with some nitrogen (N_2) and water vapor (H_2O), and other trace gases (methane, ammonia, sulfur dioxide, hydrochloric acid, and argon).

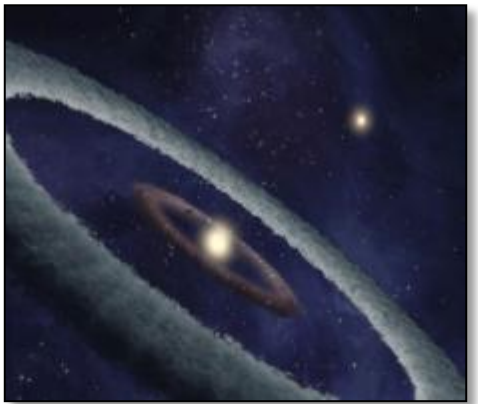


Image Credit: NASA

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As Earth continued to cool, the water vapor condensed to form clouds, and great rains began. The oceans formed, and the amount of water vapor and carbon dioxide in the atmosphere, in turn, decreased, leaving Earth with a nitrogen-rich atmosphere. Eventually, approximately 2.7 billion years ago, ancient organisms evolved to use carbon dioxide, water, and sunlight to make their food energy and release oxygen (known as photosynthesis). The oxygen content of the atmosphere slowly increased, and other forms of life were able to evolve.

A Brief Look at Earth's History

Figure 3.1 shows a brief look at Earth's history over the past 4.6 billion years. The biological, geological, and climatic events appear in reverse chronological order with the oldest event at the bottom of the table and the most recent event at the top of the table. Within each geologic era, the oldest event is also listed at the bottom. Notice that the amount of time in each era, period, and epoch varies and that for most of Earth's history, life was limited to simple marine organisms.

Figure 3.1 A Brief Look at Earth's History

The biological, geological, and climatic events listed appear in reverse chronological order, with the oldest event (at the bottom) and the most recent event (at the top).

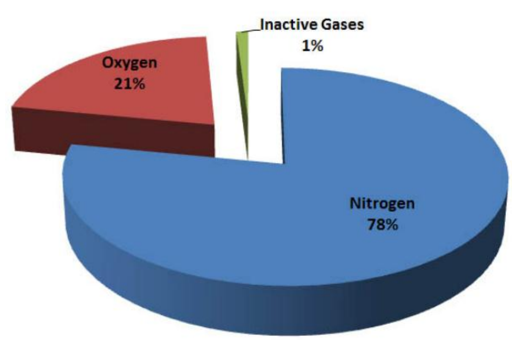
Era	Period	Epoch	Beginning of Interval	Major Biological Events of the Era	Major Geologic and Climatic Events of the Era
Cenozoic	Quaternary	Holocene or Recent	(10,000 years ago)	Human Civilization	Earth's climate has been stable for the past 8,000 years. Great Lakes formed as glacial ice melted. The peak of the last ice age was 21,000 years ago. Earth experienced several periods of glacial conditions (ice ages) and interglacial conditions.
		Pleistocene	1.7 million years ago (MYA)	Saber-toothed Cats, First Humans, Bears, Mammoths, Sloths	
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	66 MYA	Flowering Plants Horses, Cats, Dogs, Primates, Camels, Rhinoceroses, Deer, Pigs, Small Mammals	Earth became colder and drier. Volcanic activity increased in western North America. Andes, Alps, and Himalaya Mountains formed as crustal plates moved. Colorado River carved out Grand Canyon. Inland seas in North America drained away.
Mesozoic	Cretaceous			Extinction of Dinosaurs First Flowering Plants Most Dinosaurs	Asteroid impact likely caused extinction of dinosaurs. Rocky and Sierra Nevada Mountains formed. Climate was much warmer than today. Shallow seas covered much of North America. Atlantic Ocean formed. North America and Africa moved apart. Pangaea began to break up.
	Jurassic			Larger, Fiercer Dinosaurs First Birds First Small Mammals	
	Triassic		245 MYA	Many Cycads and Conifer Trees Reptiles First Dinosaurs	
Paleozoic	Permian			Many Amphibians and Reptiles First Conifer Plants	Land became drier. Basins were larger so water drained into them. Ural and Appalachian Mountains formed. Continents moved together, forming Pangaea. Coal formed in swampy regions. Shallow seas covered most of land.
	Carboniferous Pennsylvanian Mississippian			First Reptiles Coal Forming Swamps	
	Devonian			First Amphibians, Sharks and Insects	
	Silurian			Coral Reefs Form First Land Plants	
	Ordovician			First Fish (Vertebrates)	
	Cambrian		570 MYA	First Invertebrates; Trilobites, Brachiopods	
Precambrian			4.6 billion years ago	Simple Marine Life, Bacteria, Algae, Jellyfish	Ozone layer formed. Outgassing caused the atmosphere to form and eventually the oceans. Meteorites bombarded Earth. Solid Earth divided into core, mantle, crust. Earth formed approximately 4.6 billion years ago.

M.Y.A. = million years ago

Earth's Atmosphere

Which Gases Make Up Earth's Atmosphere?

Earth's relatively thin atmosphere primarily consists of a mixture of nitrogen (78%) and oxygen (21%) gases. The remaining 1% contains several inactive gases (i.e., argon, neon, helium, hydrogen, and xenon) and several other gases that vary in concentration (i.e., water vapor, carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons [CFCs]). Although water vapor and carbon dioxide make up a very small amount of the gases in Earth's atmosphere, they are very important because of their ability to absorb heat. Throughout the upcoming modules, you will learn much more about why and how the concentrations of water vapor and carbon dioxide vary.



Composition of the Atmosphere

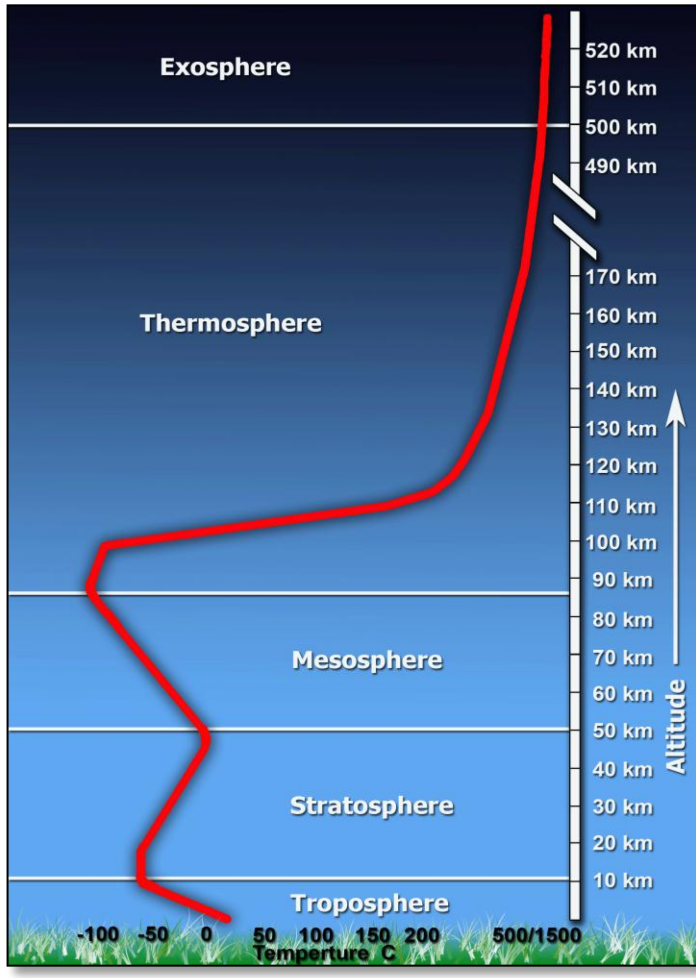
How Is Earth's Atmosphere Structured?

Earth's atmosphere is relatively thin, extending up to at least 500 kilometers (300 miles) above the planet's surface. The atmosphere is structured in different layers according mainly to variations in temperature.

