# Climate Risk Management for Banks and Financial Institutions

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# 1: The Science Behind Earth's Climate and Climate Change

**"There is no such thing as a special category of science called applied science; there is science and its applications, which are related to one another as the fruit is related to the tree that has borne it."**. -Louis Pasteur.

This chapter covers the basic science that underpins the earth's climate and climate change. It is important to get this understanding to fully grasp the causes and consequences of climate change and attendant risks. The level of scientific knowledge required is no more than what is taught at high school level. For completeness, there are some mathematical equations that we will encounter in this chapter. However, non-mathematically minded readers can skip those as each such equation comes with an intuitive explanation.

There are three key factors which influence the earth's climate – solar energy we get from the sun; the earth's reflectivity, that is, how much of that energy is reflected to space; and third, the greenhouse effect. These three factors have shaped the earth's climate over the last 4.54 billion years. Understanding how these three factors act individually and their interactions is fundamental to climate change and managing risks emanating from climate change.

However, before we examine these three factors in greater detail, let us get some basic science out of the way.

**Electromagnetic Waves and Spectrum**

Broadly defined, a wave carries energy from one place to another. The two main types of waves are mechanical waves and electromagnetic waves. Mechanical waves cannot travel through vacuum, and they require a medium to travel. Common mechanical waves are sound waves, water waves and seismic waves.

However, the waves which are of interest to us from a climate change and global warming perspective are the electromagnetic waves, which are created by a fusion of magnetic and electric fields. Electromagnetic waves can travel through vacuum. Some of the common electromagnetic waves are X-rays, radio waves, and microwaves. The energy we get from the sun in the form of ultraviolet waves, which is also an electromagnetic wave.

Before we get to the electromagnetic spectrum, a useful concept to understand is the wavelength. Wavelength defines how long a wave is: it is the distance between peak of one wave to the peak of the next wave, which is the same as the bottom of one wave to the bottom of the next wave (see Figure 1)

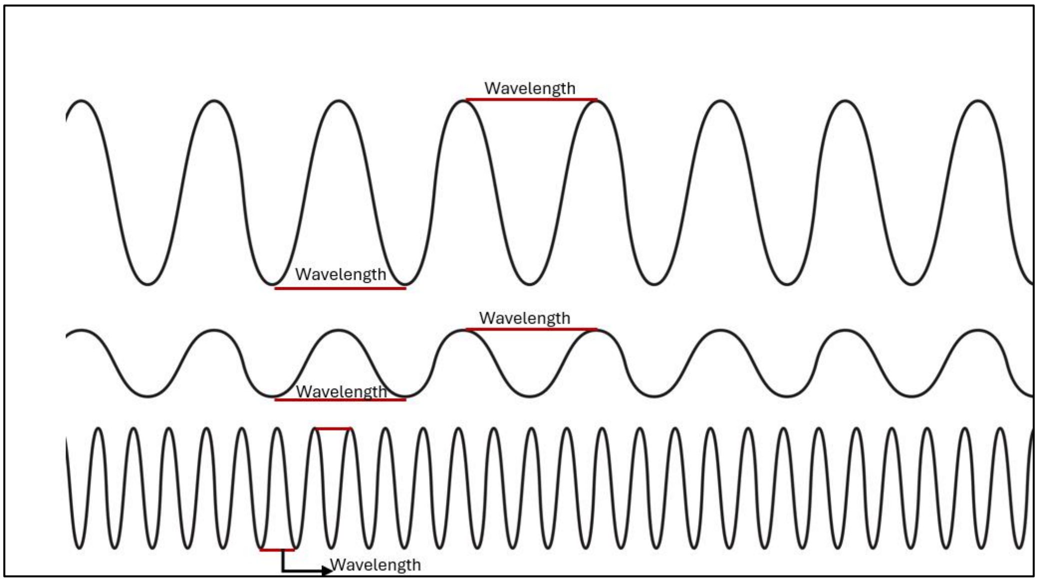


Figure 1: Wavelength

The Electromagnetic Spectrum represents the range of all types of electromagnetic radiation. The defining characteristic which differentiates radiation on the electromagnetic spectrum is their wavelength. Radiation is ordered based on their wavelengths. Figure 2 depicts the electromagnetic spectrum. On the extreme left are gamma rays which have very short wavelengths, followed by X-rays and ultraviolet radiation. As we can observe, the visible spectrum, or the radiation our eyes can detect, represents just a minor part of various types of radiation that exist. On the other end of the spectrum are infrared rays and radio waves.

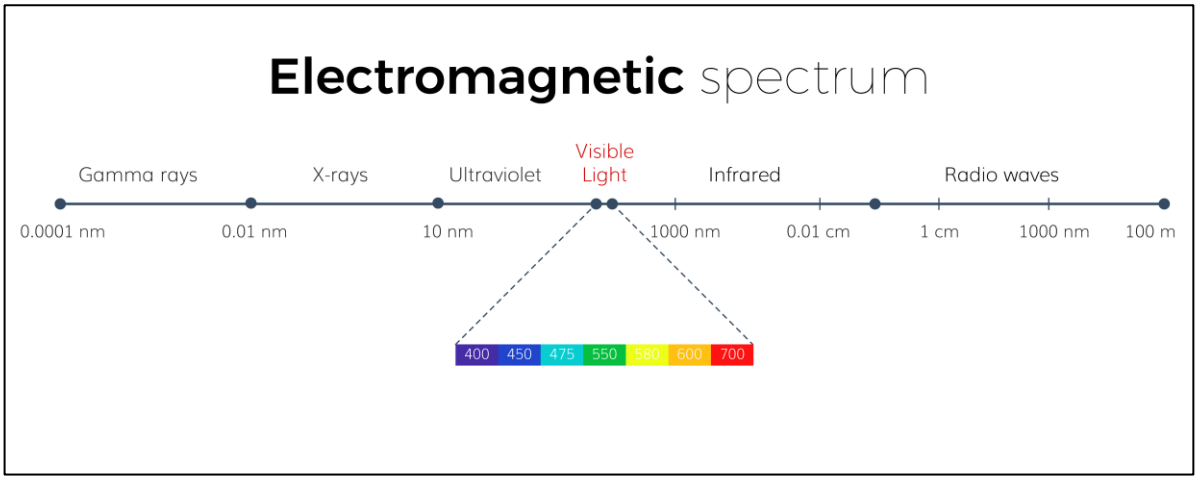


Figure 2: The Electromagnetic Spectrum (the numbers indicate the wavelengths of radiation)

