

## Happer's Statement: CO<sub>2</sub> will be a major benefit to the Earth



<https://thebestschools.org/special/karoly-happer-dialogue-global-warming/happer-major-statement/>

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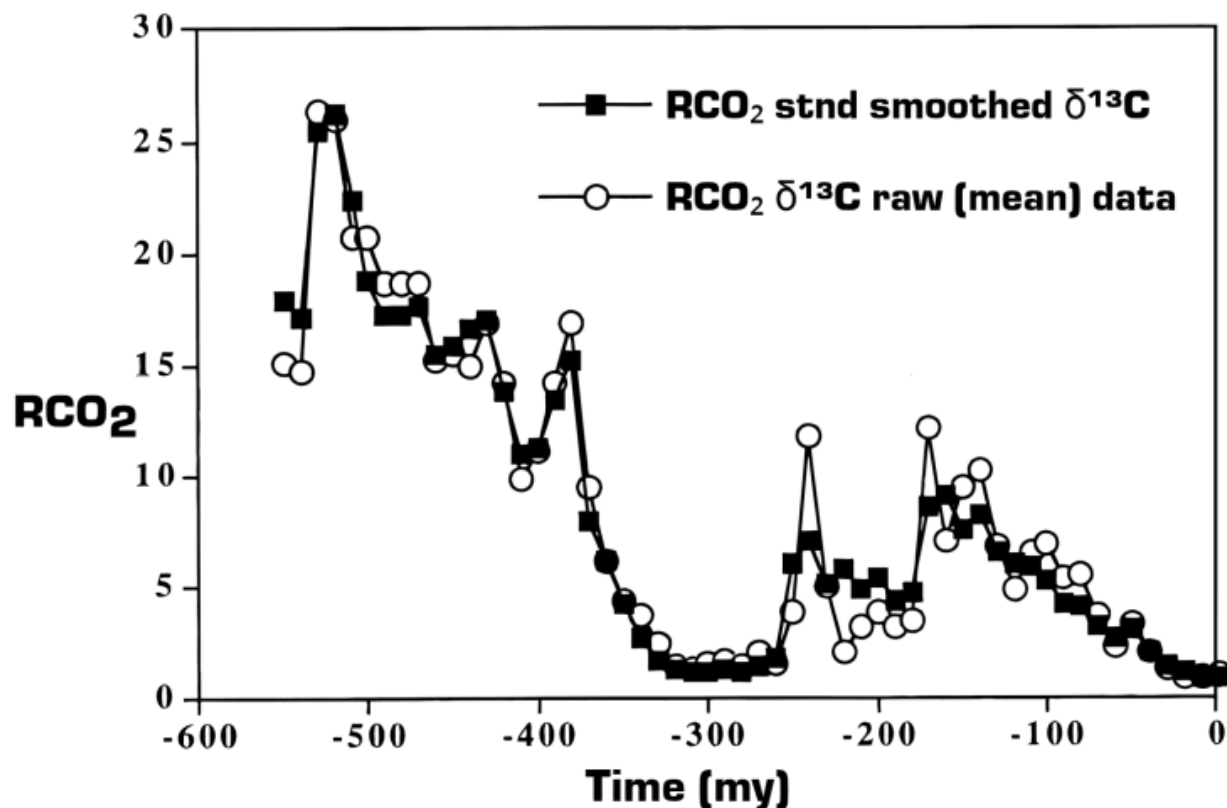
*[Ed. Note: This web page was partially downloaded from the wayback machine. The figures are renumbered. Minor typos are fixed, otherwise it is exactly as originally posted, other than being reformatted to a pdf. Andy May]*

## Introduction

Some people claim that increased levels of atmospheric CO<sub>2</sub> will cause catastrophic global warming, flooding from rising oceans, spreading tropical diseases, ocean acidification, and other horrors. But these frightening scenarios have almost no basis in genuine science. This Statement reviews facts that have persuaded me that more CO<sub>2</sub> will be a major benefit to the Earth.

Numbers are very important for a sensible discussion of climate. So, I have included a few key equations and simple derivations of important results for readers with a technical background. I hope that less technically minded readers will not be put off by the equations. Most of the discussion should be understandable to anyone with an interest in the science of climate. I have also included Internet references for those who would like to dig deeper.

TheBestSchools.org's [Interview](#) of me, to which I will occasionally refer, included Fig. 1. This shows the estimated CO<sub>2</sub> levels during the Phanerozoic eon that began about 550 million years ago with the Cambrian, the first geological period with abundant, well-preserved fossils.



**Figure 1.** The ratio,  $RCO_2$ , of past atmospheric CO<sub>2</sub> concentrations to average values (about 300 ppm) of the past few million years. This particular proxy record comes from analyzing the fraction of the rare stable isotope <sup>13</sup>C to the dominant isotope <sup>12</sup>C in carbonate sediments and paleosols. Other proxies give qualitatively similar results.

The important message of Fig. 1 is that CO<sub>2</sub> concentrations have been much higher than present values over most of the history of life. Even though CO<sub>2</sub> concentrations were measured in thousands of parts per million by volume (ppm) over most of the Phanerozoic, not the few

hundred ppm of today, life flourished in the oceans and on the land. Average pH values in the ocean surface were as low as  $\text{pH} = 7.7$ , a bit lower than the  $\text{pH} = 8.1$  today. But this was still far from acidic,  $\text{pH} < 7$ , because of the enormous natural alkalinity of seawater. The mean global temperature was sometimes higher and sometimes lower than today. But the temperature did not correlate very well with  $\text{CO}_2$  levels. For example, there were ice ages in the Ordovician, some 450 million years ago, when the  $\text{CO}_2$  levels were several thousand ppm.[\[2\]](#)

Discussions of climate today almost always involve fossil fuels. Some people claim that fossil fuels are inherently evil. Quite the contrary, the use of fossil fuels to power modern society gives the average person a standard of living that only the wealthiest could enjoy a few centuries ago. But fossil fuels must be extracted responsibly, minimizing environmental damage from mining and drilling operations, and with due consideration to costs and benefits. Similarly, fossil fuels must be burned responsibly, deploying cost-effective technologies that minimize emissions of real pollutants such as fly ash, carbon monoxide, oxides of sulfur and nitrogen, heavy metals, volatile organic compounds, etc.

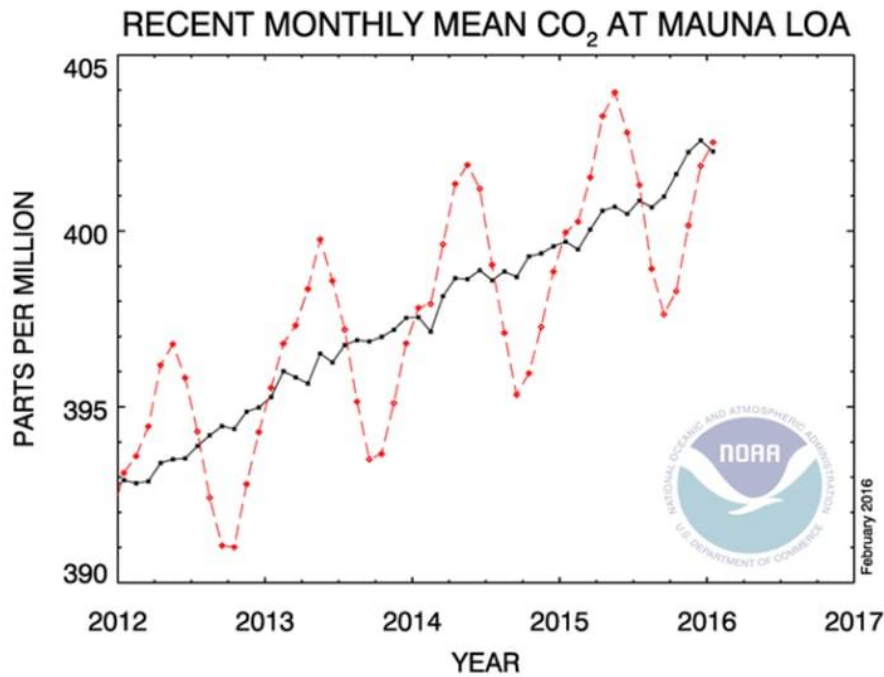
Extremists have conflated these genuine environmental concerns with the emission of  $\text{CO}_2$ , which cannot be economically removed from exhaust gases. Calling  $\text{CO}_2$  a “pollutant” that must be eliminated, with even more zeal than real pollutants, is Orwellian Newspeak.[\[3\]](#) “Buying insurance” against potential climate disasters by forcibly curtailing the use of fossil fuels is like buying “protection” from the mafia. There is nothing to insure against, except the threats of an increasingly totalitarian coalition of politicians, government bureaucrats, crony capitalists, thuggish nongovernmental organizations like Greenpeace, etc.

Fig. 1 summarizes the most important theme of this discussion. It is not true that releasing more  $\text{CO}_2$  into the atmosphere is a dangerous, unprecedented experiment. The Earth has already “experimented” with much higher  $\text{CO}_2$  levels than we have today or that can be produced by the combustion of all economically recoverable fossil fuels.

The thing that hath been, it is that which shall be; and that which is done is that which shall be done: and there is no new thing under the sun.[\[4\]](#)

## **Life on Earth does better with more $\text{CO}_2$ .**

There is no doubt that the concentrations of  $\text{CO}_2$  are increasing. For example, Fig. 2 shows  $\text{CO}_2$  concentrations measured at an altitude of about 3400 meters on the side of the volcano, Mauna Loa, on the island of Hawaii.



**Figure 2.** Atmospheric fraction  $f$  of CO<sub>2</sub> measured at Mauna Loa, Hawaii,<sup>[5]</sup> at 19° N latitude. Similar observations are available from a dozen other observatories, from the South Pole to Point Alert at 82° N latitude in the Canadian Arctic.<sup>[6]</sup>

As can be seen from the month-by-month data of Fig. 2 (the red dashed lines) CO<sub>2</sub> values decrease rapidly in the northern-hemisphere summer because photosynthesis by growing plants sucks CO<sub>2</sub> from the air. CO<sub>2</sub> values increase in the winter when photosynthesis diminishes but respiration of the biosphere continues. The average growth rate of atmospheric CO<sub>2</sub> at this writing (2016), the slope of the black trend line, is about  $df/dt = 2$  ppm per year. This corresponds to about half of the CO<sub>2</sub> emissions from burning fossil fuels, cement manufacture, land-use changes, and other human causes.<sup>[7]</sup> The other half of the emissions are absorbed by the oceans and land.

Local values of CO<sub>2</sub> can be very different from those of Fig. 2. For example, exhaled human breath typically consists of  $f = 40,000$  ppm to 50,000 ppm of CO<sub>2</sub>, a fact that should make one wonder about the campaign to demonize CO<sub>2</sub> as a “pollutant.” Without strong ventilation, CO<sub>2</sub> levels in rooms filled with lots of people commonly reach 2000 ppm with no apparent ill effects. On a calm summer day, CO<sub>2</sub> concentrations in a corn field can drop to  $f = 200$  ppm or less, because the growing corn sucks so much CO<sub>2</sub> out of the air.<sup>[8]</sup> The US Navy tries to keep CO<sub>2</sub> levels in submarines below  $f = 5000$  ppm to avoid any measurable effect on sailors<sup>[9]</sup> and NASA sets similar limits for humans in spacecraft.<sup>[10]</sup>

As illustrated in Fig. 3, both humans and power plants exhale mostly nitrogen and about 1% argon. The remainder consists almost entirely of carbon dioxide, water vapor, and oxygen. Humans exhale about the same fraction of water vapor as a power plant, but less carbon dioxide and more oxygen. The large fraction of oxygen remaining in human breath is why

mouth-to-mouth resuscitation works. The “smoke” from the stacks of the power plant, or from the girl’s breath on a frosty day, is condensed water vapor.  $\text{CO}_2$  is completely transparent. Humans exhale about 1 kg of  $\text{CO}_2$  per day, so the 320 million people of the United States “pollute” the atmosphere with about 320,000 metric tons of  $\text{CO}_2$  per day. Talk about a “carbon footprint”!

