Handbook of Climate Risk Management

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Contents

1. Short Preface

This book draws inspiration from the raison d'etre of The Economist, an English weekly newspaper, founded in 1843 "*to participate in a severe contest between intelligence, which presses forward, and an unworthy, timid ignorance obstructing our progress*."

Terms like sustainability, climate risk, biodiversity protection, decarbonization, climate scenarios, climate value-at-risk, climate stress testing, net-zero targets have recently entered the business and management consulting lexicon at a ferocious pace.

The entire edifice has started resembling past management fads – such as six sigma, core competency, matrix management, and business process reengineering, among others – which have come and gone in quick succession.

This is unfortunate.

Climate change is a complex phenomenon rooted in science. The risks arising are equally complex to understand and manage. A superficialist approach will not work. This handbook takes a *first principles* approach to understanding climate change and climate risks. I have not used oversimplification, for it leads to trivialization and obstructs our ability to comprehend and act.

The handbook assumes some background in mathematics and natural sciences, but no more than that of high school level.

What really matters most is your curiosity.

Amit Tyagi

2. 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 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 immediately reflected to space; third, and most importantly, 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 go through the basic science which will help us understand these three factors.

2.1 Energy

Energy transfer is fundamental to climate science. There are three interrelated concepts: *work, energy and power*. Let us start with the very basics.

Work is said to be done when a force is applied to an object and the object moves in the direction of the force applied. Mathematically, the work done is the force (exerted in the direction of the displacement) multiplied by the magnitude of the displacement.

Work is measured in joule (J). One joule is the work done when a force of 1 newton displaces a mass through a distance of 1 meter in the direction of the force. If a force of 10 newtons is applied to an object and moves 10 meters, the work done will be 100 joules.

Energy is the ability to perform work, so obviously the *unit of energy is the same as that of work, i.e. joule*. If I applied 10 newtons of force to move an object by 10 meters, the work done by me is 100 joules, and therefore the energy expended by me is also 100 joules.

Power is a measure of the rate at which energy flows. It is defined as the rate at which work is done, or conversely, the amount of energy per unit of time. So power is work done divided by the time taken, or energy spent or transmitted divided by the time taken. *Power is measured in joules per second, which is known as watts (abbreviated as W)*. For example, a 60-watt lightbulb will consume electricity at a rate of 60 joule per second.

The sun radiates 3.86×10^{26} W of power. As this radiation passes through space, the power wanes. The solar power intercepted by the earth is 1.74×10^{17} W. This radiative power is distributed over the entire surface of the earth. If we do the math (which we will do in a later section), we find that every square meter of the earth – on average – receives 340 W of this energy. In climate science, **watts per square meter (denoted as W/m²)** is used to measure the flow of radiation.

It is very important that we get a firm grasp on W/m² as it will be used throughout this book.

If we imagine the earth as a giant football (Figure *1*) with each white and black area representing one square meter, then each of these areas get on average 340 watts of radiative power from the sun. In this analogy, the earth will have 510 trillion such areas, each getting 340 watts. As we will see later in this chapter, some of the solar radiation is immediately reflected.

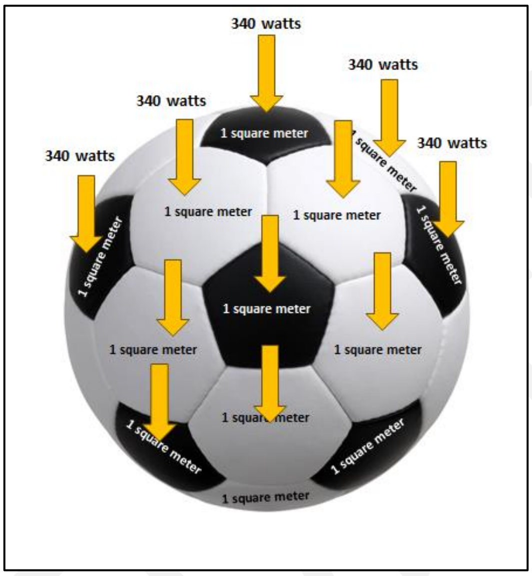

Figure 1: Earth as a giant football

2.2 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 is also in the form of an electromagnetic wave: the ultraviolet 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 2).