### Radiation and Blackbody

All the matter around us is made up of atoms, and atoms in any matter – for instance, the earth, this book, you, and I – vibrate, as long as the temperature is above absolute zero, that is, above minus 273 degrees. This vibration creates energy which is radiated. Everything around us radiates energy (outflow). Therefore, as a logical extension, everything is also receiving and absorbing energy from other objects (inflow). When the inflow and the outflow are in balance, objects maintain a constant temperature. However, if an object absorbs more energy than it radiates, it heats up; similarly, if the object radiates more energy than it absorbs, it cools down.

In physics there is a hypothetical construct of an object which absorbs all incident energy (or radiation) that hits the object and emits the same amount of radiation. Such an object is known as a "blackbody". Note that there are no perfect blackbodies in the universe. Real word objects and celestial bodies like stars and planets aren't exact blackbodies, but they're similar. Not all radiation that reaches an object is absorbed; some is reflected. However, the idea of a blackbody aids our understanding of the energy from the sun and the energy absorbed and released by the earth, which impacts our climate. So, without loss of generality, we will consider them as blackbodies.

There are three aspects of a blackbody which are interrelated: its temperature, the amount of energy it radiates, and the type of radiation.

Let us start with temperature and energy. It should come as no surprise that the warmer the object, the more energy it releases (per unit of its area). This should be obvious from everyday experience. A hot samosa releases more energy than a frozen ice cream. Sun radiates a lot more energy. There is a direct correlation between temperature and the amount of energy emitted. Mathematically, at temperature T, the total radiation (per unit area) is given by:

$$\text{Equation 1 } : \sigma T^4$$

$$\textit{Where } T \textit{ is the temperature in Kelvins and } \sigma \textit{ is known as the Stefan} - \textit{Boltzman contant,}$$

$$\textit{which is } 5.64 \times 10^{-8} W m^{-2} K^{-4}$$

Intuitive explanation: The relation between temperature and radiation is not linear. For example, If the temperature doubles, the total radiation increases 16-folds.

In addition to the amount of energy, we also need to consider the type of radiation emitted. That's where the electromagnetic spectrum comes into picture. There is a mathematical relation between the temperature, wavelength and peak energy emitted, defined by Wien's Law, named after German physicist Wilhem Wien, who was awarded the 1911 Nobel Prize in Physics for "his discoveries regarding the laws governing the radiation of heat". According to Wien's Law, for a blackbody, the wavelength ($\lambda_{peak}$) at which radiation intensity[1] is maximum is inversely related to its temperature in Kelvin. Thus, as temperature increases, the energy's peak shifts to shorter wavelengths, which corresponds to higher and energies. Mathematically:

$$\text{Equation 2 } : \lambda_{peak} = \frac{b}{T}$$

$$\textit{Where } \lambda_{peak} \textit{ is the peak wavelength, } b \textit{ is a Wien's displacement contant and } T \textit{ is the absolute temperature}$$

Intuitive explanation: Hotter objects emit most of their radiation at shorter wavelengths, and cooler objects emit most of their radiation at longer wavelengths.

[1] Formally, power radiated per unit area per unit wavelength.

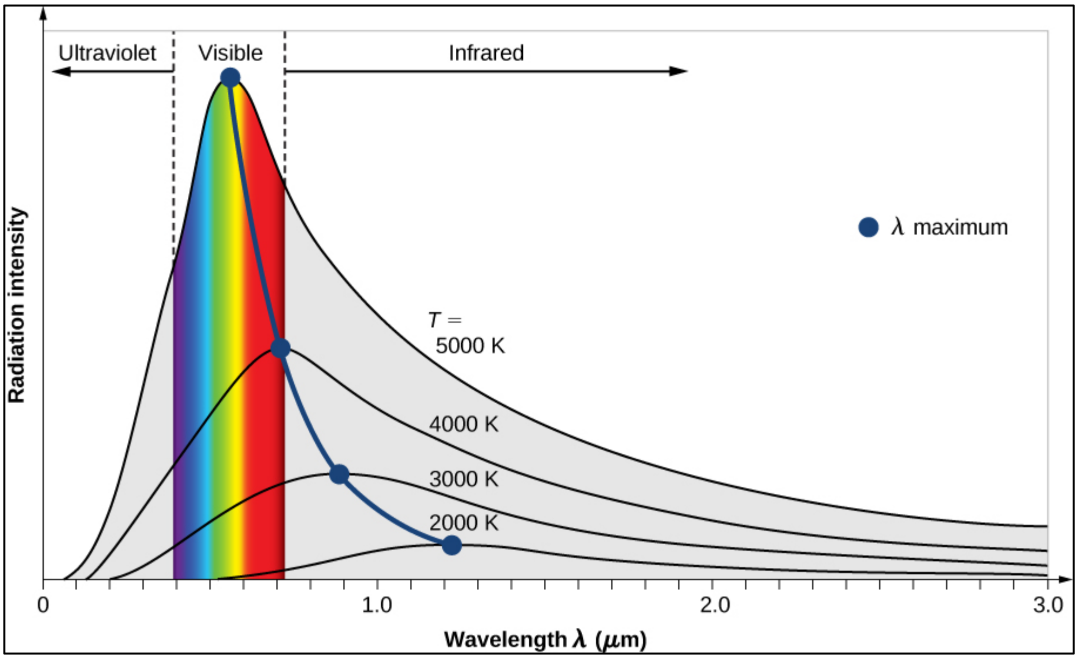


Figure 3: Radiation intensity versus wavelengths for different temperatures.