## $\text{CO}_2$ is not a pollutant!



### Power plant’s breath:

70%  $\text{N}_2$   
 5%  $\text{O}_2$   
 5%  $\text{H}_2\text{O}$   
 20%  $\text{CO}_2$

### Alice’s breath:

75%  $\text{N}_2$   
 15%  $\text{O}_2$   
 6%  $\text{H}_2\text{O}$   
 4%  $\text{CO}_2$

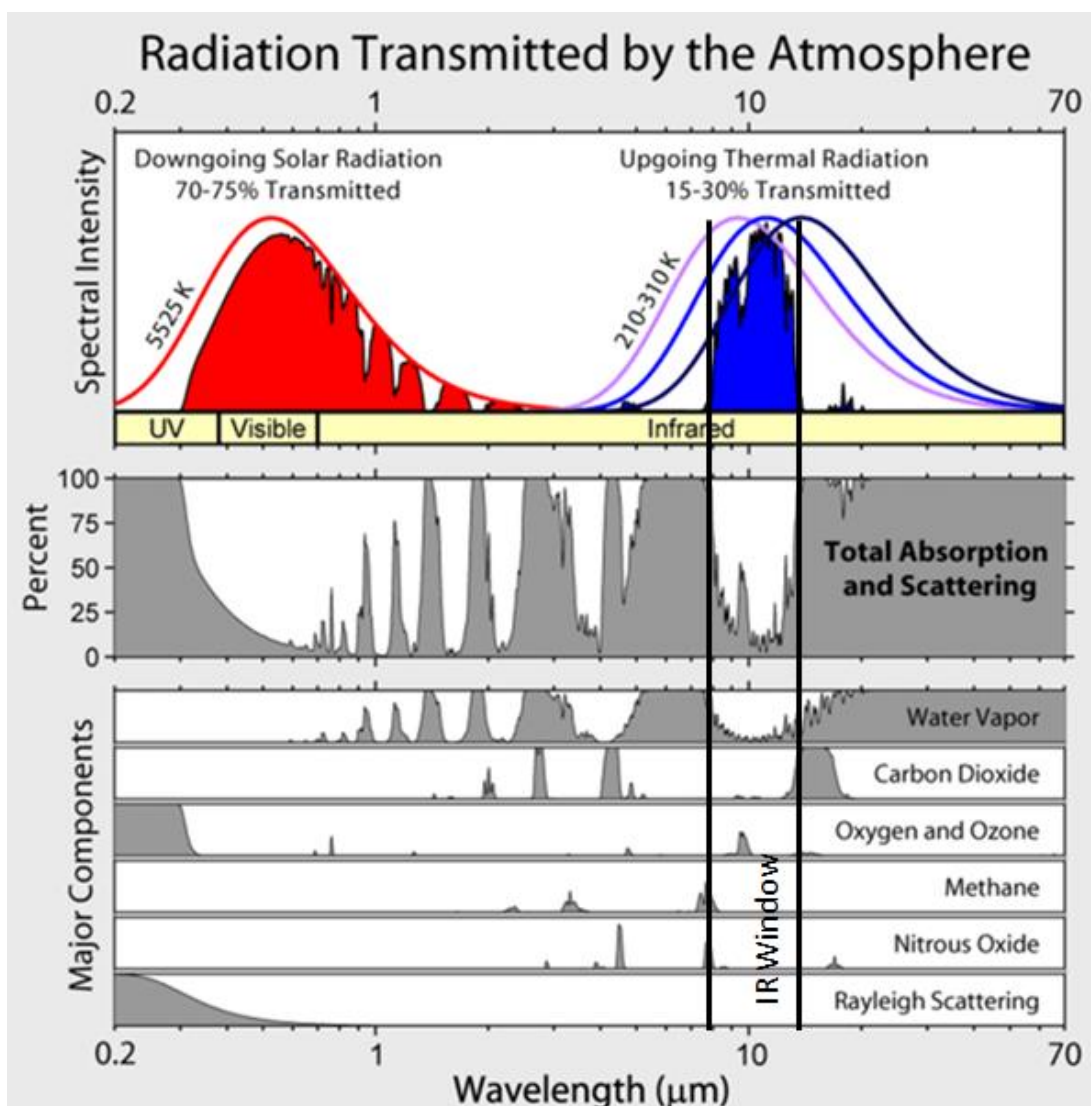
**Figure 3.** The main components of the exhaust gas of a modern power plant are similar to the components in human breath.

### Atmospheric transmission of radiation

Around the year 1861, John Tyndall (1820–1893) discovered that gaseous molecules of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and many other volatile chemicals are transparent to visible light, but can absorb invisible heat radiation, like that given off by a warm tea kettle or by the Earth’s surface and atmosphere. [\[11\]](#) Today, we call these “greenhouse gases,” and we know that the absorption is mostly due to oscillating electric dipole moments, induced by the vibrations and rotations of the molecules. The vibrations and rotations of the most abundant atmospheric gases,  $\text{N}_2$  and  $\text{O}_2$ , produce no oscillating dipole moments, so  $\text{N}_2$  and  $\text{O}_2$  do not absorb thermal radiation and

are not greenhouse gases. A dipole moment would not know which way to point in the highly symmetric  $N_2$  and  $O_2$  molecules.

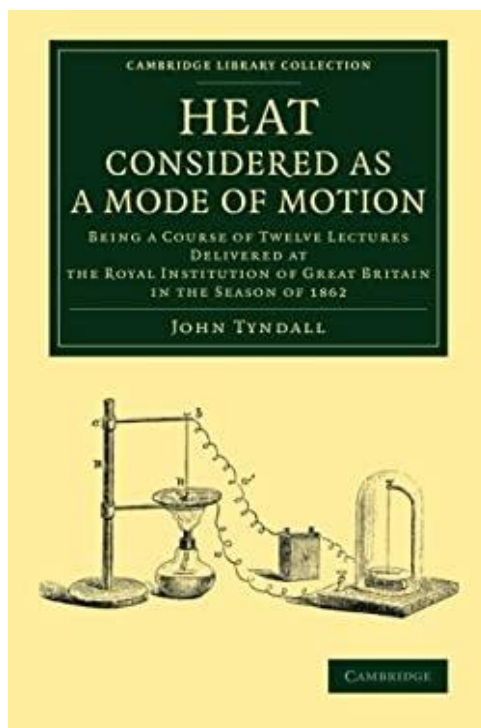
Fig. 4 shows how the different gases that compose the earth's atmosphere affect the transmission of visible light from the sun to the earth's surface, and thermal radiation from the surface to outer space. Although the atmospheric fraction of greenhouse gases,  $H_2O$  (about 1%) and  $CO_2$  (about 0.04%) is small, they can have a big effect since they act much like dyes for liquids. A few drops of dye are sufficient to turn a whole mug of beer green on St. Paddy's day, and a tiny amount of  $CO_2$  and  $H_2O$  is sufficient to substantially change the "color" of the atmosphere for an observer able to see infrared as well as visible radiation.



**Figure 4.** Fractional absorption of radiation passing from the earth's surface to space, or vice-versa, versus wavelength. [\[12\]](#)  $N_2$ , which makes up about 78% of the atmosphere, attenuates much like the bottom curve, labeled, "Rayleigh Scattering." All of the atmospheric gases are nearly transparent to sunlight, so on cloud-free days some 70% to 75% of sunlight can heat up the surface. The exact amount depends on the relative humidity, since water vapor absorbs some near-infrared sunlight. An



atmosphere of pure  $N_2$  and  $O_2$  would allow most of the surface thermal radiation to escape to space. But the small fractions of the greenhouse gases,  $CO_2$  and  $H_2O$ , permit only 15% to 30% (depending on relative humidity) of surface radiation to escape to space. The daytime surface is cooled more by rising, often humid, air than by thermal radiation. The smooth curves on the top panel are "Planck brightnesses" (not to scale) analogous to the curves of Fig. 8, but with energy per unit wavelength,  $\lambda$ , not energy per unit spatial frequency,  $\nu = 1/\lambda$ , of the radiation. The "IR window" referred to in Figure 7 is labeled.



Commenting on greenhouse warming of the Earth by water vapor in his classic book, [Heat: Considered as A Mode of Motion](#),[\[13\]](#) Tyndall makes the eloquent (and correct) statement:

Aqueous vapor is a blanket, more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapor from the air which overspreads this country, and you would assuredly destroy every plant capable of being destroyed by a freezing temperature. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost. John Tyndall

Tyndall correctly recognized in 1861 that the most important greenhouse gas of the Earth's atmosphere is water vapor.  $CO_2$  was a modest supporting actor, then as now.

## Radiative cooling of the Earth

Conduction of heat from the interior of the Earth brings an energy flux of about  $I_i = 0.08 \text{ W/m}^2$  to the surface.[\[14\]](#) This is only about 0.02% of the mean thermal energy[\[15\]](#),  $I_s = 340 \text{ W/m}^2$ , that would have to be uniformly reradiated if the Earth absorbed all the energy from the solar flux, on average,



about  $F = 4 I_s = 1360 \text{ W/m}^2$ . In contrast to Earth, Jupiter radiates almost twice as much energy as it receives from sunlight.[\[16\]](#)

The “solar constant”  $F$  was first measured precisely by the American physicist Samuel Pierpont Langley (1834–1906) during expeditions to California’s Mt. Whitney in the late 1800’s. He determined that  $F = 2 \text{ cal}/(\text{cm}^2 \text{ min})$ , which converts to a value only a few percent higher than today’s official value, since  $1 \text{ cal} = 4.184 \text{ J}$ . The solar constant is enough to vaporize about 2 mm of 20 C water per hour (the heat of vaporization is about  $580 \text{ cal}\cdot\text{cm}^{-3}$ ). Langley doubted that the energy output of the sun was exactly constant. He suspected that modest variations in  $F$  contributed to climate change. How much the variations in solar output contribute is still being debated today, as was discussed in the [Interview](#). Summarizing his fund-raising arguments for a permanent, high-altitude solar observatory in the year 1903, Langley said:

Now that great undertakings are the order of the day, let us hope that some way opens to reach the solution of a problem which so concerns the whole human race.[\[17\]](#) Samuel Pierpont Langley

Raising funds for scientific research has always entailed various degrees of hyperbole!

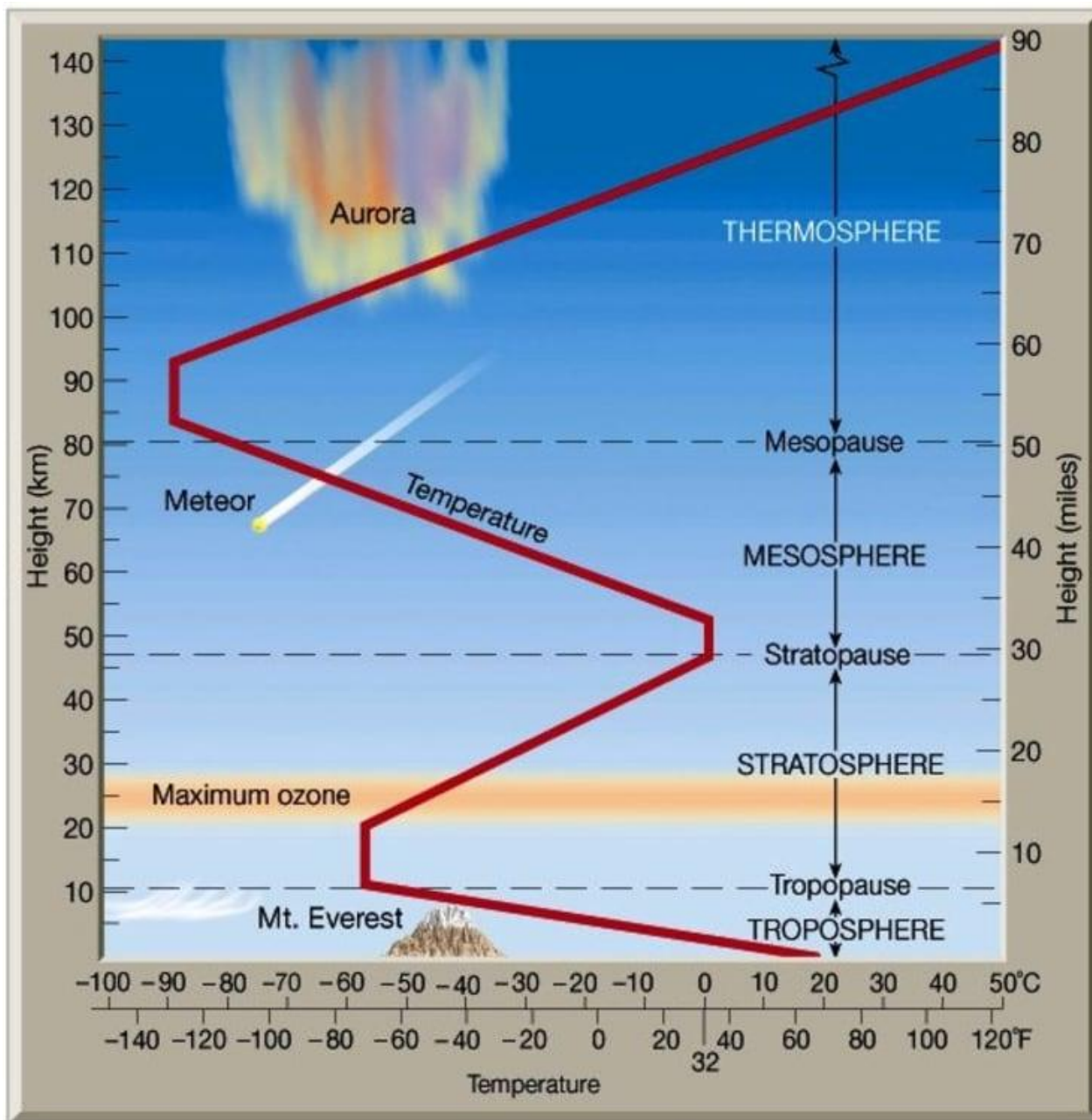
## Developing the surface temperature of the Earth

Without sunlight and only internal heat to keep warm, the Earth’s absolute surface temperature  $T$  would be very cold indeed. A first estimate can be made with the celebrated Stefan-Boltzmann formula:[\[18\]](#)

$$J = \epsilon\sigma T^4 \quad \text{eq. 1}$$

where  $J$  is the thermal radiation flux per unit of surface area, and the Stefan-Boltzmann constant (originally determined from experimental measurements) has the value  $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$ . The Slovenian experimental physicist, Jožef Stefan (1835–1893), discovered the proportionality of thermal radiation to the fourth power of the absolute temperature. Stefan’s student, Ludwig Boltzmann (1844–1906), showed that the factor of  $T^4$  was required by thermodynamics and by Maxwell’s equations for electromagnetic radiation.

