# What is the greenhouse effect?

An accessible, scientific introduction

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# 1 Introduction

We increasingly often hear about climate change in news media and in public policy discussion, but how can we assess the information we hear without a clear understanding of what climate change is, what causes it, and what its impacts are?

**Global warming**, which is the increasing average temperature of the Earth, is the main aspect of how the climate is changing this century. Some of the many anticipated (or already realized) consequences of global warming are sea level rise, amplified droughts and floods, agricultural changes, deaths of coral reefs and the ecosystems that depend on them, and more intense hurricanes/typhoons. Global warming is caused by the increase in carbon dioxide in the atmosphere: the name given for this influence that certain atmospheric gases have on temperature is the *greenhouse effect*. Considering the central role that the greenhouse effect plays in climate change and the importance of climate change to our immediate future, the goal of this document is to give an accurate and detailed explanation of the greenhouse effect.

This document is intended for a reader lacking specific scientific knowledge, so it covers the requisite principles of physics with digressions and examples to provide context for the information being presented. The greenhouse effect is a consequence of the physics of light, energy, and temperature, so we begin by discussing these concepts. From there, we present a simplified model representing the Earth in which we can calculate exactly how much the temperature changes when greenhouse gas is added, and discuss what we can learn from the model and how the real world behaves in comparison.

Scientific terms are put in bold when their definition is given by the surrounding text, and in italics otherwise.

In section 2 we summarize how the greenhouse effect works; a reader satisfied with this summary may skip the rest of the document.

In section 3 we explain how energy enters and leaves the Earth, which happens in the form of light. We discuss light and the different types (that is, wavelengths) of light, and we introduce a graph called a *spectrum* which shows what types of light are in a beam. We then describe the *blackbody effect*, which states that all objects emit light, and relates the amount and type of light emitted by an object to the temperature of the object.

In section 4 we introduce the concept of an *equilibrium* of a system, which could be a typical or average state for the system to be in; it is frequently much easier to find the equilibria of a system than to describe the exact behavior of a system as it changes over time. We discuss equilibria in the context of temperature and calculate the equilibrium temperature for the Earth in the absence of the atmosphere.

In section 5 we present a very simple model to represent the Earth and its atmosphere. Using the tools learned in the previous sections, we can calculate the equilibrium temperature of the Earth with this model, and see what exactly changes as we change the amount of greenhouse gas in the model. The finding that the temperature goes up as greenhouse gas is added is the greenhouse effect. We then explore the differences between the simple model and the real-world climate of the Earth.

In section 6 we suggest two excellent books suitable for non-scientific readers.

In appendix A we give an overview of what the atmosphere is, starting from questions like why it is thicker on the bottom and whether it has a top.

In appendix B we discuss the ozone layer and ozone hole. While they have no bearing on the greenhouse effect, they are summarized here as they are a frequent point of confusion with the greenhouse effect. The worldwide effort to control the ozone hole by regulating CFCs is also the only notable example of a global agreement to address a global environmental problem, and thus makes a useful point of comparison to the future regulation of carbon dioxide emissions.

In appendix C we briefly explain the difference between Celsius, Fahrenheit, and Kelvin, and why all three are used in various parts of this document.

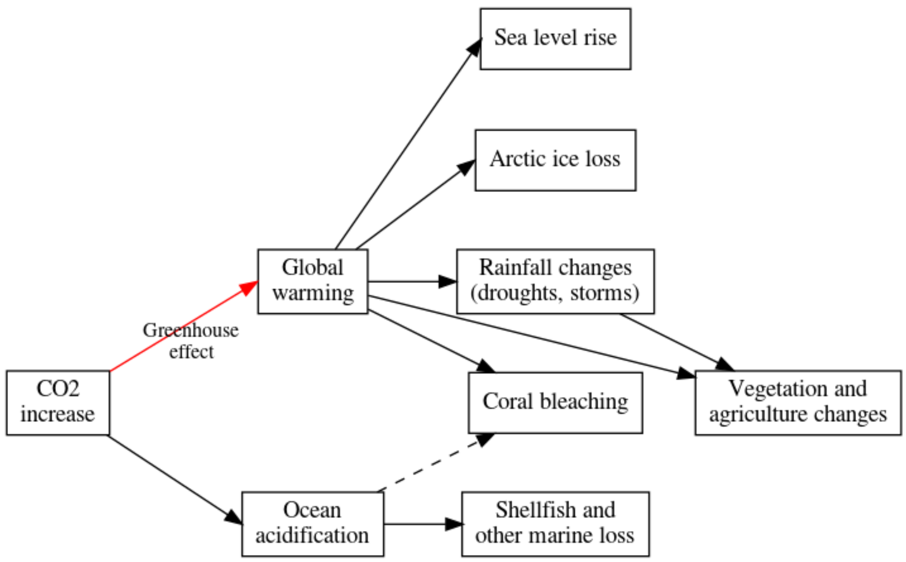


Figure 1: Major aspects of climate change in this century and their relationships. Solid arrows indicate where one aspect is the primary cause of another; the red arrow represents the greenhouse effect. Of course, this diagram is a drastic simplification, and is only meant to provide context for the greenhouse effect in climate change as a whole.

## 2 Summary

The Earth is warmed by *visible light* it receives from the Sun, and is cooled by emitting *infrared light* (which is invisible) to space. Greenhouse gases in the atmosphere are those that absorb infrared light, but not visible light. Some of the infrared light emitted by the Earth is absorbed by the greenhouse gases and returned to the Earth.

The Earth's temperature is in balance when the total energy it receives equals the total energy it emits. As infrared light is returned to the Earth by greenhouse gases, the energy the Earth receives is increased, so it must emit more energy to maintain balance. The Earth emits more light when it is warmer. In this way adding greenhouse gases to the atmosphere causes the Earth to become warmer.

# 3 Physics of light and temperature

## 3.1 Light

*Light*, also called *radiation* or *electromagnetic radiation*, is a familiar aspect of our daily lives. Light can be emitted, absorbed, reflected, transmitted, or refracted by objects, and travels in a straight line otherwise. When light strikes our eyes, it is absorbed and gives us information about the object that emitted or reflected that light, which we call "seeing" the object. Light is a type of *energy*.

A beam of light is made of many individual **photons**[1], which are indivisible parcels of light. While the brightness of a beam of light depends on how many photons are in it, not all photons are the same. The properties of a photon can be described with a single number, its **wavelength**; two photons with the same wavelength are indistinguishable[2].

The wavelength of a photon affects what objects it can interact with. For example, radio waves, which have a wavelength of 1 meter or more, can pass through walls but will interact with the antenna of a radio receiver; and the microwaves in a microwave oven, which have a wavelength of 12.2 centimeters, are easily absorbed by the water in food to heat it up but cannot pass through the small holes in the metallic screen covering the door[3].

In particular, certain wavelengths of light are able to interact with the light-sensitive cells (called "rod" and "cone" cells) in our eyes to produce sight; light of these wavelengths is called **visible light**, while light of other wavelengths cannot be seen[4]. The various wavelengths of visible light appear to our eye as different **colors**. Just as the chemicals in our food are perceived by us as having different tastes, the different wavelengths of visible light are perceived as different colors; and just as some chemicals are tasteless, some wavelengths of light cannot be seen at all.

While wavelength and color are closely related, the wavelength of a photon is a single number (a length) that describes its physical properties, but the color of a beam of light is a far more complicated property that depends on how light interacts with the human eye and how the brain interprets this interaction, and therefore is also slightly different from person to person. The longest wavelength a photon can have and be detectable to the human eye is about 0.7 microns[5]; light of this wavelength appears dull red. Longer wavelengths of light are infrared, microwave, and radiowaves, which are invisible to the eye. The shortest visible wavelength is around 0.39 microns, which appears deep blue or violet; shorter wavelengths are

[1]The photon was discovered by Max Planck and Albert Einstein around 1905; for this work Einstein received the Nobel Prize in physics.

[2]Instead of wavelength, photons are sometimes described by their **frequency** or energy. These are related by $E = h\nu = hc/\lambda$, where $E$ is the energy of the photon, $\nu$ is the frequency, $\lambda$ is the wavelength, $h = 6.626 \cdot 10^{-34}\mathrm{J \cdot s}$ is Planck's constant and $c = 3 \cdot 10^8 \mathrm{m/s}$ is the speed of light. Throughout this document we will only use wavelength.

[3]The interior of the microwave oven is surrounded on all sides by metal, forming what is called a Faraday cage which microwaves cannot escape.

[4]Except that very strong x-rays shown directly in the eye can appear faintly blue; this was discovered in 1895 before the dangers of x-rays were known.

[5]A **micron** is one millionth of a meter. "Micron" is short for "micrometer", which is also written 1 $\mu$m. A micron is about a hundred times smaller than the thickness of a sheet of paper, and is a bit smaller than the typical bacterium. We will use microns frequently in this document to describe wavelengths of light.

ultraviolet, x-rays, and gamma rays. Light with wavelengths between 0.39 and 0.7 microns are visible.

Rainbows are formed by separating the photons in a beam of light according to their wavelength; so if all the photons in a beam of visible light have the same wavelength, then its color will be one of the colors of the rainbow. Other colors, such as pink, magenta, or brown, can only be formed by a beam of light containing a mixture of photons of different wavelengths. Two different mixtures can appear to be the same color; for example, light at 0.58 microns (which appears yellow) cannot be made by a standard computer monitor, but a monitor can make a mixture of red and green that appears that same yellow color to the human eye. Some colors, called impossible or imaginary colors, cannot be produced by any beam of light, but can be seen for example using afterimages.