Figure 3 shows the intensity of blackbody radiation against wavelength of emitted radiation for various temperatures. At high temperatures, the radiation intensity peaks at shorter wavelengths and as the temperature decreases, the radiation intensity peaks at longer wavelengths. It is important to remember that a hotter object will radiate more energy than a cooler object at every wavelength.

Now let's apply Wien's law to the Sun and the Earth. Sun's surface temperature is around 5,600 Celsius, while Earth's average surface temperature is around 15 Celsius. So, the sun's radiation intensity peaks at a wavelength of about 0.5 micrometer (0.0005mm) and that of the earth peaks at a wavelength of 10 micrometer (0.01mm). On the electromagnetic spectrum, the sun's peak wavelength is in the middle of visible light range and earth's peak wavelength is in the infrared range.

Wien's Law highlights a crucial fact: *the sun primarily emits shortwave energy, while the cooler earth mainly emits longwave energy. Recognizing this distinction between the sun's and earth's energy radiation is essential for understanding the earth's greenhouse effect, which primarily concerns the longwave radiation emitted by the Earth, rather than the shortwave radiation originating from the Sun*.

**Molecular structure of greenhouse gases**

Our atmosphere comprises gases, with three of them accounting for more than 99.9%: nitrogen ($N_2$: 78%), oxygen ($O_2$: 21%) and argon (Ar: 0.93%). Other gases are in really tiny quantities, measured in parts per million molecules in the atmosphere. These include the well-known greenhouse gases, carbon dioxide, methane, nitrous oxide, and (technically speaking) ozone etc. As we will see later, water vapor is also a greenhouse gas.

Note that nitrogen and oxygen are diatomic gases (two atoms of the same element), whereas the greenhouse gases comprise more than 2 atoms.

Atoms within molecules bond by sharing electrons. When a molecule is composed of different atoms, these shared electrons might be drawn more towards certain atoms. This results in these atoms having a slight negative charge, while their counterpart atoms acquire a slight positive charge. This creates what we refer to as electric dipoles.

Looking at Figure 4, we notice that molecules of greenhouse gases like $H_2O$ and $O_3$ have a bent shape and possess a dipole that can be disturbed. The angle between $H_2O$'s arms can slightly adjust, allowing the molecule to bend more or less. Additionally, the distance between the core oxygen atom and the outer hydrogen atoms in the water molecule can expand or contract, signifying the molecule's flexibility. A molecule doesn't need a permanent bend to act as a greenhouse gas. Although $CO_2$ has a straight and balanced structure with the carbon atom sandwiched between two oxygen atoms, it can still flex. This flexing might form a subtle V-shape or lead to an imbalanced stretch, where one oxygen atom gets nearer to the carbon center while the other drifts further away, resulting in an uneven charge distribution. This behavior differs from molecules like $N_2$ or $O_2$, which comprise only two identical atoms. They can expand or contract in relation to each other, but their charge remains balanced.

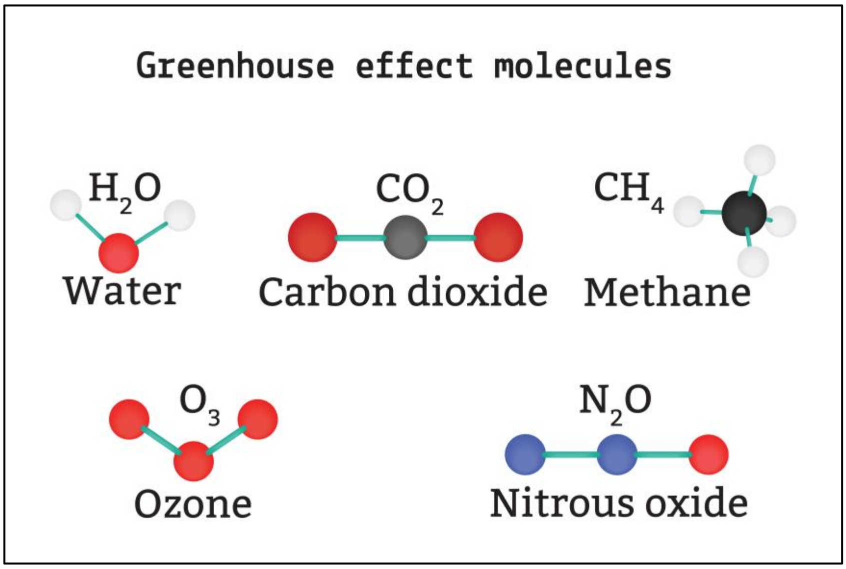



Figure 4: Greenhouse molecules
(red denotes oxygen atom, white hydrogen, black carbon, and blue nitrogen)

Sunlight, which is in the visible spectrum, has shorter wavelengths that don't match with those of prevalent atmospheric gases like $O_2$ and $N_2$, as well as greenhouse gases. Consequently, this light traverses our atmosphere without being absorbed, though it can be reflected by clouds and airborne particles. However, the wavelength of infrared light emitted from the Earth's heated surfaces does resonate with the vibrational frequencies (the bending oscillation) of greenhouse gases. When this infrared light interacts with these molecules, their vibrations intensify, heating the molecules and, subsequently, the surrounding air. Essentially, greenhouse gases capture some of the infrared radiation emanating from the Earth's warmth.