If we assume that the Earth’s surface has maximum emissivity,  $\epsilon = 1$ , and is only emitting  $J_i = 0.08 \text{ W}/\text{m}^2$  of internal heat, Eq. (1) would imply a surface temperature of only  $T_i = (J_i/\sigma)^{1/4} = 34 \text{ K}$  above absolute zero, somewhat warmer than the 20 K boiling point of liquid hydrogen, but much colder than the 78 K boiling point of liquid nitrogen. If we use Eq. (1) in the same way to calculate how warm the surface would have to be to radiate the same thermal energy as the mean solar flux,  $J_s = F/4 = 340 \text{ W}/\text{m}^2$ , we find  $T_s = 278 \text{ K}$  or 5 C, a bit colder than the average temperature (287 K or 14 C) of the Earth’s surface,[\[19\]](#) but “in the ball park.”



**Figure 5.** The temperature profile of the Earth's atmosphere.<sup>[20]</sup> This illustration is for mid-latitudes, like Princeton, NJ, at 40.4° N, where the tropopause is usually at an altitude of about 11 km. The tropopause is closer to 17 km near the equator, and as low as 9 km near the north and south poles.

These estimates can be refined by taking into account the Earth's atmosphere. In the [Interview](#) we already discussed the representative temperature profile, Fig. 5. The famous "blue marble" photograph of the Earth,<sup>[21]</sup> reproduced in Fig. 6, is also very instructive. Much of the Earth is covered with clouds, which reflect about 30% of sunlight back into space, thereby preventing its

absorption and conversion to heat. Rayleigh scattering (which gives the blue color of the daytime sky) also deflects shorter-wavelength sunlight back to space and prevents heating.

Fig. 6 was taken close to midsummer for the southern hemisphere, as one might guess from the southern locations of the white cloud tops of the intertropical convergence zone (ITCZ) — the latitude of maximum thermal convection — and where the sun is nearly overhead at noon. The rising, warm air pulls in moist surface air from the north and south to form heavy clouds, with very high tops and abundant rain. The ITCZ completes one north-south migration every year, crossing the equator approximately at the times of the spring and fall equinoxes. Over the Indian Ocean, where the migration is particularly large, reaching from nearly the Tropic of Capricorn at 23° south latitude to a bit beyond the Tropic of Cancer at 23° north latitude, the ITCZ brings the southwest monsoon to India and the flooding of the Nile to Africa. [\[22\]](#)

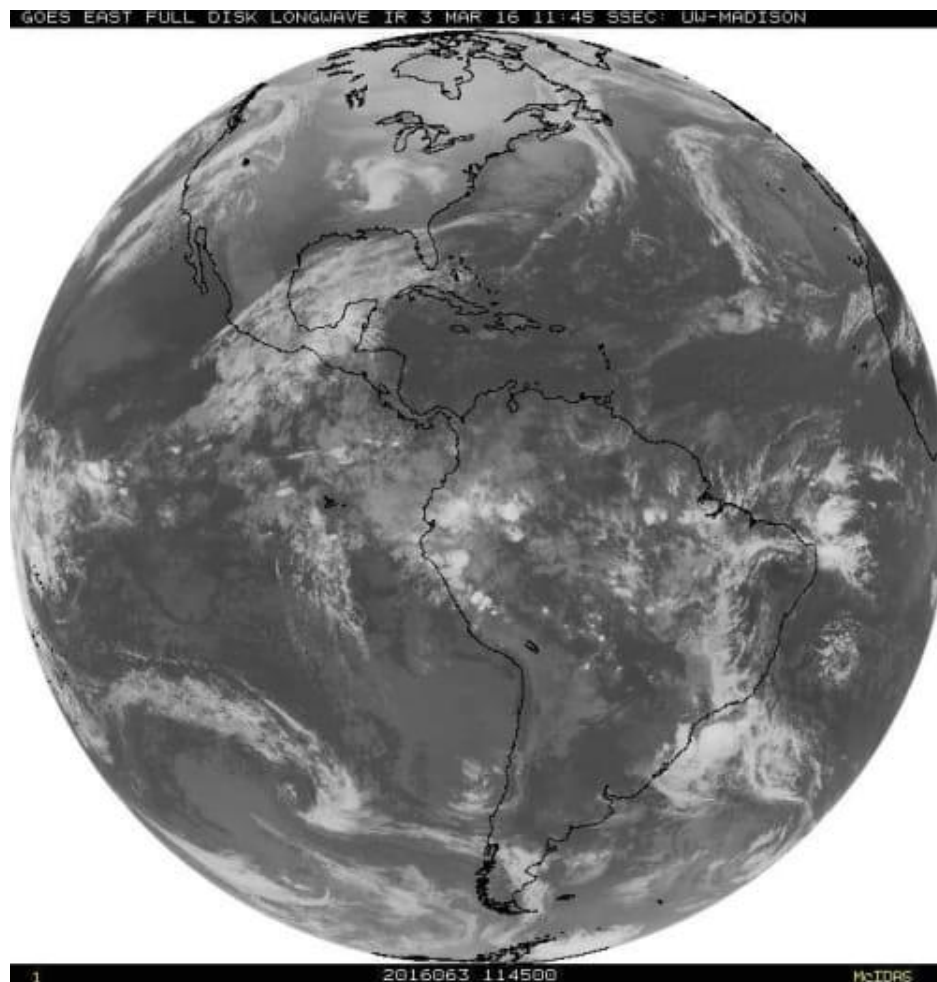


**Figure 6.** *The Earth from space. A photograph taken by Astronaut/Geologist Harrison Schmitt on December 7, 1972, during the mission Apollo 17.*

The Apollo 17 crew were lucky that the timing of their launch allowed them to see Earth in nearly full sunlight. In some missions, the astronauts looked back on the nighttime Earth.

Today, whole-Earth images analogous to Fig. 6 are continuously recorded by geostationary satellites, orbiting at the same angular velocity as the Earth, and therefore hovering over nearly the same spot on the equator at an altitude of about 35,800 km.<sup>[23]</sup> In addition to visible images, which can only be recorded in daytime, the geostationary satellites record images of the thermal radiation emitted both day and night.

Fig. 7 shows radiation with wavelengths close to  $10.7 \mu$  in the “infrared window” of the absorption spectrum shown in Fig. 4, where there is little absorption from either the main greenhouse gas,  $H_2O$ , or from less-important  $CO_2$ . Darker tones in Fig. 7 indicate more intense radiation. The cold “white” cloud tops emit much less radiation than the surface, which is “visible” at cloud-free regions of the Earth. This is the opposite from Fig. 6, where maximum reflected sunlight is coming from the white cloud tops, and much less reflection from the land and ocean, where much of the solar radiation is absorbed and converted to heat.



**Figure 7.** Radiation with wavelengths close to the  $10.7 \mu$  ( $1\mu = 10^{-6}m$ ), as observed with a geostationary satellite over the western hemisphere of the Earth.<sup>[23]</sup> This is radiation in the infrared window of Fig. 4, where the surface can radiate directly to space from cloud-free regions.

As one can surmise from Fig. 6 and Fig. 7, clouds are one of the most potent factors that control the surface temperature of the earth. Their effects are comparable to those of the greenhouse gases, H<sub>2</sub>O and CO<sub>2</sub>, but it is much harder to model the effects of clouds. Clouds tend to cool the Earth by scattering visible and near-visible solar radiation back to space before the radiation can be absorbed and converted to heat. But clouds also prevent the warm surface from radiating directly to space. Instead, the radiation comes from the cloud tops that are normally cooler than the surface. Low-cloud tops are not much cooler than the surface, so low clouds are net coolers. In Fig. 7, a large area of low clouds can be seen off the coast of Chile. They are only slightly cooler than the surrounding waters of the Pacific Ocean in cloud-free areas.

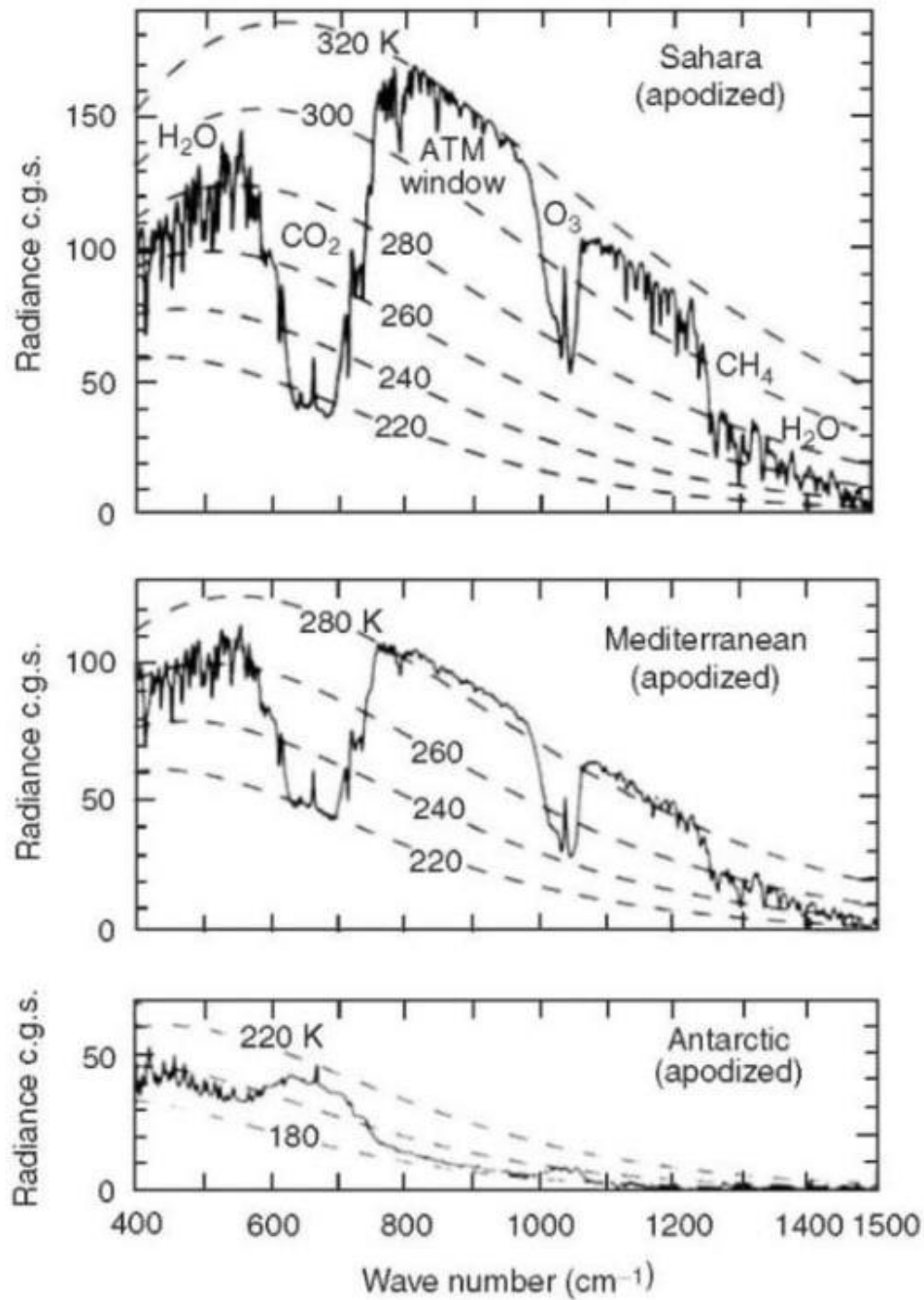
High cirrus clouds can warm the surface since they are cold and nearly opaque in the thermal infrared. They emit much less long-wave infrared radiation to space than would be emitted by the cloud-free surface. But the cirrus clouds can be nearly transparent for visible sunlight and do little to hinder solar heating of the surface. Richard Lindzen of MIT [24] has suggested that changes in the extent of cirrus clouds, in response to more or less heating of the surface, may act as a negative feedback mechanism, the “iris effect.” The iris effect might account for the remarkable temperature stability of the Earth’s surface, and explain the “faint young sun paradox” — the geological evidence for ice-free oceans in the very earliest history of the Earth, some four billion years ago when the Sun is calculated to have radiated about 30% less power than today, so that the Earth’s surface should have been cold enough to be ice covered. [25]