Troposphere

The lowest layer is known as the troposphere, which makes up approximately 75% of the total mass of the atmosphere and contains 99% of the atmosphere's water. The troposphere extends up to approximately 11 kilometers (7 miles) from the surface and is the layer where atmospheric gases are most concentrated. Nearly all weather happens in the troposphere, and the jet stream — a narrow, fast-moving "river" of wind — flows at the upper edge of this layer of the atmosphere.

Layers in the Atmosphere



Air temperature in the troposphere typically decreases as altitude increases as a result of three mechanisms of heat transfer (radiation, conduction, and convection). You will learn more about these heat transfer mechanisms in the next section on Earth's energy balance, but here is a brief overview.

Solar radiation passes through Earth's atmosphere and heats up the planet's surface. The oceans and land absorb approximately half of this incoming solar radiation while a small fraction is emitted back into the atmosphere as infrared radiation. The heat absorbed by Earth's surface is then transferred directly from the land (or the water) to the cooler air closest to the surface through conduction (the direct spread of heat from one substance to another). Once heated, this air becomes less dense (or lighter) and rises through a process called convection. As the air rises, it expands and discharges its heat as it flows upward through the troposphere. After the heat is discharged and the air cools, it becomes denser and begins to sink. Consequently, the troposphere is generally warmest near Earth's surface and coolest at its highest point.

Stratosphere

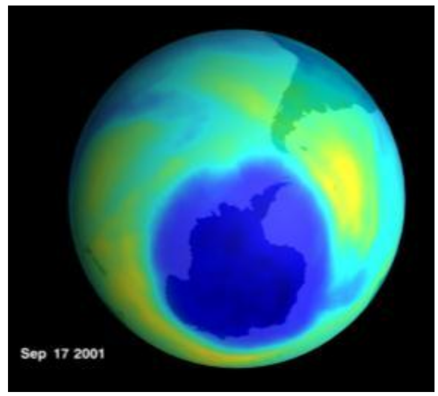
The next layer, known as the stratosphere, extends from the troposphere upward to approximately 50 kilometers (31 miles) above Earth's surface. In the stratosphere, air temperature begins to increase.

Ozone, a form of oxygen with three atoms per molecule, is concentrated in the stratosphere. Ozone absorbs most of the ultraviolet (UV) radiation coming from the sun, preventing this radiation from reaching Earth's surface. UV radiation is harmful to living things because it damages and destroys cells.

The absorption of UV radiation in this ozone layer causes temperature to increase, creating what is known as a temperature inversion — where air temperature increases with height rather than decreases, as it does in the troposphere.

The Ozone Hole

About 30 years ago, scientists discovered that the ozone layer was breaking down, so much that a large hole formed over Antarctica. Chlorofluorocarbons (CFCs) were discovered to be the cause of the decrease in ozone. Man-made CFCs are used as coolants in air conditioners and refrigerators and in aerosol spray cans. Most countries have stopped using the most harmful CFCs, and the concentration of ozone in the upper atmosphere is now increasing.



Ozone Hole – Sept. 2001.
Image Credit:* *NASA

Mesosphere

Above the stratosphere, lies the mesosphere, which stretches to approximately 90 kilometers (56 miles) above the surface of Earth. In the mesosphere, temperature begins to decrease again. The mesosphere's lower temperature results, in part, from the low concentration of ozone, so little solar radiation is absorbed in this layer. The mesosphere is dark, with air pressure so low that a human could not survive in this layer.

Thermosphere

The thermosphere lies above the mesosphere and extends approximately 600 kilometers (373 miles) beyond Earth's surface. Temperature begins to increase again in the thermosphere. The increase in temperature, or inversion, is due in part to the absorption of UV and x-ray radiation and the impact of the solar wind — a continuous stream of protons and electrons given off by the sun. Low Earth orbit (LEO) satellites — like the International Space Station — circle our planet in the thermosphere.

Exosphere

The exosphere represents the outermost layer of Earth's atmosphere. It extends from the top of the thermosphere to 10,000 kilometers (6,214 miles) above Earth's surface. In this layer, atoms and molecules escape into space, and higher altitude satellites orbit our planet.

In the next section, we will discuss the effects of radiation in more detail as well as the role this energy plays in maintaining Earth's climate.

Electromagnetic Radiation

Radiation from the Sun

Almost all of the energy available at Earth's surface comes from the sun. The sun gets its energy from the process of nuclear fusion. This process occurs in the sun's core or interior, where temperature and pressure are extremely high. During most of the sun's life, energy comes from the fusion of hydrogen nuclei. In this process (explained simply), four hydrogen nuclei are fused, forming a helium nucleus. Energy is released because the helium nucleus has a slightly lower mass than the four original hydrogen nuclei. Albert Einstein's famous formula ($E = mc^2$ or Energy = mass × the speed of light squared) explains why energy is released. This energy eventually makes its way to the outer regions of the sun and is radiated or emitted away in the form of energy, known as electromagnetic radiation. A particle of electromagnetic radiation is known as a photon. Electromagnetic radiation, also known as radiant energy (or radiation), is spread in the form of electromagnetic waves.

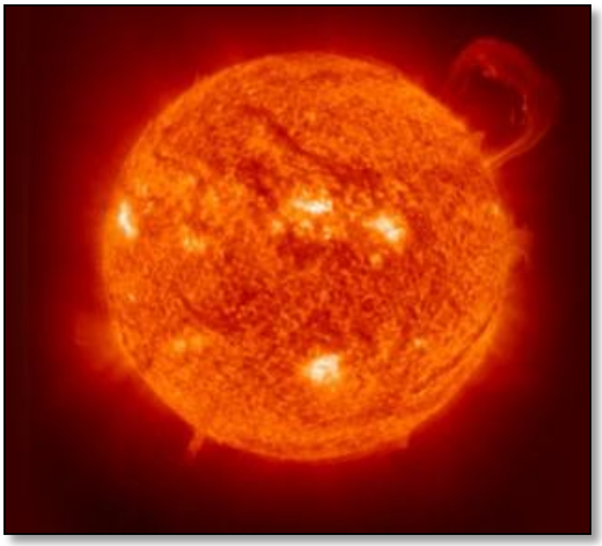
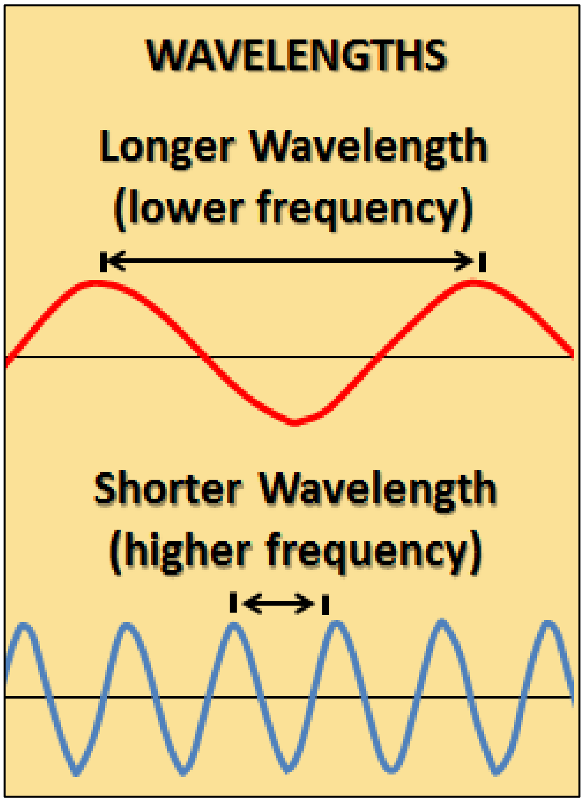


Image Credit: [***NASA***]