**Solar energy from the sun**

The surface temperature of the sun is approximately 5,500 degrees Celsius. As we have seen from Equation 1, the total radiation (per unit area) is proportional to the fourth power of the temperature, using which we find that the sun radiates 63.5 million watts per square meter (W/m$^2$). When this energy traverses into outer space from the sun, the intensity decreases as the distance from the sun increases. By the time this energy reaches the earth's outer atmosphere, it gets diluted to around 1,361 W/m$^{2.}$ This is known as the solar constant.

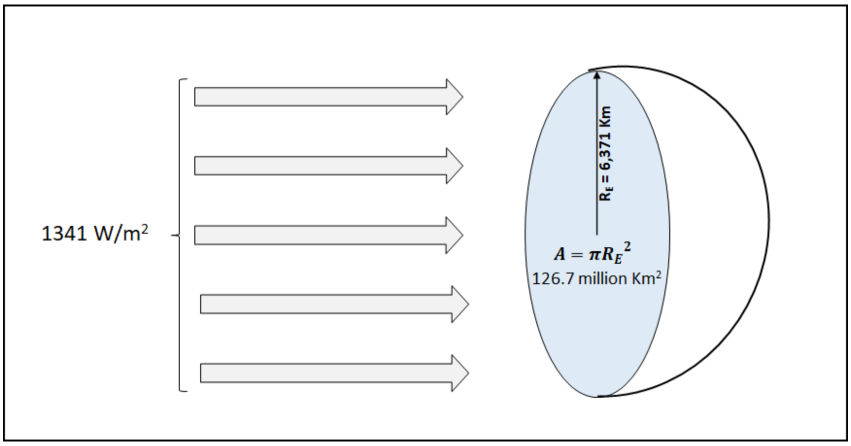



Figure 5: Incoming solar radiation

The total incoming solar energy is therefore 1,361 W/m$^2$ multiplied by the cross section are of the earth (Figure 5). Multiplying the two give us $173 \times 10^{15}$ watts, or 173 million gigawatts, which is almost 1,400 times the total installed capacity of all power plants of the world.

However, as we all know, the earth is a sphere not a disc and the surface area of a sphere is four times the area of a disc with the same radius ($4\pi R^2$). The earth spins and the incoming solar radiation is distributed over the entire surface. So, the incoming of energy of 1,341 W/m$^2$ is distributed over four times the area, and therefore, 340 W/m$^2$ (1,341 divided by 4) is the average radiation we get over a day.

But 30 percent of this radiation is immediately reflected to the space by clouds, ice, and parts of land. The technical term for the radiation amount of radiation reflected is "albedo", which we will cover in some detail later in the next section. For now, suffice to say that the earth's surface gets 70 percent of 340, that is, 238 W/m$^2$. To be in energy balance, the earth must radiate back the same amount of energy. We have seen that the amount of energy (per unit area) emitted is proportional to the fourth power of the temperature. What should be the average temperature of the earth of it must emit 238 W/m$^2$?

Using Equation 1, we find that it turns out to be *minus 18 degrees Celsius*, implying that to remain in energy balance, the earth would need to be a frozen planet. Clearly, that is not the case, and the global average surface temperature of the earth is 15 degrees Celsius. What accounts for this difference in the modelled temperature and the actual temperature? That is where the greenhouse effect of the atmosphere comes in. Before getting into the details of greenhouse effect,

**Earth's reflectivity or Albedo**

We have seen the last section, not all the solar radiation is absorbed by the earth. Around 30 percent is reflected. The technical term for the proportion of solar radiation reflected by a surface or object is Albedo.

The general principle behind albedo is that bright surfaces reflect radiation and contribute to a cooling effect on the climate, while darker surfaces absorb radiation, leading to a warming effect. For instance, the white sheets of sea ice reflect a significant amount of radiation, in contrast to darker surfaces, such as oceans, which absorb solar radiation and result in an overall warming impact.

Fresh snow reflects nearly 80 to 90 percent of the sunlight. Albedo of desert is around 40 percent, compared to grasslands which reflect 25 percent of solar energy. Greener coniferous forests have an albedo range of 8 to 15 percent. Finally, oceans reflect only 7 to 10 percent of the incoming solar radiation.[2]

In the atmosphere, clouds and aerosols are the main reflectors of the incoming solar radiation.

In fact, clouds are the largest contributor to earth's albedo, contributing to about half the solar energy reflected. Cloud reflectivity depends on a few key factors: Thickness – thicker the cloud, greater the reflectivity; size of water droplets and ice crystals in the cloud – smaller the size, brighter the cloud and hence more reflective; concentration – greater the concentration of water droplets and ice crystals, higher the reflectivity.

Interaction between clouds and aerosols also effect the cloud reflectivity but before we get there let us understand what aerosols are and their role in earth's albedo.

Aerosols are tiny particles that permeate our atmosphere. Some of the main aerosol groups are dust particles, nitrates, mineral dust, sulphates, carbon black from soot or smoke, and sea salt, among others. They mix with each other to form complex mixtures and compounds.[3]

Only 10 percent of aerosols are anthropogenic. The rest 90 percent have natural origins. Mineral dust and sea salt are among the most prevalent aerosols. Sandstorms lift tiny mineral dust particles from deserts into the air, while sea salt makes its way into the atmosphere from ocean waves, driven by the wind. Volcanic ash is another source of aerosols but the size of the particles in volcanic ash is relatively large, and they generally settle out of the atmosphere rather soon. Some fine particles make it to the stratosphere and get carried around the globe a few times.