Fig. 8 shows the measured spectral distribution of the infrared radiation from which the satellite images of Fig. 7 were made. The horizontal scale is the spatial frequency  $\nu$  of the light, the inverse of the wavelength  $\lambda$  used to label the horizontal scale of Fig. 8, that is,  $\nu = 1/\lambda$ . The smooth, dashed lines on Fig. 8 are the theoretical blackbody brightness functions, discovered by Max Planck [26] when he invented quantum mechanics in 1900:

$$B = \frac{h_p c^2 \nu^3}{e^x - 1} \quad \text{eq. 2}$$

Here,  $h_p$  ( $= 6.63 \times 10^{-34}$  J s) is Planck’s constant;  $c$  ( $= 3 \times 10^8$  m/s) is the speed of light;  $x$  ( $= h_p c \nu / (k_B T)$ ) is the ratio of the energy,  $h_p c \nu$ , of a photon of spatial frequency  $\nu$  to the characteristic thermal energy,  $(k_B T)$ ; and Boltzmann’s constant is  $k_B = 1.38 \times 10^{-23}$  J/K. The units of  $B$  are  $W/(m^2 \text{ sr cm}^{-1})$ . Here, sr (= steradian) is the unit of solid angle. There are  $4\pi$  steradians for all solid angles emanating from a point in 3-dimensional space. [27]





**Figure 8.** Spectrally resolved, vertical upwelling thermal radiation  $I$  from the Earth, the jagged lines, as observed by a satellite. [28] The smooth, dashed lines are theoretical Planck brightnesses,  $B$ , for various temperatures. The vertical units are  $1 \text{ c.g.s} = 1 \text{ erg}/(\text{s cm}^2 \text{ sr cm}^{-1}) = 1 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$ .

The Stefan-Boltzmann energy fluxes of Eq. (1) are simply the area under the Planck brightness curve, multiplied by a factor of  $\pi$  to account for upwelling radiation from all solid angles, not just vertically upward:

$$\pi \int_0^{\infty} \nu B = \sigma T^4.$$

eq. 3

Using Eq. (2) with Eq. (3) gives an exact formula,

$$\sigma = 2\pi^5 k_B^4 / (15c^2 h_P^3), \text{ eq. 3.5}$$

for the Stefan-Boltzmann coefficient, which Stefan and Boltzmann had been obliged to determine experimentally before the invention of quantum mechanics.

Except at the South Pole, the data of Fig. 8 show that the observed thermal radiation from the Earth is less intense than Planck radiation from the surface would be without greenhouse gases. Although the surface radiation is completely blocked in the bands of the greenhouse gases, as one would expect from Fig. 4, radiation from H<sub>2</sub>O and CO<sub>2</sub> molecules at higher, colder altitudes can escape to space. At the “emission altitude,” which depends on frequency  $\nu$ , there are not enough greenhouse molecules left overhead to block the escape of radiation. The thermal emission cross section of CO<sub>2</sub> molecules at band center is so large that the few molecules in the relatively warm upper stratosphere (see Fig. 5) produce the sharp spikes in the center of the bands of Fig. 8. The flat bottoms of the CO<sub>2</sub> bands of Fig. 8 are emission from the nearly isothermal lower stratosphere (see Fig. 5) which has a temperature close to 220 K over most of the Earth.

To the left of the CO<sub>2</sub> band on Fig. 8 is the radiation from rotating water molecules with their permanent electric dipole moments. The permanent dipole moment of the H<sub>2</sub>O molecule, which is bent in its equilibrium state, helps to make water vapor a particularly potent greenhouse gas. The dipole moment is also partially responsible for the “anomalous properties”[\[29\]](#) of water — its ability to dissolve salts, its high boiling temperature, etc. The CO<sub>2</sub> band is due to bending vibrations, similar to those of a xylophone bar. Because of its high symmetry, the CO<sub>2</sub> molecule, in its unbent, equilibrium state, does not have an electric dipole moment and has no “pure-rotational band” like that of H<sub>2</sub>O. The H<sub>2</sub>O band on the extreme right side of Fig. 8 is due to bending vibrations, analogous to those of CO<sub>2</sub>.

It is hard for H<sub>2</sub>O molecules to reach cold, higher altitudes, since the molecules condense onto snowflakes or rain drops in clouds. So, the H<sub>2</sub>O emissions to space come from the relatively warm and humid troposphere, and they are only moderately less intense than the Planck brightness of the surface. CO<sub>2</sub> molecules radiate to space from the relatively dry and cold lower stratosphere. So, for most latitudes, the CO<sub>2</sub> band observed from space has much less intensity than the Planck brightness of the surface.

With the exception of the absorption/emission band of the ozone molecule, O<sub>3</sub>, and stray resonances of H<sub>2</sub>O, the “atmospheric window,” from about 800 cm<sup>-1</sup> to 1200 cm<sup>-1</sup> in Fig. 8, is very nearly a segment of the Planck brightness curve  $B$  at the surface temperature,  $T_s$ . From the window radiation we see that the surface of the Sahara is about  $T_s = 320 \text{ K} = 47 \text{ C} = 117 \text{ F}$ , apparently a hot summer day.



The nearby Mediterranean Sea has a surface temperature of about  $T_s = 285 \text{ K} = 12 \text{ C} = 54 \text{ F}$ , pretty chilly. The  $\text{H}_2\text{O}$  and  $\text{CO}_2$  bands are about the same for the Sahara and the Mediterranean. The upper-atmospheric temperature profiles of nearby regions are much more similar than the surface temperatures.

Concentrations of  $\text{H}_2\text{O}$  vapor can be quite different at different locations on Earth. A good example is the bottom panel of Fig. 8, the thermal radiation from the Antarctic ice sheet, where almost no  $\text{H}_2\text{O}$  emission can be seen. There, most of the water vapor has been frozen onto the ice cap, at a temperature of around 190 K. Near both the north and south poles there is a dramatic wintertime inversion<sup>[30]</sup> of the normal temperature profile of Fig. 5. The ice surface becomes much colder than most of the troposphere and lower stratosphere.

Cloud tops in the intertropical convergence zone (ITCZ) can reach the tropopause and can be almost as cold as the Antarctic ice sheet. The spectral distribution of cloud-top radiation from the ITCZ looks very similar to cloud-free radiation from the Antarctic ice, shown on the bottom panel of Fig. 8.

## The Schwarzschild equation

The observed intensity  $I$  of upwelling radiation shown in Fig. 8 comes from the radiation emitted by the surface and by greenhouse gases in the atmosphere above the surface. The rate of change of the intensity with altitude is given by the Schwarzschild equation<sup>[31]</sup>

$$\frac{\partial I}{\partial z} = \kappa(B - I).$$

eq. 4

The radiation intensity,  $I = I(\nu, z)$ , of frequency  $\nu$  at the altitude  $z$  gets larger or smaller with increasing height, depending on whether  $I$  is smaller or larger than the local Planck brightness,  $B = B(\nu, T)$  of Eq. (2), which changes with altitude  $z$  because of the changing temperature,  $T = T(z)$ , sketched in Fig. 5. The local attenuation coefficient is:

$$\kappa = N(z) \sum_j f_j \sigma_j(\nu, z).$$

eq. 5

The total molecular number density,  $N(z)$ , decreases rapidly with altitude  $z$ . The fraction  $f_j$  of the  $j$ th greenhouse is nearly independent of altitude  $z$  for  $\text{CO}_2$ , a well-mixed greenhouse gas. The fractions depend strongly on altitude and latitude for  $\text{H}_2\text{O}$  and  $\text{O}_3$ , which are not well-mixed. The attenuation coefficient  $\kappa$  decreases with altitude, along with the molecular density  $N$ , although peak resonance cross sections  $\sigma$  can increase with altitude because of diminished pressure broadening.

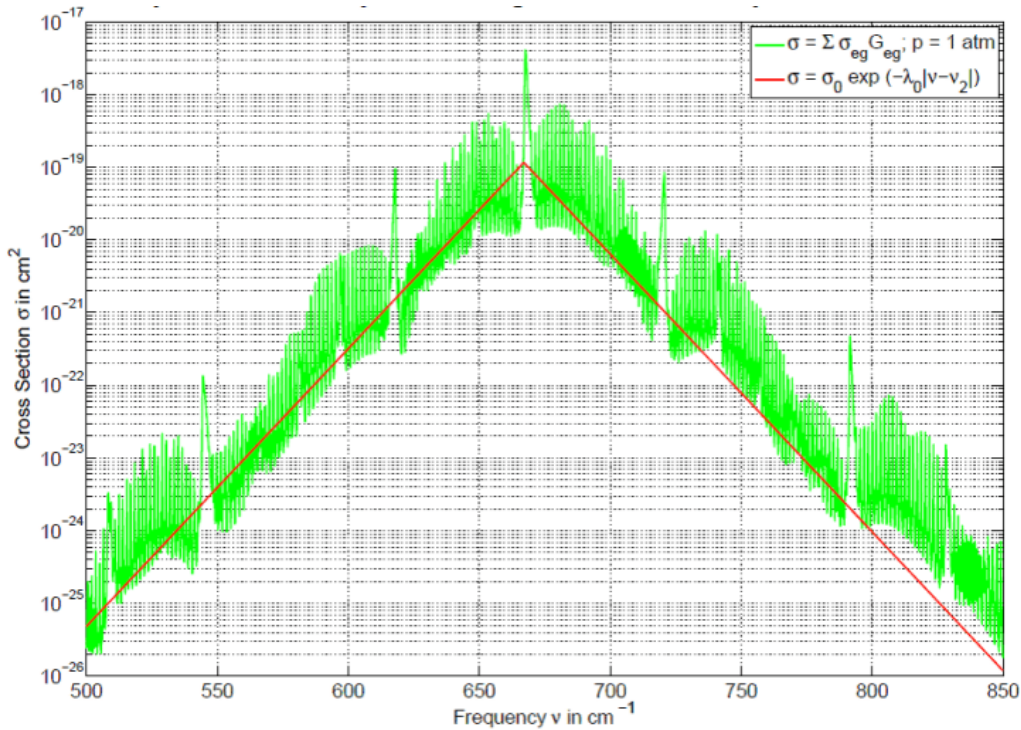
The Schwarzschild equation (4) tells us that the atmosphere tries to make the local brightness,  $I(\nu, z)$ , equal to the local Planck brightness,  $B(\nu, T)$ . If the intensity  $I$  diminishes with altitude, as it normally does in the troposphere, the energy lost from the radiation goes into heating the air molecules. If the intensity  $I$  increases with altitude, as it normally does in the middle stratosphere, the growth in radiation energy comes from cooling the air molecules.

Unlike “cavity radiation” to which the Stefan-Boltzmann formula, Eq. (1), applies, infrared radiation in the atmosphere is never even close to thermal equilibrium and cannot be described by a single temperature  $T$ . This would require that for all directions of propagation,  $\mathbf{n}$ , the thermal-radiation intensity would be equal to the local Planck brightness,  $I(\nu, z, \mathbf{n}) = B(\nu, T)$ . In contrast, the collisional exchange of energy between translational, rotational, and vibrational states of the molecules is so fast (with each molecule making more than a billion collisions per second at one atmosphere of pressure) that the distribution of molecules over their energy states is very well described by a local temperature,  $T = T(z)$ .

