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UNDERSTANDING CLIMATE CHANGE

INTRODUCTION

In the last decade or so, interest in the phenomena referred to as "Climate Change" has exploded. The media and various NGOs are being joined by politicians who are all touting the messages that "this is a recent development, it is catastrophic, and it is caused by the activities of mankind". At times, the messaging is shrill and hysterical. A sober, educated look at the scientific facts and the historical climate records is called for, and that is the purpose of this document.

There is no doubt that the climate **is** changing, just like it always has, and always will. We need to know how the climate has changed in the past, what causes the changes, what is likely to happen in the future, and what (if anything) man can (or should) do to affect this.

CLIMATE VERSUS WEATHER

When a person speaks about "weather", they are referring to how the atmosphere is behaving over the short term (hours or days), and usually about how it directly affects them (in terms of temperature, precipitation, humidity, wind, etc.). The term "climate" refers to the statistics of weather over a defined large region over a long period of time (decades or more). The difference between Climate and Weather is primarily a matter of time and area.

The words "climate" and "weather" refer to temperature, precipitation, humidity, and similar terms that describe the state of the atmosphere. This document will frequently use the term "climate change", but it is primarily addressing "global temperature change."

TEMPERATURE AND ITS MEASUREMENT

All the discussion and concern about climate change seems to focus on one aspect of climate - *temperature.*

Temperature is a measure of how hot or cold something is, and it is measured with a thermometer. Most of the world uses the Celsius system of specifying temperature, where zero degrees is the temperature at which fresh water freezes, and 100 degrees C is the temperature at which fresh water boils at sea level. The scientific world often specifies temperature in terms of degrees Kelvin (K), where zero degrees is referred to as Absolute Zero, and is the coldest temperature possible, at which all molecules and atoms become motionless. A temperature expressed in degrees Kelvin can be converted to Celsius by subtracting 273.

Discussions of climate change focus on what is commonly referred to as the "Global Temperature", which is supposed to be the average temperature of the Earth. This temperature is intended to represent that of the atmosphere that is close to the earth's surface (at an altitude of 1.5 metres). There are actually a number of problems in coming up with a meaningful number for an average temperature for the Earth, and these were thoroughly outlined in a 2006 paper by Essex, McKitrick, and Andresen entitled "Does A Global Temperature Exist?" [1]. Most climate change papers ignore or downplay the issues raised in this paper as the studies then present inferred historical temperatures, extract trends, postulate causes, and try to project the future. When published, this paper was controversial, as it cast doubt on the conclusions reached by many climate researchers, and it is now difficult to obtain a copy from freely available publication sources.

Reliable equipment for measuring temperature has been available since the early 1800's, and distributed networks of these devices have been used to record historical temperatures that are used in the study of Climate Change. Unfortunately, the number and placement of temperature recording stations has changed considerably over time, so it is often difficult to get a complete and consistent record for a specific area.

Temperature history for the period preceding the nineteenth century must be inferred by analyzing ice cores, tree growth rings, sediments, and corals. Ice cores (typically from Greenland, Antarctica, or the Arctic) are the most commonly-used "proxies", and it is possible to infer temperatures from thousands of years ago. It is also possible to estimate the historical composition of the atmosphere using ice cores, but diffusion effects may mask some of the inferred extremes (of both composition and temperature)

Cores taken from the bottom of oceans and lakes will often yield stratified sediment samples that can then be subjected to isotope analysis to determine the approximate age and certain atmospheric characteristics (including temperature and CO_2 concentration) at the time of deposition.

Although surface temperature is what humans actually "feel" on a day-to-day basis, that data can be contaminated by the "urban heat islands" that are caused by construction of roads, parking lots, and structures that change the localized reflectivity and thermal mass of the surface. Because of this, it is sometimes more meaningful to talk about the temperature of the troposphere, which is the lowest layer of the Earth's atmosphere (about 20 Km thick), and is where all weather takes place (clouds, precipitation, storms, winds). Temperatures in the troposphere can be directly measured by balloon-borne radiosondes, or inferred from satellite radiometry.

EARTH'S HISTORICAL TEMPERATURE RECORD

"**Paleoclimatology**" is the study of the earth's climate over the history of the planet's existence. The earth is approximately 4.5 billion years old, and a variety of proxies must be used to infer the climate over most of this period. For convenience, the 4.5 billion year history (referred to as the "Geological Time Scale") is divided (primarily on the basis of where rocks, fossils, and fauna were found, or major geological events are believed to have occured) into various categories defined as: Eons, Eras, Periods, and Epochs. Figure 1 is a graphic representation of the categories in the Geological Time Scale. Note that the top of the chart represents the present time:

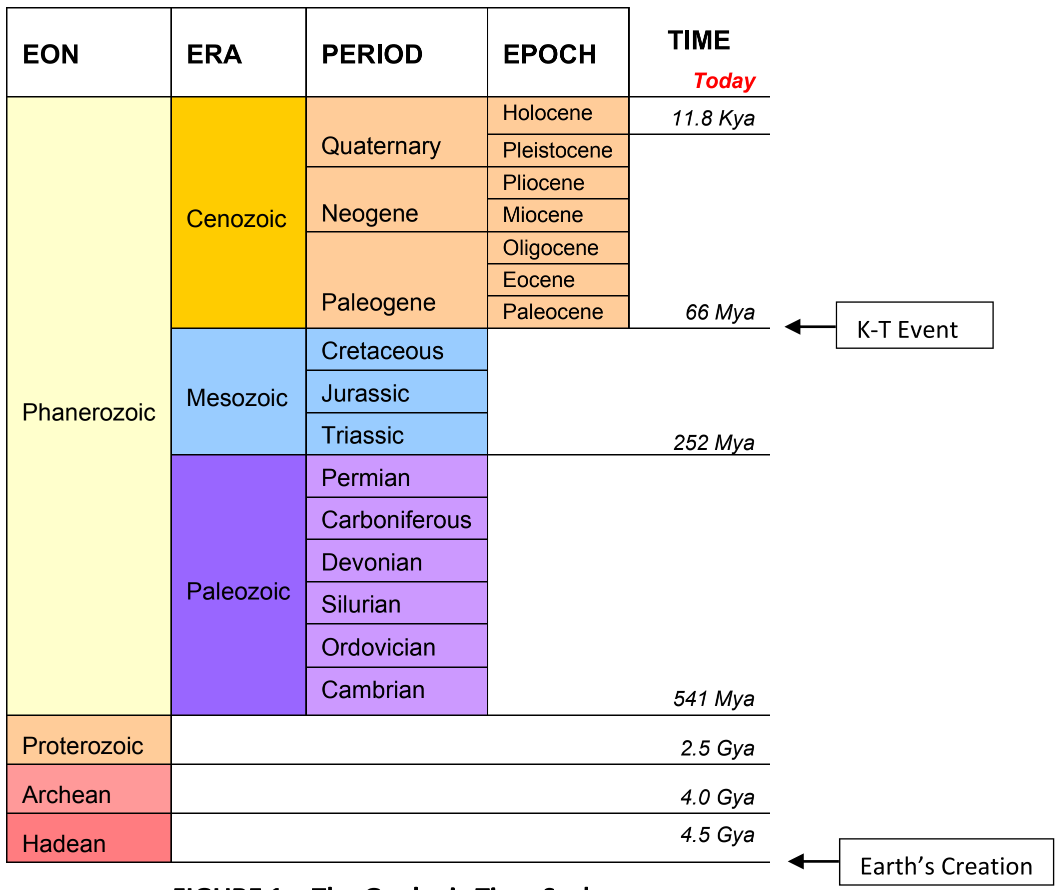


FIGURE 1 – The Geologic Time Scale

Note that the relative sizes of the cells in the above graphic are not to scale! The date scale is also highly non-linear.

Time abbreviations are:

- **Kya** = Thousand year ago
- **Mya** = Million years ago
- **Gya** = Billion years ago

NOTE - These time abbreviations will now be used throughout the rest of this document.

The earliest forms of life (bacteria and algae) appeared approximately 3.5 Gya. The first appearance of Modern Man (Homo Sapiens) was about 200 Kya. Archaeological research shows that a predecessor (Homo Erectus) first used tools about 2 Mya.