Sulphur dioxide ($SO_2$) – be it from volcanic eruptions or anthropogenic, such as fossil fuel, smelters, automobiles – reacts rapidly to form sulphuric acid ($H_2SO_4$). Sulphuric acid and water condense to form tiny droplets of aerosols, which are very effective in reflecting the incoming solar radiation.

Any sudden increase in aerosols in the atmosphere can have an immediate effect on earth's climate. The 1816 was the 'year without summer' after the enormous volcanic eruption of Mount Tambora in Indonesia in 1815. It resulted in a significant increase in aerosols in the atmosphere, which reflected a large portion of the incoming solar radiation, leading to widespread crop failures and subsequent famine globally.[4]

More recently, in 1991, Mount Pinatubo in the Philippines experienced a massive volcanic eruption, releasing over 20 million tons of sulphur dioxide into the atmosphere. This gas, when mixed with other elements, forms sulphate aerosol, which rose up to 60 kilometres above the Earth's surface into the stratosphere. The resulting particles, brighter and higher than clouds, remained suspended in the sky, unaffected by rain, and gradually settled over several years. Climate scientists anticipated a decrease in global temperatures due to this widespread sulphate

[2] "Albedo," Climate Data Information, 2020, accessed 11/13, 2023, http://www.climatedata.info/forcing/albedo/.

[3] "Aerosols: Tiny Particles, Big Impact," NASA, 2010, accessed 11/13, 2023, https://earthobservatory.nasa.gov/features/Aerosols.

[4] H. Stommel and E. Stommel, "The Year without a Summer," *Scientific American* 240, no. 6 (1979).

presence. Their predictions were accurate: Global temperatures fell by approximately 0.6 degree Celsius for around two years following the eruption.

Aerosols in general reflect solar radiation, but again it depends on the colour and composition of the aerosols. Pure sulphates and nitrates, for example, reflect nearly all radiation they encounter. Black carbon, on the other hand, absorbs radiation. Overall, the consensus is that cooling from reflective aerosols outweigh the warming impact of absorbing aerosols, and it is estimated that from 1850-1900 to 2010-2019, aerosols contributed to a cooling of 0.0°C to 0.8°C.[5]

Aerosols also interact with clouds in the formation of droplets. Aerosol particles provide tiny platforms on which the water vapor can condense and form water droplets in the clouds. The greater the amount of aerosols present, the greater the number of water droplets that can form in the clouds, which increases the concentration of water droplets, and ultimately making the clouds more effective in reflecting solar radiation. There is another indirect advantage of smaller droplets. They require more time to form raindrops or ice crystals, which eventually fall to the Earth due to gravity. This slower process contributes to a rise in a cloud's water content through ongoing condensation and increases its thickness. Clouds that are denser and hold more water in the form of small droplets are better at reflecting light. If such a cloud remains for an extended period, it can reflect more of the sun's radiation.

**The greenhouse effect**

Recall that while the radiation which impinges on the earth is shortwave radiation, the radiation emitted by the earth is longwave radiation which falls in the infrared zone of the electromagnetic spectrum. This infrared (IR) radiation interacts with the greenhouse gases in the atmosphere, notably carbon dioxide, water vapor and methane. Since frequency of this infrared radiation overlaps with the bending-vibration frequencies of the greenhouse gases, the radiation is absorbed by these gases. The infrared radiation is then re-emitted by the atmosphere in different directions: some back towards the earth surface, some to space, and some impinges on other greenhouse gas molecules. This greenhouse effect warms the atmosphere and the earth's surface.

Figure *6* shows a simplified illustration of the greenhouse effect. Some of the radiation from the sun (yellow arrows) is reflected immediately by clouds, dust and aerosols and surface ice on the earth. 70 percent of which is absorbed by the earth is then radiated as infrared radiation (the red arrows). On its way to space, some of this infrared radiation is absorbed by the greenhouse gases in the atmosphere and then emitted again in all directions, warming up the planet.

[5] The Intergovernmental Panel on Climate Change, *Climate Change 2023 Synthesis Report, Summary for Policymakers* (Geneva: IPCC, 2023).