Electromagnetic Waves

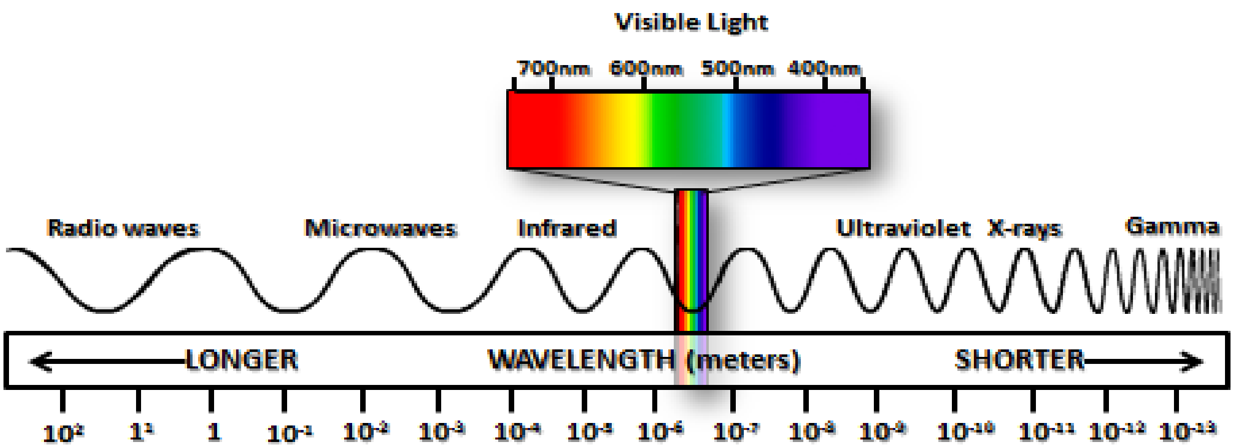
Electromagnetic waves are waves that can cause charged particles (such as electrons) to move up and down. These waves have both electrical and magnetic properties and can travel through gases, liquids, solids, and through empty space (or a vacuum) at nearly 300,000 kilometers per second (the speed of light).

Electromagnetic waves are characterized by wavelength and frequency. The wavelength is the distance between two wave crests or troughs. The highest point of a wave is called the crest, and the lowest point of a wave is called the trough. Frequency is expressed in hertz (Hz) and refers to the number of wavelengths that pass a fixed point in 1 second. The shorter the wavelength is, the higher its frequency will be. The reverse is also true. For example, radio waves have the longest wavelength and the lowest frequency.



Electromagnetic Spectrum
The electromagnetic spectrum represents the complete range of electromagnetic radiation. The region of the spectrum with a shorter wavelength than the color violet is referred as ultraviolet radiation, and the region of the spectrum with a longer wavelength than the color red is referred to as infrared radiation.

The Electromagnetic Spectrum

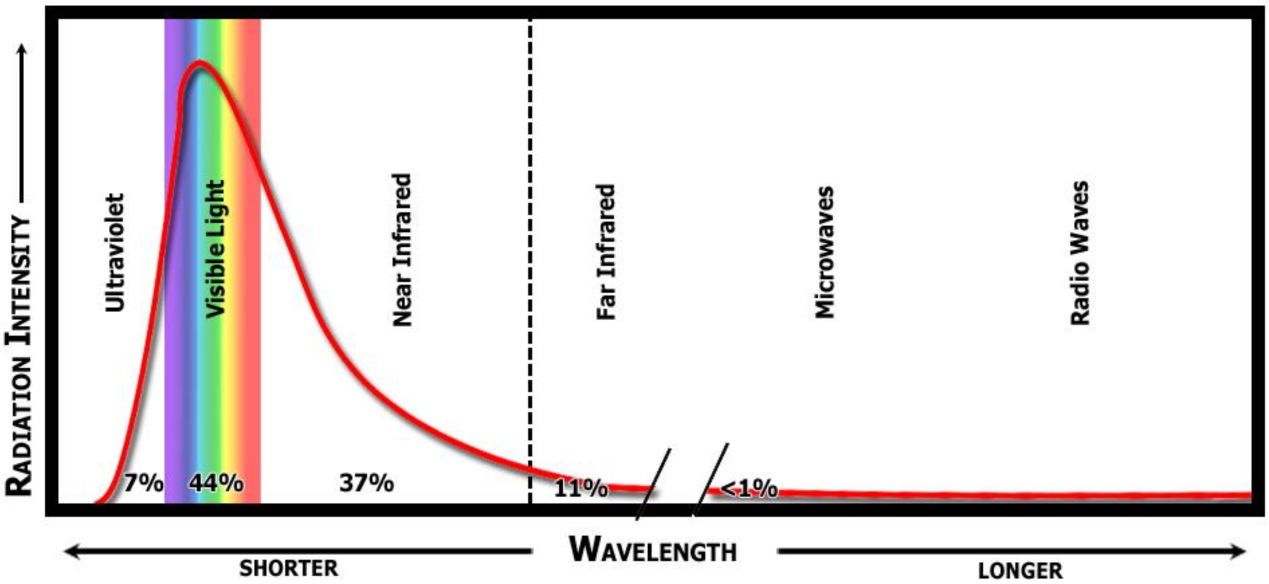


Commonly Used Metric Units

Prefix/Symbol	Meaning	Multiplier	
giga (G)	one billion	10^{9}	1,000,000,000
mega (M)	one million	10^{6}	1,000,000
kilo (k)	one thousand	10^{3}	1,000
hector (h)	one hundred	10^{2}	100
deca (da)	ten	10^{1}	10
deci (d)	one-tenth	10^{-1}	0.1
centi (c)	one-hundredth	10^{-2}	0.01
milli (m)	one-thousandth	10^{-3}	0.001
micro (µ)	one-millionth	10^{-6}	0.000001
nano (n)	one-billionth	10^{-9}	0.000000001

The energy that reaches the Earth is known as solar radiation. Although the sun emits radiation at all wavelengths, approximately 44% falls within visible-light wavelengths. The region of the spectrum referred to as visible light (light our eyes can detect) is composed of relatively short wavelengths in the range 400 nanometers (nm), or 0.4 micrometers (µm), through 700 nm, or 0.7 µm.

Sun's Electromagnetic Spectrum



Temperature and Radiation

Correlation Between Temperature and Radiation

Image Credit: Microsoft Clip Art

When an object is hot enough, you can see the radiation it emits as visible light. For example, when a stovetop burner reaches 1,000 Kelvin (K) — 726° Celsius (C) or 1,340° Fahrenheit (F) — it will glow red. All objects actually emit radiation if their temperature is greater than absolute zero. Absolute zero is equal to zero Kelvin, which is equal to −273°C or −460°F.

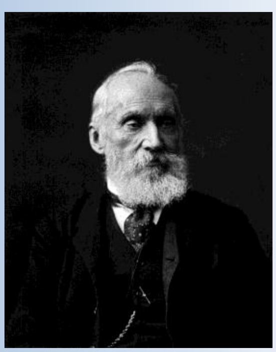


Image Credit: Wikipedia

Kelvin Temperature Scale

In the 19th century, Lord Kelvin created the Kelvin temperature scale to measure very low temperatures. Because zero Kelvin is considered to be the lowest temperature possible, it is described as absolute zero. There are no negative numbers in the Kelvin scale.

Both the sun and Earth's surface behave as blackbodies. An object that absorbs and emits all possible radiation at 100 percent efficiency is called a blackbody. For this reason, the following two laws (Stefan-Boltzmann and Wein's laws) can be used to explain the correlation between temperature and radiation for the sun and Earth.

The Stefan-Boltzmann law, a fundamental law of physics, explains the relationship between an object's temperature and the amount of radiation that it emits. This law (expressed mathematically as $E = \sigma T^4$) states that all objects with temperatures above absolute zero (0 K or −273°C or −460°F) emit radiation at a rate proportional to the fourth power of their absolute temperature.

$$\mathbf{E = \sigma T^4}$$

Stefan-Boltzmann Law

E represents the maximum rate of radiation (often referred to as energy flux) emitted by each square meter of the object's surface. This is also known as intensity and expressed as an "*I*." The Greek letter "*σ*" (sigma) represents the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2K^4$); and *T* is the object's surface temperature in Kelvin. The *W* refers to watt, which is the unit used to express power (expressed in joules per second).