The mix of wavelengths that are in a beam of light is called the **spectrum** of that beam. We can graph a spectrum by showing how much energy the beam has at different wavelengths; where the spectrum is low, the beam has very few photons around that wavelength, and where the spectrum is high, the beam has many photons around that wavelength. Two simple examples of spectra are shown in figure 2.

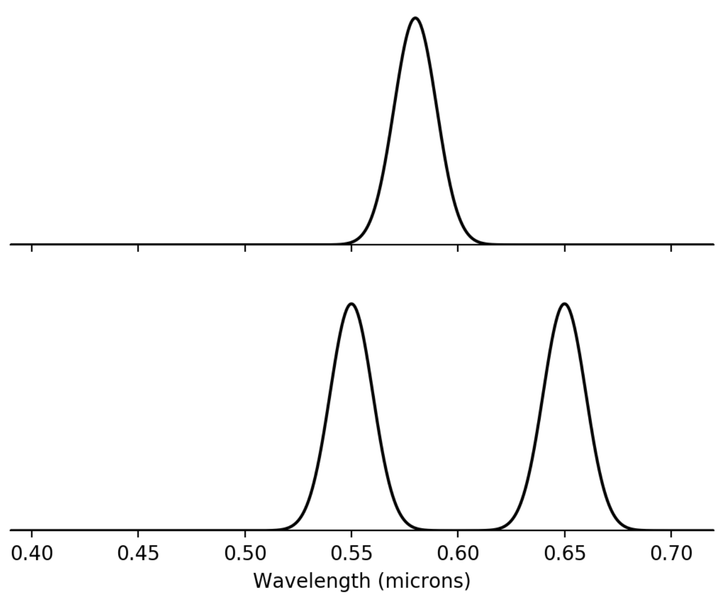


Figure 2: Spectra for two different beams of light, both of which are yellow. Above is the spectrum of a beam of light which contains only photons with a wavelength near 0.58 microns. Below is the spectrum of a beam of light which contains of a mixture of photons, some near 0.55 microns and some near 0.65 microns, like might be produced by the green and red pixels in a computer monitor.

To illustrate the usefulness of spectra for understanding light, figure 3 shows real-world observations of the spectra of light from four commercially available light bulbs. The shaded region indicates visible wavelengths of light. We can see from the spectra that the incandescent and halogen bulbs emit many more photons of long wavelengths; they will appear "warmer" (that is, with tones of yellow or red). In comparison, the fluorescent and LED bulbs will appear "cooler" (more white or blue). We can also see that the incandescent and halogen produce a great deal of infrared light that is not visible to the eye. While more than 99% of the light produced by the LED is visible light, only 15% of the light produced by the incandescent bulb and 10% of the light produced by the halogen bulb is visible. This contributes to the much greater efficiency of fluorescent and LED lighting.

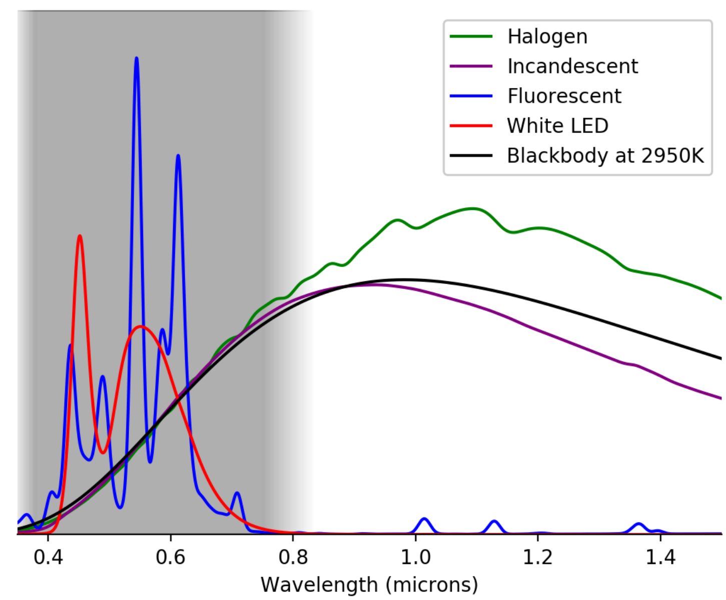


Figure 3: Spectra of real-world observations of four commercially available light bulbs. The shaded region indicates the portion of the spectrum that is visible to the eye; the other light is wasted for purposes of illumination. The spectra have been scaled so that all four contain the same amount of energy in the visible region; each of the four bulbs would have the same brightness to the eye. The LED and fluorescent lights emit almost all of their light as visible radiation, which contributes to their excellent efficiency. By contrast, the incandescent and halogen bulbs waste a great deal of energy emitting infrared light.

The simplest possible bulb, the incandescent light, works by heating an object (the filament) until it is so hot that it glows visibly due to the *blackbody effect*, which is discussed in section 3.2. The close match of the observed spectrum of the incandescent light with the theoretical spectrum of a blackbody at a temperature of 2950 K (2667 C, 4850 F), also shown in the figure, suggests that the filament of the incandescent bulb used in the experiment had a temperature near 2950 K. The only commonly available materials with a melting point above that are carbon and tungsten; while the first light bulb filaments used carbon, since around 1906 tungsten filaments have been used almost exclusively.

The poor match of the observed spectrum of the LED and fluorescent spectra with a theoretical blackbody spectrum shows that those two bulbs use a different physical process to emit light.

## 3.2 The relationship between temperature and light: blackbody radiation

It has long been understood that hot objects feel hot from a distance, although a scientific explanation of this phenomenon has only come recently. This process is different from conduction, which is the movement of heat from a hot object to an object it is touching. For example, a fire in a fireplace feels warm from a distance even before the air in the room has begun to warm up, so the warmth is not due to conduction via the air. Furthermore, a person near the fireplace feels warmer on the side facing the fire even though the air on both sides is the same temperature. This also can be observed with a hot stovetop, which feels warm from the side even though rising hot air should only be felt directly above the stovetop.

This is because every object emits light according to its temperature, which is called the **blackbody effect**; light emitted in this way is called **blackbody radiation**[6]. Since light is a form of energy, emitting light causes an object to cool down[7], and absorbing light causes an object to warm up.

It is a necessary fact of life that the hotter an object is the more blackbody radiation it emits; so if two objects of different temperature are placed near each other then the hotter object emits more light than it absorbs, cooling down, and the cooler object absorbs more light than it emits, warming up. If this were not true and instead hotter objects emitted less blackbody radiation, then hotter objects would get hotter and hotter, while cooler objects would get cooler and cooler, until everything in the universe would be either extremely hot or extremely cold[8].

An exact formula for the amount of light emitted by an object by the blackbody effect was found in 1879, called the Stefan-Boltzmann law. The amount of light emitted is

$$A\sigma T^4,$$

where $A$ is the area of the object, $T$ is its temperature relative to absolute zero (for example, using Kelvin), and $\sigma$ is a constant[9]. As an example, doubling the temperature of an object multiplies its emissions by $2^4 = 16$. Using this law we can calculate the temperature of an object by measuring its blackbody radiation; this is how infrared thermometers work. In

[6] The first person to study blackbodies was Gustav Kirchhoff in 1860, who was unable to determine the formula for blackbody radiation but called it "a problem of the highest importance"; this proved true when the discovery of the formula led to the discovery of the photon.

[7] With a very few exceptions; for example, black holes warm up when they lose energy.

[8] Since black holes become colder when they absorb energy, and they start colder than their surroundings, they just get even colder over time until they approach absolute zero; for example the black hole in the center of the Milky Way, called Sagittarius A*, is approximately $1.7 \cdot 10^{-14}$ K. The rest of the universe is currently about 2.7 K, so Sgr A* is gaining energy from its surroundings and continuing to cool down. Eventually the rest of the universe will cool down until it is even colder than Sgr A*, so Sgr A* will start losing energy over time and warm up until it eventually explodes.

[9] Real-world objects actually emit slightly less light than indicated by this formula; the proper formula is $A\epsilon\sigma T^4$ where $\epsilon$ is the **emissivity** of the object, a number between 0 and 1 that depends on the material the object is made out of and the wavelength of light that we are interested in. Most objects in daily life have an emissivity around 0.9 to 1 in infrared wavelengths. The surface of the Earth has an average emissivity of about 0.96 in infrared wavelengths. For simplicity we take $\epsilon = 1$ for the rest of this document.

fact, Josef Stefan used this law to give the first accurate estimate for the temperature of the surface of the Sun, 5700 K, by comparing sunlight to light emitted from a hot object with a known temperature. The true temperature is 5772 K.

As another example, we can use this law to estimate how much light is given off by an electric stovetop. A hot stovetop (or any object) begins to visibly glow a very dull red when it reaches around 800 K (527 C, 980 F), called the Draper point. This compares to room temperature of about 300 K (27 C, 80 F). Using the Stefan-Boltzmann law, we see that the hot stovetop emits $(800/300)^4 \approx 50$ times more light than it would at room temperature. From this, one may be able to crudely estimate that you need to be within $\sqrt{50}/2 \approx 3$ stovetop-lengths of the stovetop to significantly feel the light from a red-hot stovetop compared to surroundings at room temperature.

