Climate Change Information Brief

Radiation Transfer

Introduction

Atmospheric concentrations of carbon dioxide, methane, nitrous oxide and other greenhouse gases are slowly increasing. Some say this will soon cause runaway global warming of Earth's surface. Few realize how little scientific support there is for this concern. In fact, more carbon dioxide (CO_2) has already contributed to greater yields of agriculture and forests, and still more carbon dioxide will bring more benefits. This brief note discusses the "prime mover" of climate alarmism the modification of radiation transfer by greenhouse gases.

Life on our beautiful planet is made possible by sunlight, which both warms the Earth's surface and allows photosynthetic organisms, ranging from cultivated crops to plankton in the oceans, to convert carbon dioxide and water molecules (H_2O) into sugars and other basic molecules of life.

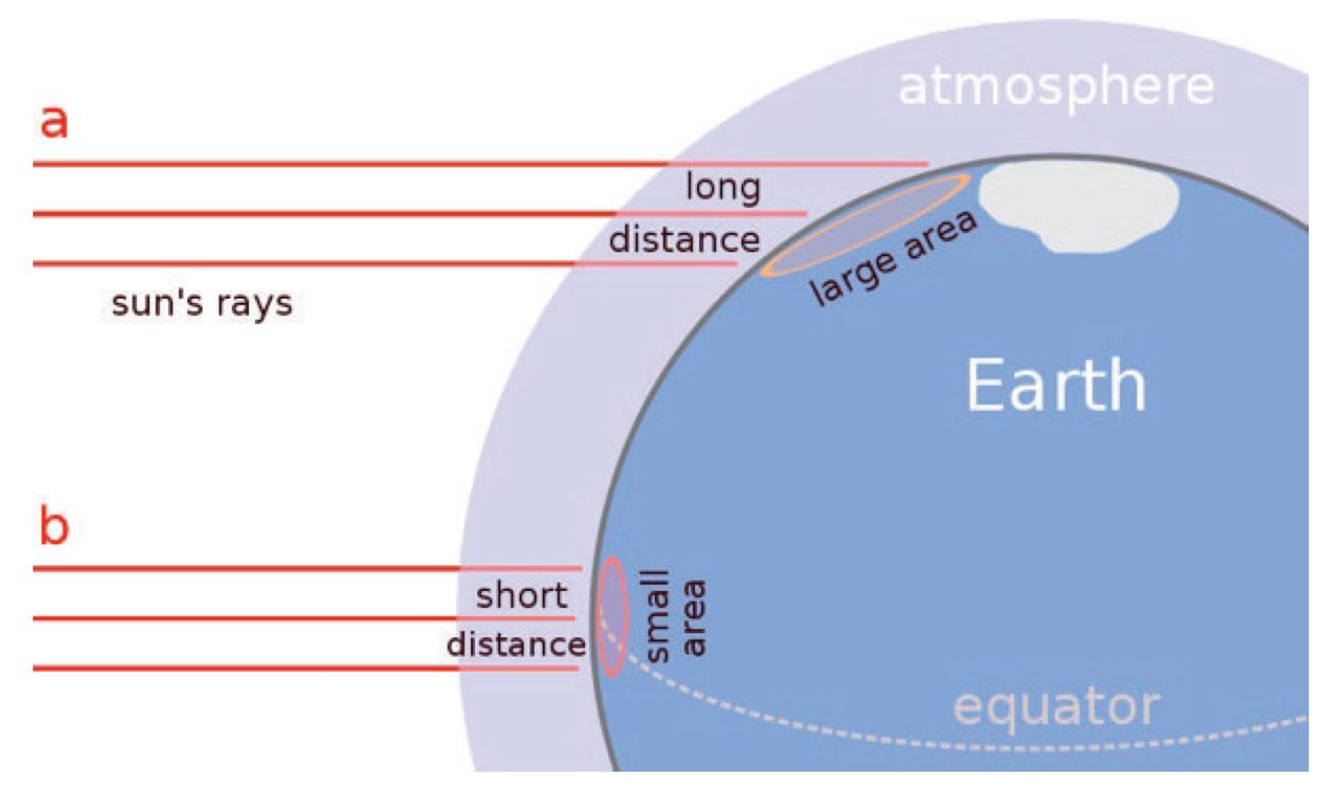
Electromagnetic Radiation

At the mean distance of Earth from the Sun, sunlight carries an energy flux of about 1,360 Watts per square meter (Wm^{-2}). We are familiar with this flux, part of which warms us when we sunbathe at the beach on a cloud-free summer day. The flux at the top of Earth's atmosphere varies a little bit over the year, since Earth's orbit around the Sun is slightly elliptical. Earth is about 3.3% closer to the Sun in early January than in early July. Since solar flux decreases as the square of the distance from the Sun, the solar flux at the top of the atmosphere is about 6.7% or 91 Wm^{-2} greater in January than in July. As we will discuss in more detail below, for cloud-free temperate latitudes, doubling the concentration of carbon dioxide would decrease thermal radiation to space by about 3 Wm^{-2}.