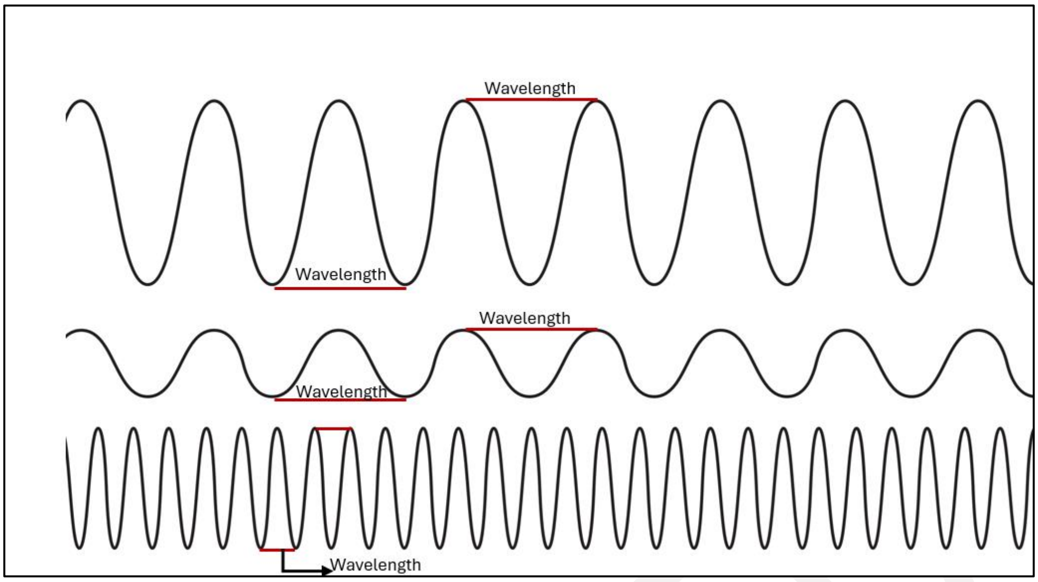

Figure 2: Wavelength

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 3 shows 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.

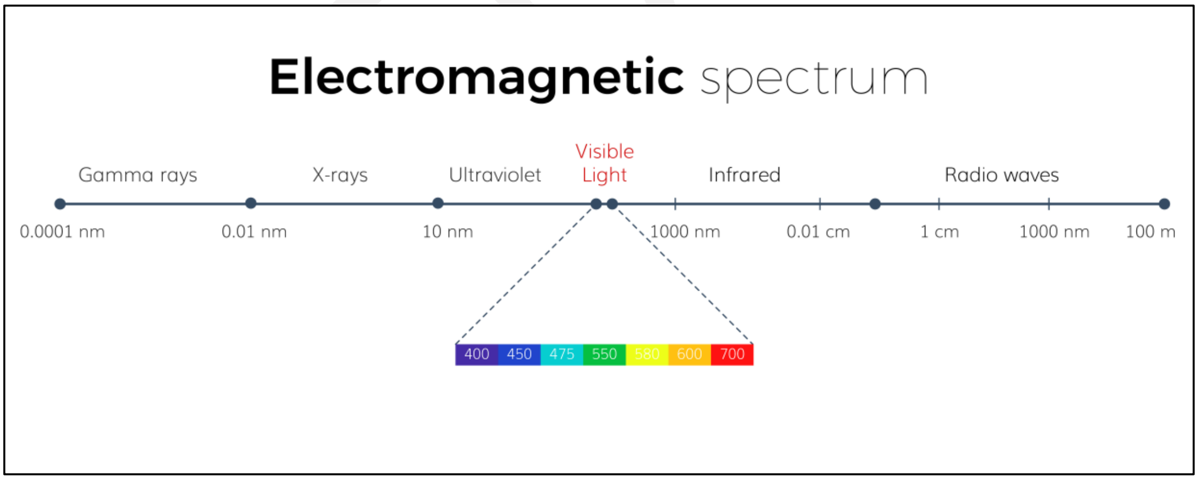

Figure 3: The Electromagnetic Spectrum (the numbers indicate the wavelengths of radiation)

2.3 Radiation and Blackbody

All the matter around us is made up of atoms. 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:

Equation 1 : σT^4

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

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

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 (λ_{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:

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

$$Where\ \lambda_{peak}\ is\ the\ wavelength\ at\ which\ radiation\ intenisty\ is\ maximum, b\ is\ Wien's\ displacement\ contant$$

$$and\ T\ is\ the\ absolute\ temperature$$

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.

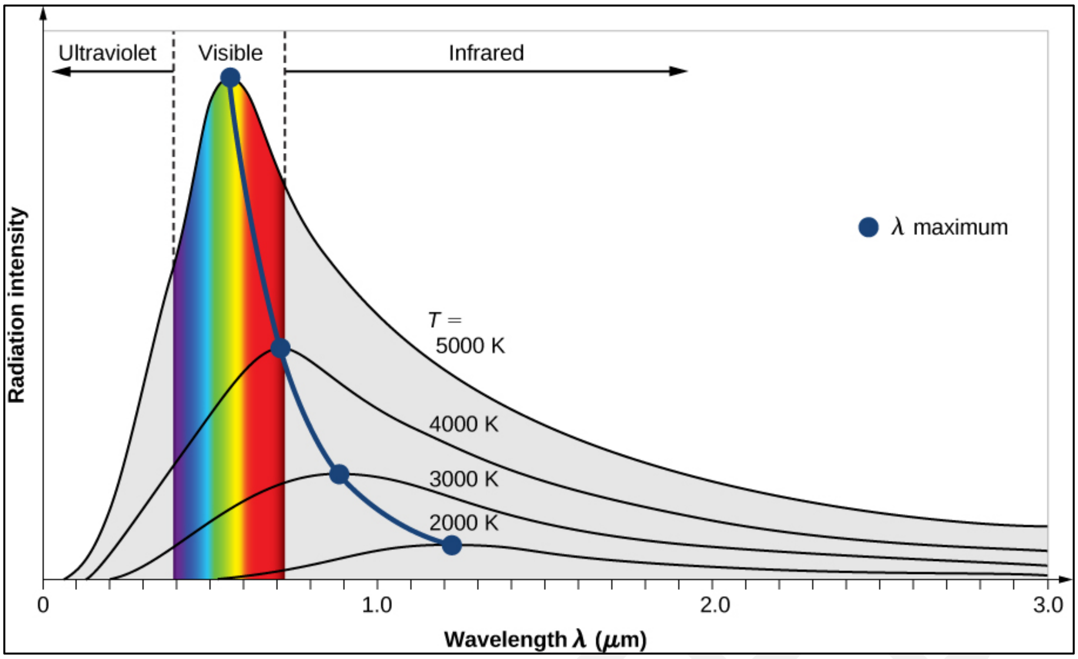

Figure 4: Radiation intensity versus wavelengths for different temperatures.