As well as knowing the total amount of blackbody radiation emitted at a specific temperature, we also know what wavelengths blackbody radiation has (that is, the radiation's spectrum). An exact formula for how much each wavelength occurs in blackbody radiation is called Planck's law[10]. Planck's law tells us that blackbody radiation is mostly near a specific wavelength, and that the hotter an object is the shorter that wavelength is. A room temperature object will mostly emit light near 14 microns, which is infrared light, and an object at the Draper point of 800 K will mostly emit light nearer 5 microns, which is still infrared. The Sun, however, mostly emits light of wavelengths near 0.7 microns, so it is easily visible to the eye.

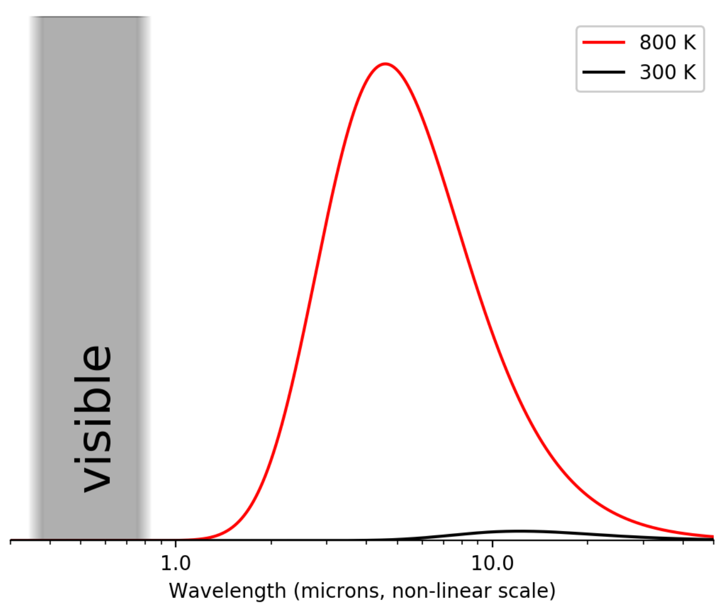


Figure 4: Blackbody spectra for a temperature of 800 K, compared to room temperature of 300 K. The hotter object emits far more light in total, and also emits sufficient visible light to glow a dull red.

In figure 4, we see a comparison of the emissions from a blackbody (such as a stovetop,

[10] Planck discovered this law in 1900; Einstein used it to predict the existence of the photon in 1905.

which is a good approximation to a blackbody) at a temperature of 800 K against the same object with a temperature of 300 K; the object emits 50 times more light when hot. Almost all of the light emitted is infrared; the hot object emits 10 million times more infrared light than visible light, which is marked with the shaded region of the diagram. While we can't see the infrared light at all, there is so much of it that we can feel it as heat when nearby. However, we have no trouble seeing the visible emissions of the stovetop because our eyes are tremendously sensitive at detecting visible light – so much so that laboratory tests have found that people can sometimes detect a single photon in ideal conditions.

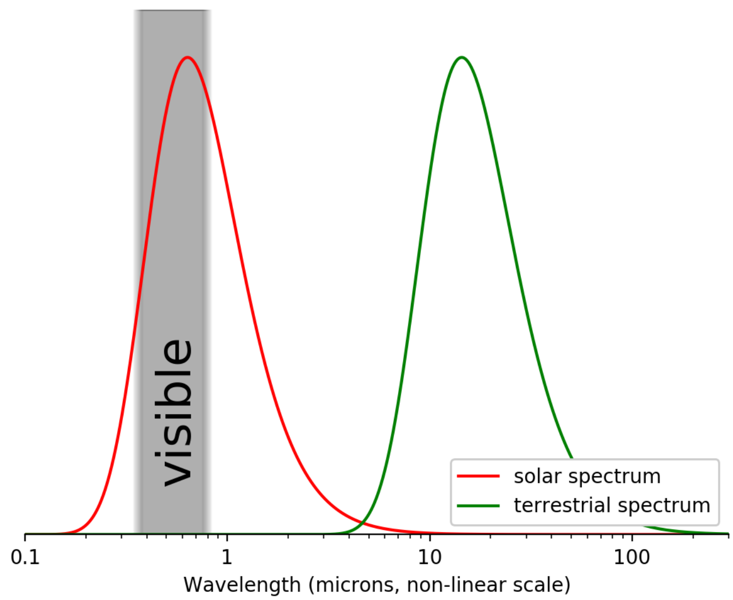


Figure 5: Simplification of light entering and leaving the Earth. For this figure, we assume that the Sun and Earth are perfect blackbodies, each with a uniform temperature; in particular we assume that the Earth has no atmosphere. The total amount of energy that the Earth absorbs from the Sun equals the amount of energy that the Earth emits to space; in section 4 we will discuss *thermal equilibrium*, which describes this state of balance. However, while the total amount of energy is the same, the wavelengths of the light are very different. The Sun emits roughly 46% of its energy as infrared, 44% of its energy as visible light, and 10% of its energy as ultraviolet (which is mostly absorbed by the ozone layer; see appendices A and B), but the Earth emits essentially all of its energy as infrared that is totally invisible to the eye.

An idealized comparison of the sunlight that reaches the Earth and of the light that the Earth emits to space is given in figure 5. While the amount of energy that enters the Earth equals the amount of energy that leaves the Earth, causing the Earth to be in balance, the wavelength of the incoming and outgoing light is different.

In the context of climate science and the greenhouse effect, the term **longwave radiation** is used to describe blackbody radiation emitted by the Earth (including the Earth's surface, oceans, the atmosphere, clouds, etc.) and the term **shortwave radiation** is used to describe blackbody radiation emitted by the Sun. Since objects on the Earth tend to be much colder than the surface of the Sun, longwave radiation has much longer wavelength than shortwave radiation. Specifically, since objects on the Earth are about 20 times colder than the surface of the Sun, they emit radiation that has a wavelength about 20 times longer.

Because of the large gap between the wavelengths of longwave and shortwave radiation, certain chemicals will interact strongly with one type of radiation but not with the other. The most common gases in our atmosphere, oxygen and nitrogen, are transparent to both longwave and shortwave radiation. However **greenhouse gases** such as water vapor, carbon dioxide and methane are opaque to longwave radiation but transparent to shortwave radiation. These gases interfere with longwave radiation emitted by the Earth so that it does not cool as effectively, but do not interfere with shortwave radiation from the Sun, so they cause a net warming effect called the **greenhouse effect**. The details of this process will be explored in the following sections. Conversely, sulfur dioxide in the stratosphere can form sulfate particles that, like clouds, are partially reflective of sunlight and thus cool the Earth by decreasing how much shortwave radiation it receives.

# 4 Temperature of the Earth

## 4.1 Equilibrium temperature

So far we have been using temperatures without any discussion about what temperature is or what it measures. Though the technical details of temperature are tricky[11], in everyday life and for the purposes of this document we can consider **temperature** as a measure of how much thermal energy is in an object. There are two important properties of temperature: adding heat to an object causes its temperature to increase[12], and when two objects are allowed to freely exchange energy then heat will flow from the hotter object to the colder object. As we discussed in section 3.2, if these two properties were not true then life would not be possible.

We say an object is in **thermal equilibrium** with its surroundings if its temperature is not changing over time. This is the same thing as saying there is no net flow of heat in or out of the object. What happens if an object was at thermal equilibrium but is transiently heated up? The object is hotter than before and will therefore lose heat faster than before; for example, through blackbody radiation, which is greater the hotter an object is. Since the object will now have a net flow of heat outwards, it will cool down over time. Similarly, if an object was at thermal equilibrium and is transiently cooled down, it will experience a net flow of heat inwards and heat up over time.

Therefore we expect that in general an object will have a unique **equilibrium temperature**, that is, the one temperature at which it would be at thermal equilibrium with

[11] Temperature is typically defined as the derivative of the energy of a system with respect to the entropy of the system ($T = dU/dS$, where $U$ is energy and $S$ is entropy). In particular, infinite temperatures or temperatures below absolute zero are possible and have been created in laboratory conditions. Due to a quirk of the definition of temperature, negative temperatures are hotter than infinite or positive temperatures.

[12] One major exception is phase changes like ice melting or liquid water evaporating; another of course is black holes, as mentioned earlier.

its surroundings. Above this temperature, the object will cool down, and below this temperature, the object will heat up, and at this temperature the object will be in thermal equilibrium. The equilibrium temperature depends on the object's surroundings and the interactions between the object and its surroundings. If these change, then the equilibrium temperature can also change. For example, consider a room heated by a heater on a cold day; the room reaches some steady temperature at which the heat it gains from the heater is balanced by the heat lost to the outside. Opening a window decreases the equilibrium temperature, so the room will cool off until it approaches this new equilibrium temperature.

By analyzing the equilibria of a system we often find it much easier to understand how the system changes over time. The most direct approach to studying the changes in a system, which I would call the "dynamic" method, is to determine the current state of the system and how that state is changing. For example, if we know the current temperature of an object, and we know how the temperature is changing, then we can predict the future temperature of the object. Alternatively we can analyze the equilibria of a system, which I call the "static" method. The static method loses information about transient fluctuations or detailed behavior of the system, but it often is better at giving an overall understanding of the behavior of the system. The static method is also usually easier and more robust to model error[13].