To solve the Schwarzschild equation for the intensity,  $I = I(\nu, \infty)$ , at the “infinite” altitude of the satellite, we need to specify the value of the upwelling intensity,  $I = I(\nu, z_s)$ , at the surface altitude,  $z_s = 0$ . To good approximation this is equal to the Planck brightness at the surface altitude and temperature,  $T_s = T(z_s)$ .

$$I(\nu, z_s) = B(\nu, T_s) = B_s.$$

eq. 6



**Figure 9.** The absorption cross section of a  $\text{CO}_2$  molecule at the surface pressure (1 atmosphere) and a temperature of 300 K. The parameters of the red, straight-line approximation are  $\sigma_0 = 1.27 \times 10^{-19} \text{ cm}^2$ ,  $\lambda_0 = 0.0805 \text{ cm}$ ,  $\nu_2 = 669.2 \text{ cm}^{-1}$ . The green “exact” cross sections came from the HITRAN database[32] for  $\text{CO}_2$ .

## Logarithmic forcing by $\text{CO}_2$

Fig. 9 shows the radiation absorption cross section  $\sigma_j(\nu, z)$  of Eq. (5) for a  $\text{CO}_2$  molecule. The exact, “line-by-line” cross section is the complicated green curve of Fig. 9, consisting of thousands of resonance absorption lines of vibrational-rotational transitions. But quite a good fit can be made with the triangular red approximation.[33] Since Fig. 9 is plotted on a logarithmic scale, the cross section corresponding to the red triangle can be written as

$$\sigma(\nu) = \sigma_0 e^{-\lambda_0 |\nu - \nu_2|}. \quad \text{eq. 7}$$

Here  $\nu_2 = 667 \text{ cm}^{-1}$  is the resonant bending-mode frequency of a non-rotating  $\text{CO}_2$  molecule. The empirically determined exponential line-shape parameter is  $\lambda_0 = 0.0805 \text{ cm}$ , and the peak cross section is  $\sigma_0 = 1.27 \times 10^{-19} \text{ cm}^2$ . The form of Eq. (7) is peculiar to the  $\text{CO}_2$  molecule, and that functional form is not a good approximation to the absorption cross section of the main greenhouse molecule,  $\text{H}_2\text{O}$  or the less important molecules,  $\text{O}_3$  and  $\text{CH}_4$ . The approximation of Eq. (7) works as well for higher altitudes as for the surface. However, slightly different parameters  $\sigma_0$  and  $\lambda_0$  must be used at higher altitudes because the distribution of  $\text{CO}_2$  molecules over internal vibration-rotation states is temperature-dependent.

The probability that a photon emitted by the surface will escape to space without absorption by CO<sub>2</sub> molecules is

$$w = w(\nu) = e^{-fn\sigma(\nu)}.$$

eq. 8

In Eq. (8),  $\sigma(\nu)$  is the altitude-averaged cross section of CO<sub>2</sub> molecules. The column density of all air molecules is

$$n = \int_0^{\infty} dz N(z) = 2.15 \times 10^{25} \text{ cm}^{-2}.$$

eq. 9

This is the number of molecules in a 1 cm<sup>2</sup> column of air, extending from the surface to outer space, that would have a mass of 1.03 kg and would give one normal atmosphere of pressure on the surface. CO<sub>2</sub> molecules comprise a fraction  $f$  of all the molecules.

The cross section of Fig. 9 falls off so rapidly with detuning,  $|\nu - \nu_2|$ , of the photon frequency  $\nu$  from the band-center frequency  $\nu_2$ , that to first approximation the surface escape probability is “binary,” as illustrated in Fig. 4 by the panel labeled “Carbon Dioxide.” This is a plot of  $1 - w$  versus wavelength. For small detunings,  $|\nu - \nu_2|$ , of the photon frequency,  $\nu$ , the troposphere will be opaque, with  $w = 0$ . Then the blackbody radiation of the surface will be completely attenuated and except the spike at band center, the satellite will record the Planck brightness  $B_t$  of the tropopause, at the altitude  $z_t = 11$  km (at Princeton), and of the nearly isothermal lower stratosphere at a temperature of about  $T_t = T(z_t) = 220$  K. For large detuning, both the troposphere and stratosphere will be transparent, and a photon emitted from the surface will escape freely to space. Then the intensity observed by the satellite will be the Planck brightness  $B_s$  at the surface temperature  $T_s$ . So, we expect to be able to approximate the brightness observed by the satellite as

$$I = B_s w + B_t (1 - w),$$

eq. 10

where in analogy to Eq. (6),

$$B_t = B(\nu, T_t).$$

eq. 11

The simple approximation of Eq. (10) is plotted in Fig. 10. There is good, semi-quantitative agreement with the measurements of Fig. 8. The main difference is the absence of resonance-line structure in the simple theory of Fig. 10, and the also the absence of bands from the greenhouse gases H<sub>2</sub>O and O<sub>3</sub>.

The dashed line in Fig. 10 is the intensity for a doubling of CO<sub>2</sub> concentrations from the present value of 400 ppm to 800 ppm with no change in the temperature profile of Fig. 5. Doubling the CO<sub>2</sub> concentration makes little difference, and simply leads to a slight broadening of the width,  $\Delta\nu$ , of the band.

To understand the band broadening quantitatively, we define the two “band edge frequencies” as those frequencies  $\nu_{\mp}$  for which the escape probability Eq. (8) is  $w = e^{-1} = 0.37$ , that is:

$$fn\sigma(\nu_{\mp}) = fn\sigma_0 e^{-\lambda_0|\nu_{\mp}-\nu_2|} = 1.$$

eq. 12

Taking the natural logarithm of both sides of Eq. (12) and recalling that  $\ln(1) = 0$  and  $\ln(xy) = \ln(x) + \ln(y)$ , we find that the band-edge frequencies are

$$\nu_{\mp} = \nu_2 \mp \frac{1}{\lambda_0} \ln(f / f_0), \text{ where } f_0 = 1 / n\sigma_0 = 0.4 \text{ ppm.}$$

eq. 13

For example, at the CO<sub>2</sub> concentration of the year 2015,  $f = 400$  ppm, the band-edge frequencies are  $\nu_- = 582 \text{ cm}^{-1}$  and  $\nu_+ = 756 \text{ cm}^{-1}$ , the projections of the black dots of Fig. 10 on the horizontal axes.

The width of the CO<sub>2</sub> band is:

$$\Delta\nu = \nu_+ - \nu_- = \frac{2}{\lambda_0} \ln(f / f_0).$$

eq. 14

Doubling the CO<sub>2</sub> concentration from  $f$  to  $2f$  will increase the band width by:

$$\Delta(\Delta\nu) = \frac{2}{\lambda_0} \ln(2) = 17.2 \text{ cm}^{-1}.$$

eq. 15

The radiation intensity to space will be changed by approximately:

$$\Delta J = -\Delta B \Delta(\Delta\nu)\pi = -\Delta B \times 54.1 \text{ cm}^{-1}.$$

eq. 16

The factor of  $\pi$  in Eq. (16) is to account for upwelling from all solid angles, not just vertically upward. The effective difference in surface and tropospheric brightness is:

$$\Delta B = \frac{1}{2} [B_s(\nu_+) + B_s(\nu_-) - B_t(\nu_+) - B_t(\nu_-)].$$

eq. 17

From inspection of Fig. 8, we see that a difference of surface and tropospheric brightness is about  $\Delta B = 75 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$  over the Mediterranean, and according to Eq. (16), doubling the  $\text{CO}_2$  concentration would decrease the radiation to space by:

$$\Delta J = -4.04 \text{ W}/\text{m}^2.$$

eq. 18

As one can see from Fig. 8,  $\Delta B$  varies substantially with latitude and so will the change in radiation to space  $\Delta J$  of Eq. (16). At the south pole, with its temperature inversion, and with  $\Delta B = -30 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$ , doubling the  $\text{CO}_2$  concentration will increase, not decrease, the radiation to space.

Using the Stefan-Boltzman equation (1), and accounting for the loss of surface radiation in the  $\text{CO}_2$  band by assuming an effective emissivity,  $\epsilon = 0.8$ , we see that a temperature rise:

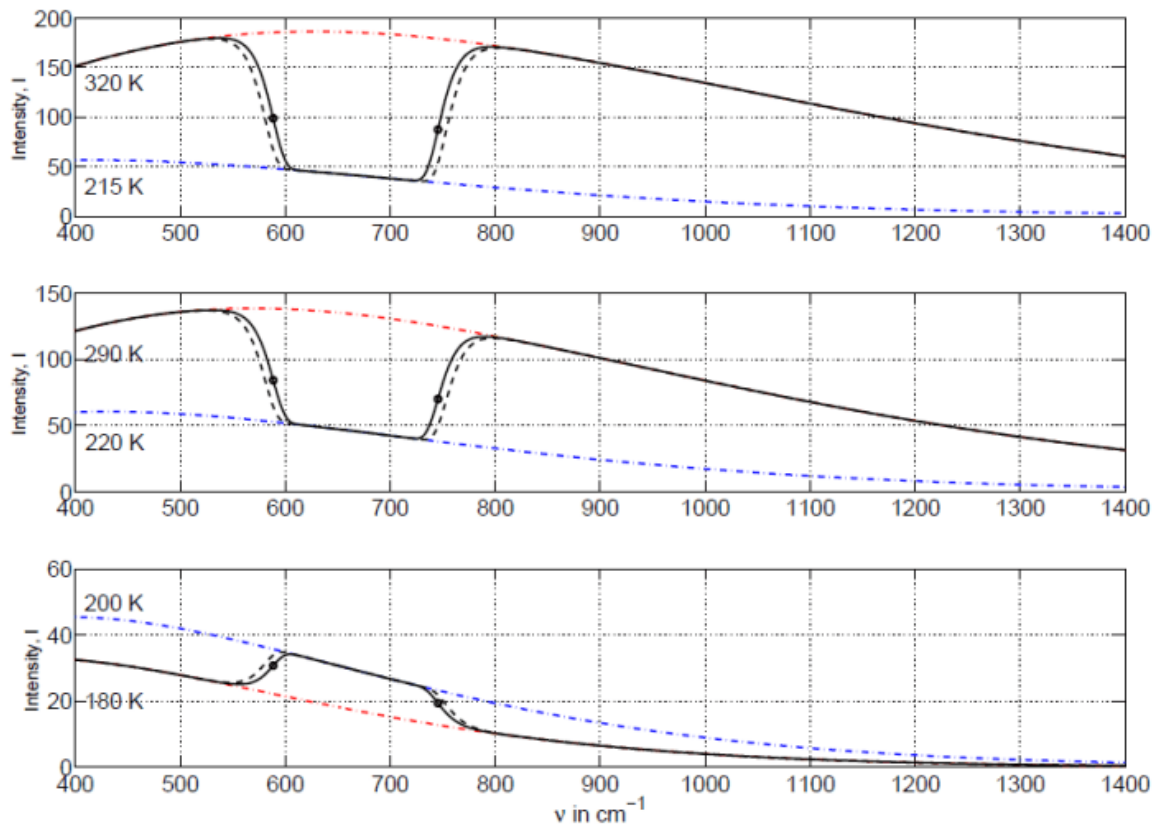
$$\Delta T = \frac{\Delta J}{4\epsilon\sigma T^3} = 0.92 \text{ K},$$

eq. 19

would compensate for the slight loss of radiation to space, Eq. (19), from doubling the  $\text{CO}_2$  concentration. Of course, the large variation of  $\Delta B$  with latitude and the effects of  $\text{H}_2\text{O}$  and

$O_3$  shown in Fig. 8 need to be taken into account. But the message of the discussion above is that simple, feedback-free estimates give a climate sensitivity  $S$  — the warming from a doubling of the  $CO_2$  fraction  $f$  — of about  $S = 1$  K.

Most climate models do not focus on the thermal radiation to space, which we have discussed above, but on the “radiative forcing” of the change of radiation transport at, or just above, the tropopause. [34] This is because heating and cooling of the stratosphere and troposphere are nearly independent. Surface and tropospheric warming should be similar, with 10% to 20% more tropospheric warming than surface warming because of the release of latent heat into the troposphere from ascending air. The basic physics of radiation to space and radiative forcing at the tropopause are similar. Both will be proportional to  $\ln(f/f_0)$ , though with different constants of proportionality and slightly different values of  $f_0$ .