To tell whether we really have a climate emergency (we don't) numbers are more important than rhetoric and emotion. The representative decrease of clear-sky thermal radiation to space from doubling carbon dioxide concentrations, 3 Wm^{-2}, is an important number to remember. Other important numbers are the mean solar flux, 1360 Wm^{-2} or the 91 Wm^{-2} change in this flux from summer to winter. If 3 Wm^{-2} sounds small in comparison, it is indeed very small. Great efforts are needed to concoct a "scientific" argument that 3 Wm^{-2} is worth worrying about.

Any doubling of carbon dioxide concentrations will produce the same 3 Wm^{-2} decrease of flux to space whether we consider doubling the pre-industrial value of 280 parts per million (ppm) to 560 ppm, which could happen by about the year 2100 at the current rate of increase around 2 ppm/year. Doubling the current 410 ppm atmospheric concentration to 820 ppm would take about two centuries.

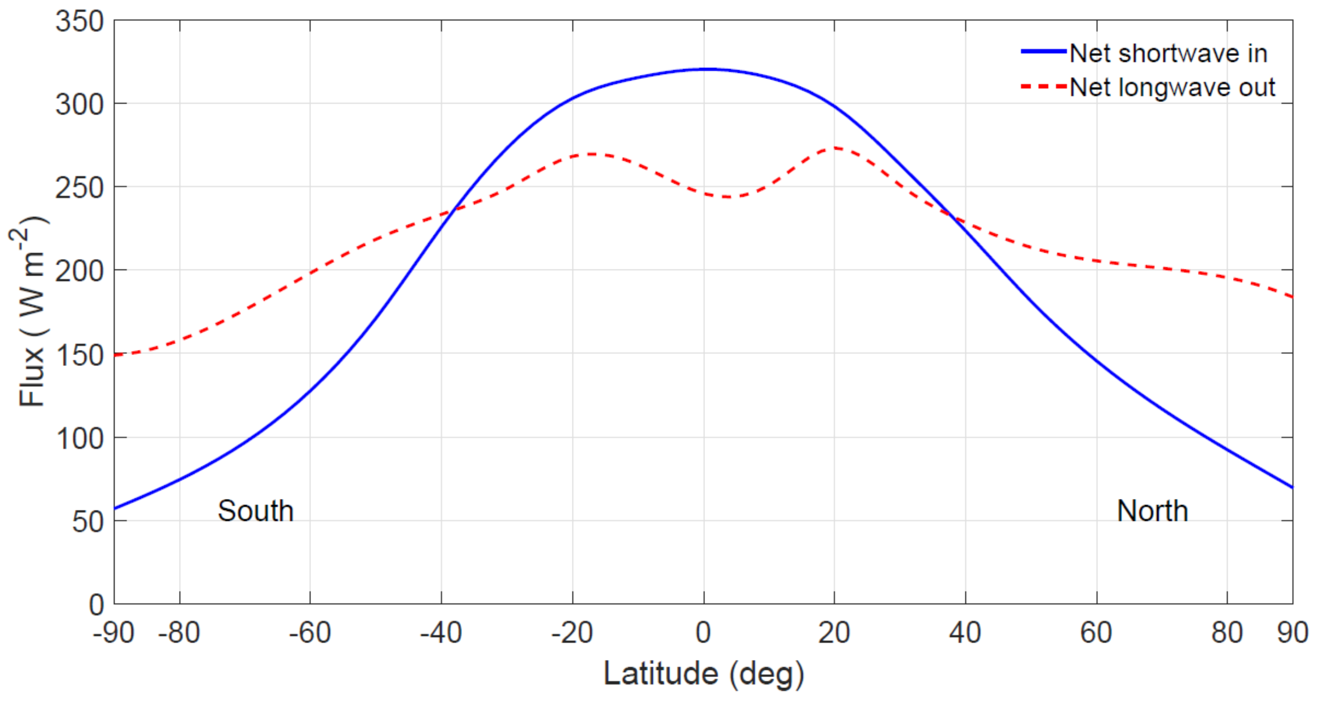
The Earth's surface is heated all day by sunlight, as illustrated by the figure below. The atmospheric thickness is greatly exaggerated in the figure. At typical temperate latitudes, some 99% of the mass of the atmosphere is below an altitude of about 20 miles (31 km). The radius of the Earth is about 4000 miles (6400 km) so 20 miles is only about 0.5% of the Earth's radius. The atmosphere is a very thin skin, more like the skin of an apple than the thick blanket one might imagine from looking at the figure below.