Figure 4 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 °C, while Earth's average surface temperature is around 15 °C. 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 the 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*.

2.4 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 tiny quantities, measured in parts per million (ppm) molecules in the atmosphere. These include the well-known greenhouse gases: carbon dioxide, methane, nitrous oxide, and (technically speaking) ozone. 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 a molecule are bonded 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 5, 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, making the molecule flexible. 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.

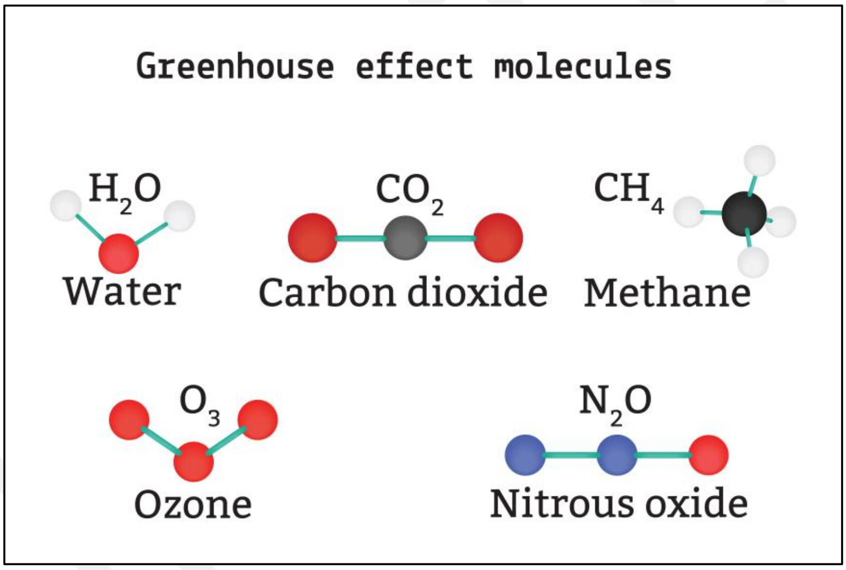

Figure 5: Greenhouse molecules
(red denotes oxygen atom, white hydrogen, black carbon, and blue nitrogen)

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 the infrared light emitted from the earth's surface does resonate with the vibrational frequencies (the bending oscillation) of greenhouse gases. When this infrared light interacts with these molecules, their vibrations intensify absorbing the radiation, heating the molecules and, subsequently, the surrounding air. Essentially, greenhouse gases capture the infrared radiation emanating from the earth's warmth.

2.5 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*.

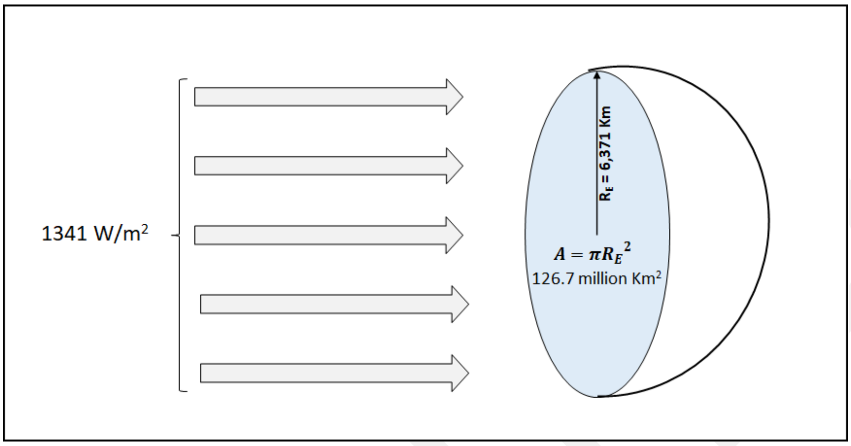

Figure 6: Incoming solar radiation

The total incoming solar energy is therefore 1,361 W/m^2 multiplied by the cross-section area of the earth (Figure 6). Multiplying the two give us 173×10^{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.

But 30 percent of this radiation is immediately reflected to the space by clouds, ice, and parts of land. The technical term for the 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 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 would be the average temperature of the earth if it must emit 238 W/m^2?

Using Equation 1, we find that it turns out to be ***minus 18* °C**, 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 °C. What accounts for this difference in the modelled temperature and the actual temperature? That is where the greenhouse effect of the atmosphere comes in. We will cover the greenhouse effect in detail in the next chapter.

The following section focuses on the earth's reflectivity, which is one of the three key determinants of our climate.

2.6 Earth's reflectivity or Albedo

We have seen the last section that 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 an 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 the 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 the earth's albedo, contributing to about half the solar energy reflected. Cloud reflectivity depends on a few key factors: Thickness – the thicker the cloud, the greater the reflectivity; size of water droplets and ice crystals in the cloud – the smaller the size, the brighter the cloud and hence more reflective; and concentration – greater the concentration of water droplets, 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 the 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 year 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

[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.

atmosphere, which reflected a large portion of the incoming solar radiation, leading to widespread crop failures and subsequent famine.[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, formed 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 presence. Their predictions were accurate: Global temperatures fell by approximately 0.6 °C 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 the 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 make 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.