Looking at Figure 1, note the boundary between the Mesozoic Era and the Cenozoic Era, which occurred about 66 Mya. Just prior to this time boundary, dinosaurs were quite common, but it is believed that a massive asteroid hit the earth 66 Mya, and devastated the global environment, causing the mass extinction of three quarters of the plant and animal species on Earth, including the dinosaurs. This is known as the K-Pg extinction event, or "K-T Event".

Reliable historical temperature information from the period before the K-T Event is difficult to obtain, but the period afterwards (the last 66 million years) can be estimated using a variety of proxies.

A compressed graphic of the earth's temperature record since the K-T Event is shown in Figure 2, which uses a variety of proxy data to produce a continuous record:

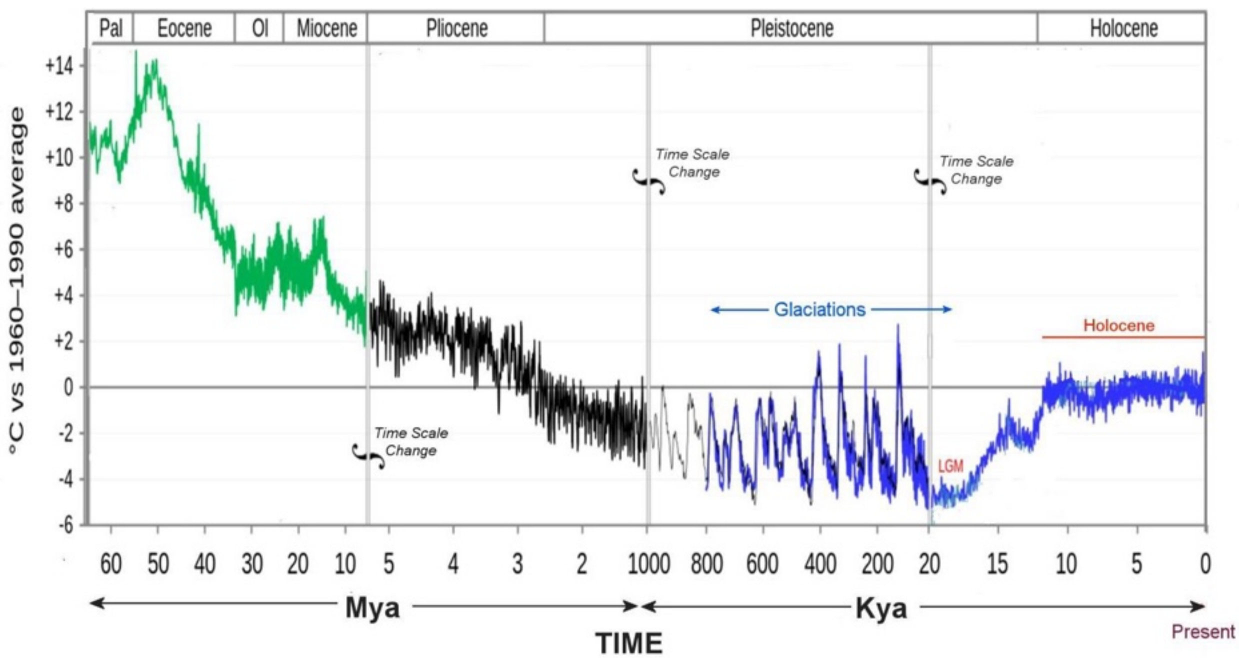


FIGURE 2 – Compressed, non-linear record of the Earth's average temperature since the K-T Event.

(This chart was created by simplifying the image available at: https://commons.wikimedia.org/wiki/File:All_palaeotemps.png)

Note that there are several scale changes on the horizontal axis ("Time"), and it is plotted logarithmically, which greatly expands the more recent times. The "LGM" note shows the time of the "Last Glacial Maximum", when glaciers covered more than 8% of the earth's surface, and the sea level was about 400 feet lower than today. Note that the region marked as "Holocene" represents the last 11.8 Kya where the temperature has been relatively steady. From about 12 Kya to about 800 Kya, the temperature oscillates as the Earth experiences a series of glaciations.

Figure 2 illustrates that the relatively stable temperature experienced during the recent Holocene is an anomaly, and the normal condition has a much "noisier" temperature record. Of course, the horizontal scale changes distort the picture somewhat. Chart 3 plots just the last 800,000 years, using a linear time scale:

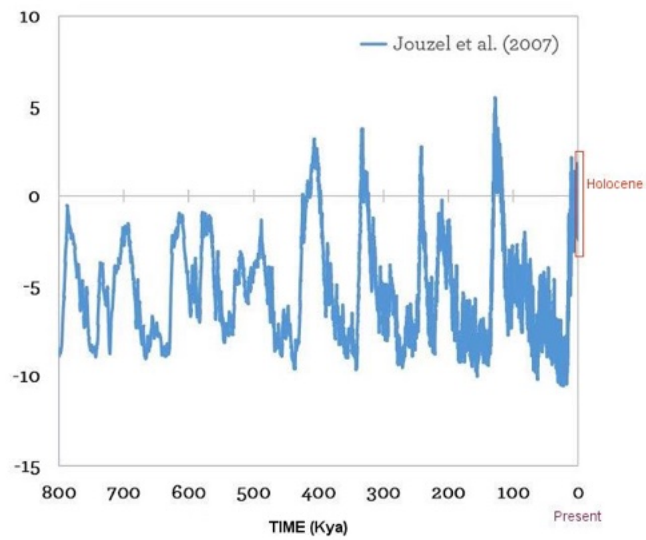


FIGURE 3 – 800,000 year temperature record, showing the cyclic glacial periods.
The area within the narrow red box is the Holocene, which is expanded below.

This chart is based on analysis of ice cores taken in the Antarctic. Of course, this is not the actual Earth's global temperature, but it is indicative of it. What is plotted is the temperature variation from the average temperature over the past 1,000 years. The glacial cycles are clearly shown, and the entire Holocene period (inside the red box) is shown as a relatively short period at the extreme right side of graph. Looking at this graphic, a casual observer would probably conclude that: **a)** getting alarmed about temperature trends over the past decade or century seems unsupportable, and **b)** we appear to be in an interglacial period, and should possibly start thinking about a new ice age in a few thousand years.

Let's now expand the time scale still further. Figure 4 looks at the temperature record of just the Holocene period (the region shown inside the red box in the graphic above):

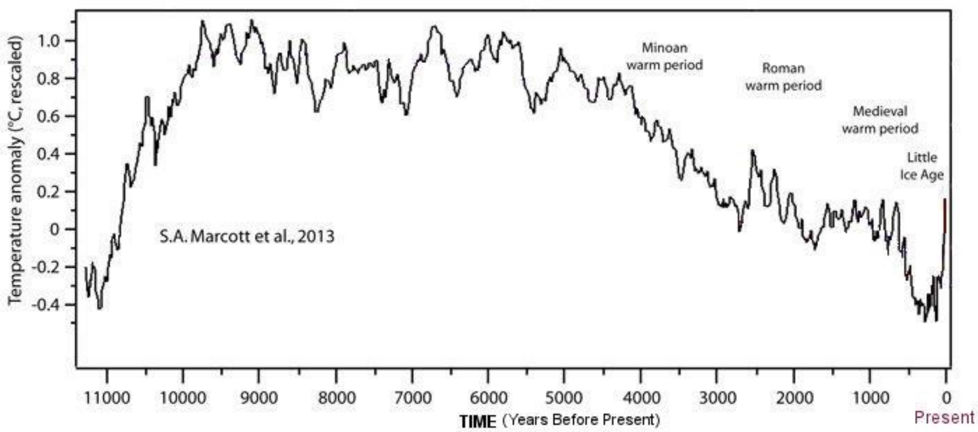


FIGURE 4 – Average global temperature during the Holocene (the past 11,700 years)

Looking at graphs 2 through 4, we can conclude that, since the K-T event, the global temperature has been slowly declining, with cyclic variations in the past 800,000 years that have resulted in a series of glaciations. We are currently between glaciations, enjoying a relatively constant temperature, with minor perturbations.

EARTH'S SOURCES OF HEAT

Heat is just a form of energy, and it is commonly measured in units of Joules. It exists as a property that is contained within a material (solid, liquid, or gas), and can be thought of as the kinetic energy of the movement of the material's molecules and atoms. The term "temperature" relates to the amount of heat in an object.

Heat always flows from a hotter object to a cooler object. The rate of heat transfer is measured in Watts, which are defined as "Joules per Second".