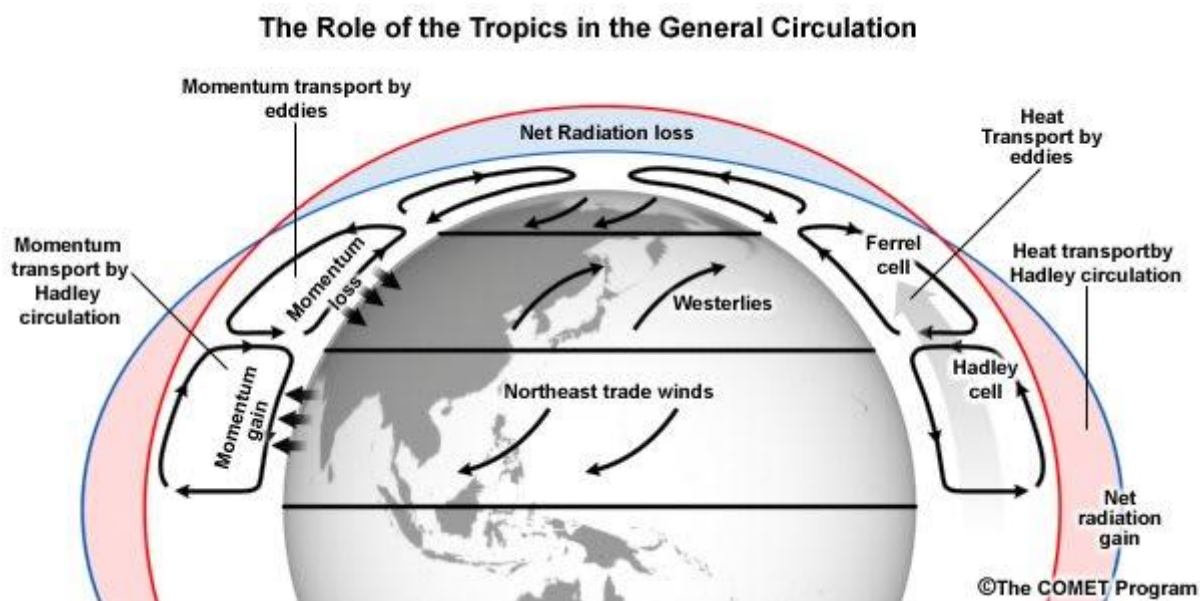


**Figure 10.** The simple theoretical estimate Eq. (10) of the thermal emission from the earth for comparison with the actual measurements of Fig. 8. The solid lines are the nadir intensities that a satellite would observe for today’s  $CO_2$  fraction,  $f = 400$  ppm, and the filled black circles are the left and right band edges of Eq. (13). The dashed [black] line, the nadir intensity for twice today’s  $CO_2$  concentration,  $f = 800$  ppm, differs only at the edges of the band. Radiative transfer is very insensitive to  $f$ . The vertical units are  $mW/(m^2 sr cm^{-1})$ .



## Convection

Radiation, which we have discussed above, is an important part of the energy transfer budget of the earth, but not the only part. More solar energy is absorbed in the tropics, near the equator, where the sun beats down nearly vertically at noon, than at the poles where the noontime sun is low on the horizon, even at midsummer, and where there is no sunlight at all in the winter. As a result, more visible and near infrared solar radiation (“short-wave radiation” or SWR) is absorbed in the tropics than is radiated back to space as thermal radiation (“long-wave radiation” or LWR). The opposite situation prevails near the poles, where thermal radiation releases more energy to space than is received by sunlight. Energy is conserved because the excess solar energy from the tropics is carried to the poles by warm air currents, and to a lesser extent, by warm ocean currents. The basic physics is sketched in Fig. 11. [35]



**Figure 11.** Most sunlight is absorbed in the tropics, and some of the heat energy is carried by air currents to the polar regions to be released back into space as thermal radiation. Along with energy, angular momentum — imparted to the air from the rotating Earth’s surface near the equator — is transported to higher northern and southern latitudes, where it is reabsorbed by the Earth’s surface. The Hadley circulation near the equator is largely driven by buoyant forces on warm, solar-heated air, but for mid latitudes the “Coriolis force” due to the rotation of the earth leads to transport of energy and angular momentum through slanted “baroclinic eddies.” Among other consequences of the conservation of angular momentum are the easterly trade winds near the equator and the westerly winds at mid latitudes.

## Numerical Modeling

Predictions about what more CO<sub>2</sub> will do to the Earth’s climate are based on numerical modeling of the fluid flows in the atmosphere and oceans. The state of the atmosphere is determined by many numerical quantities. One of the most important is the wind velocity  $\mathbf{v}$  of air “parcels” located at each position  $\mathbf{r}$  above the Earth’s surface. We assume that the parcels are small enough that all the air in a single parcel has nearly the same velocity  $\mathbf{v}$ , temperature  $T$ , pressure  $p$ . The volume of the

atmosphere is very large. If we agree to consider only the atmosphere within a spherical shell of radial thickness  $\Delta R = 100$  km, surrounding the earth with its radius  $R = 6371$  km, the volume of the atmosphere would be  $V = 4\pi R^2 \Delta R = 5.1 \times 10^{10}$  km<sup>3</sup>. If we were to be satisfied with a uniform “1 km grid size,” we would need to store about 255 billion numbers to characterize the state of the dry atmosphere. For each grid point we need three velocity projections,  $\mathbf{v}_x$ ,  $\mathbf{v}_y$ , and  $\mathbf{v}_z$  — say to the east, to the north, and vertically up — and for dry air, two thermodynamic quantities, for example, the pressure  $p$  and the mass density  $\rho$ . Unless the atmospheric properties were the same throughout the 1 km<sup>3</sup> “grid-point” volume, this huge collection of numbers would still not be a very realistic representation of the atmosphere’s state. In practice, one would use larger grid volumes in the upper atmosphere, where there is less spatial variation of winds, temperature, etc.

To model the time evolution of the wind velocity and other parameters describing the atmospheric state, we need differential equations analogous to the Schwarzschild equation (4) for the change of radiation with altitude. The rate of change of the velocity  $\mathbf{v}$  with time  $t$  is given by the celebrated Navier-Stokes equation,

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = \mathbf{g} - \frac{1}{\rho} \nabla p - 2\boldsymbol{\Omega} \times \mathbf{v} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) + \nu \nabla^2 \mathbf{v}. \quad (20)$$

Here,  $\mathbf{g}$  is the acceleration of gravity (9.8 m/s “straight down” at Princeton),  $\rho$  is the mass density (1.3 kg/m<sup>3</sup> at sea level),  $p$  is the air pressure,  $\nabla$  is the spatial gradient operator, which gives the vector rate of change with distance,  $\boldsymbol{\Omega}$  is the vector rotation rate of Earth ( $2\pi$  radian/day around the south-north axis), and  $\nu$  is the kinematic viscosity of air ( $1.6 \times 10^{-5}$  m<sup>2</sup>/s for 25 C air at sea level).

The Navier-Stokes equation (20) is the compressible-fluid version of Newton’s second law,  $a = F/m$ , that is, the acceleration,  $a = dv/dt$  — or the time rate of change of velocity  $\mathbf{v}$  of a particle of mass  $m$  — is the ratio of the force  $F$  acting on the particle to the mass. The acceleration of gravity  $\mathbf{g}$  characterizes the gravitational attraction of the fluid parcel by the Earth, and the term proportional to  $-\nabla p$  describes the buoyant force from the slightly higher pressures  $p$  at the bottom of the fluid parcel than at the top. The pressure-gradient forces and the gravity forces acting on fluid parcels nearly cancel in most situations, a fact first pointed out by Archimedes in 212 BC. [\[36\]](#)

Since the Navier-Stokes equation is normally used for a coordinate system that rotates with the earth, it includes a velocity-dependent Coriolis acceleration, the term with only one factor of  $\boldsymbol{\Omega}$  in Eq. (20). The Coriolis acceleration is very important and is responsible for the northeasterly trade winds, the westerly mid-latitude winds, and the easterly polar winds shown in Fig. 9. The rotation also causes a centripetal acceleration, the term with two factors of  $\boldsymbol{\Omega}$  in Eq. (20), which is small and often lumped with the acceleration of gravity  $\mathbf{g}$ . The frictional forces of one fluid layer sliding across another are given by the last term, proportional to the kinetic viscosity coefficient  $\nu$ . Except very near the Earth’s surface, the frictional accelerations are negligible compared to the other terms.

The conservation of fluid-mass is described by an equation analogous to the Navier-Stokes equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0.$$

eq. 21

Equations (20) and (21) give us four of the five equations needed to model the dry atmosphere, with the five independent variables  $v_x$ ,  $v_y$ ,  $v_z$ ,  $p$ , and  $\rho$ . To get a fifth equation, we must turn to the thermodynamics of the air parcels. It is often convenient to use the entropy per unit mass,  $s$ , as a thermodynamic variable. Then a complete set of equations for calculating the evolution of dry air could include the fifth equation,

$$\frac{\partial s}{\partial t} + \nabla \cdot s \mathbf{v} = \frac{\dot{q}}{T}.$$

eq. 22

By far the biggest contributors to the heating rate  $\dot{q}$  (in units of W/kg) on the right of the equation are radiative heating by sunlight, and heating or cooling by absorption or emission of thermal radiation. Conduction of heat from neighboring parcels and viscous heating are much less important.

Eq. (20) gives the rate of change of velocity  $\mathbf{v}$ , in terms of the pressure  $p$  and the mass density  $\rho$ . The rate of change of the mass density  $\rho$  is given by Eq. (21), but there is no corresponding equation for the rate of change of the pressure  $p$ . However, the two independent thermodynamic variables, entropy density  $s$  and mass density  $\rho$ , are sufficient to define the pressure  $p$ , so Eqs. (20), (21), and (22) are a complete set for determining changes in the state of the atmosphere. For example, to within an additive constant for  $s$ , the thermodynamic variables  $s$ ,  $p$ , and  $\rho$  are related by the “equation of state,”[\[37\]](#)

$$s = \frac{fk_B}{2m} \ln(p / \rho^\gamma). \quad (23)$$

Here, the mean mass of an air molecule is  $m = 4.8 \times 10^{-26}$  kg, while the number of thermal degrees of freedom for dry atmospheric air is very nearly  $f = 5$ , that is, 3 for translation plus 2 for rotation. The vibrational degrees of freedom of  $N_2$  and  $O_2$  are nearly “frozen out” at the relatively low temperatures of the Earth’s atmosphere. The ratio of heat capacity at constant pressure to heat capacity at constant volume is  $\gamma = 1 + 2/f$ , or very nearly,  $\gamma = 1.4$ .

Including water vapor, clouds, and precipitation further complicates the modeling considerations outlined above. Climate model builders have a hard job.

## Equilibrium Climate Sensitivity

If increasing CO<sub>2</sub> causes very large warming, harm can indeed be done. But most studies suggest that warmings of up to 2 K will be good for the planet,<sup>[38]</sup> extending growing seasons, cutting winter heating bills, etc. We will denote temperature differences in Kelvin (K) since they are exactly the same as differences in Celsius (C). A temperature change of 1 K = 1 C is equal to a change of 1.8 Fahrenheit (F).

The great Swedish chemist Svante Arrhenius (1859–1927) seems to have been the first to make a quantitative estimate of the warming from CO<sub>2</sub>. In 1896, on page 265 of his pioneering paper, “On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground,”<sup>[39]</sup> Arrhenius states that decreasing  $f$ , fraction of CO<sub>2</sub> in the air, by a factor of 0.67 = 2/3 would cause the surface temperature to fall by  $\Delta T = -3.5$  K and increasing  $f$  by a factor of 1.5 = 3/2 would cause the temperature to increase by  $\Delta T = +3.4$  K. Summarizing his estimates, Arrhenius stated,

Thus, if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase very nearly in arithmetic progression.