During daylight hours, the Sun heats the Earth. The heating rate is proportional to $\cos\theta$, where θ is the angle between the sunlight and the local vertical axis. The heating rate maximizes when the Sun is directly overhead and $\theta = 0$, for example, at noon on the Equator during the spring or fall equinoxes. On average, much less sunlight occurs near the poles, because the Sun spends much of its time just above the horizon, where $\cos\theta$ is almost zero, or below the horizon during the long polar winter. But on a mid-summer day, the North Pole receives more sunlight in 24 hours than any other location on Earth, at any time of the year.

Despite its thinness, the Earth's atmosphere, together with the oceans that cover about 70% of the Earth's surface, have a very large effect on how the heat from the Sun returns to space. This is because the atmosphere and the oceans transport heat very efficiently by convection from equatorial regions, where the yearly-averaged solar heating is maximum, to the poles where there is minimum heating. Like Earth's poles, many homes are convectively heated from a central furnace by warm air blown through heating ducts or by hot water flowing to radiators.

The basic facts of heat convection of Earth are illustrated in the figure below. For equatorial regions, more solar energy flows in than is radiated back to space (the continuous blue curve is above the dashed red curve). For polar regions, much less solar energy flows in than is radiated back to space (the dashed red curve is above the continuous blue curve.) Excess solar energy absorbed in the tropics is transported to the poles by mass flow in the atmosphere and oceans. Both poles are much warmer during their respective winters than they would be without convective transport of heat from the tropics. There is nothing to convect heat into the vacuum of outer space. So solar heat must eventually return to space as thermal radiation. But the heat can be emitted thousands of miles from where it was absorbed.