The earth has its own internal heat sources, such as its radioactive core, but these are very small. The earth's temperature is primarily a function of the electromagnetic energy received from the sun (so-called "solar radiation"). In the absence of the sun or any internal heat sources, the earth's temperature would be close to absolute zero, which is -273°C, or 0°K.

The sun is the primary source of energy for the earth. It is a so-called "black body radiator", and a broad spectrum of electromagnetic wavelengths is emitted, but the peak wavelength is at about 502 nm, which corresponds to green-blue light. This peak wavelength is a function of the temperature of the sun's surface. The total amount of energy emitted by the sun across all wavelengths varies as the fourth power of the sun's surface temperature. The sun's surface temperature is 5,772 degrees K and the total energy radiated in all directions is 3.8×10^{26} Watts.

As a spherical black body radiator, the sun emits its solar radiation uniformly in all directions. The power density observed at distances far from the sun's surface can easily be calculated using geometry.

The distance from the Earth to the Sun varies during a calendar year, but today has an average of 147 million Km. The black body radiation originating from the sun (across all wavelengths) therefore has an average illuminating power density of approximately 1367 Watts/m^2 at the top of the earth's atmosphere.

Using basic geometry, it can easily be shown that (ignoring all atmospheric effects), this is equivalent to a perpendicular average flux across the entire surface of the Earth of 341.2 Watts/m^2.

Looking at just the major factors, The amount of solar energy being absorbed by the Earth's surface is dependent on four parameters:

1. The energy being emitted by the sun. (both the total amount, and its spectral distribution)
2. The distance between the sun and the earth. (this affects the received energy in an inverse square law relationship)
3. Influences of the earth's atmosphere. (shading, reflection, absorption, radiation, etc.)
4. Characteristics of the surface of the earth (such as its reflectivity at various wavelengths) that determine how much total solar energy is absorbed, and how much is reflected. The term "Albedo" is used to quantify this characteristic: albedo is defined as the ratio of solar irradiance that is diffusely reflected by a surface to the irradiance received by that surface. [2]

The energy emitted by the sun has been changing over time. It is believed that about 3 or 4 Gya, the sun's output was about 70% of today's values, but that it has been relatively constant during the Holocene. Some studies have shown a small cyclic variation with a period of 1500 years.

Darker, cooler areas (at about 3,800° K) on the surface of the Sun (so-called "sun spots") vary over an 11 year cycle. The magnitude of these spots also varies over a much longer cycle that is suspected might be caused by "tides" on the sun's surface due to gravitational effects from the orbits of Jupiter, Saturn, Earth, Mercury, and Uranus. Continuing analysis of this has added credibility to this theory.[3] Other theories based on relativistic causes or inter-planetary electric fields have also been proposed. Here is a historical record of observed sunspot numbers over the past 400 years:

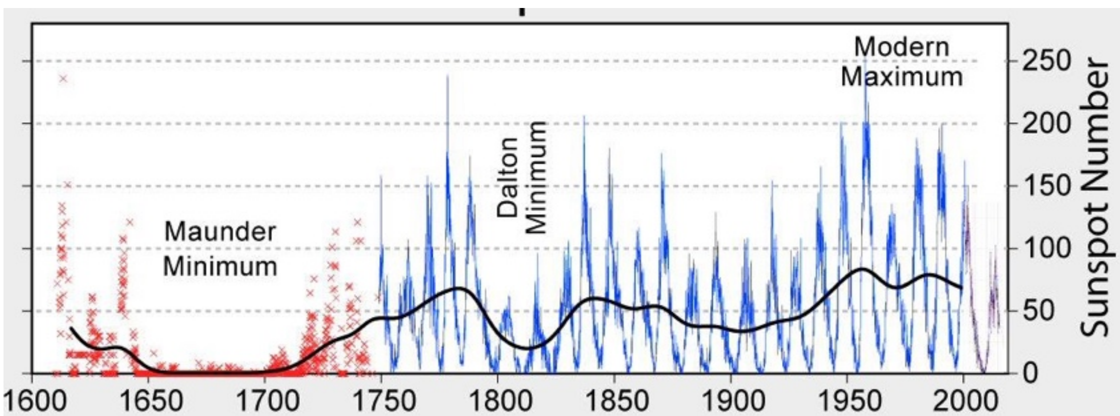


FIGURE 5 – Sunspots over the past 400 years

The net effect of these cycles is to change the outgoing radiation from the sun that eventually strikes the Earth's atmosphere.

These cycles also have a major effect (by at least a magnitude factor of 10) in radiation of extreme ultraviolet (EUV), which can strongly affect the chemistry and thermal characteristics of the earth's upper atmosphere.[4] Ultraviolet radiation from the sun affects the formation of ozone and clouds.

Here is a closer look at the last 5 sunspot cycles. Cycle 25 is expected to peak in the summer of 2025.

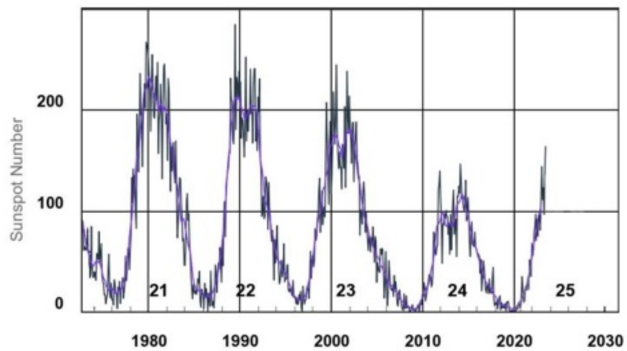


FIGURE 6 – Recent sunspot cycles.

The 11 year sunspot cycles strongly affect the state of ionization of the ionosphere, and therefore have a major effect on the highest radio frequency that can be used to cover long distances (using "skip") in the shortwave radio bands.

The amount of incoming solar energy that actually reaches the earth's surface is affected by many atmospheric variables: clouds, scattering, absorption, water vapour, etc.

If it were not for the atmosphere, the earth would be a much colder place. Energy received from the sun would heat the earth's surface, but "black body radiation" from the earth's surface would radiate much of this energy into space. An equilibrium average global temperature of approximately -18°C would result in the amount of radiating energy being equal to the absorbed solar energy. The atmosphere stops a significant portion of this heat loss by acting as a "greenhouse", thereby warming the earth to comfortable temperatures. We will now discuss how the atmosphere functions as a "greenhouse".

THE GREENHOUSE EFFECT

The sun emits energy in the form of electromagnetic radiation (EM radiation). In order to understand the greenhouse effect, we will first review this type of radiation. Depending on its wavelength, EM radiation can represent radio waves, visible light, ultraviolet (UV) light, infrared (IR) radiation, X-rays, etc. The following spectrum chart illustrates this:

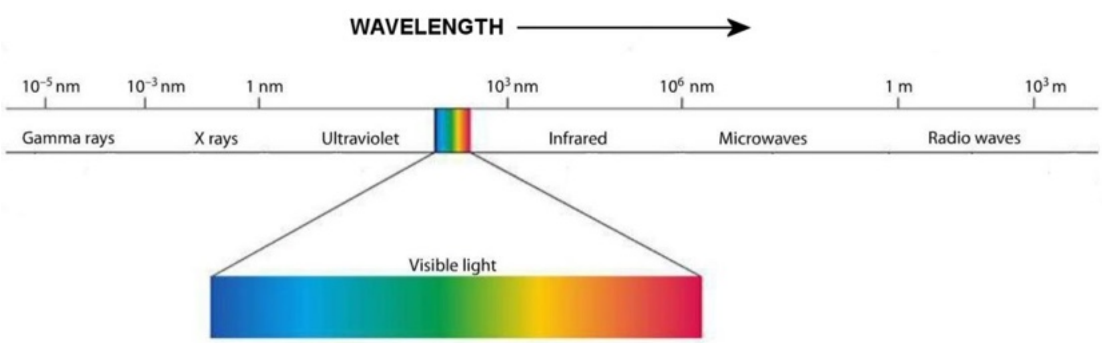
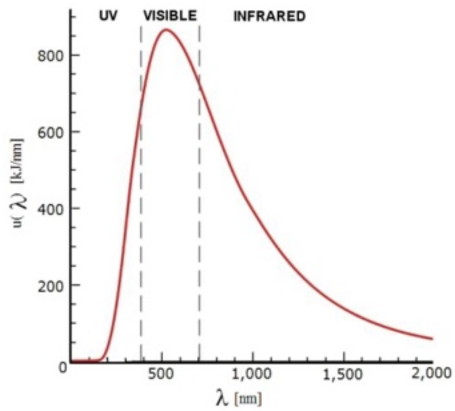