In the specific example of studying the temperature of the Earth, the dynamic method requires knowing the current temperature of the Earth, exactly how much energy the Earth is receiving from the Sun at each point in time, and exactly how much energy the Earth is losing to space at each point of time. Knowing these three things we can calculate the temperature of the Earth at any point in the future. Of course, this is totally infeasible because, for example, the amount of sunlight reflected back into space depends on how many clouds there are and what shape they have, which rapidly changes within hours. If we tried to make predictions in this way they would become wildly inaccurate almost immediately because any small error compounds upon itself[14].

Alternatively, using the static method we first measure how much energy the Earth is typically receiving from the Sun, and then calculate the temperature at which the Earth would emit as much energy as it is receiving. This calculation tells us the equilibrium temperature of the Earth, that is, the temperature at which it radiates the same amount of energy as it receives, so that the Earth's temperature does not change. While this method does not explain any oscillations or fluctuations around the predicted equilibrium temperature, it does capture the most important features that are relevant to the Earth's temperature.

## 4.2 Temperature of the Earth with no atmosphere

We now have the pieces to understand what temperature the Earth would have in the absence of an atmosphere. The Earth gains energy through light received from the Sun; some of this light is reflected back to space but most of it is absorbed by the Earth's surface. The proportion of light reflected back to space is called the **albedo** of Earth, and it equals

[13] **Model error** refers to details of the real-world system which are omitted in the mathematical model. Regardless of how detailed and precise the model is, there will always be some further detail that is missing.

[14] Which is not to suggest that such predictions are impossible, just that this naive approach is not viable.

approximately 30%[15]. The Earth loses energy by radiating it to space due to the blackbody effect, that any warm object emits light; the amount of energy lost this way depends on the Earth's temperature. The equilibrium temperature of the Earth is the temperature at which the energy gains from the Sun are equal to the energy losses due to the blackbody effect.

The rate at which energy is received from the Sun is equal to

$$\pi R^2(1-\alpha)S$$

where $R$ is the radius of the Earth, $\alpha$ is the albedo of the Earth, and $S$ is the **insolation** of the Earth (the amount of energy in sunlight received by the Earth, per area and per time). The reason for the factor of $\pi R^2$ is that, from the perspective of the Sun, the Earth appears to be a disc of radius $R$, so that $\pi R^2$ is the total *effective* area illuminated by the Sun[16]. Since the albedo $\alpha$ is the proportion of light reflected back to space, $1-\alpha$ is the proportion absorbed.

From the Stefan-Boltzmann law, the rate at which energy is radiated from the Earth due to the blackbody effect is

$$4\pi R^2\sigma T^4$$

where again $R$ is the radius of the Earth, $\sigma$ is the Stefan-Boltzmann constant, and $T$ is the temperature of the Earth. Here $4\pi R^2$ is the surface area of a sphere with radius $R$.

At the equilibrium temperature $T_e$ the energy received and emitted is equal, so

$$\pi R^2(1-\alpha)S = 4\pi R^2\sigma T_e^4.$$

If we know the values of $\alpha, S$, and $\sigma$ we can solve for $T_e$:

$$T_e = \left(\frac{1-\alpha}{4\sigma}S\right)^{1/4}.$$

Observe that the radius $R$ of the Earth has no effect; if the Earth were larger, it would absorb more sunlight and also emit more blackbody radiation.

If we use sensible values[17] for $\alpha, S$, and $\sigma$, we compute the equilibrium temperature

$$T_e = 255 \text{ K}$$

or -18 C or -1 F.

The temperature of an astronomical body computed in this way, by ignoring all atmospheric effects, is called the **effective temperature**; specifically, we find the effective temperature of an object by measuring how much light it emits and using the Stefan-Boltzmann

[15] Of course, if the Earth had no atmosphere it would have a significantly different albedo, among many other major differences.

[16] While the surface area of the Earth is $4\pi R^2$ and half of that is exposed to sunlight at any time, the amount of sunlight a location receives depends on the angle the Sun is above the horizon, and the average illuminated location receives half as much light as it would receive under direct, full sunlight.

[17] We take albedo $\alpha = 0.3$, insolation $S = 1366$ W m$^{-2}$, and Stefan-Boltzmann constant $\sigma = 5.67 \cdot 10^{-8}$ W m$^{-2}$K$^{-4}$. As per a previous footnote, we use an emissivity $\epsilon = 1$. If we use a more realistic $\epsilon = 0.96$, we get $T_e = 257$ K.

law to determine the temperature needed to emit that much light. In fact, when we previously spoke about the temperature of the surface of the Sun, we really meant the effective temperature of the Sun[18]. A distant astronomer attempting to measure the temperature of the Earth would be measuring its effective temperature.

The effective temperature of the Earth differs from the true temperature of the surface of the Earth in two important ways:

1. The effective temperature is a single number, while the true temperature varies with location.

2. The surface temperature is affected by the atmosphere, in particular the greenhouse effect.

The effective temperature can be thought of as a suitable average[19] of the temperature across all locations. These spatial variations are important to weather and the climate but do not directly pertain to the greenhouse effect, so we will not discuss them here.

# 5 Greenhouse effect

In this section we will be using what we have learned about light and temperature to create a simple model of the Earth with its atmosphere, which we can solve to see what effect changing the atmosphere has on the temperature of the modeled Earth.

The model is not *quantitative*, meaning that it is not accurate enough for the numerical results from the model to agree with the true numbers, but it is *qualitative*, meaning that the overall behavior of the model agrees with the overall behavior of the Earth. Therefore by understanding how the model works we can improve our understanding of the Earth system; in particular, the way the greenhouse effect works in the model is the same way that the greenhouse effect works on the Earth.

## 5.1 Simple model of Earth with atmosphere

Consider figure 6 of the Earth[20] and its atmosphere, with energy flowing between them.

The arrows in the diagram represent energy flowing between the different objects in the form of light; we ignore other forms of energy transfer[21]. On the left of the diagram is

[18] Like the gas planets, the Sun does not have a solid surface, but instead gradually becomes denser and more opaque closer to the center. The "surface" is defined somewhat arbitrarily in terms of a certain level of opacity. The exact temperature at this depth would be difficult to measure, but is likely very close to the effective temperature.

[19] Rather than the typical arithmetic mean, the fourth root of the arithmetic mean of the fourth powers is the suitable average. This is always warmer than the arithmetic mean, although not significantly so for the Earth.

[20] We mean "the surface of the Earth" when we say "the Earth", as the interior of the Earth only very slowly exchanges heat with the surface, so it can be ignored.

[21] All energy exchanged with the Sun or with space is in the form of light, but some of the energy exchanged between the Earth and the atmosphere is in other forms. In particular, hot water molecules that physically move from the surface into the air bring a large amount of energy with them, called *latent heat*. Heat

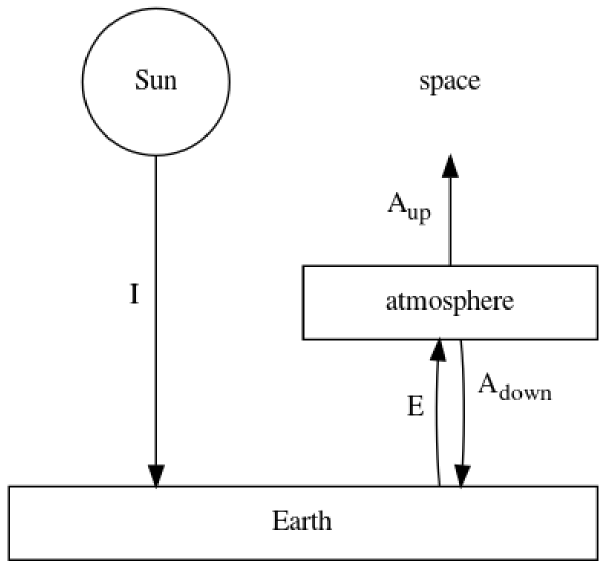


Figure 6: Diagram representing energy flowing between the surface of the Earth, the atmosphere, the Sun, and space.

shortwave radiation, that is, visible light. The variable $I$ is the rate at which energy from the Sun is being absorbed by the surface of the Earth; we assume that none of this shortwave radiation is absorbed by the atmosphere. We omit from the diagram light from the Sun that strikes the Earth (or clouds in the atmosphere) and is reflected to space; $I$ is only the portion that is absorbed. Recall from section 4.2 that

$$I = \pi R^2(1-\alpha)S.$$

On the right of the diagram is longwave radiation, that is, infrared light. The variable $A_{\mathrm{up}}$ is the rate at which radiation leaves the top of the atmosphere to space; some of this is emitted by the atmosphere, and the rest is emitted by the Earth and passed through the atmosphere. The variable $A_{\mathrm{down}}$ is the rate at which radiation emitted by the atmosphere strikes the Earth. Finally, the variable $E$ is the rate at which radiation is emitted by the Earth, which will either be absorbed by the atmosphere or transmitted to space.[22]

For the reasons discussed in section 4.1 we are interested in the equilibrium of the system, that is, when the total amount of energy entering each object equals the energy leaving that object.

conduction plays a lesser role.

We also omit geothermal heating, which is energy flowing from the interior of the Earth to the surface. This is estimated to be 47 TW, or 0.092 watts per square meter.

[22] We briefly remark on the arrows that are absent from the diagram. The most interesting omission is the arrow from the Sun to the atmosphere; we have already commented on that. A tiny fraction of the light emitted to space goes on to strike the Sun or other bodies, but we are uninterested in where exactly it goes once it leaves the Earth. Space is filled with *cosmic microwave background radiation*, so there should be arrows representing microwave light from space to each of the other objects, but the amount is so tiny as to be totally insignificant – only 1.6 GW of it reach the Earth, or 3 microwatts per square meter. Finally, the Sun emits a tremendous amount of light into space that does not strike the Earth, but we are not interested in that.