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

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

3. The greenhouse effect

"You could warm Mars up, over time, with greenhouse gases.". -Elon Musk.

3.1 Our place in the solar system

In his book *The Pale Blue Dot*, Carl Sagan, an American astronomer and popular science writer, wrote "Our posturing, our imagined self-importance, the delusion that we have some privileged position in the Universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark."[1] The quote was inspired by an image of Earth taken by Voyager 1 on 14 February 1990 when it was roughly 6.4 billion kilometers from Earth. Our planet is seen as a minuscule speck of light, appearing as a mere 0.12 pixel-sized crescent amidst a backdrop of scattered rays of light.

However, there are reasons to believe that we do have some privileged position in the Universe. Be it by some divine design or a fortunate happenstance, our planet has an oxygen-rich atmosphere, we have enough water, an ozone layer that protects us, and a temperature which is neither too hot nor too cold for biological life to flourish. Despite our search, we haven't yet found any such goldilocks planet in the known universe.

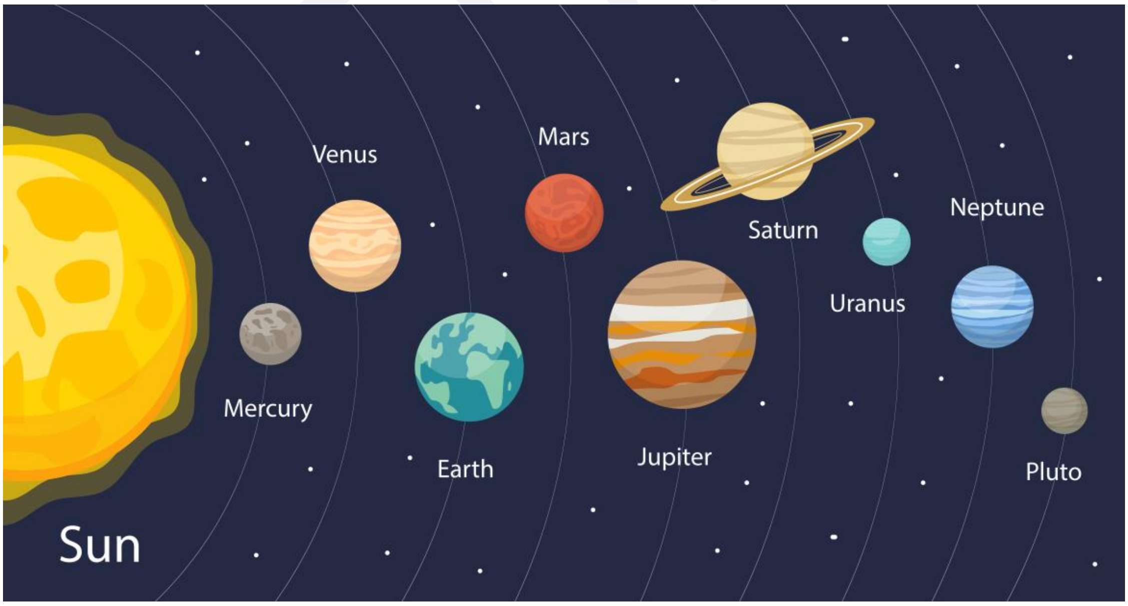

Figure 7: The solar system

Temperature plays a key role in sustaining life on Earth, and as we shall see later in this chapter, greenhouse gases and the resulting greenhouse effect is what makes our planet's temperature habitable. Among the planets in our solar system, Earth is a clear anomaly in terms of its temperature (Figure 8).

[1] Carl Sagan, *Pale Blue Dot A Vision of the Human Future in Space* (New York: Ballentine Books, 1994).