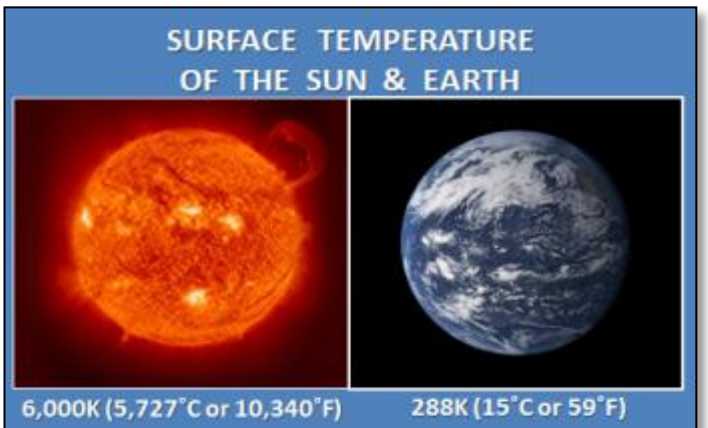


Image Credit: NASA (Sun & Earth)

Using the Stefan-Boltzmann law, let's compare the sun's average surface temperature of approximately 6,000K (5,727°C or 10,340°F) with Earth's average surface temperature of just 288K (15°C or 59°F). Consistent with the Stefan-Boltzmann law, the sun emits more radiation than Earth.

Wien's law, another law of physics, (expressed mathematically as λ_{max} = constant/T) explains the relationship between the object's temperature and the wavelength it emits.

$$\boldsymbol{\lambda_{max} = \text{constant}/T}$$

Wien's Law

The wavelength at which maximum radiation is emitted is expressed by the Greek letter "λ" (lambda). *T* is the object's temperature in Kelvin, and the constant is 2,897 µm (micrometers). The higher the object's temperature, the faster the molecules will vibrate and the shorter the wavelength will be.

Consequently, Wein's law explains why the hot sun emits radiation at relatively shorter wavelengths, with the maximum emission in the visible region of the spectrum, whereas the relatively cool Earth emits almost all of its energy at longer wavelengths in the infrared region of the spectrum. For this reason, solar radiation is often referred to as shortwave radiation, and terrestrial radiation as longwave radiation.

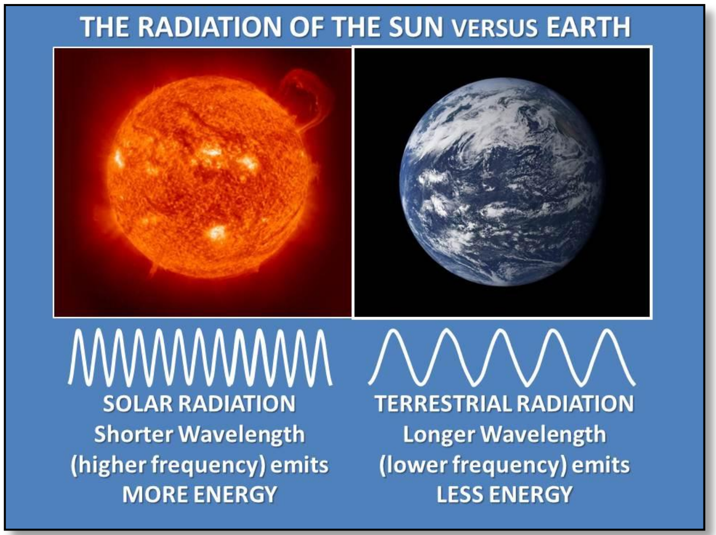
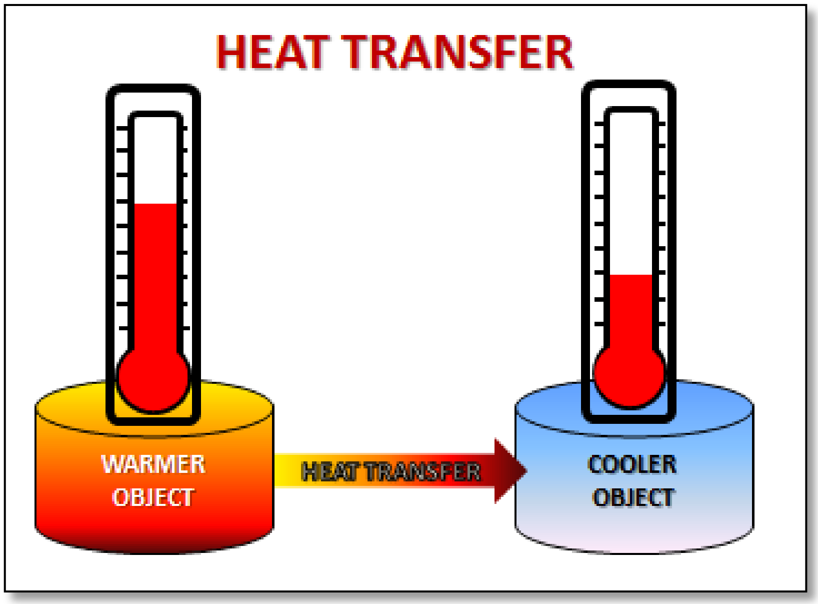


Image Credit: NASA (Sun & Earth)

Heat Transfer in Earth's Atmosphere

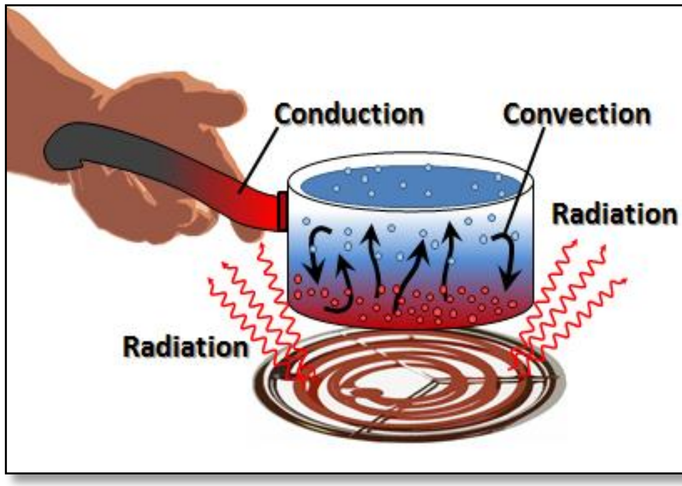
Understanding the basic mechanism of heat transfer within Earth's atmosphere and between its surfaces (land and water) and the atmosphere will help you learn how Earth's energy balance works to regulate our climate. To begin, let's review the difference between heat and temperature.

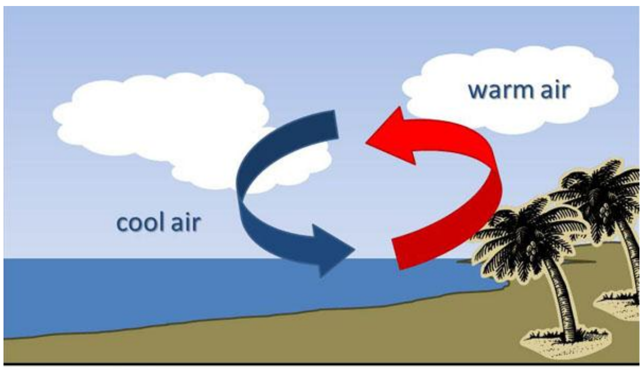


Heat is energy in the process of being transferred from one substance (or object) to another. This process occurs when there is a temperature difference between the two substances. Heat is always transferred from a warmer object to a cooler one. **Temperature** is a measurement of the average speed of the atoms and molecules that make up a substance.