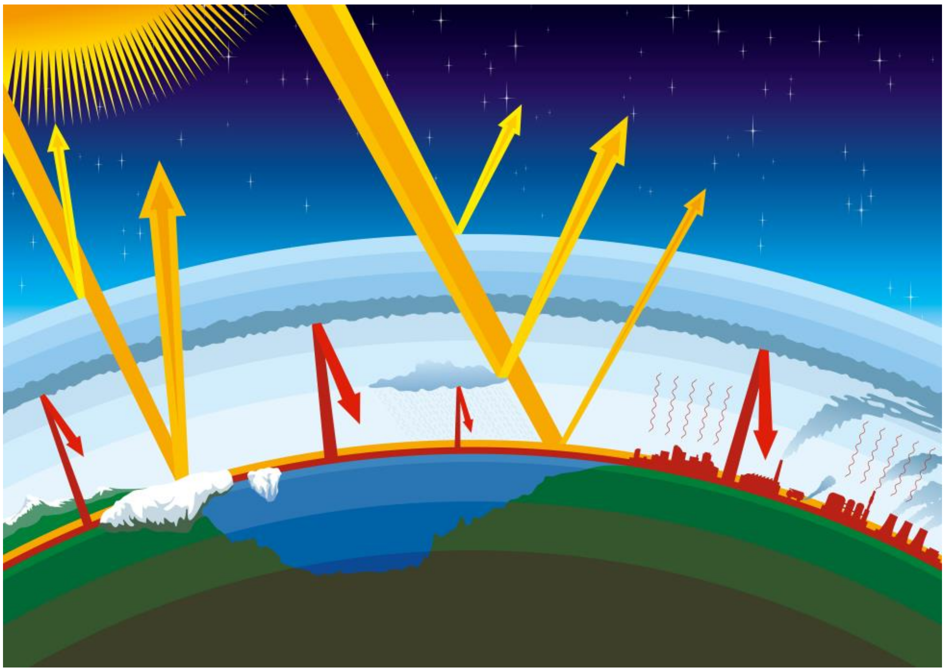


Figure 6: Simplified illustration of the greenhouse effect

It is important to note that the radiation is emitted by the greenhouse gases in all directions, not just back to the earth. The earth then absorbs and re-radiates the energy. Some of the radiation is emitted from one greenhouse gas molecule to the other, which repeats the random process. Part of the radiation is also emitted toward space.

The overall impact of this process of absorption and re-emission is that energy is retained in the earth's climate system for a more extended period than it would be in the absence of greenhouse gases. This retention results in a higher temperature on the earth than if these gases were not present. Specifically, the surface of the earth and the lower atmosphere experience the most significant warming. This is because the interactions between gases, which facilitate energy exchange, occur most frequently near the surface where the gas concentration is highest.

We will now mathematically model[6] the greenhouse effect, assuming that the atmosphere is a single homogeneous layer (Figure 7). While this obviously is not the case, the model results give us reasonably good approximation of the earth's temperature. *If you don't want to get into the mathematical details, feel free to skip the model as we have already covered the intuitive explanation above*.

[6] E Tziperman, *Global Warming SCience* (New Jersey: Princeton University Press, 2023).

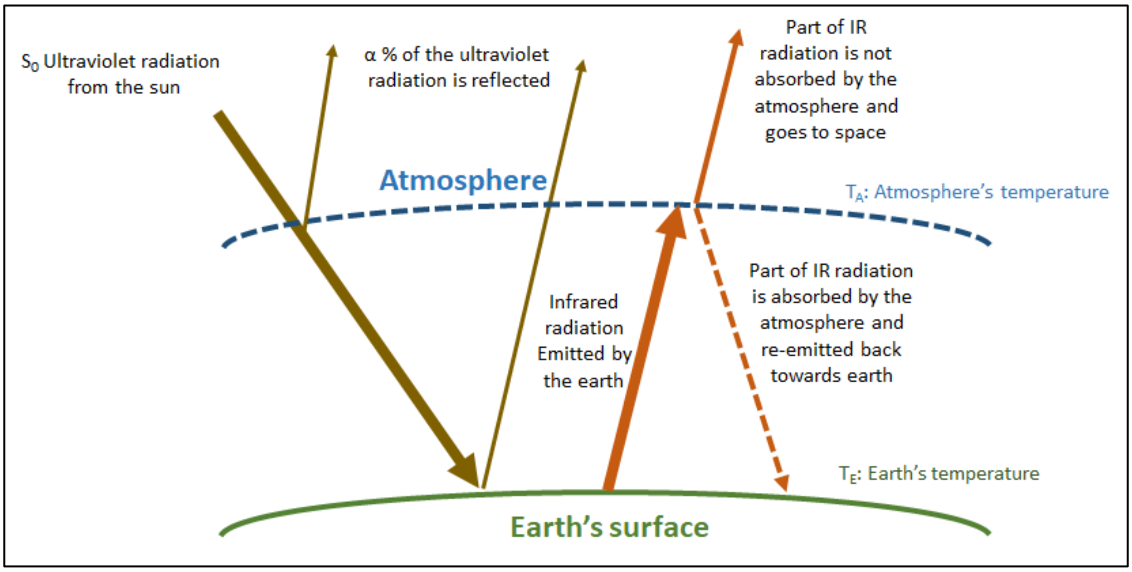



Figure 7: Simple one layer atmosphere model

Here $S_0$ is the solar constant, which has value of 1,361 W/m$^2$. As we have seen, the average incoming solar radiation the earth's surface receives is one-fourth of that, because the earth is spherical, and the surface area of a sphere is four times the surface area of a disc having the same radius (Figure 5). We also know that α % of that incoming radiation is reflected immediately, where the value of α is 30 percent. Therefore, the net incoming radiation (per unit area) is:

$$\frac{S_0}{4} \times (1 - \alpha) \text{ W/m}^2$$

So, to start with, the earth must radiate this energy in the form of infrared (IR) radiation. When emitted, only fraction (since the atmosphere is not a blackbody) of this radiation is absorbed by the atmosphere, which we denote by $\epsilon$. Similarly, the atmosphere only emits the same fraction $\epsilon$ of the radiation of a blackbody with the same temperature. $\epsilon$ is known as longwave absorptivity / emissivity of the atmosphere. A reasonable estimate of $\epsilon$ is 0.75. The atmosphere then emits radiation at the following rate, both upwards and downwards toward the earth's surface.

$$\epsilon \sigma T_A^4 \text{ W/m}^2$$

Here $T_A$ is the temperature of the atmosphere.

Therefore, the total radiation the earth needs to emit is the sum of the two: first originally coming from the sun and then the one emitted back toward the earth by the atmosphere.