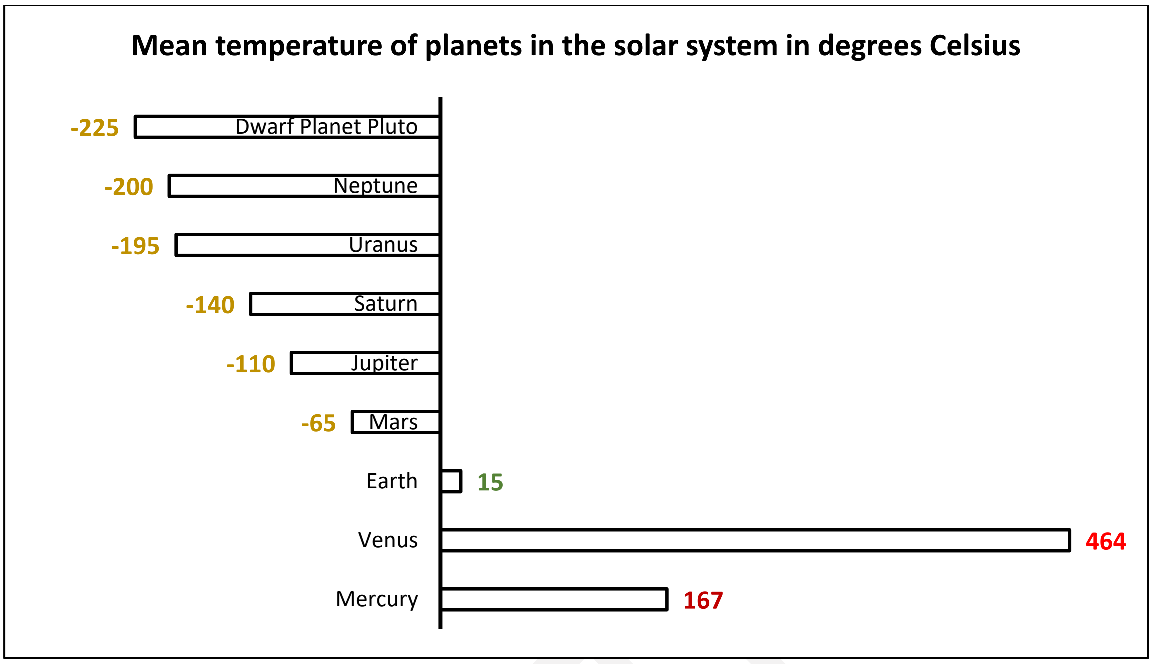

Figure 8: Mean temperature of planets in the solar system in degrees Celsius[2]

To drive the point home, we just need to look at the two of our neighboring planets in the solar system – Venus and Mars (Figure 7).

In terms of mass and size, Venus is not too dissimilar to Earth. But while Earth's average surface temperature is 15°C, Venus scorches at 464°C. The Venusian atmosphere is mainly made up of carbon dioxide, which retains solar energy and makes the surface temperature very high – extremely potent greenhouse effect. In fact, Venus is the hottest planet of our solar system, even hotter than Mercury, which is much closer to Sun. That's the power of greenhouse gases.

Mars stands in complete contrast to Venus. The red planet has virtually no atmosphere, although there are traces of carbon dioxide. Lacking an atmosphere, Mars is hardly able to retain solar energy, and experiences extreme temperature differences between night and day, with an average surface temperature of -65°C.

3.2 Earth: the goldilocks planet and the greenhouse effect

How is it that our planet has a carefully calibrated average surface temperature of 15°C?

Recall from chapter 2 that while the radiation which impinges on the earth is shortwave radiation, the radiation emitted by the earth is longwave radiation that 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's surface, some to space, and some impinges

[2] "Solar System Temperatures," NASA, 2020, accessed 11/17, 2023, https://science.nasa.gov/resource/solar-system-temperatures/#acf-downloads.

on other greenhouse gas molecules. This greenhouse effect warms the atmosphere and the earth's surface.

Figure 9 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 (recall section 2.6).

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, warming up the planet.

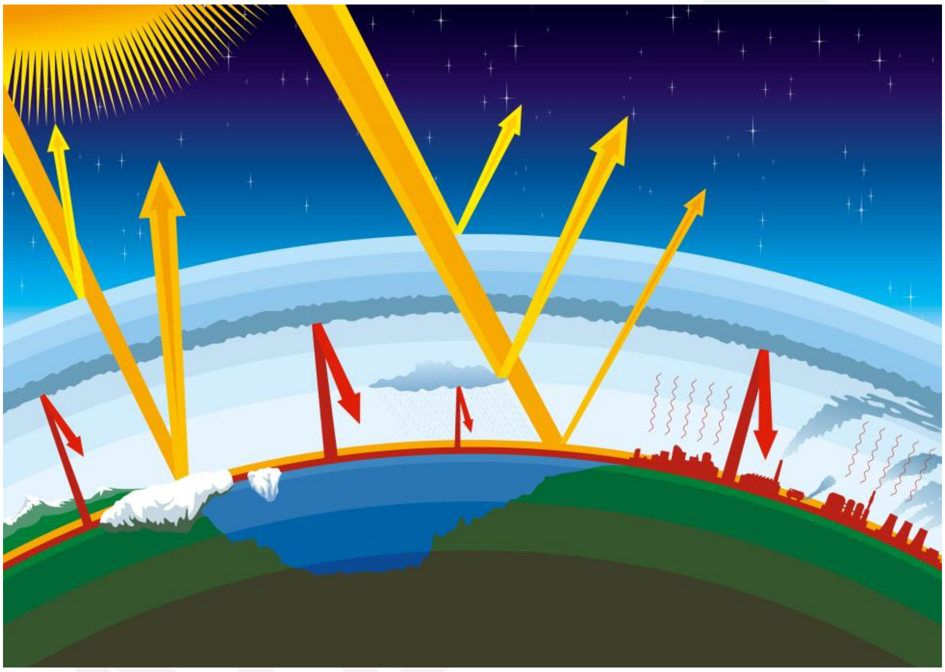

Figure 9: Simplified illustration of the greenhouse effect

Note that while the majority of the radiation emitted by the greenhouse gases is towards the earth's surface, some is emitted towards space, and some impinges on other greenhouse gas molecules. The earth then absorbs and re-radiates the energy.

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 the highest.

We will now mathematically model[3] the greenhouse effect, assuming that the atmosphere is a single homogeneous layer (Figure 10). 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*

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

mathematical details, feel free to skip the model as we have already covered the intuitive explanation above.