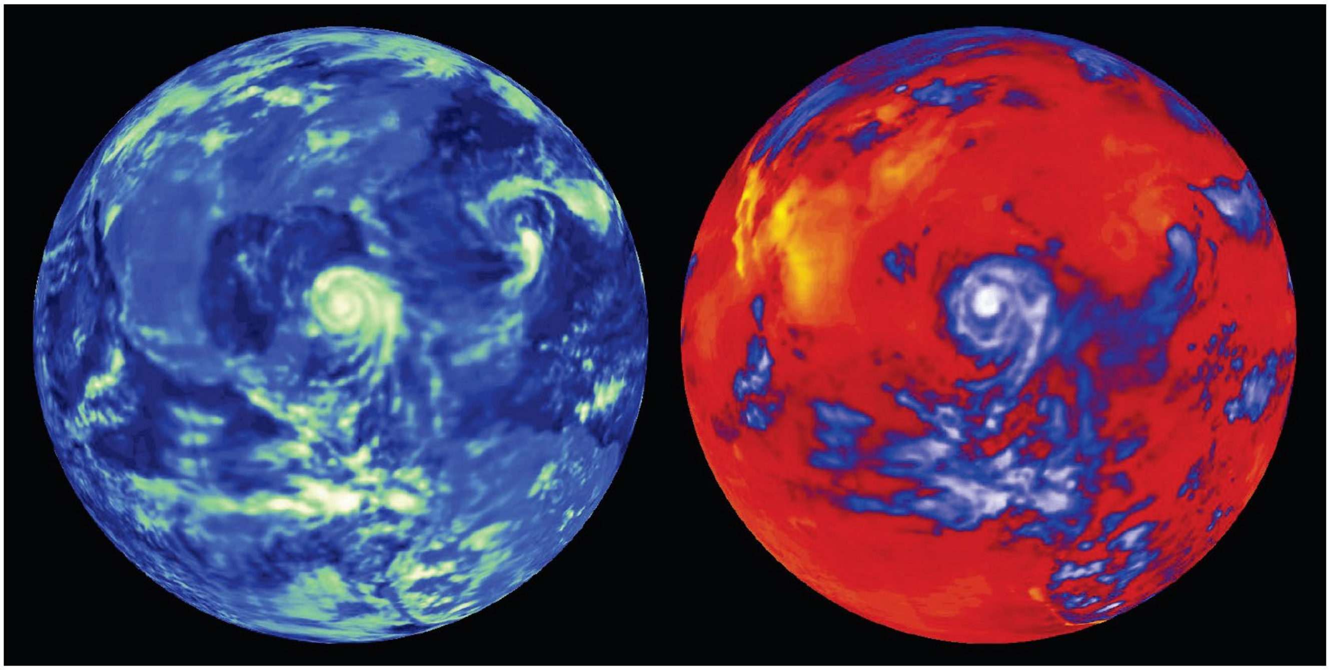
Energy flux (Wm^{-2}) as a function of latitude. The continuous blue curve is the yearly average of incoming short-wave solar radiation (visible, near infrared, and ultraviolet) absorbed by the Earth. The dashed red curve is the yearly average of the outgoing thermal radiation (longwave infrared) released to space by the Earth. The data are from satellite observations[1]. Figure adapted from PhysicalGeography.net[2].

How much thermal radiation is released to space at some latitude and longitude of the Earth's surface is determined by the temperature that area appears to have when observed from space. But what is that temperature? For temperate latitudes, the temperature drops steadily from about 59°F (15°C) at the surface to -58°F (-50°C) at the tropopause, an altitude of about 6.9 miles (11 km). This is the boundary between the convecting air of the lower atmosphere and the nearly stable air of the stratosphere above. Jet planes like to fly near the tropopause to avoid the turbulence of the lower atmosphere. The atmospheric temperature increases with altitude above the tropopause because of the absorption of ultraviolet sunlight by the ozone layer at altitudes of 19 to 25 miles (30 to 40 km).

The emission rate of thermal radiation by cloud tops or by land and ocean surfaces is proportional to T^4, the fourth power of the absolute temperature T. As we discuss below, the emission of thermal radiation to space is more complicated and more affected by greenhouse gases in cloud-free areas of the Earth. Thermal emission, the dashed red line of the previous figure, has a minimum at the Equator, where the solar heating is a maximum. This is because, on average, more cloud cover exists close to the Equator than 20° to 30° north or south latitude, at what sailors used to call the "horse latitudes". Here, cloud formation is suppressed by subsiding, dry air that was driven to high altitudes near the Equator by intense solar heating. Much of the moisture of the rising air is lost to rainfall. The high, cold cloud tops near the equator release less thermal energy to space than the warm land and sea surfaces and cloud-free air of the horse latitudes.

Data from NASA's "Clouds and the Earth's Radiant Energy System" or CERES[3] can provide valuable insight into heat transport by Earth's atmosphere. An example is seen in the figure on the next page which shows two images from a CERES satellite centered over the Gulf of Mexico. The visible image on left is close to true color. It shows a faint outline of the North and South American continents, and part of the Atlantic and Pacific Oceans. A hurricane is situated in the middle of the Gulf and its spiral white cloud tops are clearly visible.