FIGURE 7 – The electromagnetic spectrum

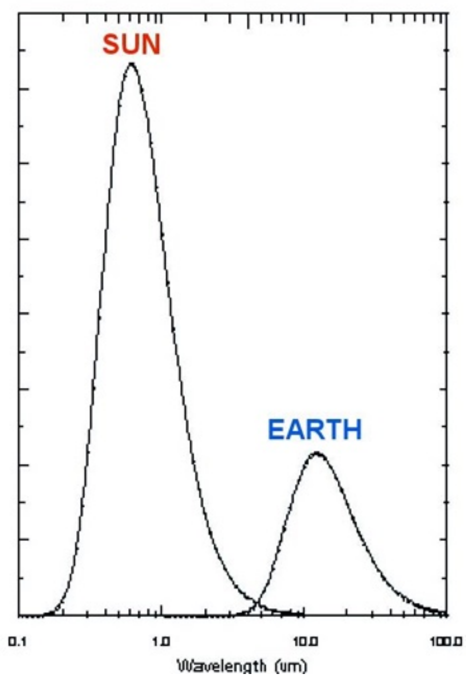
The sun does not emit a single wavelength: it is a so-called "black body emitter", and as such, emits a range of different wavelengths of EM radiation based on its surface temperature (5,772°K). Solar energy is distributed across this series of wavelengths (λ) as shown below:



The sun's EM radiation is distributed into three broad ranges: 7% in the UV portion of the spectrum, 44% in the visible spectrum, and 48% in the infrared region.

FIGURE 8 – Spectral distribution of the sun's electromagnetic radiation

The earth itself also acts as a "black body emitter". Its average surface temperature is about 287°K, and its emitted spectrum is therefore centred in the IR range, as shown below:



This diagram plots the relative intensity of the black body radiation from the sun and the earth as a function of wavelength.

Black body radiation consists of a continuous spectrum of emitted wavelengths. The peak radiation is at a wavelength that is inversely proportional to surface temperature, and the total emitted energy varies as the fourth power of the surface temperature. These relationships are defined by the Stefan-Boltzman Law [5], Planck's Law [6], and Wein's Displacement Law.[7]

FIGURE 8 – Black body radiation from the sun and earth

Look for the moment at EM energy that travels from the sun to the surface of the earth. A portion of the energy is re-radiated by the earth's surface, and it has to pass through the atmosphere on both trips. The atmosphere's gases have an effect on the energy: the dominant factor is absorption, which is often a function of wavelength. The amount of absorption varies with the concentration of the gas in accordance with the Beers-Lambert Law.[8] The greenhouse effect is caused by the fact that water vapour and other so-called "greenhouse gases" exhibit differing absorption and reflectivity characteristics between the shorter-wavelength incoming solar EM energy (centred at about 500 nm, as shown in the preceding diagrams) and the longer-wavelength IR energy (in the range of 10µm) that is emitted by the earth's surface. Some of the outbound IR energy from the earth's surface is absorbed by the greenhouse gases, causing heating, and this in turn sets up its own black body radiation both toward the earth and into space, as well as heating air in the lower troposphere. Some of the IR energy is absorbed, raising the gas's molecules to a higher atomic state, which then results in a re-radiation (at the same wavelength) in all directions (including back toward earth). The net effect is that energy is "trapped" in the lower levels of the atmosphere, and as a result the earth's surface is much warmer than it would be in the absence of these greenhouse gases. Note that it is believed there are "escape holes" in the two polar regions (roughly coincident with the ozone holes) that potentially allow trapped heat energy to escape from the earth: more research is needed in this field.

Also note that the greenhouse effect is not linearly proportional to the concentration of the greenhouse gases: it varies with the logarithm of the concentration.[9] The temperature increase contribution caused by a rise of CO_2 concentration from 400 to 500 ppmv (parts per million by volume) is much less than that caused by a rise from 200 to 300 ppmv. This fact is seldom mentioned in popular literature which discusses the possible climactic danger of increasing CO_2 levels [10].

GREENHOUSE GASES

There are many different greenhouse gases. Major components of the atmosphere by volume are listed below:

Nitrogen	78% or 780,000 parts per million by volume (ppmv)	
Oxygen	21% or 210,000 ppmv	
Argon	1% or 10,000 ppmv	
Water Vapour	0.001% to 5% or 10 to 50,000 ppmv	(*A Greenhouse Gas*)
Carbon Dioxide	410 ppmv	(*A Greenhouse Gas*)
Neon	18 ppmv	
Helium	5 ppmv	
Methane	2 ppmv	(*A Greenhouse Gas*)

Looking at the above list, Water Vapour (H_2O), Carbon Dioxide (CO_2), and Methane (CH_4) are all "greenhouse gases". Water vapour is not visible to the human eye, but when this vapour condenses to form small water droplets, the resulting clouds or fog are easily seen. Water vapour is the dominant greenhouse gas, but CO_2 receives most of the publicity!

Water Vapour is the primary Greenhouse gas, representing up to 100 times the concentration of CO_2 in the atmosphere. The atmosphere's water vapour is primarily the result of evaporation of the earth's lakes and oceans. As the Earth's temperature rises, more evaporation will occur, increasing the level of atmospheric water vapour, thereby increasing its Greenhouse Effect, and therefore causing more warming. This "positive feedback" tends to increase the effect of other external factors that affect Global Temperature. Offsetting this, there is a "negative feedback" mechanism, whereby higher levels of water vapour result in more clouds which reflect incoming solar energy back into space. Other greenhouse gases include Nitrous Oxide (N_2O), and Ozone.

In order to understand and quantify the effect of the various greenhouse gases, we need to look at their absorption spectra, which show how the absorption of each gas varies as a function of the wavelength. Figure 9 has three "panels", with a common horizontal axis representing the wavelength.

Figure 9C is a chart showing the individual absorption spectra for Water Vapour (H_2O), Carbon Dioxide (CO_2), Oxygen and Ozone (O_2 and O_3), Methane (CH_4), and Nitrous Oxide (N_2O). It also shows the spectral absorption due to Rayleigh Scattering, which is the scattering of shorter wavelengths of light on individual air molecules, giving the sky its characteristic blue colour. All of these absorption spectra block specific wavelength bands, and the composite (shown in grey in Figure 9B) represents the total attenuation of electromagnetic energy passing through the atmosphere due to both absorption and scattering. The composite is the <u>sum</u> of the individual absorption and scattering spectra.

If you look at Figure 9A, you will see the spectrum of the incoming solar energy in red. The continuous red curve shows the spectral intensity of the incoming solar radiation before it passes through the atmosphere, and the somewhat ragged red area below the curve represents the spectral intensity of the radiation that makes it all the way through the atmosphere, hitting the Earth's surface.

Figure 9A also shows a purple continuous line that represents the spectrum of the outgoing black body radiation from the earth's surface. The shape and position of this curve will vary somewhat, depending on the temperature of the surface. The ragged purple area below the curve shows the spectral intensity of the outgoing radiation by the time it reaches the top of the atmosphere.

Both the smooth red curve and smooth purple curve are drawn as having the same peak height, but this is for illustrative purposes only. The magnitude of the red curve (the incoming solar flux) is actually much higher than the purple curve (the outgoing energy), as illustrated previously in Figure 8.

In looking at Figure 9C, it can be seen that the absorption peak of CO_2 in the region of 14 microns is largely "blanketed" by the absorption from water vapour.