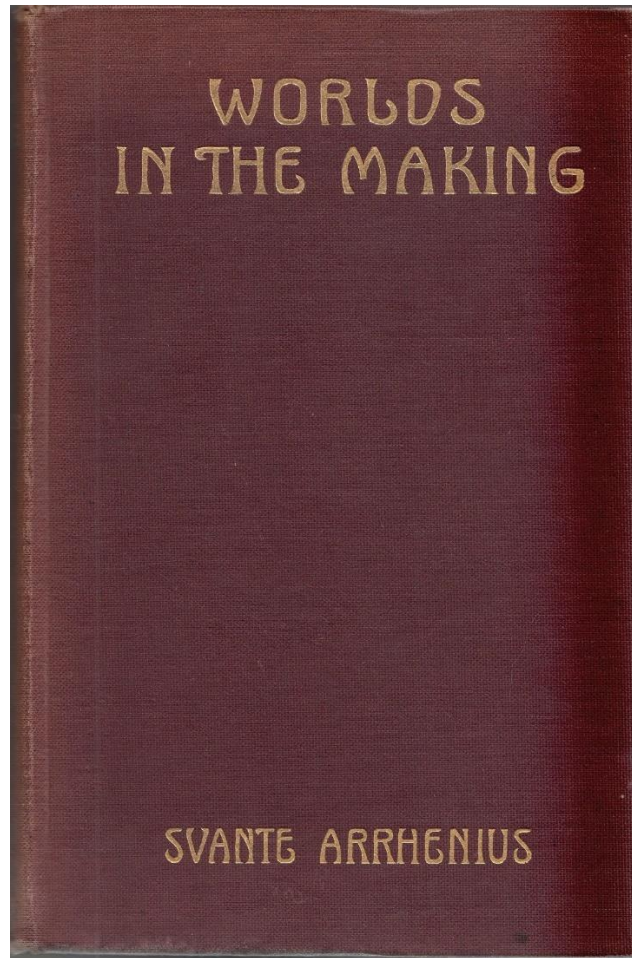
The mathematical expression of this statement most often used is that the surface-temperature increase,  $\Delta T = T_2 - T_1$ , due to increasing the fraction of CO<sub>2</sub> from  $f_1$  with temperature  $T_1$  to  $f_2$  with temperature  $T_2$  should be given by the equation,

$$\Delta T = S \log_2(f_2 / f_1).$$

eq. 24

Here,  $S$  is the most important single parameter in the debate over climate change.

Here,  $\log_2(x)$  denotes the base-2 logarithm of  $x$ . For example,  $\log_2(1) = \log_2(2^0) = 0$ , or  $\log_2(4) = \log_2(2^2) = 2$ . The doubling sensitivity  $S$  is how much the Earth’s average surface temperature will increase if the atmospheric concentrations of CO<sub>2</sub> doubles.  $S$  is the most important single parameter in the debate over climate change. The logarithmic dependence of Eq. (24) comes from the peculiar dependence of the CO<sub>2</sub> cross section on frequency, shown in Fig. 9, which leads to a band width proportional to  $\ln(f/f_0)$ , as shown in Eq. (14).



If a 50% increase of  $\text{CO}_2$  were to increase the temperature by 3.4 K, as in Arrhenius's original estimate mentioned above, the doubling sensitivity would be  $S = 3.4 \text{ K}/\log_2(1.5) = 5.8 \text{ K}$ . Ten years later, on page 53 of his popular book, [Worlds in the Making: The Evolution of the Universe](#),<sup>[40]</sup> Arrhenius again states the logarithmic law of warming, with a slightly smaller climate sensitivity,  $S = 4 \text{ K}$ :

If the quantity of carbon dioxide in the air should sink to one half its present percentage, the temperature would fall by 4 K; a diminution by one-quarter would reduce the temperature by 8 K. On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the Earth's surface by 4 K and if the carbon dioxide were increased by fourfold, the temperature would rise by 8 K. Svante Arrhenius

Convection of the atmosphere, water vapor, and clouds all interact in a complicated way with the change of  $\text{CO}_2$  to give the numerical value of the doubling sensitivity  $S$  of Eq. (21). Remarkably, Arrhenius somehow guessed the logarithmic dependence on  $\text{CO}_2$  concentration  $f$  before Planck's discovery of how thermal radiation really works.

The most recent report of the Intergovernmental Panel for Climate Change (IPCC) states that [\[41\]](#)

equilibrium climate sensitivity is likely in the range 1.5 K to 4.5 K (high confidence).  
IPCC AR5

As the Roman poet Horace remarked: *Parturient montes, nascetur ridiculus mus*: [\[42\]](#)

Mountains will go into labor, a ridiculous mouse will be born.

More than a century after Arrhenius, and after the expenditure of many tens of billions of dollars on climate science, the official value of  $S$  still differs little from the guess that Arrhenius made in 1912:  $S = 4$  K. Could it be that the climate establishment does not want to work itself out of a job?

An equivalent form of Eq. (24) is

$$\frac{f_2}{f_1} = 2^{\Delta T/S}. \quad (25)$$

For a constant rate of increase,  $R = df/dt$ , of the  $\text{CO}_2$  concentration from  $f_1$  at the present time  $t_1$  to  $f_2$  at a later time  $t_2$ , we can write:

$$f_2 = f_1 + R \Delta t, \text{ where } \Delta t = t_2 - t_1. \quad (26)$$

Substituting Eq. (26) into Eq. (25) and solving for  $\Delta t$ , we find

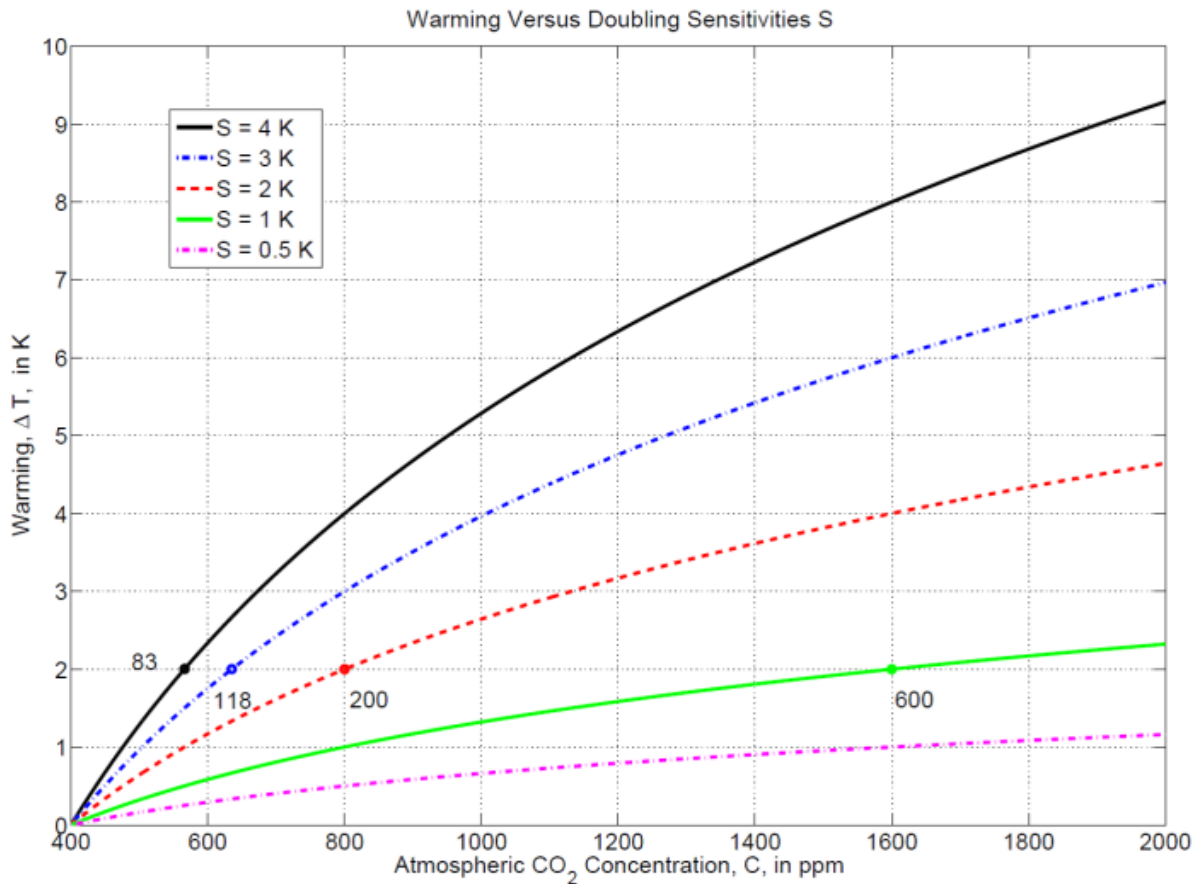
$$\Delta t = \frac{f_1}{R} (2^{\Delta T/S} - 1). \quad (27)$$

From Eq. (27) we find that for a current  $\text{CO}_2$  concentration of  $f_1 = 400$  ppm and at the current rate of increase,  $R = 2$  ppm/year, the time to raise the temperature by  $\Delta T = 2$  K is



$$\Delta t = 200(2^{2K/S} - 1) \text{ years.} \quad (28)$$

Fig. 12 shows the dependence of equilibrium temperature rise  $\Delta T$  versus  $\text{CO}_2$  concentration,  $f$ . The solutions of Eq. (24) are given for various possible doubling sensitivities,  $S$ . The concentrations,  $f$ , required for an equilibrium temperature rise by  $\Delta T = 2$  K are indicated by the points on the curves and are labeled by the time  $\Delta t$ , in years, needed for doubling at the present rate of increase,  $R = 2$  ppm/year, of atmospheric  $\text{CO}_2$ .



**Figure 12.** Warming from  $\text{CO}_2$  from Eq. (24) for various sensitivities,  $S$ . We have used Eq. (27) to calculate the corresponding time,  $\Delta t$  (in years), needed to increase the temperature by 2 K. Observations indicate that the doubling sensitivity is close to the feedback-free value of  $S = 1$  K, for which 600 years would be needed at the present growth rate,  $R = 2$  ppm/year.

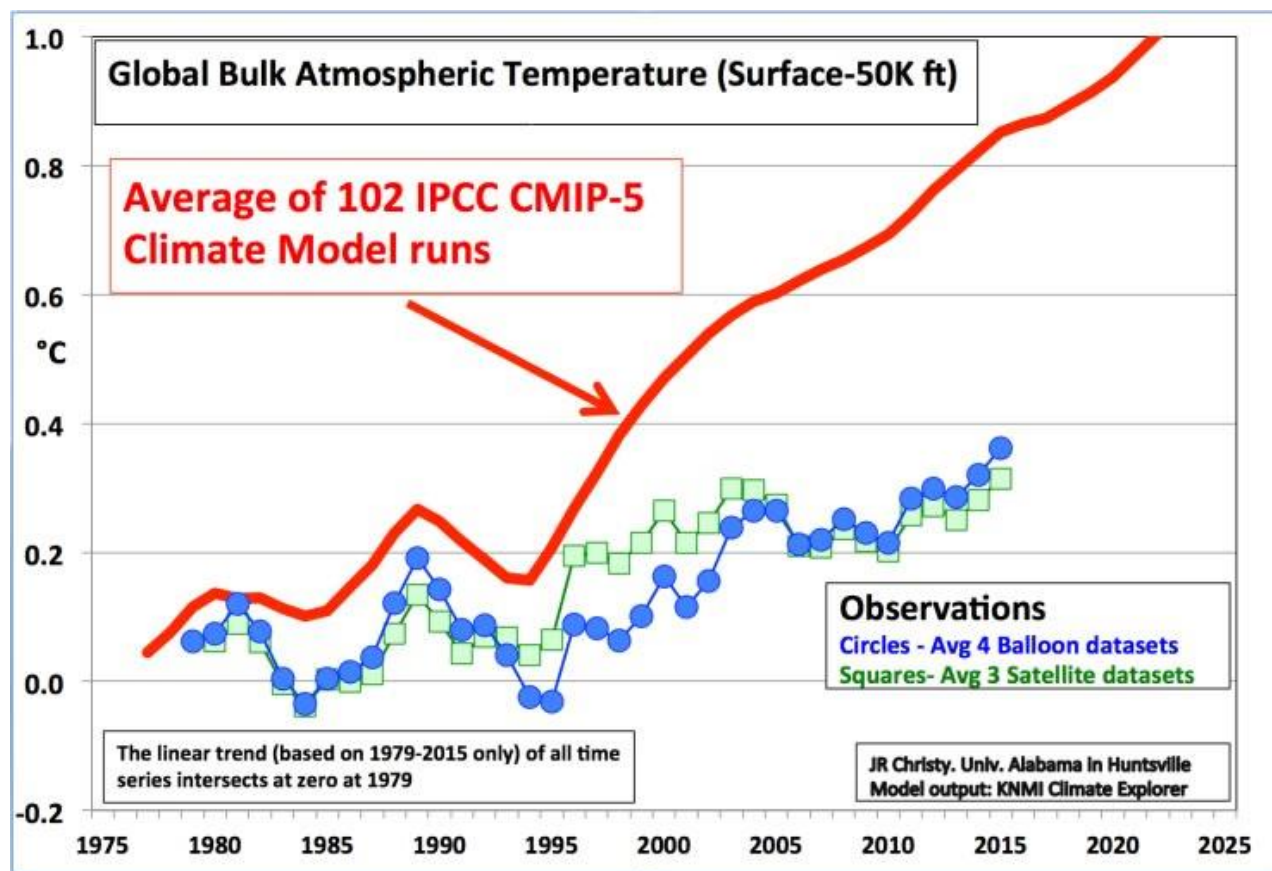
The warming  $\Delta T$  of (24) is a value averaged over the entire surface of the Earth and over an entire year. It is a very small number compared to the temperature differences between day and night, or



between winter and summer at most locations on the Earth. The warming from CO<sub>2</sub> is expected to be greater at night than during the day, and greater near the poles than near the equator. Because some time is needed to warm the oceans, the warmings in some finite time — the “transient climate sensitivities” — are a bit smaller than the equilibrium climate sensitivities,  $S$ , especially for short time intervals.