So far we have only introduced very mild assumptions into the model, so we are unable to draw any substantial conclusions from it yet. However before we go further let us look at what we can conclude so far.

Let $T$ be the average[23] temperature of the Earth. Then as in section 4.2, we know that

$$E = 4\pi R^2 \sigma T^4$$

where $R$ is the radius of the Earth.

At this point in the calculations in 4.2 we solved for the effective temperature $T_e$ that satisfied the equality $E = I$. However, the introduction of the atmosphere changes this equation. Since the Earth is at equilibrium, the total flow of energy in and out of the surface is equal, giving the equality

$$\begin{aligned} E &= I + A_{\text{down}} \\ 4\pi R^2 \sigma T^4 &= \pi R^2 (1-\alpha) S + A_{\text{down}}, \end{aligned}$$

where the additional term $A_{\text{down}}$ is downward heating from the atmosphere, which has the effect of increasing the temperature $T$ of the surface of the Earth, demonstrating the greenhouse effect. Our goal is to find the temperature $T$ of the Earth, which will require calculating $A_{\text{down}}$ and $A_{\text{up}}$.

Since the atmosphere is at equilibrium, we also have

$$E = A_{\text{up}} + A_{\text{down}}.$$

Combining this equation with $E = I + A_{\text{down}}$ gives us $I = A_{\text{up}}$, which is to say that the total amount of sunlight the Earth absorbs equals the total amount of light it emits, much as we would expect[24].

### 5.1.1 Simple model: no greenhouse gas

To solve for the temperature $T$ of the Earth, we need the values of $A_{\text{down}}$ and $A_{\text{up}}$, or equivalently we need to know what fraction of the energy $E$ emitted by the Earth is absorbed by the atmosphere or transmitted through it to space. We know that $E = A_{\text{down}} + A_{\text{up}}$ but that is not sufficient information by itself. To find these values we need some kind of additional assumption about the physics of the atmosphere.

The simplest assumption to understand is the total absence of gases that interact with infrared light, so that the atmosphere has no greenhouse gas. In this case, all light from the Earth is transmitted directly to space, and the atmosphere neither absorbs nor emits any infrared light.

[23] Whenever we say the "average" temperature of a (convex) object in the context of blackbody radiation, we mean the fourth root of the arithmetic mean of the fourth power of the surface temperature, weighted by surface area and emissivity. That is, we use exactly the average that makes the Stefan-Boltzmann law work with the result. For objects like the Earth, where the temperature does not vary tremendously from one location to another, this average is close to the ordinary arithmetic mean. For tidally-locked or slowly rotating objects like Mercury or the Moon, the distinction can be very important.

[24] In fact, direct measurements of light going in and out of the Earth agree with each other up to the accuracy with which they can be measured.

In this case, we have $E = A_{\text{up}}$ and $A_{\text{down}} = 0$. Then $E = I$ and we get exactly the situation of section 4.2, so that the temperature of the surface of the Earth equals the effective temperature: $T = T_e$.

### 5.1.2 Simple model: atmosphere has one layer, with ample greenhouse gas

The next simplest assumption that can be made about the Earth's atmosphere is to assume that it is a single uniform temperature, which is usually described by saying it has a "single layer". The crucial consequence of this assumption is that the downward emissions $A_{\text{down}}$ from the atmosphere equals the upwards emissions.

If we further assume that there is so much greenhouse gas in the atmosphere that all of Earth's emissions $E$ are absorbed by the atmosphere, then $A_{\text{up}}$ consists only of upwards emissions from the atmosphere. From the uniform temperature assumption, we get $A_{\text{down}} = A_{\text{up}}$, so

$$A_{\text{down}} = \frac{1}{2}E.$$

Combining with $E = I + A_{\text{down}}$ we get

$$\begin{aligned} E &= I + \frac{1}{2}E \\ E &= 2I \\ 4\pi R^2 \sigma T^4 &= 2\pi R^2 (1-\alpha) S \end{aligned}$$

so

$$T = 2^{1/4} T_e = 1.1892 T_e = 303 \text{ K}.$$

This is 30 C or 86 F, somewhat above the true average temperature of the Earth.

As more and more greenhouse gas is added to the atmosphere, the assumption that the atmosphere can maintain a uniform temperature would break down as the emissions from the Earth can't penetrate past the very bottom of the atmosphere. Each successive layer of greenhouse gases added to the atmosphere causes the temperature to increase by a factor of $2^{1/4}$, so that every fourth layer doubles the temperature. If we modify the model to accommodate anti-greenhouse gases[25] which absorb visible light and transmit infrared light, then each layer of anti-greenhouse gases decreases the temperature by a factor of $2^{-1/4}$, canceling out one layer of greenhouse gases.

### 5.1.3 Simple model: atmosphere has one layer, with some greenhouse gas

Continuing the assumption that the atmosphere is a single layer of uniform temperature, now we consider the situation that the atmosphere has some greenhouse gas, such that a portion of the Earth's emissions $E$ are absorbed, with the rest transmitted unchanged. Let $\lambda$ be the fraction of emissions that are absorbed, so that the atmosphere absorbs $\lambda E$ and transmits

[25] Hazy conditions can have an anti-greenhouse-like effect, although the mechanism is not exactly the same; for example, major volcanic eruptions cool the Earth for a few years by putting sulfur aerosols in the stratosphere. There are no actual anti-greenhouse gases, as far as I know.

$(1-\lambda)E$. Since half of the atmosphere's emissions are downwards, we get $A_{\text{down}} = \frac{\lambda}{2}E$, so that

$$E = I + \frac{\lambda}{2}E$$
$$E = \frac{1}{1-(\lambda/2)}I,$$

and therefore $T = (1-(\lambda/2))^{-1/4}T_e$.

When $\lambda = 0$, we recover the situation of section 5.1.1 with no greenhouse gas, and get $T = T_e$. When $\lambda = 1$, we find again the result of section 5.1.2, and get $T = 2^{1/4}T_e$. As we vary the amount of greenhouse gas in the atmosphere from no gas to ample gas, $\lambda$ varies between 0 and 1, and the temperature calculated from the model varies from $T_e$ to $2^{1/4}T_e$, increasing as greenhouse gas is added. This illustrates how adding greenhouse gases to the atmosphere causes the temperature to rise.

## 5.2 Real-world greenhouse effect

We have considered several simple examples of atmospheric models where we were able to calculate the temperature that the surface of the Earth would have to maintain the system in equilibrium. While the greenhouse effect acts in the real world to raise the temperature of the Earth in just the same way as it acts in the model, there are many additional complications to the real climate system that our simple examples do not represent. With the aid of detailed observations of the atmosphere it is possible to build sophisticated computer simulations of the climate; but our simple model is sufficient to understand the basic principles underlying the greenhouse effect.

In our "single layer" model (section 5.1.3), we assumed that the atmosphere was a single uniform temperature. The real atmosphere has temperatures that wildly vary with height, and the greenhouse gases in the atmosphere are only sensitive to specific wavelengths of infrared light, with different gases located in different concentrations in different parts of the atmosphere.

We briefly discuss the structure of the atmosphere; a more detailed explanation can be found in appendix A. The lowest layer of the atmosphere, called the **troposphere**, is the bottom 10 to 15 km of the atmosphere and contains about 80% of its mass. The troposphere is well-mixed because it is heated from below[26]. While infrared radiation is one way that energy goes upwards in the troposphere, another major component is hot air rising. Above the troposphere is the stratosphere, which is well stratified into distinct layers because it is heated from above by the the ozone layer.

The main greenhouse gases located in the Earth's atmosphere are water vapor, carbon dioxide, methane, and ozone, listed in decreasing order of their contribution to the greenhouse effect. Ozone is mostly located in the ozone layer in the stratosphere. While ozone only has

[26]This fact is how real-world greenhouses work, which is totally unrelated to the greenhouse effect. A greenhouse prevents the air near the ground from rising and mixing with the air above, causing hot air to be trapped near the surface. It has nothing to do with blocking infrared radiation, as can be demonstrated by placing a small vents in the roof and sides of a greenhouse, which causes it to cool to ambient temperatures.

a small greenhouse effect, it plays a very important role in Earth's climate and ecosystem because it absorbs ultraviolet radiation.

Methane is a very efficient greenhouse gas compared to carbon dioxide, but it is present at a much lower concentration. Most methane released into the atmosphere decays to carbon dioxide within about 10 years. Levels of atmospheric methane today are approximately 3 times the natural amount, with the main sources being natural gas mining and livestock.

Carbon dioxide is a very stable gas that is only removed in significant amounts through photosynthesis and diffusion into the surface of the ocean. When excess carbon dioxide is added to the atmosphere, most of it remains for hundreds of years, and some remains for tens of thousands of years. Because of its stability, carbon dioxide is well-mixed through all layers of the atmosphere and plays a key role in the greenhouse effect.

Today carbon dioxide is about 410 ppm in the Earth's atmosphere, of which about 130 ppm is from artificial sources. Natural levels of carbon dioxide vary from 180 ppm to 280 ppm on a timescale of about 100 000 years[27]. The main artificial source of carbon dioxide is fossil fuel burning.