On the right of the figure on the next page is an image the same area with thermal infrared detectors. Here, red colors denote more thermal infrared, blue colors for less, and white colors for almost none. The cloud tops in the center of the hurricane, and the "deep convection" clouds in the eastern Pacific Ocean are at very high altitudes, close to the tropopause, where the temperatures are -58°F (-50°C) or less. Very little thermal infrared radiation is emitted by such cold clouds. Lower, slightly warmer cloud tops emit more infrared and are colored in blue. The red regions either are cloud-free areas where the warm sea or land surface can be seen by the satellite, or they are areas of low stratus clouds, with relatively warm cloud tops. Much more thermal energy is emitted to space from these regions.



Images of the Earth over the Gulf of Mexico taken simultaneously by CERES satellite instruments with visible sunlight (left) and with longwave thermal infrared light (right). Much sunlight is reflected from high spiral clouds of the hurricane in the Gulf and from the “deep convection” clouds of the eastern Pacific Ocean. For the thermal image on the right, red colors denote high intensity radiation, blue for low intensity radiation, and white for almost no radiation. The high clouds emit very little thermal infrared light since they are so cold, typically -58°F (-50°C) or less. The cloud-free areas of the oceans and land are very warm and emit intense thermal radiation.

Frequencies of Thermal Radiation

For cloud-free regions of the Earth (on average, about half of the Earth’s surface) the emission of radiation to space is especially complicated since the radiation comes from various altitudes, ranging from zero altitude, the surface, for “infrared windows,” to high in the stratosphere for emission frequencies in the absorption bands of the greenhouse molecules carbon dioxide or ozone (O_3). The “frequency” of thermal radiation is often given as a spatial frequency, cm^{-1}. This is the number of peaks you would count per cm, along the direction of propagation, if you could take a “snapshot” of the wave.

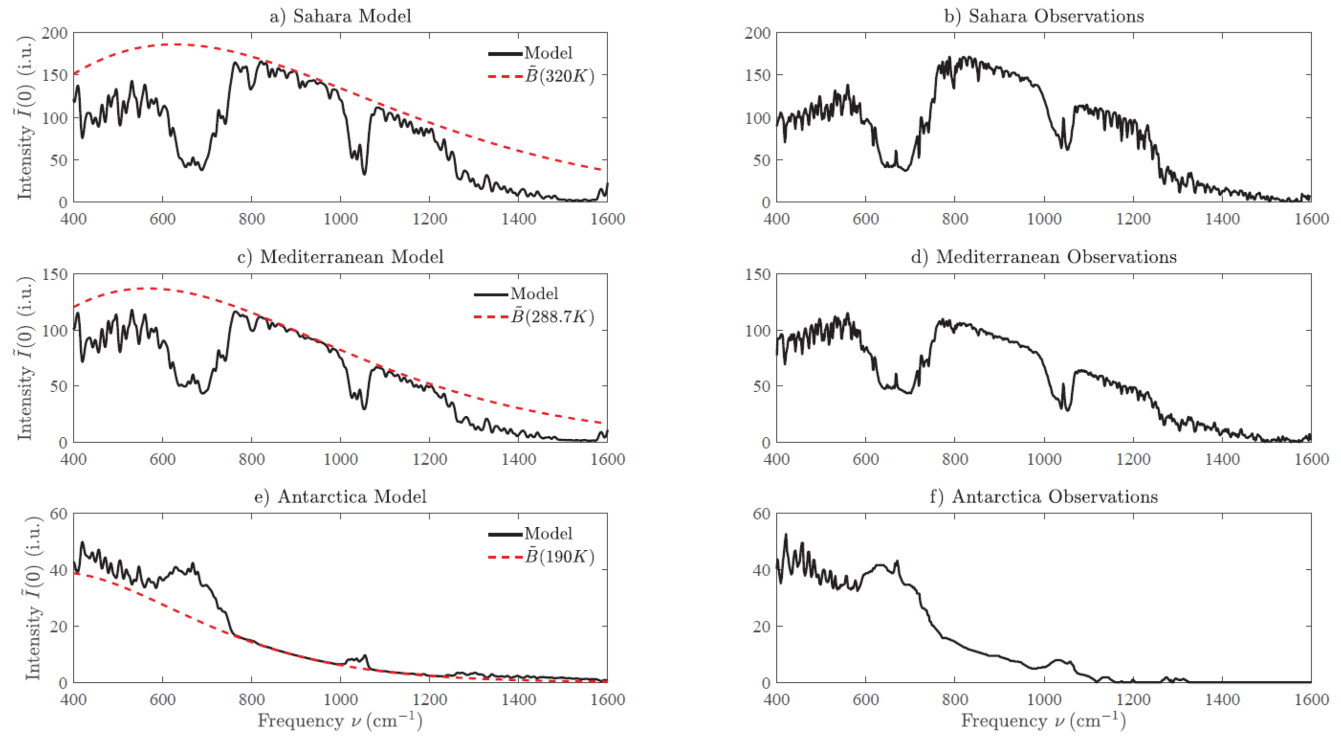
The greenhouse molecules of Earth’s atmosphere absorb and emit radiation at characteristic frequencies, much like soprano violins emit high acoustic frequencies, violas emit lower frequencies and string basses emit very low frequencies. Clear air absorbs and emits much like an orchestra of greenhouse molecules. Water molecules are both the string basses and the soprano violins of the atmosphere. Water dominates atmospheric opacity for very low and very high thermal radiation frequencies while carbon dioxide molecules are like violins, absorbing and emitting thermal radiation at intermediate frequencies.