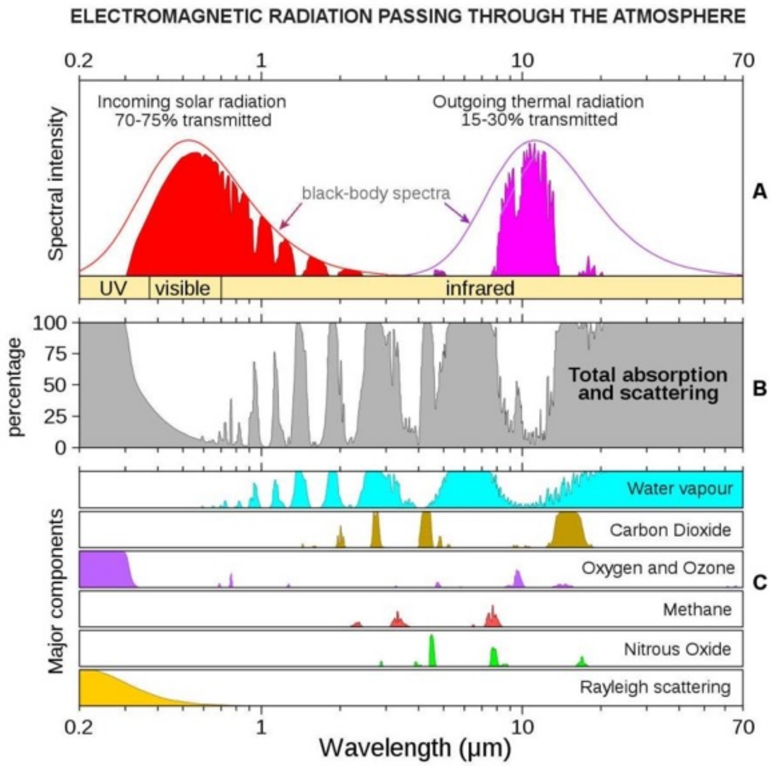


FIGURE 9 – Effect of spectral absorption of electromagnetic radiation passing through the atmosphere. Panel B shows the total absorption and scattering of EM energy passing through the atmosphere as a function of wavelength. It is the sum of the spectral components in panel C**.**

The incoming energy density (measured in Watts per square metre) at the surface of the Earth is proportional to the total area of the ragged red area in the top panel. The energy density (in Watts/m^2) transmitted into space by the Earth's black body radiation is equal to the area of the ragged purple area in the top panel. The energy that is absorbed by the atmosphere causes heating of the gas molecules, so they in turn will have their own black body radiation whose spectrum and intensity will be a function of the temperature. In looking at the overall atmosphere, it can be seen that there will be many paths for energy to flow, and the best way to analyze this will be to divide the atmosphere into layers, and do radiative calculations on each. This is obviously going to get very complex, as the pressure and temperature will vary between each layer. There is a sophisticated computer program known as "Hitran" that can be used to do these calculations, and a simpler, easy-to-use spin-off called "Modtran" that is freely available on the University of Chicago web site.

Modtran allows the user to specify a locality on the Earth (tropical, mid-latitude, subarctic, etc), the season, local conditions (clear sky, clouds, precipitation, etc), and set concentrations of various gases (CO_2, CH_4, Water Vapour, Ozone, and Freon). The user specifies whether the analysis should be done for energy going up or going down, and what the virtual observer's altitude is in Km. The program then calculates and plots the energy flux in W/m^2 as a function of wavelength. The total energy flux is the area under the displayed curve. Note that the default wavelength display along the horizontal axis is in "wavenumber" units, as this is commonly used by scientists for spectrometry work. A wavenumber is the reciprocal of wavelength, and is equal to the number or complete cycles of a waveform per cm. For comparison purposes, Figure 10 displays two output displays from Modtran of the same atmospheric conditions, one using wavenumbers, and one using wavelengths:

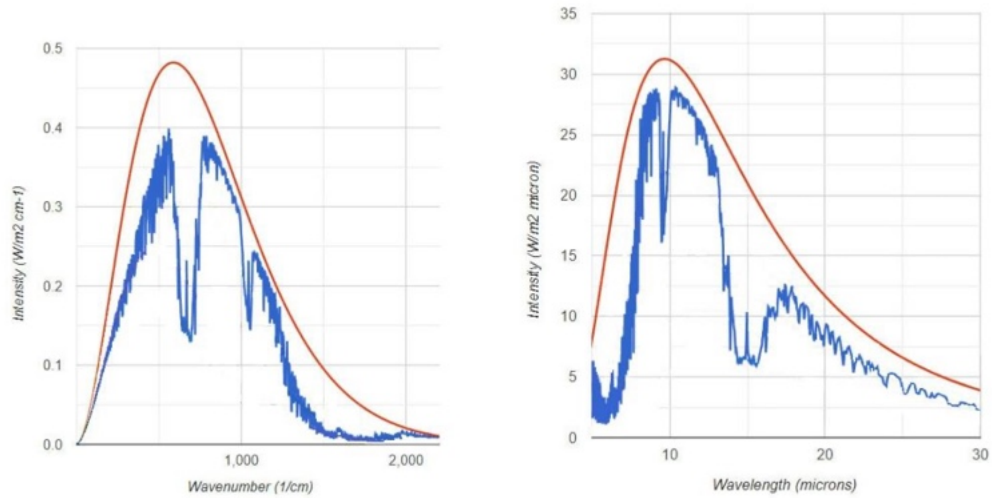


FIGURE 10 – Modtran spectral data using Wavenumber and Wavelength displays. Both of these graphs plot the same intensity data on the vertical axis. Wavenumber is the inverse of wavelength. To convert wavenumber (cm^{-1}) to wavelength (μ), divide 10,000 by the wavenumber.

EFFECT OF GREENHOUSE GAS CONCENTRATION

As discussed earlier in this paper, the presence of so-called "Greenhouse Gases" (often abbreviated to "GHG") in the atmosphere reduces the amount of EM energy that is radiated into space from the earth's surface. The net effect is to increase the total net energy that is absorbed by the surface, thereby increasing the earth's temperature. This additional effective power density at the surface is referred to as "radiative forcing", and is measured in W/m^2. Hitran and Modtran allow the amount of forcing to be determined for various atmospheric conditions and concentrations of GHG.

In December of 2020, highly pertinent paper was published by W.A. van Wijngaarden of York University and W. Happer of Princeton University entitled: "Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases".[11] The researchers used Hitran to predict the effect of various concentrations of Water Vapour, Carbon Dioxide, Ozone, Nitrous Oxide, and Methane in the atmosphere, and then used satellite spectral measurements to confirm the data. Figure 11 below is a simplified version of Figure 4 in their paper, with extraneous information removed. They have used Hitran to look from an altitude of 86 Km at the energy density originating at the earth's surface as a function of Wavenumber (the inverse of wavelength). The blue curve shows a typical black body radiation curve for a body at 288 K in the absence of any atmospheric greenhouse gases. The green curve shows the energy radiated with normal concentrations of all greenhouse gases, but with the CO_2 concentration set to zero. The black curve is the same, but with a 400 ppm CO_2 concentration level. The red curve is the same, but with the CO_2 concentration increased to 800 ppm.

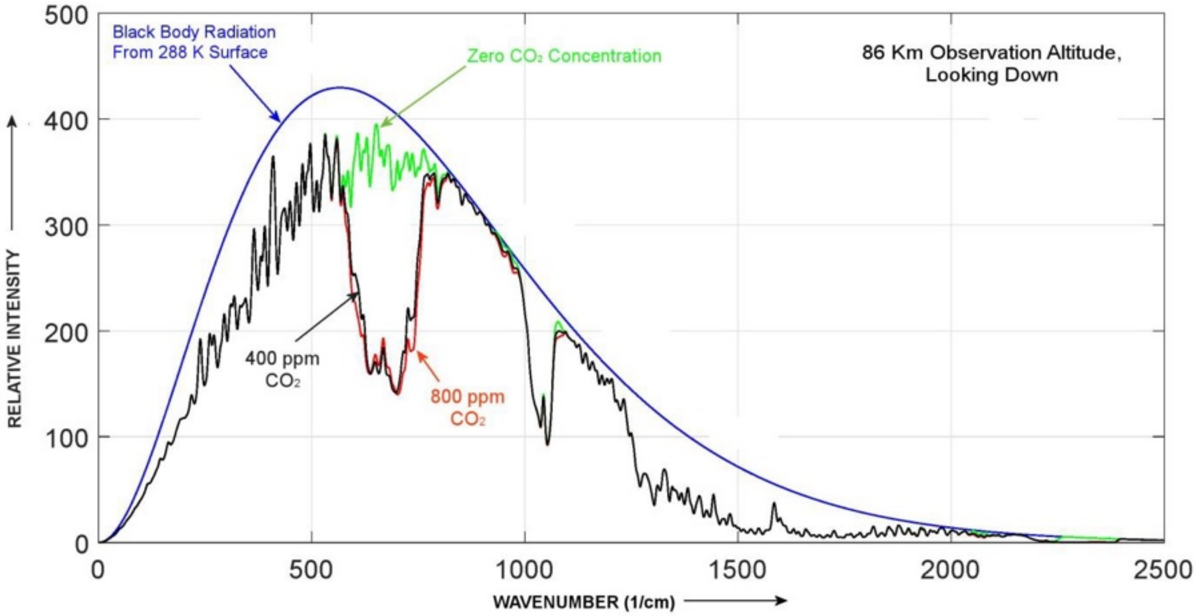


FIGURE 11 – Effect of CO_2 concentration on the upward energy density at the top of the atmosphere. This graphic is a simplified version of Figure 4 from the Wijngaarden and Happer paper, with extraneous information removed. This shows the effect of varying CO_2 concentrations, while other GHG concentrations are kept constant.