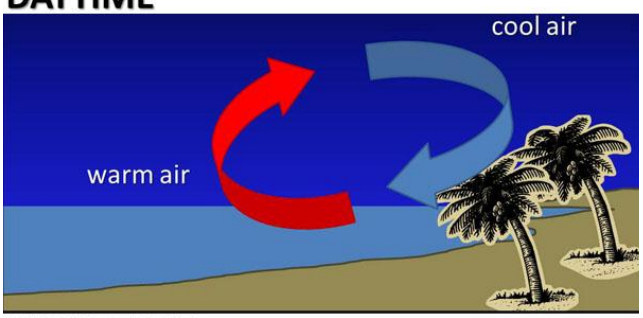
In the previous section, you learned about radiation. Radiation is the mechanism by which solar energy reaches Earth. When Earth absorbs the sun's energy (most of which arrives in the form of visible light), the energy changes into heat. Some of that energy, in turn, is then radiated away from Earth's surface. Because the atmosphere is heated from below, the temperature in the troposphere decreases with height. Heat energy is also spread throughout Earth's atmosphere through conduction and convection.

Conduction is the direct spread of heat from a warmer substance (in this case, land or water) to a cooler substance (the atmosphere). Conduction occurs as molecules transmit vibration (kinetic energy) to adjacent molecules. The heat energy transfers when molecules collide with one another. Therefore, conduction, as a heat transfer mechanism, occurs at Earth's surface where the air is in direct contact with the surface.





DAYTIME

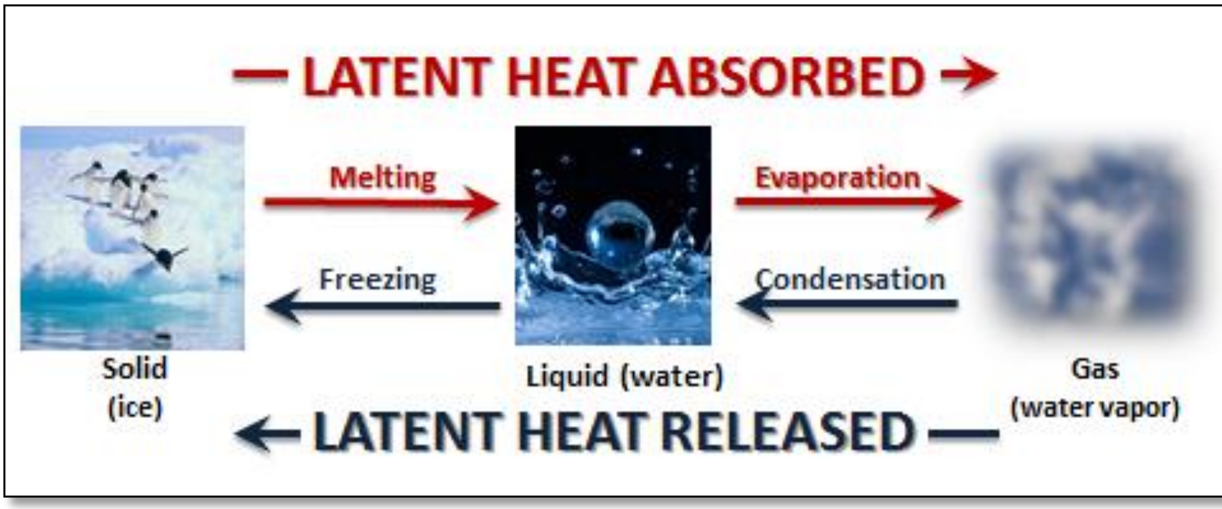


NIGHTTIME

Heat is transferred vertically in the troposphere by **convection.** Convection is the spread of heat in a fluid, defined as a gas or liquid in which atoms and molecules are moving relatively freely. Consequently, convection can occur in the atmosphere or in bodies of water. Convection currents form when there is unequal heating of the atmosphere or water. As air or water warms, it expands and becomes less dense than the air or water above, and it rises. As air or water cools, its density increases and it sinks.

Conduction and convection work together to transfer heat. We can sense the resulting change in temperature, so these heat transfer mechanisms are known as **sensible heating**.

Another type of important heat transfer process affecting the climate system occurs when water undergoes a change in phase. In other words, it changes from a liquid, solid, or gas (water vapor) into a different form or phase (melting ice is an example of a phase change). The reason that heat is transferred as water changes phase is due to the hydrogen bond between molecules of water. Extra energy is needed to break this strong bond and change water from one phase to another.



When water changes phase, heat is exchanged between the water and its surroundings — the water either absorbs or releases heat depending on the phase change. This type of heat is called **latent heat**, because that heat is stored or hidden until the phase change occurs.

Heat is *absorbed* when water changes from a liquid to a gas (water vapor). This energy that is absorbed gives the molecules the extra motion that is needed to escape the surface of the liquid to become a gas. This process is known as evaporation, and the absorption of heat is called the **latent heat of evaporation** (or latent heat of vaporization). When the solid phase (ice) changes to a liquid, melting occurs and heat is also absorbed.

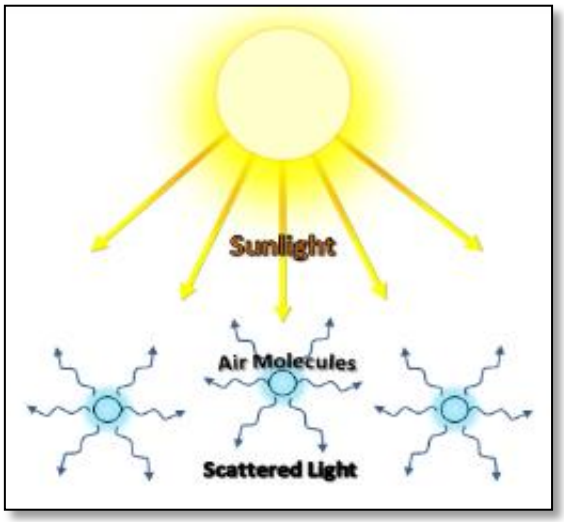
Heat is *released* when water changes from a gas (water vapor) to a liquid. This happens as warm and humid air rises through the atmosphere into cooler temperatures. Cooler air cannot hold as much moisture, so the water vapor condenses. The latent or hidden heat is then released, which is why this process is known as the **latent heat of condensation**. Heat is also released when water's liquid phase changes to a solid phase (or freezes).

Earth's Energy Balance

You have learned that Earth's *surface* absorbs and emits radiation at the same rate. This balance in the rate of Earth's absorption and emission occurs at 255K (−18°C or 0°F), but Earth's average temperature is *actually* much warmer (288K, 15°C, or 59°F). This difference can be explained when you take into consideration the atmosphere. Even though Earth's *atmosphere* absorbs and emits infrared radiation, it *does not* absorb and emit equally. Certain gases in the atmosphere absorb some wavelengths of radiation (transferring their energy into heat), while other gases are transparent and allow radiation to pass through freely, without absorption taking place. You will understand Earth's radiation balance after analyzing how the energy budget is calculated. And you will gain a better understanding of how Earth's temperature is regulated after reading the upcoming sections on Earth's energy balance and the greenhouse effect.

What Happens to Incoming Solar Radiation?

The solar radiation Earth receives primarily consists of shorter wavelengths of visible light. As Wein's law explains, the sun's high temperature emits solar radiation of mostly shorter wavelengths. This incoming solar radiation may be scattered, reflected, or absorbed.



Scattering of solar radiation occurs when the radiation strikes very small objects in Earth's atmosphere, such as air molecules, tiny water droplets, ice crystals, or aerosols (tiny airborne particles), which disperse the solar radiation in all directions. Air molecules and aerosols scatter solar radiation in the atmosphere. Air molecules are much smaller than the wavelengths of visible light striking them. Therefore more of the blue, shorter wavelengths of light are scattered than the red, longer wavelengths of light. This is the reason why the sky appears blue during the daytime. Water droplets and ice crystals that make up clouds scatter light equally at all wavelengths and therefore appear white.

Reflection of solar radiation occurs when the radiation is sent directly backward from a surface. The fraction (or percentage) of radiation reflected back is known as **albedo**. Albedo varies greatly from one location to another on Earth, depending on the type of surface (for example, land or water), the extent of snow or vegetation coverage, and the angle of the incoming solar radiation. Glaciers and ice sheets have high albedos, reflecting 80% to 90% of the radiation reaching their surfaces. The albedo of clouds varies depending on their thickness, with an average albedo of 55%. Water reflects a small amount of solar radiation.