Since water molecules in cold air can condense to form rain or snow, the concentration of water molecules is much smaller in the stratosphere than in the troposphere. Stratospheric air is “dehumidified” by the cold tropopause. Most the absorption and emission of water vapor occurs in the relatively warm lower atmosphere. Carbon dioxide molecules, which cannot condense in Earth’s atmosphere, have nearly the same concentration in the stratosphere as in the troposphere. Most carbon dioxide emissions to space originates from the lower stratosphere.

Some examples of the “symphony” of greenhouse gas frequencies observed from space is shown in the figure on the next page. The graphs on the right show the intensity of upward radiation measured at three different latitudes, over the Mediterranean, over the Sahara Desert, and over Antarctica. The graphs on the left are intensities modelled with the Schwarzschild equation, the $E = mc^2$ of radiation transfer. It is interesting to note the Karl Schwarzschild found one of the first solutions to Einstein’s general theory of relativity. As one can see from the figure, the modeled intensities agree very well with observed intensities at all three latitudes. For the modelled intensities, the dashed red line shows the Planck intensity that would be observed if the Earth’s surface had the same temperature but there were no greenhouse gases. The difference between the jagged black curves of the Schwarzschild equation and red curve is the amount by which the current concentration of greenhouse gases in Earth’s atmosphere has decreased the radiation to space, compared to no greenhouse gases at all.