In examining Figure 11, look at the "area under the curves". The total area under the blue curve indicates the energy density being radiated from the surface of the earth in the absence of any greenhouse gases. The area under the green curve shows the effect of adding normal concentrations of H_2O, CH_4, O_3, and N_2O to the atmosphere, but no CO_2. The black curve adds 400 ppm of CO_2, which is approximately what the normal concentration in the atmosphere was in 2021. The red curve shows the effect of doubling the CO_2 concentration to 800 ppm. It can be seen that the forcing effect of incremental increases to CO_2 concentration is much less at higher concentrations, and this is consistent with the logarithmic effect predicted by the Beer-Lambert Law. The Wijngaarden and Happer paper determined that the difference in area under the red curve compared to the area under the black curve, which corresponds to a doubling of CO_2 concentration was a "forcing" of 3.0 Watts/m^2.

The Wijngaarden and Happer paper included similar analysis for the other greenhouse gases. In each case, all concentrations were held constant, except the gas being examined. The researchers determined that the radiative forcings resulting from a doubling of the "normal" concentrations were as follows:

H_20	8.1 W/m^2
CO_2	3.0 W/m^2
O_3	2.5 W/m^2
N_2O	1.1 W/m^2
CH_4	0.7 W/m^2

TABLE 1 – Radiative Forcings caused by a doubling of specific greenhouse gases in the atmosphere

The temperature effect of these radiative forcings due to a doubling of concentration is not straightforward, as it needs to include feedback effects and the change in vertical temperature profile in the atmosphere in order to restore "radiative-convective equilibrium". This is discussed at length in the Wijngaarden and Happer paper, where it is calculated that a doubling of CO_2 concentration (resulting in a 3.0 W/m^2 increase of radiative forcing) will result in an increase in the earth's surface temperature of 1.4 to 2.3 degrees C, depending on the water vapour profile. As mentioned, the paper's authors used the sophisticated computer tool and database known as "Hitran" for their research. It is also possible to use a simple tool like the freely available and easy-to-use (but less sophisticated) program known as "Modtran", and achieve results that agree within about 10% of Wijngaarden and Happer's numbers.

In order to explore the sensitivity of radiative forcing to the atmospheric concentration of CO_2, Modtran was used to plot changes in upward IR heat flux from the earth's surface as the concentration was varied. All other concentrations and program parameters were left at their default values. What was calculated was the upward infrared energy flux from the earth's surface, looking down from an altitude of 70 Km. The computed results from Modtran were "normalized" to a reference value that coincides with the flux associated with a CO_2 concentration of 425 ppmv., and the results are plotted in Figure 12.

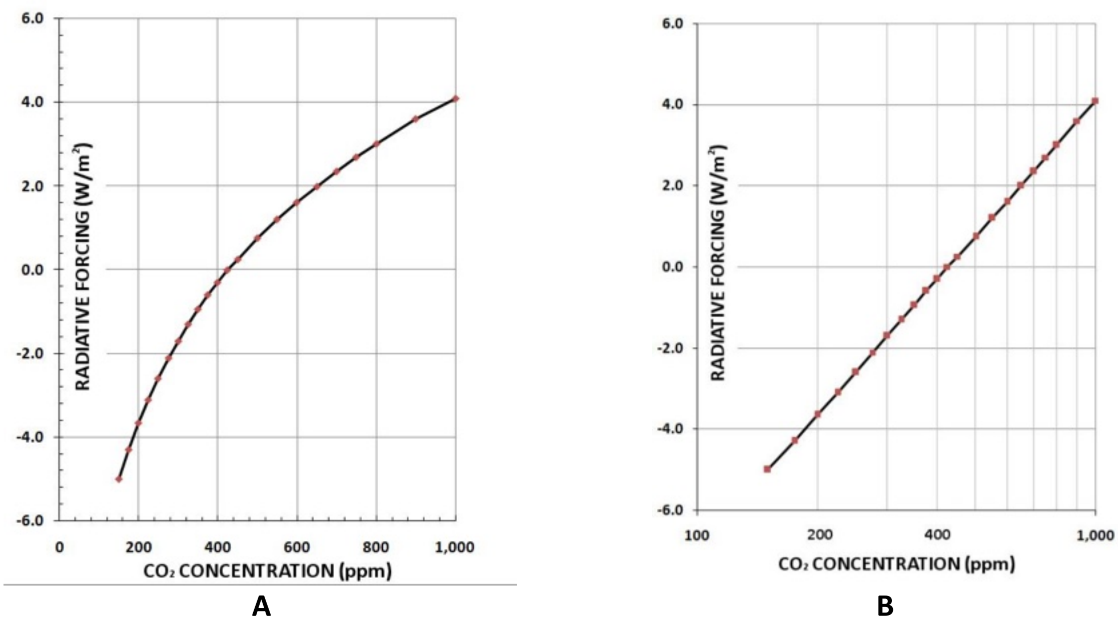


FIGURE 12 – Radiative Forcing as a function of CO_2 concentration in the atmosphere

The same data is plotted in both graphs, using either a linear CO_2 concentration scale (panel A), or a logarithmic scale (panel B). This illustrates the logarithmic response to concentration changes, as predicted by the Beers-Lambert Law.

Figure 12A is plotted with a linear horizontal axis showing atmospheric CO_2 concentrations of between 150 and 1000 ppmv. Below 150 ppm, vegetation would not be able to survive on the earth, and all the previous assumptions become invalid. The plotted curve clearly indicates the logarithmic effect of CO_2 concentration that is described in the Beers-Lambert Law (sometimes referred to as the "Saturation Effect"). This is reaffirmed in Figure 12B, which plots the same data using a semi-log graph.

Using the data that is plotted in Figure 12, we can look at the slope of the curve about the CO_2 concentration values of 425 ppmv (roughly equal to today's ambient value), and observe that the effect of small changes to the concentration is approximately equal to 20 milliwatts/m^2 for each ppm of additional CO_2 concentration in the atmosphere. Using the same argument and assumptions as used in the Wijngaarden and Happer paper, this will result in a global temperature increase of 9 to 15 millidegrees C for each ppm of additional CO_2 concentration in the atmosphere, depending on the water vapour profile Both of these approximations are useful in analyzing various future scenarios, so they are highlighted below:

Sensitivity to changes in atmospheric CO_2 concentration from a starting value of 425 ppm:

Radiative Sensitivity: ~ 20 mW/m^2 per ppm change in atmospheric CO_2 concentration

Temperature Sensitivity: ~ 9 to 15 mdeg C per ppm change in atmospheric CO_2 concentration

Note – these are approximations only, and are intended to evaluate the effect of small changes to the atmospheric CO_2 concentration about nominal values of 425 ppm.

As a useful "rule of thumb" for evaluating the effect of various proposed programs, the approximation can be stated in a different manner, as presented in the red box below:

The earth's temperature increases by between 9 and 15 thousandths of a degree C for every 1 ppm increase in the atmospheric CO_2 concentration (*depending on the amount and distribution of water vapour*).

In 2022, an important paper was published by Kubicki et al of the Military University of Technology in Poland that was entitled: "Climatic Consequences Of The Process Of Saturation Of Radiation Absorption In Gases". [12] This comprehensive paper reviews many other publications, articles, and experimental reports, focussing on the absorbance characteristics of varying concentration levels of atmospheric CO_2, and the possible climatic effects of further increases beyond the current level (about 425 ppm). The authors make a compelling case for stating that current concentration levels of CO_2 in the atmosphere are saturated (from an IR absorbance standpoint), and further build-up of CO_2 will have negligible climatic effect. This is a more extreme view than the commonly-accepted absorbance model that is based on the Beer-Lambert exponential attenuation relationship: further study is clearly warranted in this area!