3.3 Greenhouse effect: a simple mathematical model

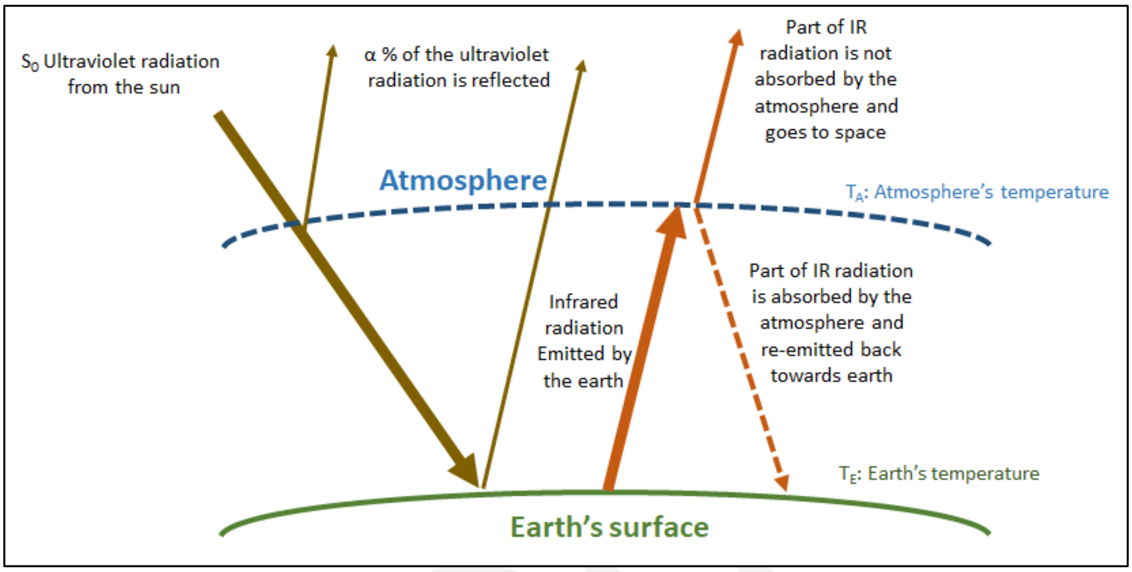

Figure 10: Simple one layer atmosphere model

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 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 6). 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, a fraction (since the atmosphere is not a blackbody) of this radiation is absorbed by the atmosphere, which we denote by ϵ. Similarly, the atmosphere only emits the same fraction ϵ of the radiation of a blackbody with the same temperature. ϵ is known as longwave absorptivity / emissivity of the atmosphere. A reasonable estimate of ϵ 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:

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

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

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

Where T_A is the temperature of the atmosphere. Note that the atmosphere emits energy both upwards (into space) and downwards (towards 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; α is 0.75; and σ 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 °C, reasonably close to the average surface temperature of 15 °C. 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 also increases. How will that impact the earth's temperature?

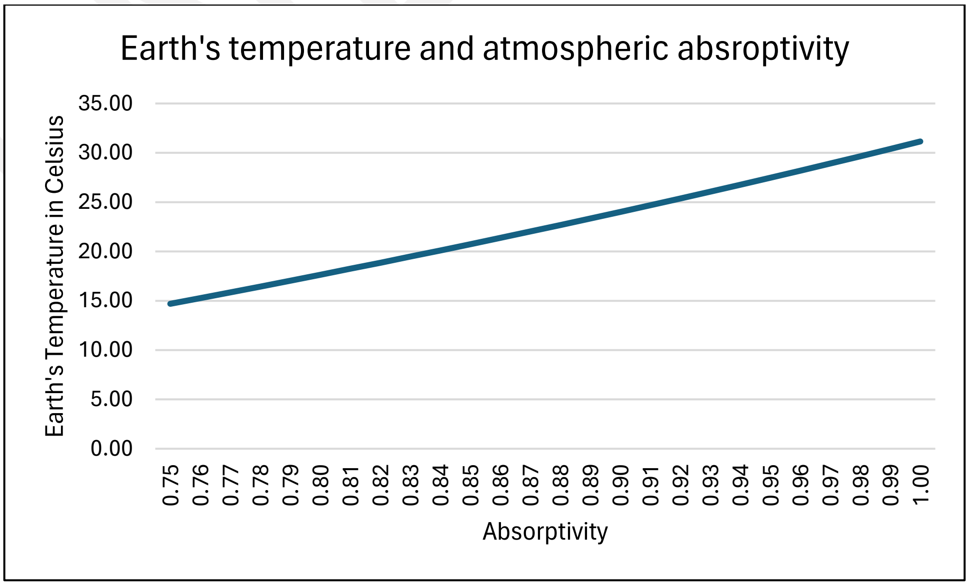

Figure 11: Earth's temperature and atmospheric absorptivity

As see in Figure 11, 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 ϵ = 1), then the earth's average temperature would be 31.15 °C, more than double the actual temperature.

3.4 Real greenhouse mechanism

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 12). 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 5.0°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.