The Effect of Greenhouse Gases

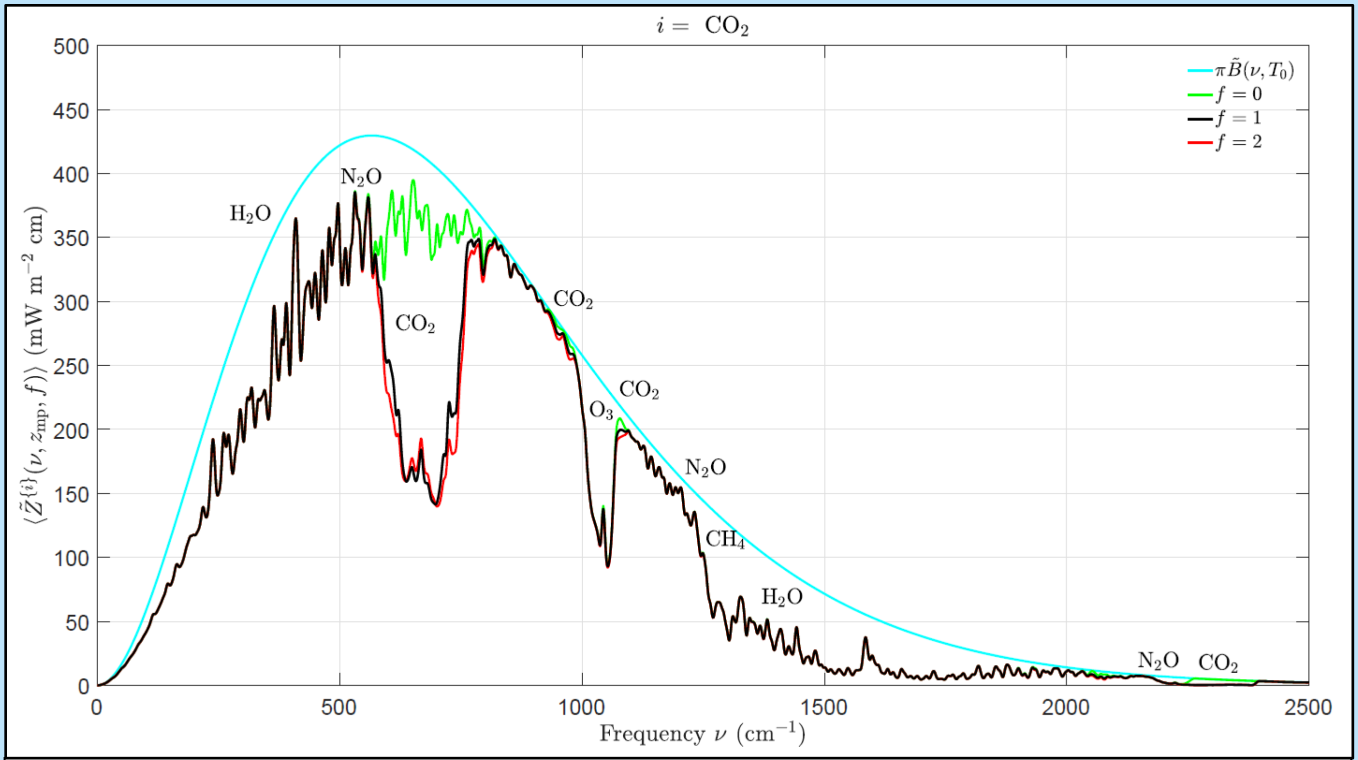
From this figure, one can see that for the Mediterranean and the Sahara, greenhouse gases substantially decrease the radiation to space. Quantitatively, one finds that for temperate latitudes, greenhouse gases decrease the radiation flux to space by a factor of about 0.70. Because of the T^4 law for thermal emission by black surfaces, one could get the same decrease of flux by removing all greenhouse gases and decreasing the temperature from $T = 59°\text{F}$ (15°C) to $(T - \Delta T)$, where the temperature decrease, ΔT, is defined by $\left(T - \frac{\Delta T}{T}\right)^4 = 0.70$. The equation can be readily solved to find $\Delta T = 45°\text{F}$ (25°C). This simple example illustrates how important greenhouse gases are for life on Earth. The surface temperature with no greenhouse gases would be 14°F (-10°C), well below the freezing point of water. Without greenhouse gases, Earth would be a lifeless snowball with all water frozen.



Thermal radiation intensities at the top of the atmosphere observed with a Michaelson interferometer in a satellite[4] (right) and theoretically modelled intensities[5] (left). Three latitudes are shown: The Sahara Desert, the Mediterranean Sea, and Antarctica. The intensity unit is 1 i.u. = 1 mW m^{-2} cm sr^{-1}. Radiative forcing is negative over wintertime Antarctica since the relatively warm greenhouse gases in the troposphere – mostly carbon dioxide, ozone, and water – radiate more to space than the cold ice surface, at a temperature of $T = -117.4$°F (-83°C), could radiate through a transparent atmosphere.