CARBON DIOXIDE

Carbon Dioxide (CO_2) is just one of the five major greenhouse gases. It is the second most abundant greenhouse gas, as illustrated in Figure 13. It is the component that receives most of the publicity (usually negative), and that governments are trying to control through legislation.

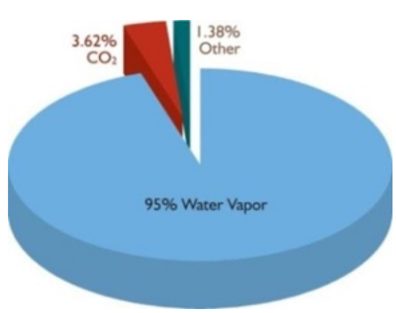


FIGURE 13 – Major Greenhouse Gases

The current concentration of atmospheric CO_2 is approximately 410 parts per million (ppm) by volume. It has been much higher in the past during the Jurassic and Cambrian periods (before the K-T event). Since the K-T Event, the concentration slowly declined from about 1500 ppm to about 250 to 300 ppm during the cyclic ice ages, and started increasing again a few hundred years ago. The concentration has reached just over 410 ppm in 2023. The current rate of rise is slightly over 2 ppm per year.

In March of 2021, a paper appeared in the "Annual Review Of Earth And Planetary Sciences" journal which was entitled "Atmospheric CO_2 Over The Past 66 Million Years From Marine Archives" [13]. The authors estimated atmospheric CO_2 concentrations by analyzing boron isotopes and alkenones from marine sediments, and compared them to other proxies with good correlation. Figure 14 presents the composite data in a chart that is derived from Figure 8 of the paper.

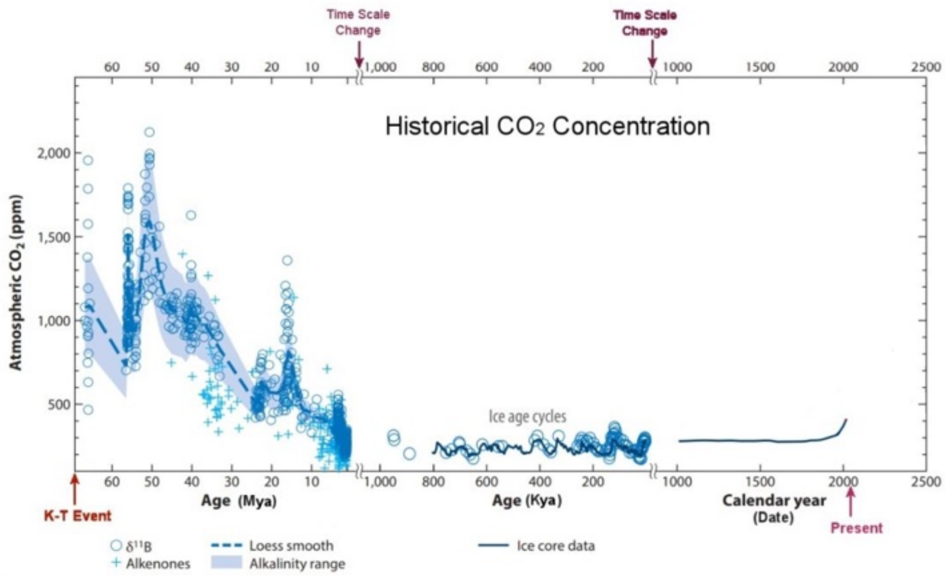


FIGURE 14 – 66 Million Years Of Historical CO_2 Concentration Data From Marine Samples. This chart shows historical CO_2 concentration estimates from marine sediments using Boron Isotopic analysis (circles), Alkenones (crosses), and Ice Core data (straight line). Note the Horizontal time scale changes.

Turning now to more recent times, it is instructive to compare the plots of surface temperature and CO_2 concentration over the past few hundred thousand years, using Antarctic ice core sample data. Figure 15 compares these two parameters.

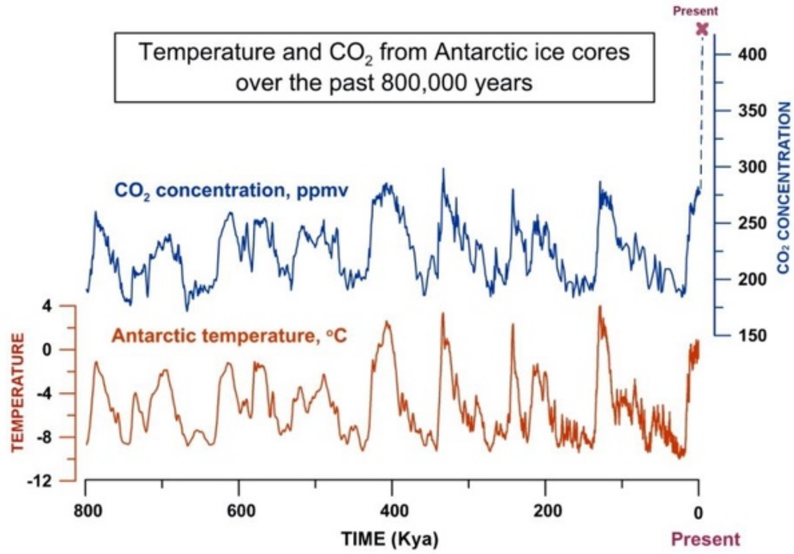


FIGURE 15 – Temperature and CO2 Concentration From Antarctic Ice Cores

The horizontal scale represents thousands of years before the present. This appears to show a very strong correlation, but there is still much debate as to whether or not the temperature changes occur before or after (by several hundred years) changes to the CO_2 concentration. In other words, did changes to the CO_2 concentration cause changes **to** the global temperature, or were the CO_2 concentration changes caused **by** the changing temperature? A closer examination of the data shows that CO_2 concentrations actually start to increase about 800 years **after** temperatures start to rise. It is known that increasing temperatures cause CO_2 outgassing from soil and the oceans, so either hypothesis is possible.

In 1993, the Greenland Ice Sheet Project 2 (GISP2) completed 5 years of coring through the ice, all the way to bedrock. The resulting ice core (3 Km long) was analyzed using isotope ratio techniques to determine the temperature throughout the Holocene. Figure 16 shows the data (plotted as deviations from the average of the period), together with historical CO_2 concentration derived from ice cores taken in Antarctica (EPICA Dome C). There is a remarkable lack of correlation.

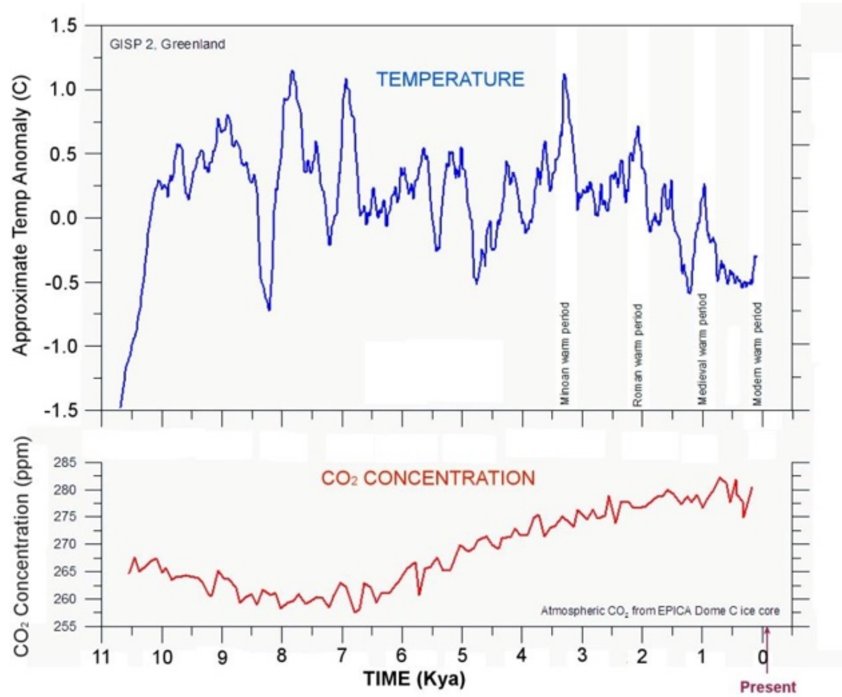


FIGURE 16 – Temperature and CO2 Concentration During the Holocene. Ice cores in Greenland and Antarctica were analyzed to provide this data. There does not appear to be a correlation between temperature and CO2 concentration during this period.