Water is the most important gas in the atmosphere and has a direct effect on almost every aspect of the climate. While water is chemically unreactive in atmospheric conditions, it readily condenses from vapor into liquid or solid, making clouds, and sometimes precipitating out. Because of this, almost all water vapor is located in the warm air nearest the surface, with very little found at higher altitudes. Since water is mostly confined near the surface it does not have as large a greenhouse effect as it would if it were evenly mixed throughout the atmosphere.

Furthermore, water rapidly enters or leaves the atmosphere in response to changes in weather conditions, with warmer conditions typically increasing the amount of water. This gives other greenhouse gases a compounding effect: any warming caused by the addition of carbon dioxide to the atmosphere results in an increase in water concentration, causing further warming. In extreme cases this could cause a "runaway" greenhouse effect, as is thought to have happened to Venus. Finally, water forms clouds when it condenses, which have complicated and hard to understand effects on the climate, and are capable of either warming or cooling the Earth depending on what altitude they are.

These gases are capable of absorbing different wavelengths of infrared light, as seen in figure 7. The **attenuation** of light due to a gas is what fraction of light would be absorbed by the gas – that is, how opaque it is, or the opposite of how transparent it is. For example, a photon with a wavelength of 13 microns emitted by the surface of the Earth going directly upwards has about a 50% chance of being absorbed by a water molecule, assuming it is not scattered or absorbed by any other gas. At 15 microns we see that both water and carbon dioxide are capable of absorbing almost all light emitted by the surface of the Earth, whereas around 11 microns, called the **infrared atmospheric window**, most light emitted by the surface of the Earth passes to space without being absorbed by the atmosphere.

Although the atmosphere absorbs almost all emissions from the surface of the Earth at specific wavelengths, that does not mean that light of that wavelength is not emitted to space. Recall that in the single-layer model, even when the atmosphere was totally opaque

[27]Before the industrial revolution, the natural level of carbon dioxide was already at roughly 280 ppm, at the high end of the natural cycle.

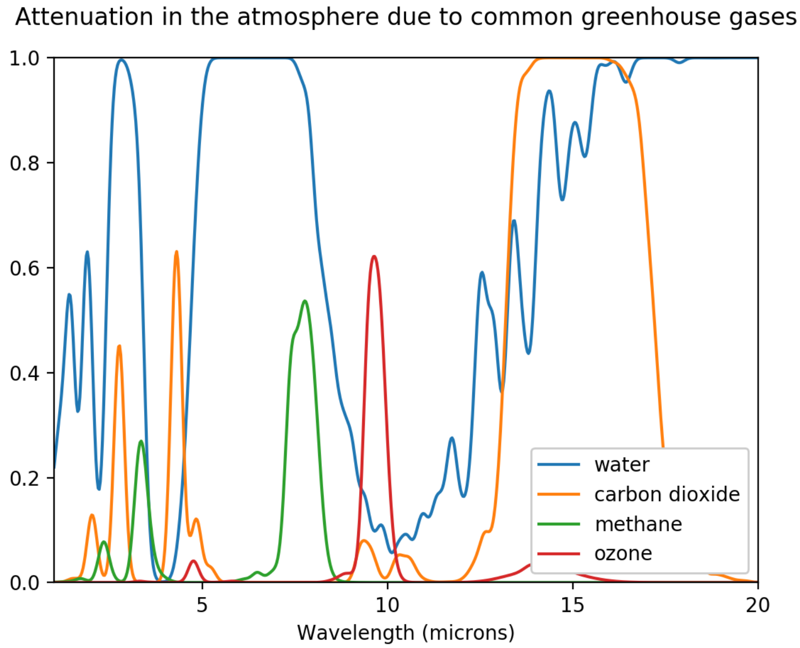


Figure 7: Attenuation of infrared light due to various gases. When the Earth emits infrared light, it can pass through the atmosphere unaffected or be absorbed by the atmosphere. For the four most important greenhouse gases, this figure shows the fraction of light at each wavelength that would be absorbed by that gas, assuming no other gas absorbs it instead. For example, the water and carbon dioxide in the atmosphere are separately capable of absorbing nearly 100% of light at a wavelength of 16 microns. At 13 microns, water and carbon dioxide are separately capable of absorbing roughly 50% of the emissions, so together they absorb about 75%.

to infrared radiation, infrared radiation still reached space because the atmosphere itself was emitting it. Therefore, at wavelengths like 7 microns and 15 microns where the atmosphere is very effective at absorbing the Earth's radiation, *almost all light at those wavelengths that reaches space was emitted by the atmosphere*. Because the atmosphere is colder than the surface of the Earth, the atmosphere is less effective at emitting heat to space. In particular, this gives us another perspective for understanding the Earth's effective temperature, which we defined in section 4: the effective temperature measures the temperature of the part of the atmosphere that is emitting infrared radiation directly to space[28].

Another way to describe this situation is that instead of the surface of the Earth radiating energy directly to space, instead energy flows from the surface to the atmosphere in the form of infrared radiation, and then from the atmosphere to space. The atmosphere itself has many layers, with the lower layers warming the upper layers. The surface of the Earth must be warmer than the atmosphere, as otherwise energy would not flow from the surface to the atmosphere; and likewise each layer of the atmosphere must be warmer than the layers

[28] Or more specifically, the average of the temperatures of the various parts of the Earth and atmosphere, weighted according to what proportion of the emissions to space come from that part.

above it so that energy will flow from the lower layers to the upper layers[29]. The more layers there are, the hotter the surface of the Earth needs to be to push the same amount of heat outwards. Since the surface continues to receive the same amount of energy from the Sun no matter how many layers of greenhouse gases are added, if not enough heat is being expelled from the surface, then the surface will simply heat up until there is.

The total effects of the greenhouse gases in the Earth's atmosphere can be seen in figure 8. The figure presents typical infrared emissions from the Earth when the surface of the Earth is 294.2 K (21 C, 70 F) and there are no clouds. The blue line illustrates the emissions of a perfect blackbody the same size and shape of the Earth at 294.2 K. In the absence of the atmosphere, the Earth's emissions would be very close to the blue line; note that the emissions are closest to the blue line in the infrared atmospheric window around 8 to 12 microns. However, in the presence of the atmosphere, certain regions of the Earth's emission spectrum are dominated by emissions from the atmosphere, which is cooler than the surface of the Earth. The green and red lines show blackbody spectra of other temperatures; for example, this allows us to estimate that the emissions near 15 microns, which are caused by carbon dioxide, come from a layer of the atmosphere with a temperature near 225 K (-48 C, -55 F).

Observe the close relationship between the attenuation of the four gases, particularly water and carbon dioxide, and the features of the Earth's infrared spectrum. The wavelengths that are strongly attenuated by the gases are those that have much lower emissions to space. Particularly, notice that at wavelengths where water strongly attenuates, the spectrum has a temperature of about 255 K, and at wavelengths where carbon dioxide strongly attenuates, the spectrum has a temperature of about 225 K. This suggests that the highest levels of the atmosphere with high concentrations of water typically have a temperature of around 255 K, whereas the highest levels of the atmosphere with sufficient carbon dioxide typically have a temperature of around 225 K.

Since water is typically only found in the lowest parts of the atmosphere (see appendix A), whereas carbon dioxide is uniformly found throughout, in the region near 15 microns where both water and carbon dioxide strongly attenuate, it is carbon dioxide that determines the temperature of the emissions to space. (The small spike right at 15 microns is due to carbon dioxide found in the upper stratosphere.)

## 5.3 What happens if carbon dioxide is increased?

Figure 8 was made using a *radiative transfer model*, which uses the same ideas presented in section 5.1 but with much greater sophistication. Given the temperature of the surface and a description of the temperature and chemical composition of each level of the atmosphere, the radiative transfer model highly accurately computes the emission and absorption of radiation at every level, taking into account the different properties of each chemical at every wavelength[30].

[29] Although note that this simplified explanation ignores the ozone layer, where temperatures actually increase with height. Ozone absorbs ultraviolet radiation, which comes only from the Sun, and not from the Earth, so this causes the reverse behavior of temperature increasing with height.

[30] Our simple model of section 5.1 only considered two wavelengths of light, shortwave and longwave. The model used to make figure 8, LBLRTM, simulated 15 million different wavelengths, which was smoothed to