As one can see from this figure, the observed thermal radiation intensity from the Earth can hardly be distinguished from that modeled with the Schwarzschild equation. So, one would naturally wonder how much change in the thermal radiation flux to space would be predicted by the same Schwarzschild equation if the concentrations of carbon dioxide and other greenhouse gases are doubled. One might think doubling carbon dioxide would have a rather large effect, since this figure shows that the current concentration of carbon dioxide, which causes the gap in the spectrum centered about 667 cm^{-1} to absorb about 30 Wm^{-2} of the flux that would reach space if there were no carbon dioxide.

The answer to this question is shown in the following figure. Here, the smooth cyan curve is the radiation that would reach space from the Earth's surface, at a temperature of 59.9°F (15.5°C), if there were no greenhouse gases at all. This Planck flux a factor of π times larger than the vertical Planck intensities shown in the previous figure, since the flux includes the intensity from all upward directions, not simply vertically up as in the previous figure. The black jagged curve is the predicted Schwarzschild flux to space for current concentrations of all the important greenhouse gases, assuming 400 ppm of carbon dioxide. The red jagged curve is the Schwarzschild flux to space if carbon dioxide concentrations are doubled to 800 ppm. The red curve is indistinguishable from the black curve except in the carbon dioxide band, where the red curve is below the black one at the band edges (due to the changed carbon dioxide emission in the troposphere), but above the black curve in the center of the band (due to the increased carbon dioxide emissions in upper stratosphere). The net is a reduction of radiation to space of S = 3 Wm^{-2}, where S is the flux increment due to doubling of carbon dioxide concentrations (the flux sensitivity). The first 400 ppm of carbon dioxide added to the atmosphere decreases the radiation flux to space by about 30 Wm^{-2}. Adding an equal 400 ppm of carbon dioxide to get a concentration of 800 ppm only decreases the flux by 3 Wm^{-2}. Because of the radiative properties of the carbon dioxide molecule, if the carbon dioxide concentration is increased from $C1$ to $C2$, the flux to space will change from $F1$ to $F2$ where $(F1 - F2) = S \log_2(C2/C1)$. Thus, adding yet another 400 ppm of carbon dioxide to the atmosphere, to increase the total concentrations from $C1$ = 800 ppm to $C2$ = 1200 ppm, would decrease the flux to space by $S \log_2(1200/900)$ = 1.75 Wm^{-2}.



The spectral forcing at current levels of carbon dioxide, CO2 (the black curve with $f = 1$), or if concentrations of carbon dioxide are doubled (the red curve with $f = 2$), or if all carbon dioxide is removed (the green curve with $f = 0$).

Conclusion

In summary, the figure above shows that the flux changes from doubling the concentrations of greenhouse gases, a very substantial change, reduces the radiation to space by only a few Wm^{-2}. This is only a few per cent of the several hundred Wm^{-2} in the natural flux to space, or the 91 Wm^{-2} change of solar flux between winter and summer. And cloud cover, like that shown in the figure on page 5 (*i.e.*, the images of the Earth over the Gulf of Mexico), further diminishes the influence of greenhouse gases. It is very hard to convince people with technical common sense that such small changes will have any harmful consequences.

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[1] Dewitte, S., and N. Clerbaux (2017): Measurement of the Earth radiation budget at the top of the atmosphere – A review. *Remote Sensing*, **9**, 1143.

[2] *Radiation Balance: PhysicalGeography.net*. http://www.physicalgeography.net/fundamentals/7j.html

[3] CERES comparison Earth images in visible and long-wave infrared radiation. https://earthobservatory.nasa.gov/images/2645/aqua-ceres-first-light

[4] Hanel, R.A., and B.J. Conrath (1970): Thermal emission spectra of the Earth and atmosphere from the Nimbus 4 Michaelson Interferometer Experiment. *Nature*, **228**, 143-145.

[5] van Wijngaarden, W.A., and W. Happer (2020): Dependence of Earth's thermal radiation on five most abundant greenhouse gases. http://arxiv.org/abs/2006.03098