Total energy that the earth emits:

$$\frac{S_0}{4} \times (1 - \alpha) + \epsilon \sigma T_A^4$$

Let $T_E$ denote the earth's temperature. The energy balance equation for the earth then can be written as:

Equation 3: $$\frac{S_0}{4} \times (1 - \alpha) + \epsilon \sigma T_A^4 = \sigma T_E^4$$

Similarly, the atmosphere's energy balance equation will be:

Equation 4: $$\epsilon \sigma T_E^4 = 2 \epsilon \sigma T_A^4$$

Where $T_A$ is the temperature of the atmosphere. Note that the atmosphere emits energy both upwards (into space) and downwards (on the earth), hence the term on the right-hand side is multiplied by 2. Substituting the value of $\epsilon\sigma T_A^4$ from Equation 4 in Equation 3, we get:

$$\frac{S_0}{4} \times (1-\alpha) + \frac{\epsilon\sigma T_E^4}{2} = \sigma T_E^4$$

Where $S_0$ is 1,361; $\alpha$ is 0.75; and $\sigma$ is the known Steffan-Boltzmann constant. The only unknown is $T_E$, which we can find by simply rearranging the above equations as:

Therefore

$$T_E = \sqrt[4]{\left(\frac{\left(\frac{S_0}{4}\right)(1-\alpha)}{\sigma(1-\epsilon/2\,)}\right)}$$

Solving for $T_E$ gives us 14.7 degrees Celsius, reasonably close to the average surface temperature of 15 degrees Celsius. Note that this simplistic model assumes a single layer atmosphere, still gives reasonable results.

If we continue with this simplistic model and suppose that as the stock of greenhouse gases increases the absorptivity of the atmosphere increases from, how will it effect the earth's temperature?

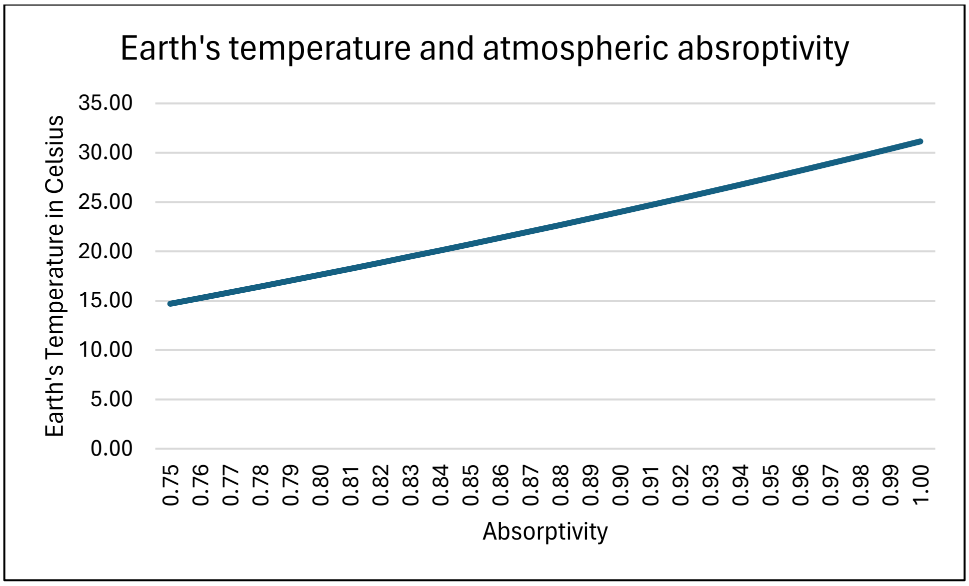


Figure 8: Earth's temperature and atmospheric absorptivity

As the absorptivity of the atmosphere increases, it absorbs more infrared radiation coming from the earth and thereby increasing the earth's average surface temperature. If the atmosphere absorbed all the infrared radiation coming from the earth (that is $\epsilon$ = 1), then the earth's average temperature would be 31.15 degree Celsius, more than double the actual temperature.

While this way of looking at the greenhouse effect is simple and intuitive, the real mechanism by which temperature increases as greenhouse gases increase is slightly more complex.

To understand that let us look at the layers of our atmosphere (Figure 9). The Troposphere, which extends up to around 12 kilometers, is the lowest layer. As we move up the troposphere, the temperature decreases. The rate of decrease varies from 5°C to 9.0°C per kilometer. The technical term for this is *lapse rate*. However, in the stratosphere the lapse rate reverses, and the temperature increases due to the absorption of solar radiation by the ozone layer.