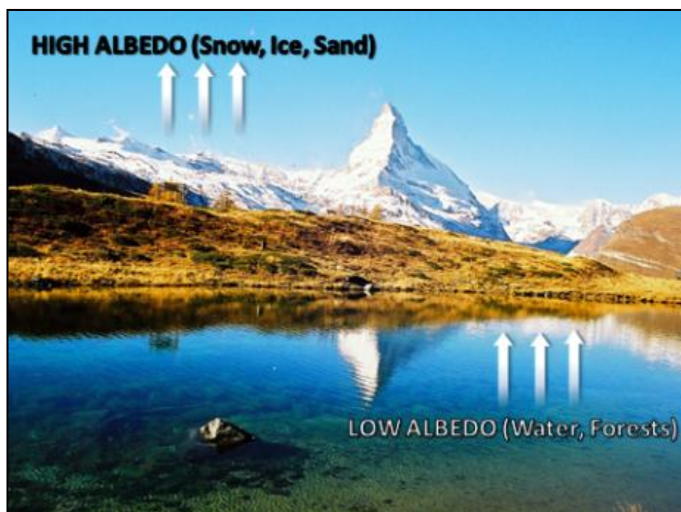


Image Credit: Microsoft Clip Art

In the next module, you will learn more about the albedo and the role it plays in Earth's climate system.

Absorption is different from scattering and reflection, because absorption involves more than a change in the direction of the radiation. Absorption of radiation involves the conversion of electromagnetic radiation into heat energy.

Image Credit: Microsoft Clip Art

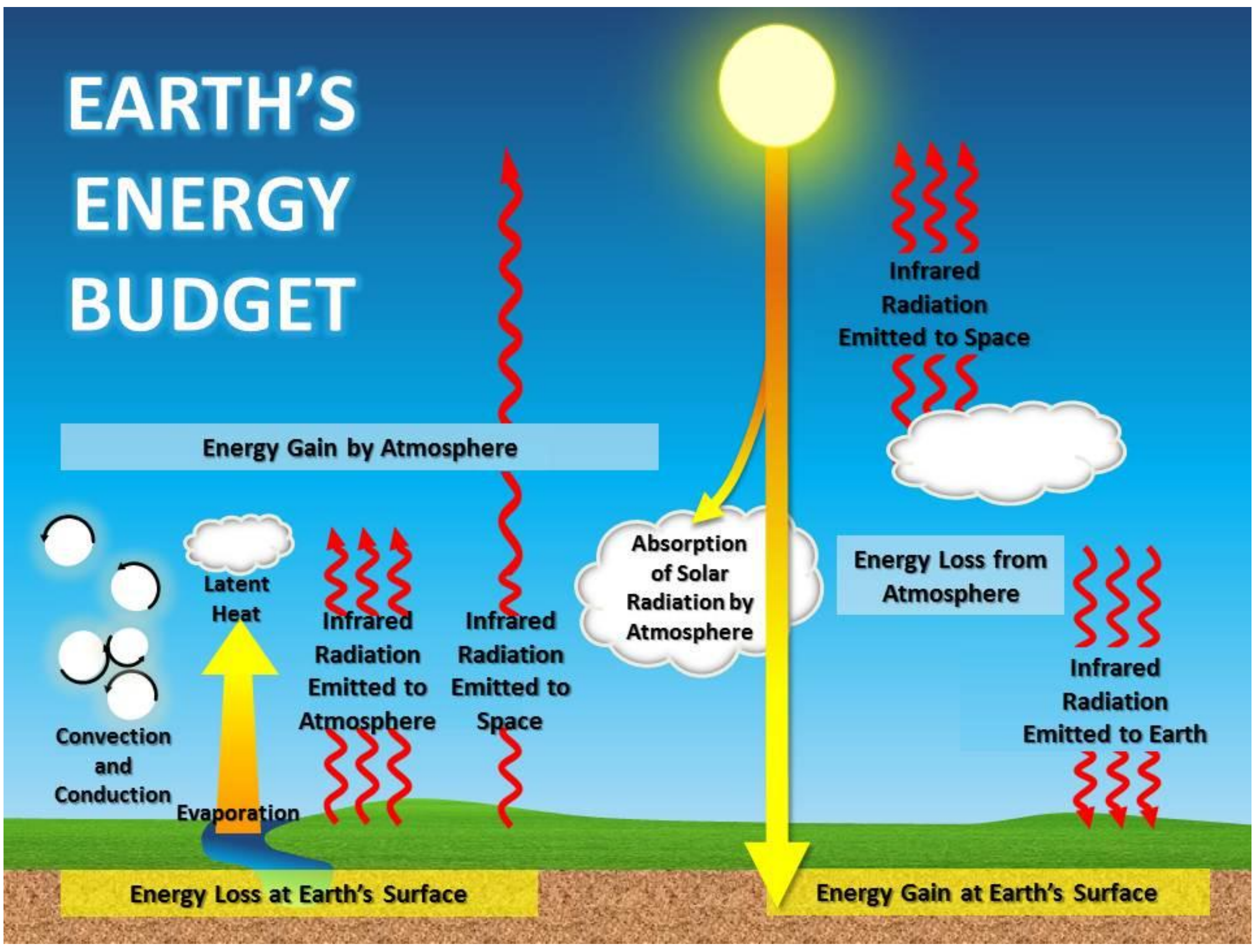
How Do We Calculate Earth's Global Radiation Balance?

Earth's energy balance refers to the balance between the amount of incoming solar radiation and outgoing terrestrial radiation. In a 1-year period, the overall average flow of energy to and from Earth must balance, or the global mean (average) temperature of Earth would change. The following describes how incoming and outgoing radiation balance.

The average amount of solar energy falling on one square meter of level surface at the top of Earth's atmosphere is about 342 watts. A watt is a unit of power equal to 1 joule of energy per second, so radiation intensity is the rate of energy flow (joules per second) per square meter.

What Are a Joule and a Newton?

A joule (J) is a unit of energy or work equivalent to the energy expended when applying a force of 1 newton (N) to move an object 1 meter. A joule is expressed mathematically as 1 kilogram (kg) × meter^2 (m^2) ÷ second^2 (s^2). A newton is defined as a unit of force equal to the force needed to accelerate 1 kg of mass 1 meter per second.



Incoming Solar Radiation

To simplify the explanation of how global radiation balances over a 1-year period, we will use a measurement of 100 units in place of 342 watts (noted above) as the base unit of measurement for incoming solar radiation falling on 1 square meter.

Of the 100 units of incoming solar radiation, 30 are scattered or reflected back to space by the atmosphere and Earth's surface. This means that solar radiation of 240 watts per square meter (70% of 342 W/m^2) makes it through Earth's atmosphere. Of the 30 units that are scattered or reflected, 6 units are scattered by the air, water vapor, and aerosols in the atmosphere; 20 units are reflected by clouds; and 4 units are reflected by Earth's surface. The atmosphere and clouds absorb 19 units of the incoming solar radiation. This leaves 51 units (100 − 30 − 19 = 51) of solar radiation that is absorbed at Earth's surface.

Outgoing Terrestrial Radiation

These incoming 51 units consist of shorter wavelength solar radiation (mostly in the visible region of the electromagnetic spectrum), which is absorbed by land, water, and vegetation. Remember that in the process of being absorbed, the radiation is converted into heat energy. Some of this absorbed radiation or heat energy is then emitted away from Earth's surface as longer wavelength infrared radiation.

To understand how incoming solar radiation and outgoing terrestrial radiation are balanced, we will need to look at the energy gains and losses at Earth's surface and in the atmosphere.

To learn more, proceed to the Investigation

***Earth's Energy Budget: How Is the Temperature of Earth Controlled*?**

The Greenhouse Effect

Joseph Fourier.
Image Credit: [Wikipedia]

In 1827, Joseph Fourier, a French mathematician and physicist, wondered why Earth's average temperature is approximately 15°C (59°F). He reasoned that there must be some type of balance between the incoming energy and the outgoing energy to maintain this fairly constant temperature. His calculations indicated that Earth should actually be much colder (−18°C or 0°F).