CO_2 is a colourless and odourless gas. It is used by plant life for photosynthesis. If the atmospheric concentration were to fall below about 150 ppm, plant life on earth would cease to exist. Many European greenhouses intentionally artificially increase the CO_2 concentration in order to stimulate the growth of the plants inside. Atmospheric CO_2 is part of the earth's "Carbon Cycle", whereby carbon is transformed between many different forms as part of naturally-occurring cyclical processes. The Carbon Cycle is a complex, much studied, but poorly understood process. Note that popular literature often talks about "Carbon" (a solid) when they are actually referring to CO_2 (a gas). Carbon is the sixth element in the periodic table, and the total number of Carbon atoms in, on, and around the earth is fixed (in the absence of nuclear reactions). Although the number of Carbon atoms is fixed, it can exist in combination with other elements to create the various forms that we are familiar with (vegetation, animal and human life forms, calcites, diamonds, hydrates, fossil fuels, Methane, CO_2, etc). A greatly simplified illustration of the carbon cycle is shown in Figure 17.

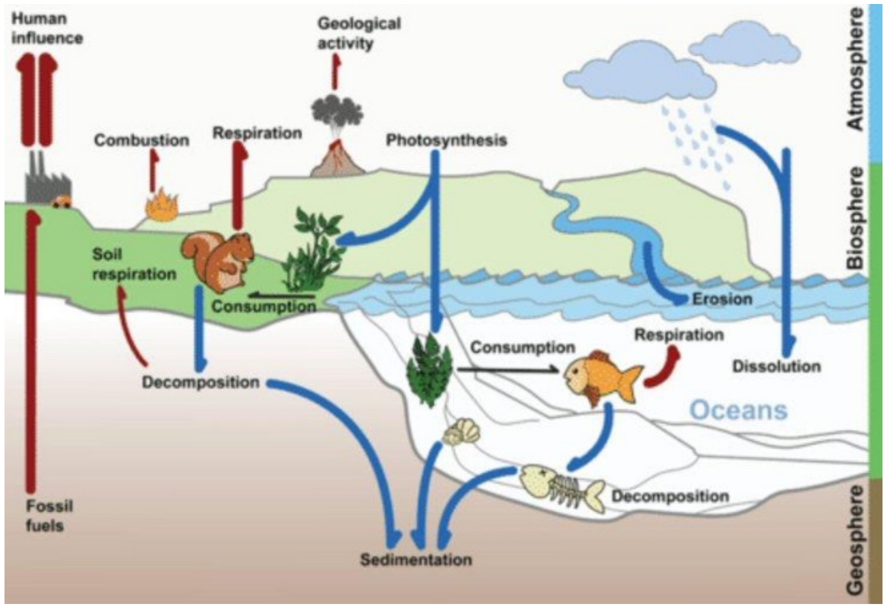


FIGURE 17 – The Carbon Cycle. In looking at this diagram, it is important to recognize that the amount of carbon remains constant, but it is just manifesting itself in different forms in a continuous, cyclic process.

Many human activities result in the release of CO_2 into the atmosphere.[14] The dominant ones are those involving the combustion of fossil fuels. Typical sources are heating, internal combustion engines, external combustion engines (thermal power plants), cement production, and industrial processes. There are also many natural mechanisms that release CO_2 into the atmosphere: the decay of organic material, respiration, dissolution, calcification, outgassing, fires, volcanoes, etc. CO_2 is taken out of the atmosphere by other natural "sink" phenomena: photosynthesis and absorption into water being the major mechanisms. The current estimates are that 4 to 5 percent of the current atmospheric CO_2 is due to human activities. This implies that the atmosphere contains 16 to 21 parts per million of man-made CO_2.

There have been many studies to estimate the emissions of anthropogenic CO_2 by sector, and its disposition amongst various “sinks”. One exceptionally detailed study was published by Earth System Science Data in 2022, entitled “Global Carbon Budget 2022”.[15] Figure 18 is an illustration taken directly from Figure 3 of the paper.

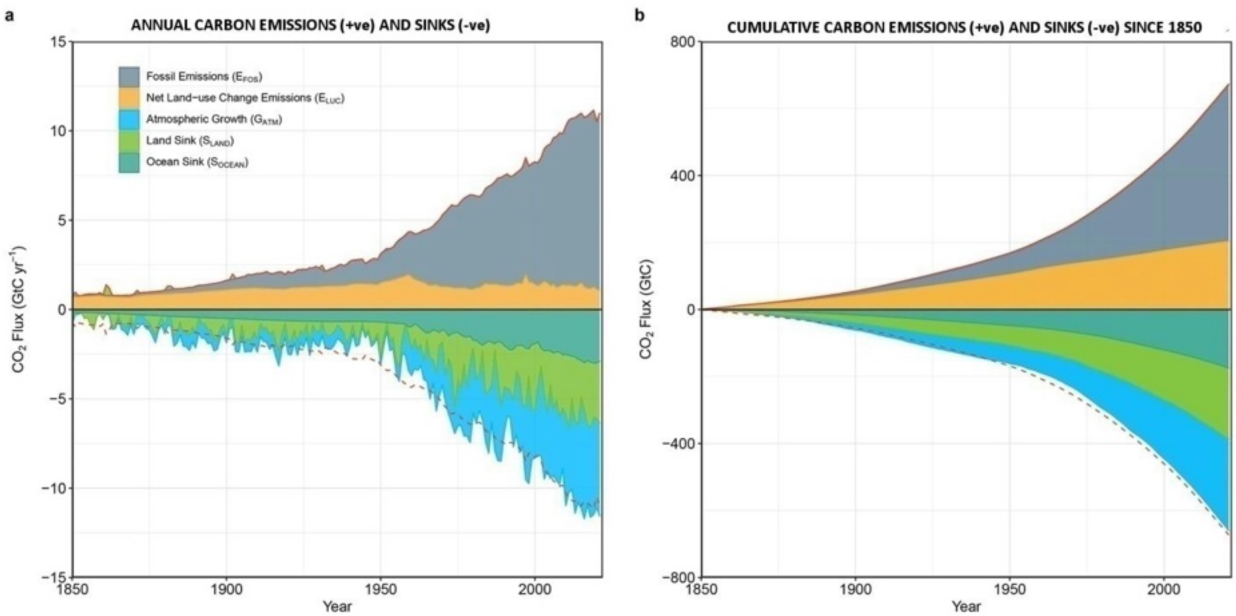


FIGURE 18 – The Global Carbon Budget. The left figure shows global annual anthropogenic emissions (above the horizontal axis), and corresponding sinks (below the line). The right figure shows cumulative data since 1850. Note that these are plotting Gigatonnes of Carbon. To convert to Gigatonnes of CO_2, multiply by 3.66. To convert Gigatonnes of Carbon to equivalent ppmv of CO_2, multiply by 2.12. The dotted red line below the horizontal axis reflects the inverse of the summation above the line. The fact that the dotted line does not exactly line up with the bottom of the blue area is an artefact of the multiple data sources that were used.

Note that Figure 18 is plotting the mass flux of carbon. Multiply by 3.7 to get the equivalent values of CO_2 mass. This is a confusing state of affairs, and results in the media stating that "we have to take the carbon out of the atmosphere", despite the fact that carbon is a solid and CO_2 is a gas! Figure 18 is drawn so that the total area below the horizontal axis is the same as the area above the axis: the blue "Atmosphere Growth" is defined in such a way to make the balance equal zero. In other words, the total area of the blue is indicative of the amount of anthropogenic CO_2 in the atmosphere.

There are many sources of anthropogenic CO_2. Here is a breakdown of the main contributing sectors, as outlined by Hannah Ritchie and Max Roser in a summary entitled "Greenhouse Gas Emissions"[16]. These are global numbers, for the year 2016:

Energy Production For Transport:	*Road (cars, trucks)*	11.9%
	Aviation	1.9%
	Ships	1.7%
	Rail and pipeline	0.7%
Energy Production for Industry		24.2%
Energy Production for Buildings		17.5%
Energy Production (other)		15.3%
Industrial Processes (concrete, chemicals)		5.2%
Waste (landfills, wastewater)		3.2%
Agriculture, Forestry, and Land Use		18.4%