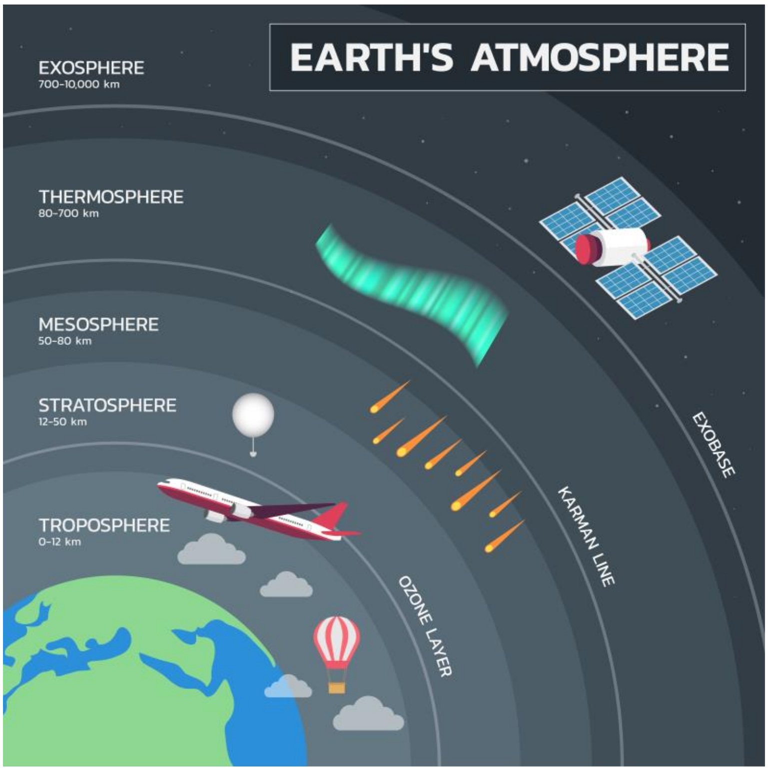
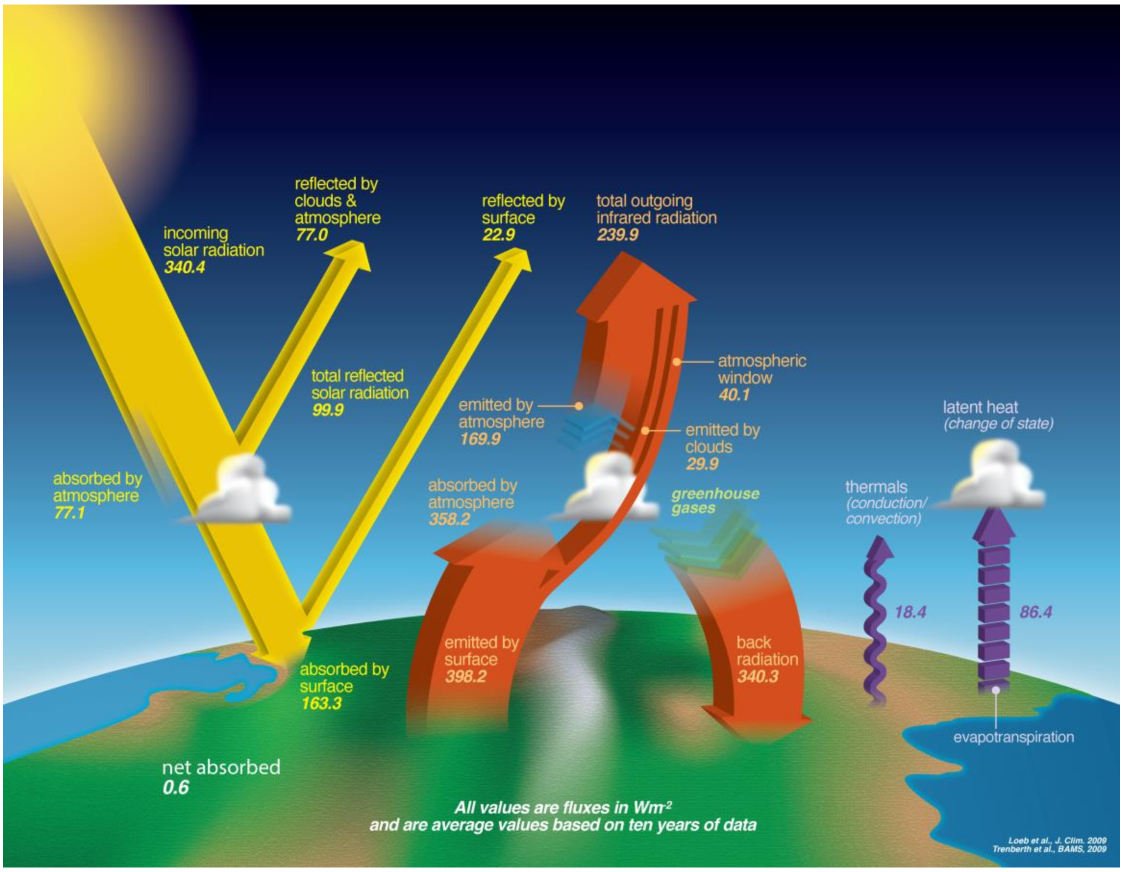


Figure 9: Layers of the earth's atmosphere.

Recall that the infrared radiation emitted by the earth's surface is absorbed and re-emitted (in both upwards and downwards direction) by the air above it. This process continues till such height that the air above gets so thin that the radiation emitted escapes to outer space without being absorbed. The height at which this happens is known as the **emission height**. The altitude of the emission height, along with the air temperature at this elevation, determines the flux of the infrared radiation exits the atmosphere. Increasing the amount of greenhouse gases raises the emission height. This happens because additional greenhouse gas molecules above the original emission level capture some of the radiation. For instance, when the concentration of carbon dioxide is doubled, the height at which emissions occur increases by approximately 150 meters.

In summary, rising levels of greenhouse gases cause the emission height to increase, resulting in surface warming. This warming is driven by two critical factors: the emission height is influenced by the concentration of carbon dioxide, and within the troposphere, the temperature of the atmosphere decreases as altitude increases.

An important concept in climate science which is linked to greenhouse gases is **radiative forcing**, which is the difference between incoming solar radiation and outgoing infrared radiation emitted by the earth. So, the radiative forcing resulting from an increase in atmospheric $CO_2$ levels refers to the radiation absorbed by the additional gas, which is then prevented from escaping to outer space across all wavelengths. This assumes that the temperature, moisture content, and cloud cover in the troposphere remain unchanged from their states prior to the increase in $CO_2$.




Let us first balance the incoming radiation with the total outgoing radiation at total earth system level (including the atmosphere):

*Incoming solar radiation = 340*

This should be equal to the total outgoing as below:

Radiation reflected by clouds and atmosphere = 77

Radiation reflected by the earth's surface = 22.9

Total outgoing infrared radiation = 239.9

*Adding the above: 77 + 22.9 + 239.9 = 340*

"Albedo." Climate Data Information, 2020, accessed 11/13, 2023, http://www.climatedata.info/forcing/albedo/.
"Aerosols: Tiny Particles, Big Impact." NASA, 2010, accessed 11/13, 2023, https://earthobservatory.nasa.gov/features/Aerosols.
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