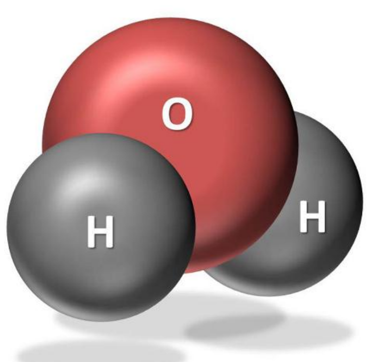
To have an average temperature of 15°C (59°F), Fourier knew that there had to be another process occurring in the atmosphere — something similar to the way a greenhouse retains heat. A greenhouse's glass enclosure allows visible light to enter and be absorbed by the plants and soil. The plants and soil then emit the absorbed heat energy as infrared radiation. The glass of the greenhouse then absorbs that infrared radiation, emitting some of it back into the greenhouse and thus keeping the greenhouse warm even when the temperature outside is lower.

Image Credit: Microsoft Clip Art

Because the two processes are similar, the name "greenhouse effect" was coined to describe Fourier's explanation. However, part of a greenhouse's warmth results from the physical barrier of the glass, which prevents the warmer air from flowing outward. So despite the fact that the atmospheric greenhouse effect has some processes in common with an actual greenhouse, the overall mechanisms driving the greenhouse effect are different and more complex.

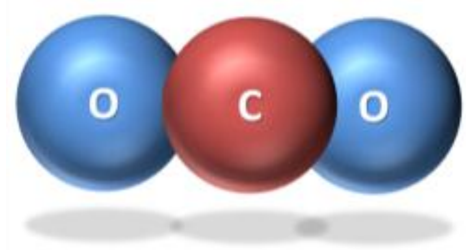
Earth's Greenhouse Gases

You have already learned that Earth's atmosphere is composed primarily of nitrogen and oxygen. These gases are transparent to incoming solar radiation. They are also transparent to outgoing infrared radiation, which means that they do not absorb or emit solar or infrared radiation. However, there are other gases in Earth's atmosphere that do absorb infrared radiation. These gases are known as **greenhouse gases**. Below are the most important greenhouse gases that influence Earth's climate system.

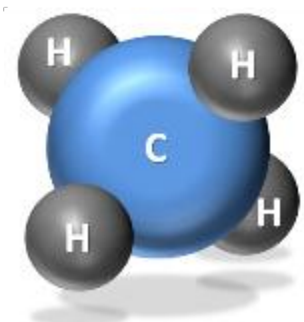


Water vapor (H_2O) is the strongest greenhouse gas, and the concentration of this gas is largely controlled by the temperature of the atmosphere. As air becomes warmer, it can hold more moisture or water vapor. When the air becomes saturated (or holds as much moisture as the air can at that temperature), the excess moisture will condense into cloud droplets. And if these droplets are large enough, they will fall as precipitation.

Carbon dioxide (CO_2) is also an important greenhouse gas. It has a long lifetime in Earth's atmosphere. Carbon dioxide strongly absorbs energy with a wavelength of 15 µm (micrometers). This makes carbon dioxide a good absorber of wavelengths falling in the infrared radiation region of the spectrum.



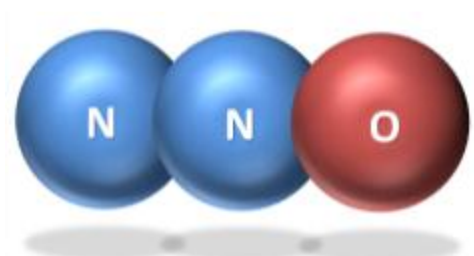
Carbon dioxide constantly moves into and out of the atmosphere through four major processes: photosynthesis, respiration, organic decomposition (or decay) and combustion or the burning of organic material. You will learn more about carbon dioxide and the carbon cycle in Module 3.

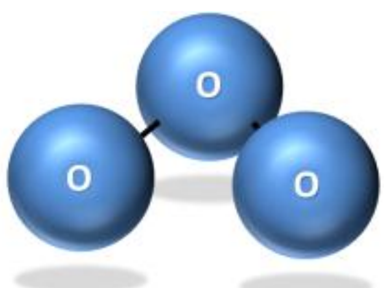


Methane (CH_4) is 30 times stronger than carbon dioxide as an absorber of infrared radiation. Methane, however, is present in smaller concentrations than carbon dioxide, so its net contribution to the greenhouse effect is not as large. Methane is also relatively short-lived (lasting approximately 8 years) in the atmosphere. Methane is produced when bacteria decompose organic plant and animal matter in such places as wetlands (e.g., marshes, mudflats, flooded rice fields), sewage treatment plants, landfills, and the guts of cattle and termites. Scientists are concerned about the concentration of methane increasing in regions where the Arctic and alpine permafrost is thawing and releasing methane as it warms.

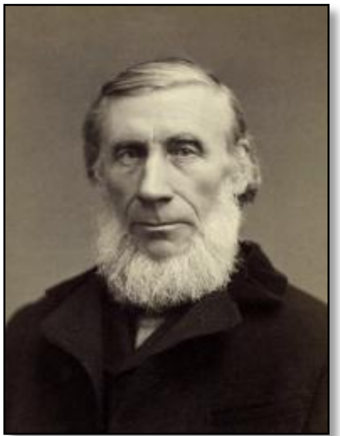
Halocarbons are composed of carbon, chlorine, fluorine, and hydrogen. They include chlorofluorocarbons (CFCs), which are man-made gases commonly used in refrigerators and air conditioners. Concentrations of CFC gases in the atmosphere are the highest of any of the halocarbons, and they can absorb more infrared radiation than any other greenhouse gas. The impact of 1 molecule of a CFC gas is equivalent to 10,000 molecules of carbon dioxide.

Nitrous oxide (N_2O), a relatively long-lived gas, has increased in atmospheric concentration due mainly to agriculture. Nitrate (NO_3^-) and ammonia (NH_4^+) are used as fertilizers. Bacteria convert a small amount of this nitrate and ammonia into the form of nitrous oxide. Internal combustion engines also produce nitrous oxide.





Ozone (O_3) is also a relatively minor greenhouse gas because it is found in relatively low concentrations in the troposphere (the lowest layer of the atmosphere). In the troposphere, it is produced by a combination of pollutants — mostly hydrocarbons and nitrogen oxide compounds.



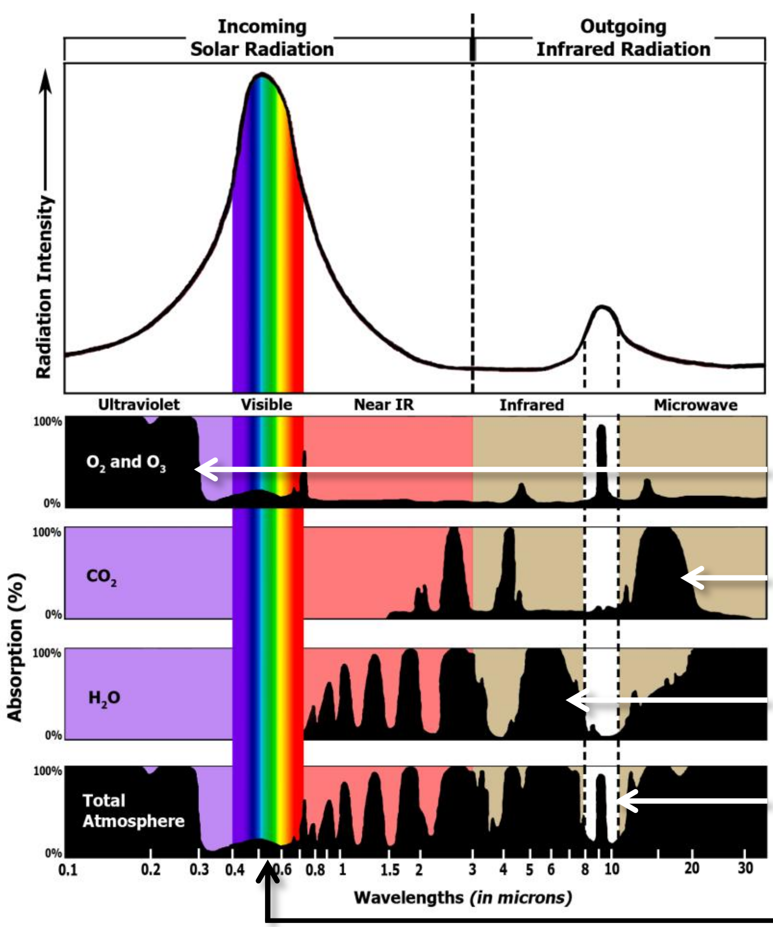
John Tyndall.
***Image Credit:* [Wikipedia]**

Another pioneer of the science of the greenhouse effect was John Tyndall, an Irish scientist who was fascinated by the growth and formation of glaciers. In the 1860s, Tyndall, wanted to test his ideas explaining how Earth maintained a fairly constant temperature. He began a series of experiments to measure the amount of radiant heat (infrared radiation) that certain gases could absorb and transmit. Tyndall found that water vapor and carbon dioxide were good absorbers and emitters of infrared radiation.