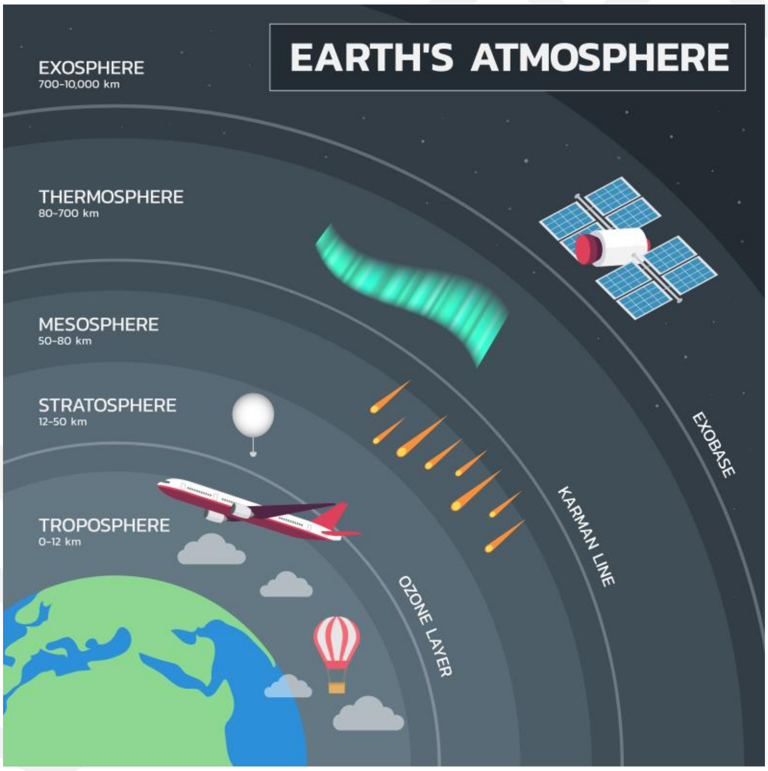

Figure 12: Layers of the earth's atmosphere.

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 that 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.

3.5 Radiative forcing

An important concept in climate science that is also linked to greenhouse gases is radiative forcing. It is the difference between incoming solar radiation and outgoing infrared radiation emitted by the earth.

For example, 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.

A somewhat counterintuitive fact is that as we increase the concentration of CO_2 in the atmosphere, radiative forcing does not increase linearly or exponentially. The radiative forcing of CO_2 depends logarithmically on its concentration. This means that when the CO_2 concentration increased from 200 parts per million (ppm) to 400 ppm, the earth's climate system retains an additional 3.93 W/m^2, i.e., that was the radiation absorbed by the additional gas. Logarithmic dependence means that the CO_2 concentration would have to double again from 400 to 800 ppm to absorb the same amount of radiation. Or simply put, each doubling of CO_2 leads to the same increase in temperature.

The total anthropogenic radiative forcing from 1750 to 2019 was 2.72 W/m^2, which means that due to human activities, an additional 2.72 W/m^2 was retained by the earth (including the atmosphere).

3.6 Other greenhouse gases and global warming potential

We have looked at CO_2 as the main greenhouse gas. It is released into the atmosphere by burning fossil fuels like coal, natural gas, and oil, as well as from solid waste, tree and plant matter, and certain chemical processes such as cement production.

CO_2 is not the only greenhouse gas.

Other greenhouse gases include methane (CH_4), nitrous oxide (N_2O) and fluorinated gases such as hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride.

Methane comes from coal, natural gas, oil production and transportation. It's also produced by agricultural practices involving livestock, changes in land use, and the breakdown of organic waste in municipal solid waste landfills. Nitrous oxide is emitted from agricultural and industrial activities, the burning of fossil fuels and solid waste, and during wastewater treatment. Fluorinated gases are used in various household, commercial, and industrial applications.

While some of these gases have much stronger radiative forcing than carbon dioxide, they last in the atmosphere for a much shorter period. One kilogram of methane, for example, results in a significantly higher absorption of radiation (and temperature increase) compared to one kilogram of carbon dioxide. But methane lasts in the atmosphere roughly for a decade, while carbon dioxide remains in the atmosphere for thousands of years.

To make an apples-to-apples comparison of various greenhouse gases, we use a measure known as Global Warming Potential (GWP). GWP of a greenhouse gas is its radiative forcing effect relative to carbon dioxide, considering both its absorbing strength and its lifetime, over a specified period (usually 100 years).

In other words, GWP quantifies the amount of energy absorbed by the emissions of one ton of a greenhouse gas over a certain timeframe, in comparison to the energy absorbed by the emissions of one ton of carbon dioxide.

Since CO_2 is used as the base, its GWP is taken as 1. Methane emitted by fossil fuels has a GWP of 29.8 and nitrous oxide has a GWP of 298.[4] What this means is that adding 1 ton of methane is equivalent to 29.8 tons of CO_2 in terms of global warming impact over 100 years; similarly adding 1 ton of nitrous oxide is equivalent to 298 tons of CO2.

3.7 The role of water vapor as a greenhouse gas

Water vapor is the most abundant greenhouse gas in our atmosphere. It accounts for nearly half of the earth's greenhouse effect. Don't let this statement mislead you into thinking that water vapor is the main driver of global warming. It isn't. Instead, it is the consequence of global warming, and increased water vapor in the atmosphere amplifies the warming caused by other greenhouse gases.

Warming of the earth's temperature due to greenhouse gases like carbon dioxide and methane leads to greater evaporation both from water and land. Warmer air can hold more moisture, which results in an increase in atmospheric water vapor. This happens because at higher temperatures, water vapor is less likely to condense and fall as precipitation. Since water vapor is a potent greenhouse gas, this causes further warming. This warming, in turn, causes moisture to increase further, which increases the temperature even more.

It is estimated that the water vapor feedback loop (described above) doubles the heating impact of CO_2 alone.

[4] IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2021).