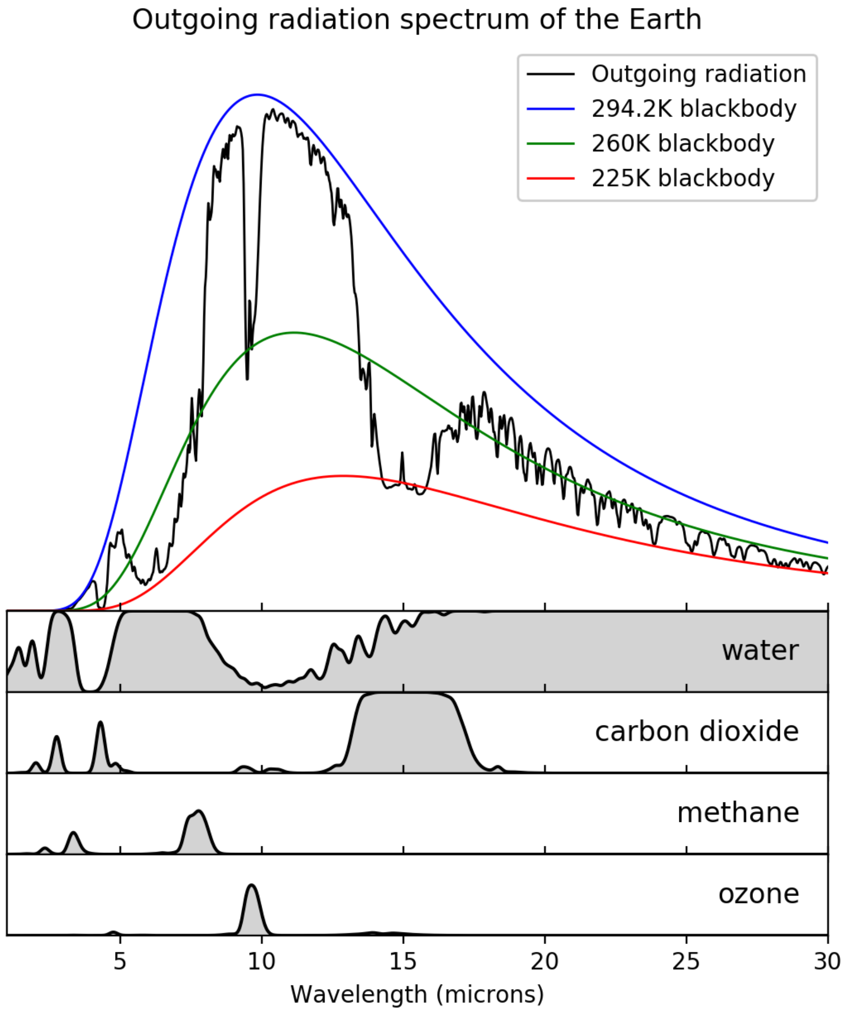


Figure 8: The spectrum of infrared emissions leaving the top of the atmosphere. The spectrum is compared to emissions of ideal blackbodies at temperatures of 294.2K, 260K, and 225K, which allows one to estimate the temperature of the layers of the atmosphere most responsible for emissions at a particular wavelength. The 294.2K blackbody emission spectrum was shown in the right half of figure 5, where it was described as a simplified representation of Earth's emission spectrum. The attenuation due to four greenhouse gases is shown below the spectrum; this was also shown in figure 7.

So, what happens if the amount of carbon dioxide is increased in the atmosphere? As we

about 1000 wavelengths in the final graph – without this smoothing the graph would have been so spiky as to be totally unreadable. Numerous other details we ignored in our simple model were properly simulated by LBLRTM. The atmospheric composition used is the US Atmospheric Standard of 1976, which defined a carbon dioxide concentration of 314 ppm, far below the current value of 410 ppm as of 2018.

saw in the previous sections, adding carbon dioxide should increase the temperature of the Earth; but with the use of a highly accurate radiative transfer model, it seems that it should be easy to give a quantitative and exact answer. Indeed, if we re-run the radiative transfer model with the same surface temperature but a higher concentration of carbon dioxide, we find that the "holes" in the emission spectrum corresponding to attenuation from carbon dioxide become slightly deeper and wider, so that less infrared emissions reach space, and a higher surface temperature is needed to maintain the same infrared emissions.

While this gives a first decent estimate of the increase in temperature due to an increase in carbon dioxide, it assumes that the temperature and composition of the atmosphere is unchanged by the addition of carbon dioxide. However, as the surface temperature rises, the temperature of the lowest layers of the atmosphere also rises. Since warmer air holds much more water, this increases the amount of atmospheric water, which is the most potent greenhouse gas.

This process by which any warming causes an increase in atmospheric water, thereby causing further warming, is called the **water vapor feedback** process. This makes the climate more sensitive to changes in temperature – any perturbation is amplified. Fortunately, this amplification is self-limiting, and does not compound upon itself endlessly[31].

It is the existence of climate change feedbacks like the water vapor feedback that makes it very challenging to accurately predict how much the temperature will rise when carbon dioxide is added to the atmosphere. Water vapor feedback is an example of a *linear feedback* process where every time a bit of carbon dioxide is added, the amount of water vapor goes up a bit in response. Much more difficult are *nonlinear feedback* processes, particularly so-called "tipping points" which have no observable effect on the climate until a critical threshold is reached, at which point there is a very large feedback effect.

Many of these nonlinear feedback processes are poorly understood and difficult to predict, or sometimes not even known if they exist or not. One widely speculated process regards the release of *methane clathrates*, which are vast reserves of methane trapped in ice buried under the ocean floor, particularly in the arctic. Estimates of the size of these reserves vary widely, but are typically on the order of thousands of gigatons of carbon. If this methane were to be released to the atmosphere by the melting of the ice, it would cause a large and rapid rise in temperature. Some scientists believe that a process like this was responsible for certain sudden climate changes in the past[32], and measurements have found an increase in methane releases in the arctic, but the role of methane clathrates in climate change is still unknown.

A nonlinear feedback process which scientists have more understanding of is the *ice-albedo feedback*, a process by which rising temperatures causes ice to melt, which lowers the albedo of the Earth (as ice is very reflective), which then warms the planet further. This is particularly important in the arctic, where highly-reflective ice covers sea, which has very low reflectivity. A simplified perspective of the arctic ice-albedo feedback is the idea

[31] It is thought that Venus entered in a water vapor feedback process that was *not* self-limiting, and just grew forever in a **runaway greenhouse effect** until its oceans boiled away entirely. It is also expected that Earth will eventually enter a similar runaway greenhouse effect in about one billion years, and that artificial climate change will not be able to trigger this early.

[32] Specifically the Permian-Triassic extinction event of 252 million years ago and the Paleocene-Eocene Thermal Maximum of 55 million years ago.

that the arctic supports two stable states: a high ice state, where cold global temperatures allow a large ice cap, whose high albedo encourages cold temperatures; or a low ice state, where warm global temperatures cause a small ice cap, so that the low albedo of dark ocean waters encourages warm temperatures. It is speculated that intermediate ice levels are unstable, which explains why the Earth has sharply transitioned between glacial periods[33] and interglacial periods instead of smoothly varying. Again, the extent to which this will play a role in the climate response to an increase in carbon dioxide is hard to predict.

# 6 Further Reading

A very short and easy to read introduction to climate change is **What We Know About Climate Change** by Kerry Emanuel. The book is about as long as this work and is targetted to a non-scientific audience. In addition to reviewing the material covered here (without any equations), the book discusses what climate change is, how we know it is happening, what the effects of climate change are, and what can be done about climate change.

**Sustainable Energy – Without the Hot Air** (`withouthotair.com`) by David MacKay is an excellent, readable introduction to energy in modern society, and is also targetted to non-scientists. The book discusses the major uses of energy and the major available sources of energy, and invites the reader to consider how to balance these against each other in a future without fossil fuels. The reader is empowered with the information necessary to come up with their own energy plan, and in doing so is forced to confront with the difficulty of finding an agreeable plan where energy production satisfies energy demand.

[33] Popularly called “ice ages”.

# A What is the atmosphere?

The **atmosphere** is a mixture of gases that lies on the surface of the Earth due to gravity. It tries to expand to fill the volume it is in like all gases, but it is drawn to the Earth by the Earth's gravity. The balance[34] between outward expansion and gravity causes it to be thickest at the surface of the Earth and thinner at higher altitudes. There is no sharp upper boundary to the atmosphere: it just continues to become thinner. (Similarly, the Sun and the gas giants do not have a sharp boundary between them and space either.)

Half of the atmosphere is within 5.5 km (3.5 miles) of the surface of the Earth. A commercial plane at a cruising altitude of 11 km (7 miles) is above 80% of the Earth's atmosphere, with only 20% of the Earth's atmosphere between it and space.

## A.1 Gases in the atmosphere

The main components of the Earth's atmosphere are listed in this table:

| | | |
|---|---|---|
| Nitrogen | $N_2$ | 78% |
| Oxygen | $O_2$ | 21% |
| Argon | Ar | 1% |
| Water | $H_2O$ | 0.25% |
| Carbon dioxide | $CO_2$ | 0.04% |
| Neon | Ne | 18 ppm |
| Helium | He | 5 ppm |
| Methane | $CH_4$ | 1.9 ppm |
| Ozone | $O_3$ | 0.4 ppm |

All of these chemicals except water and ozone are roughly uniformly distributed through the atmosphere; that is, at any location at any altitude you expect the air to be about 21% oxygen.

Nitrogen, argon, neon, and helium are all chemically unreactive and do not play a significant role in the climate.

Oxygen, of course, plays an important role in life. In fact, the Earth's atmosphere did not have any oxygen for the first two billion years, until photosynthesis created the oxygen we have in our atmosphere today. While oxygen does not directly have a significant role in the climate, its appearance in the atmosphere is linked with enormous climactic upheavals that took place at the same time[35].

Carbon dioxide and methane are important greenhouse gases, and the effects of greenhouse gases are discussed in detail in the body of this document. Carbon dioxide is mostly unreactive but is necessary for photosynthesis. Methane is only mildly reactive in atmospheric conditions, having a lifetime of 10 years in the troposphere or 120 years in the stratosphere, forming carbon dioxide. Methane is the main source of water in the upper stratosphere.

[34] called *hydrostatic equilibrium*

[35] called the *Great Oxygenation Event*, which may have caused a "snowball Earth"

Water is the most exceptional of the components of the Earth's atmosphere because it can readily change between gas, liquid, and solid at conditions typical in the atmosphere. Liquid and solid water will sometimes, depending on conditions, form large enough droplets or crystals to fall out of the atmosphere, whereas water vapor of course does not. Since the transition between phases strongly depends on the temperature, and temperature changes greatly with altitude, this means that the amount of water varies strongly with altitude. In particular, almost all of the water in the atmosphere is very near the surface; water that rises far above the surface of the Earth typically cools so much that it condenses to liquid or solid form and falls. In comparison, most of the other gases listed above are evenly mixed through the whole atmosphere.