The relative importance of a greenhouse gas depends on its abundance in Earth's atmosphere and how much the gas can absorb specific wavelengths of energy.

An effective absorber of infrared radiation has a broader absorption profile, which means that it can absorb a wider spectrum of wavelengths. Water vapor and carbon dioxide can absorb radiation wavelengths in the range of 4 µm to 80 µm, except those between 8 µm and 12 µm. Ozone can absorb wavelengths between 9 µm and 10 µm, but as you have learned, it is found in low concentrations. The sun's ultraviolet wavelengths are strongly absorbed by the ozone in the stratosphere.

Greenhouse Gas Absorption Wavelengths



The graphic shows the absorption bands of ozone, carbon dioxide, water vapor and total atmosphere. Gases in the atmosphere absorb energy at different wavelengths on the electromagnetic spectrum. This graphic explains why the wavelengths in the visible light range of the electromagnetic spectrum are able to reach Earth's surface and why the wavelengths in the infrared radiation range are emitted to space.

Ultraviolet light is absorbed by ozone.

Both water vapor and carbon dioxide can absorb radiation wavelengths in the range of 4 µm to 80 µm, except those between 8–12 µm.

"Atmospheric Window" – There is little absorption from 8–12 µm which allows infrared radiation to be emitted to space.

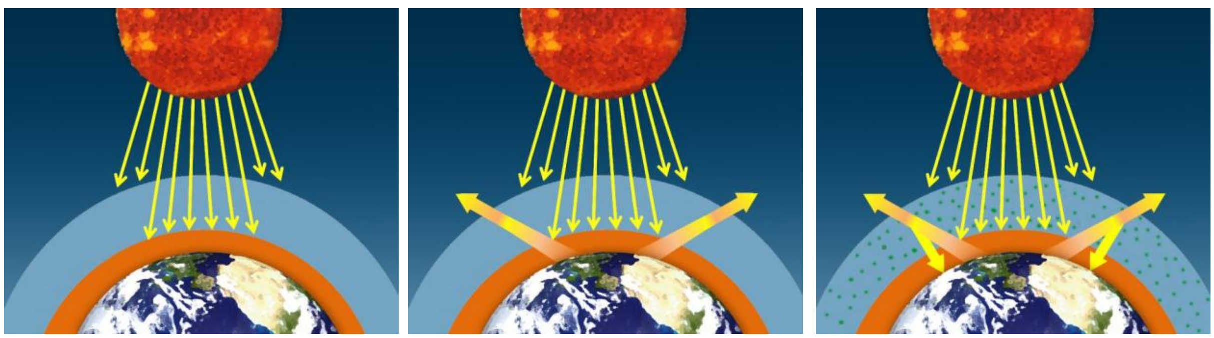
Visible light is transmitted through the atmosphere (little absorption).

How the Greenhouse Effect Works

The sun's visible wavelengths of radiation pass easily through the atmosphere and reach Earth. Approximately 51% of this sunlight is absorbed at Earth's surface by the land, water, and vegetation. Some of this energy is emitted back from the Earth's surface in the form of infrared radiation.

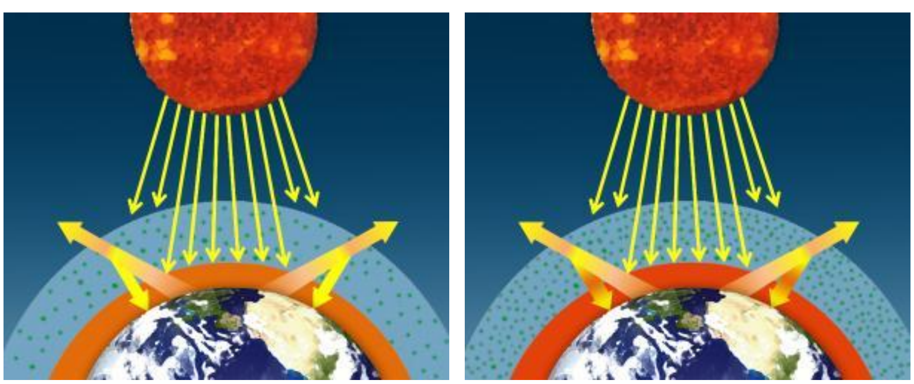
Water vapor, carbon dioxide, methane, and other trace gases in Earth's atmosphere absorb the longer wavelengths of outgoing infrared radiation from Earth's surface. These gases then emit the infrared radiation in all directions, both outward toward space and downward toward Earth. This process creates a second source of radiation to warm to surface (visible radiation from the sun and infrared radiation from the atmosphere) which causes Earth to be warmer than it otherwise would be. This process is known as the **natural greenhouse effect** and keeps Earth's average global temperature at approximately 15°C (59°F). To review, Fourier's calculations indicated that Earth should actually be much colder (−18°C or 0°F) if Earth did not have a natural greenhouse effect.

The Natural Greenhouse Effect



If the concentration of greenhouse gases increases, then more infrared radiation will be absorbed and emitted back toward Earth's surface, creating an **amplified greenhouse effect.**

A Natural Greenhouse Effect Versus an Amplified Greenhouse Effect



When averaged over the course of a year, the amount of incoming solar radiation received from the sun has balanced the amount of outgoing energy emitted from Earth. This equilibrium is called Earth's energy or radiation balance. Relatively small changes in the amounts of greenhouse gases in Earth's atmosphere can greatly alter that balance between incoming and outgoing radiation. Earth then warms or cools in order to restore the radiative balance at the top of the atmosphere. This temperature increase or decrease can be calculated using the Stefan-Boltzmann Law ($E = \sigma T^4$).

Energy: The Driver of Climate - Review

You have learned that the balance between incoming energy from the sun and outgoing energy from Earth ultimately determines Earth's climate. This is actually explained by the first law of thermodynamics (or the law of conservation of energy).

Incoming solar energy from the sun primarily consist of shorter wavelengths of energy, mostly in the visible part of the electromagnetic spectrum. To balance the absorbed incoming energy, Earth must, on average, emit the same amount of radiation back into space. Because Earth is colder than the sun, it emits radiation at much longer wavelengths (in the infrared part of the spectrum). Greenhouse gases in Earth's atmosphere absorb some of this infrared radiation, which is then re-emitted back toward Earth's surface to maintain an average global temperature of approximately 15°C (59°F).

The Stefan-Boltzman law explains that if the incoming and outgoing energy are not balanced, a planet either cools or warms. An imbalance in the overall energy budget can result as the concentration of greenhouse gases increases. Greenhouse gases absorb and emit infrared radiation back to Earth. Balance to the energy budget can be restored if Earth's average global temperature increased.

Human civilization has advanced and spread across the planet throughout a very brief period of recent geologic history. During this time, Earth's average global temperature has changed very little. In the next module, you will investigate whether the recent warming trends is unusual. You will also compare trends for Earth's temperature over different lengths of time, from decades to over 100's of thousands of years. You will also analyze temperature trends for different geographic regions.