3.8 Earth's energy balance

We have examined the three main factors which influence the earth's climate and temperature. The incoming solar radiation, the earth's reflectivity (or albedo), and the greenhouse effect. Before concluding this chapter, we look at how these three factors interact and balance the earth's energy budget.

Figure 13 shows the energy flows to and from the earth[5]. All the figures are in W/m^{2}.

Incoming solar radiation of 340 W/m^2 means we are getting on an average 340 joules every second over every square meter of the earth's surface. Of this, roughly 30 percent, or 100 W/m^2, is reflected immediately, mainly by clouds and aerosols, and partly by the earth's surface. The rest is absorbed by the surface (160 watt/m^2) and atmosphere (80 watt/m^2).

As we can see, the radiation emitted by the earth's surface is 398 W/m^2, which is much higher than the initial solar radiation absorbed by the surface. This is because the surface must emit the energy which comes from the atmosphere due to greenhouse effect. The radiation from greenhouse gases coming back is known as back radiation (342 W/m^2).

In addition to the infrared radiation emitted by the earth's surface, two additional heat transfer mechanisms operate: convection and conduction in the form of thermals and change of state of water through evapotranspiration resulting in latent heat transfer.

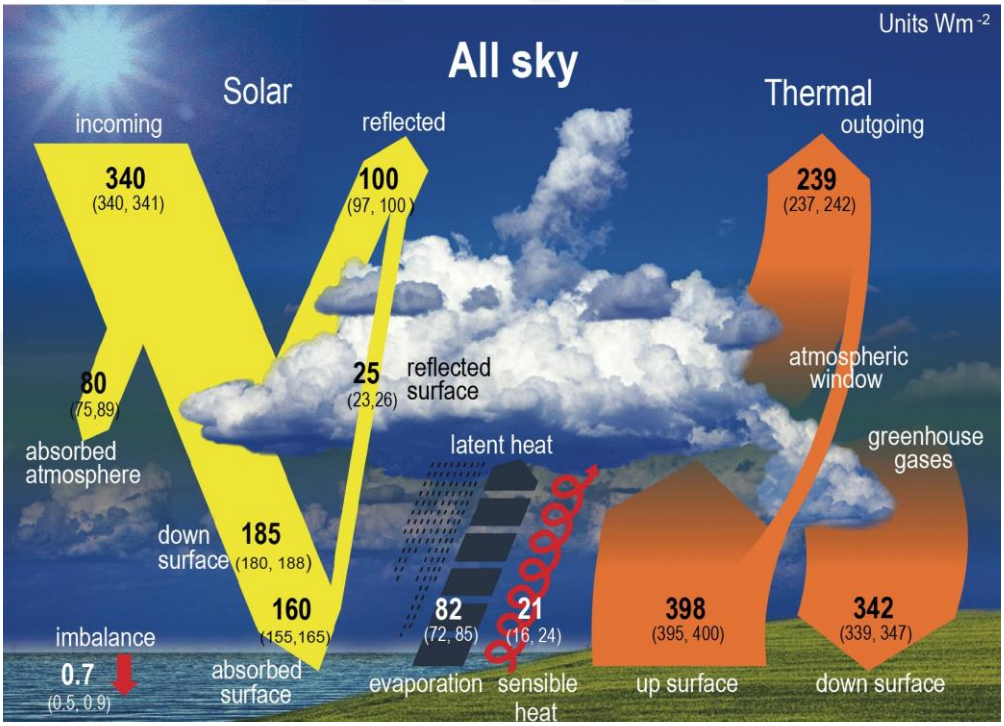

Figure 13: Earth's Energy Balance

[5] Figure 7.2 in IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

At overall level, the net incoming solar radiation must balance the outgoing radiation (both reflected and radiated)

$$\begin{aligned} &Incoming\ solar\ radiation\ (340\ \ W/m^2) \\ &\qquad = Radition\ reflected\ by\ clouds, atmosphere, Earth\ surface\ (100\ \ W/m^2) \\ &\qquad + total\ outgoing\ infrared\ radiation\ (239\ \ W/m^2) \end{aligned}$$

The right-hand side adds up to 339 which is marginally lower than the incoming solar radiation (340). Without the rounding effect, this imbalance of 0.7 W/m^2 is shown as net absorbed in Figure 13.

This energy imbalance results from increases in greenhouse gases absorbing thermal radiation that would otherwise be emitted to space. But ultimately, the outflow must equal inflow, and the earth will eventually have a new (higher) equilibrium temperature with outflow balanced with inflow.

How much of a difference does 0.7 W/m^2 make? The answer lies in what is termed *Climate Sensitivity*, which is a fundamental measure of climate change.

3.9 Climate Sensitivity

Climate sensitivity is defined as the change in the surface temperature in response to a change in the atmospheric carbon dioxide concentration or other radiative forcing.

In case of energy imbalance, we can interpret climate sensitivity as the surface temperature change resulting from the energy imbalance in the system, once the system has adjusted and reached a new equilibrium state.

We have seen before that radiative forcing of doubling carbon dioxide is estimated to be 3.93 W/m^2. This leads to a temperature increase of 3°C. So, the energy imbalance of 0.7 W/m^2 will translate to a temperature increase of 0.54°C. Note that these are central estimates and there is always a margin of uncertainty around these estimates.

To make it easier to remember, we can say that every additional 4 W/m^2 results in a temperature increase of 3°C. *This is an important relationship*.

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