Furthermore, since water readily enters and leaves the atmosphere through evaporation and precipitation, the amount of water in the atmosphere changes rapidly in just weeks. We see this in our day-to-day lives when we notice that one day is much more or less humid than normal. The other gases listed above typically remain in the atmosphere for very long periods of time.

## A.2 Layers of the atmosphere

The atmosphere is typically divided vertically into various layers. The layers differ from each other in their temperature and the types of phenomena that occur in each layer.

The bottom 10 to 15 km of the atmosphere is called the **troposphere**, and contains about 80% of the atmosphere. The troposphere is heated from below because the bottom is touching the Earth's surface, which is warmed directly by sunlight. Because the troposphere is heated from below and hot air rises, it is a very active part of the atmosphere, and almost all of the weather that we are interested in occurs here. In particular, almost all of the water is in the troposphere, so clouds predominantly appear in this layer. The name "troposphere" refers to the constant "turning over" of the air there.

Above the troposphere and continuing to 50 km is the **stratosphere**. The important difference between the troposphere and the stratosphere is that the stratosphere is mostly heated from above, by the ozone layer. Because it is heated from above, and heat rises, the stratosphere is very stable and mixes slowly (that is, it is *stratified*, giving it its name). In particular, it does not mix readily with the troposphere. This can be observed in large thunderstorms that form "anvil" clouds with wide flat tops; the anvil cloud top is the boundary between the troposphere and the stratosphere. Particularly strong thunderstorms can form "overshooting tops" where some clouds stick out above the anvil into the stratosphere.

The **mesosphere**, until 80 km, and **thermosphere**, until 500 to 1000 km, are the next layers in the atmosphere. The upper boundary of the thermosphere depends strongly on daily variations in solar activity, referred to as *space weather*. The International Space Station orbits at 400 km in the thermosphere, and slowly falls over time due to drag from the air. It is boosted by rockets a small amount approximately once a month.

Above the thermosphere is the **exosphere**, at which point the air is so thin that it no longer acts like a gas; instead, each of the molecules behaves independently of the others.

# B What is ozone?

Ozone is a molecule with three atoms of oxygen, written $O_3$. Ozone is a highly reactive chemical that is very damaging to the lungs in both brief and prolonged exposure. Ozone is mostly located in the ozone layer in the stratosphere but can also be found near the surface.

Ozone located at the surface is mostly, though not entirely, due to man-made activity. It is formed when other dangerous pollutants such as NO and $NO_2$ react with sunlight, and is typically associated with smog. Ozone pollution is frequently caused by car emissions and, in China and India, coal burning, but has been dramatically reduced in the West due to strict car emission standards.

The ozone in the **ozone layer** is both created and destroyed by reactions with sunlight. The intense ultraviolet radiation is strong enough to destroy the bond in $O_2$, releasing free oxygen atoms, which quickly react with other $O_2$ to form $O_3$. Ozone is even better than $O_2$ at absorbing ultraviolet radiation because its bonds are weaker, although it can be destroyed by the radiation in the process.

Because ozone absorbs ultraviolet radiation, the ozone layer greatly decreases the amount of ultraviolet light that reaches the surface. Therefore the ozone layer is beneficial to human health, and is speculated by some to even be necessary for complex life on land.

The location of the ozone layer is caused by a balance between intensity of sunlight and the amount of oxygen in the atmosphere. The ozone layer doesn't go higher because the atmosphere becomes so thin that there isn't enough oxygen for the reactions that make ozone to proceed quickly. The ozone layer doesn't go lower because the ultraviolet light necessary to make ozone is all absorbed by the time sunlight gets that far.

## B.1 The ozone hole

The **ozone hole** is a decrease in the amount of ozone in the ozone layer above Antarctica during spring. The ozone over Antarctica began to diminish around 1980, reaching one third of the natural amount by 1990; ozone levels in Antarctica have remained low since 1990, although there is some weak indication that ozone levels may have recently been increasing slowly.[36] Ozone levels in the rest of the world have decreased by a lesser amount of around 5%.

Concern over the loss of ozone began in 1974 with the discovery that certain chemicals, called CFCs, could efficiently destroy ozone when exposed to ultraviolet radiation. CFCs are stable, non-reactive chemicals with low toxicity and a boiling point near room temperature; these properties made them well suited for use in aerosol cans, refrigerators, and fire extinguishers. Before the development of CFCs by Thomas Midgley Jr., highly toxic or explosive chemicals were often used for those purposes. Besides his research in CFCs, Midgley is best known for the development of leaded gasoline, which caused the worst man-made environmental crisis of American history (and arguably world history) by poisoning tens of millions

[36] The reason why the last bit of the Antarctic ozone layer was not destroyed is because the stratosphere does not mix well, as discussed in Appendix A, and the upper-most part of the Antarctic stratosphere does not have the right conditions for destroying ozone.

of American children, and many more worldwide.[37] However, the great stability of CFCs also meant that they could remain in the atmosphere for hundreds of years.

In 1984, on-the-ground observations in Antarctica revealed astonishingly low amounts of ozone in the stratosphere. NASA independently reported satellite measurements confirming the decline starting around 1980, although the satellite measurements were so low that they were initially believed to be a measurement error.

The announcement of the sudden destruction of the ozone layer in Antarctica brought immediate alarm, though the cause of the ozone hole remained unclear at first. It was soon confirmed that CFCs were responsible for the ozone hole through a previously unknown series of chemical reactions that were specific to the atmospheric conditions in Antarctica. In 1986 the Montreal Protocol was passed, banning CFCs globally, with the phase-out beginning in 1991. The Montreal Protocol is one of very few treaties to be ratified by every UN member and is directly responsible for averting disaster.

Today, the ozone hole poses a minor health hazard to people in and near Antarctica. There is not much reliable scientific data on the effects of a missing ozone layer on human health, but a study has found that a region in southern Chile experiences 50% more skin cancer than normal. (The exact shape and size of the ozone hole varies from year to year, and it can sometimes reach South America.) The ozone hole has a significant effect on the climate in Antarctica. Recall from Appendix A that the stratosphere is warmed by the ozone layer; in the absence of ozone, the stratosphere is cooler than usual, so wind circulation around Antarctica has strengthened significantly in response to the colder temperatures. These winds drive major ocean circulation patterns, so the stronger winds have changed the ocean circulation, leading to changes in sea ice formation, temperature, and precipitation in Antarctica. For this reason, the climate of Antarctica has been behaving anomalously for the last several decades compared to the rest of the world.

Computer models suggest that the ozone layer may return to normal levels around 2060. Without regulation of CFCs it is predicted that more than half of ozone worldwide would have been destroyed by then. The EPA estimates that the Montreal Protocol will have prevented 300 million cases of skin cancer and 2 million skin cancer deaths among Americans born before 2100.

While CFCs are greenhouse gases, their concentration is too low to contribute significantly to the greenhouse effect. Carbon dioxide does not have a significant effect on the ozone hole either directly or indirectly through climate change, and conversely the ozone hole does not contribute significantly to global climate change.

Ozone is itself a greenhouse gas, although because of its small concentration in the Earth's atmosphere it only contributes about 5% to the greenhouse effect.

# C Temperature units

In this document we use a mixture of three different scales for describing temperature: degrees Celsius (formerly called "centigrade"), which is the international standard temperature

[37] While the worldwide banning of leaded gasoline and the banning of leaded paint in the US and EU has greatly decreased the amount of lead in the environment, exposure to environmental lead continues to kill 140 000 people every year and contribute to 600 000 new cases of intellectual disability in children annually.

for day-to-day use; degrees Fahrenheit, which is standard in the United States for day-to-day use; and Kelvin, which is typically used within physics and other sciences when discussing temperatures far from room temperature or for theoretical physics. The reason for the difficulty converting between this different scales is that Celsius and Fahrenheit do not have zero temperature at zero degrees, but rather at -273.15 C and -459.67 F, respectively. Indeed, both of those scales were invented and popularized long before the scientific community reached a consensus that there was such a thing as zero temperature (called *absolute zero* to avoid confusion with other temperatures like 0 C or 0 F) or how cold it was compared to known temperatures.

To rectify these shortcomings, Lord Kelvin invented a temperature scale with zero temperature at zero degrees and was the first to reliably calculate the difference between that temperature and known temperatures, building off of contemporary work in thermodynamics by him and other scientists. This Kelvin scale was scaled so that the difference between two temperatures is the same number of degrees as in the Celsius scale, so as a result one can convert from Celsius to Kelvin by simply adding 273.15 degrees, which has the effect of shifting the zero to the correct place. To convert between Fahrenheit and the other two scales requires both shifting and multiplying by a constant.

Celsius and Fahrenheit continue to be more useful than Kelvin for describing temperatures near room temperature (for which Kelvin can be unwieldy), but are very inconvenient in the context of thermodynamics. Climate science in general, and this document in particular, is mostly concerned with physical processes that take place near room temperature, but explains these processes with thermodynamics, and so uses both Celsius and Kelvin according to what is convenient in each context. (American meteorology continues to primarily use Fahrenheit for historical reasons.)