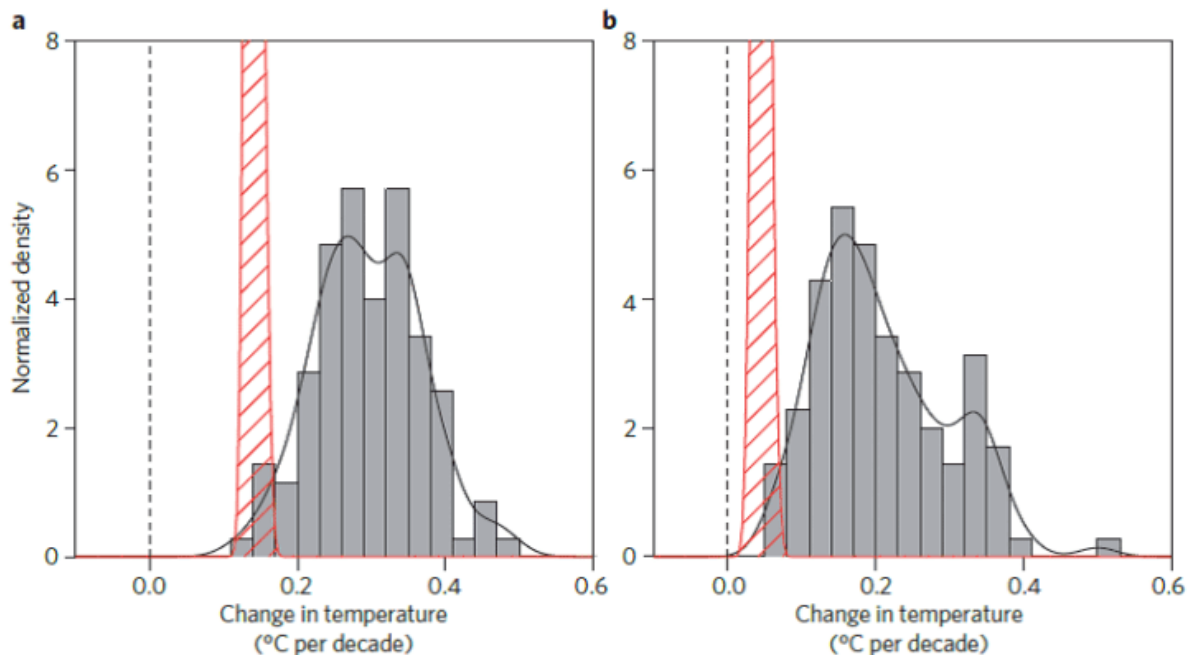
## Overestimate of $S$

Contrary to the predictions of most climate models, there has been very little warming of the Earth’s surface over the last two decades. An example is shown in Fig. 13, due to John Christy.[\[43\]](#)



**Figure 13.** A comparison of lower atmospheric temperatures, measured with balloons and satellites, with climate model predictions. The climate models, on which economic models and government policies are predicated, predict much more warming than has been observed.

The discrepancy between models and observations is also summarized by Fyfe, Gillett, and Zwiers, as shown in Fig. 14.[\[44\]](#)



**Figure 1** | Trends in global mean surface temperature. **a**, 1993–2012. **b**, 1998–2012. Histograms of observed trends (red hatching) are from 100 reconstructions of the HadCRUT4 dataset<sup>1</sup>. Histograms of model trends (grey bars) are based on 117 simulations of the models, and black curves are smoothed versions of the model trends. The ranges of observed trends reflect observational uncertainty, whereas the ranges of model trends reflect forcing uncertainty, as well as differences in individual model responses to external forcings and uncertainty arising from internal climate variability.

**Figure 14.** A comparison of the surface warming predicted by climate models with observed warming.

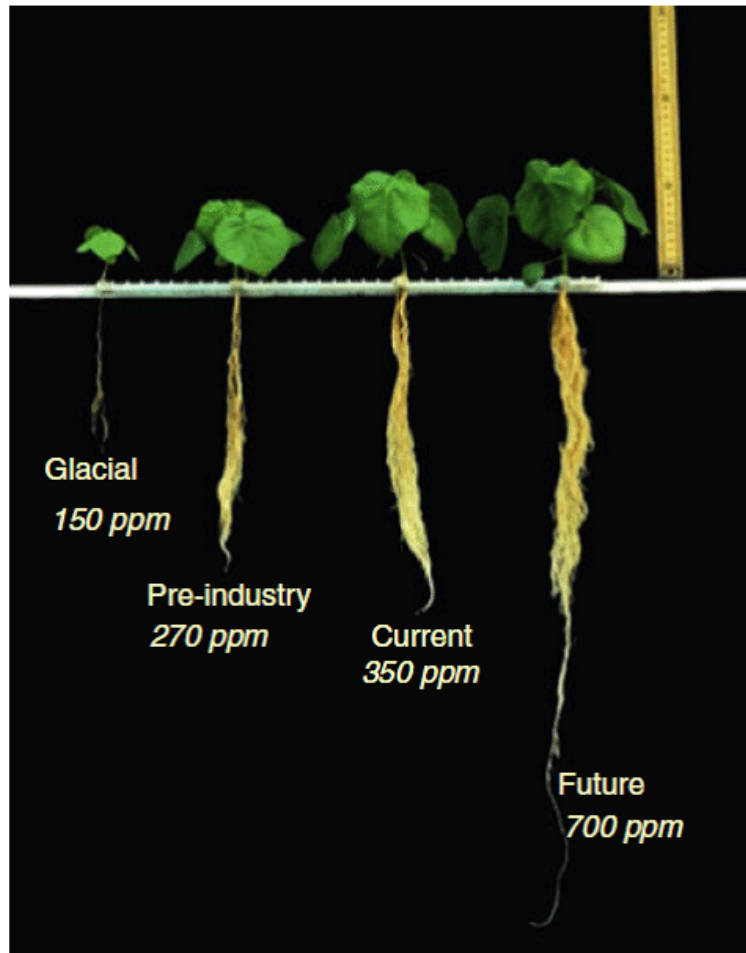
As one can see from Fig. 14, the warming observed over the period 1993–2012 has been about half the predicted value, while the observed warming during the period 1998–2012 has been about one fifth of the model predictions. And the discrepancy may well be worse than indicated by Fyfe, *et al.*, who used surface temperature records that are plagued with systematic errors, like urban heat island effects,<sup>[45]</sup> that give an erroneous warming trend to the Earth’s surface temperature. The satellite data of Fig. 7 do not have these systematic errors. Fig 14 shows data from a network of surface stations, but Fig. 13 shows the temperature change of the lower atmosphere, from the surface to 50,000 ft. The release of latent heat, as water vapor of rising air condenses to liquid water droplets and ice, should cause 10% to 20% more warming of the lower atmosphere than of the surface.

At this writing, more than 50 mechanisms have been proposed to explain the discrepancy of Fig. 14. These range from aerosol cooling to heat absorption by the ocean. Some of the more popular excuses for the discrepancy have been summarized by Fyfe, *et al.* But the most straightforward explanation for the discrepancy between observations and models is that the doubling sensitivity, which most models assume to be close to the “most likely” IPCC value,  $S = 3$  K, is much too large.

If one assumes negligible feedback, where other properties of the atmosphere change little in response to additions of CO<sub>2</sub>, the doubling efficiency can be estimated to be about  $S = 1$  K, for example, as we discussed in connection with Eq. (19). The much larger doubling sensitivities claimed by the IPCC, which look increasingly dubious with each passing year, are due to “positive feedbacks.” A favorite positive feedback is the assumption that water vapor will be lofted to higher, colder altitudes by the addition of more CO<sub>2</sub>, thereby increasing the effective opacity of the vapor. Changes in cloudiness can also provide either positive feedback which increases  $S$  or negative feedback which decreases  $S$ . The simplest interpretation of the discrepancy of Fig. 13 and Fig. 14 is that the net feedback is small and possibly even negative. Recent work by Harde indicates a doubling sensitivity of  $S = 0.6$  K.[\[46\]](#)

## Benefits of CO<sub>2</sub>

More CO<sub>2</sub> in the atmosphere will be good for life on planet earth. Few realize that the world has been in a CO<sub>2</sub> famine for millions of years — a long time for us, but a passing moment in geological history. Over the past 550 million years since the Cambrian, when abundant fossils first appeared in the sedimentary record, CO<sub>2</sub> levels have averaged many thousands of parts per million (ppm), not today’s few hundred ppm, which is not that far above the minimum level, around 150 ppm, when many plants die of CO<sub>2</sub> starvation.[\[47\]](#) An example of how plants respond to low and high levels of CO<sub>2</sub> is shown in Fig. 15 from the review by Gerhart and Ward.[\[48\]](#)



**Figure 15.** The response of seedlings of velvetleaf (*Abutilon theophrasti*), a  $C_3$  plant, to various  $CO_2$  levels. Velvetleaf can barely survive at the  $CO_2$  level of 150 ppm, which are approached at glacial maxima, when much of the  $CO_2$  has been absorbed by the cool oceans.

All green plants grow faster with more atmospheric  $CO_2$ . It is found that the growth rate is approximately proportional to the square root of the  $CO_2$  concentrations, so the increase in  $CO_2$  concentrations from about 300 ppm to 400 ppm over the past century should have increased growth rates by a factor of about  $\sqrt{4/3} = 1.15$ , or 15%. Most crop yields have increased by much more than 15% over the past century. Better crop varieties, better use of fertilizer, better water management, etc., have all contributed. But the fact remains that a substantial part of the increase is due to more atmospheric  $CO_2$ . A particularly dramatic example of the response of green plants to increases of atmospheric  $CO_2$  is shown in Fig. 16.[\[49\]](#)



**Figure 16.** Dr. Sherwood Idso with Eldarica pine trees grown in various amounts of CO<sub>2</sub> in experiments done about 10 years ago when the ambient concentration of CO<sub>2</sub> was 385 ppm. Photos taken by Craig Idso.

We owe our existence to green plants that convert CO<sub>2</sub> molecules and water molecules, H<sub>2</sub>O, to carbohydrates with the aid of sunlight. Land plants get the carbon they need from the CO<sub>2</sub> in the air. Other essential nutrients — water, nitrogen, phosphorus, potassium, etc. — come from the soil. Just as plants grow better in fertilized, well-watered soils, they grow better in air with several times higher CO<sub>2</sub> concentrations than present values.

The current low CO<sub>2</sub> levels have exposed a design flaw, made several billion years ago by Nature when she first evolved the enzyme, Ribulose-1,5-bisphosphate carboxylase/ oxygenase, or “RuBisCO” for short. RuBisCO is the most abundant protein in the world. Using the energetic molecules, adenosine triphosphate, or ATP, produced by the primary step of photosynthesis, RuBisCO converts CO<sub>2</sub> to simple carbohydrate molecules that are subsequently elaborated into sugar, starch, amino acids and all the other molecules on which life depends. A sketch of RuBisCO was given in Fig. 33 of the [Interview](#).

The “C” in the nickname RuBisCO, which stands for “carboxylase” in the full word, remind us of the CO<sub>2</sub> molecule that RuBisCO was designed to target. At current low levels of atmospheric CO<sub>2</sub>, much of the available CO<sub>2</sub> is used up in full sunlight and this spells trouble for the plant. The last letter “O” in the nickname RuBisCO, which stands for “oxygenase” in the full name, remind us that an alternate enzyme target is the oxygen molecule, O<sub>2</sub>. If RuBisCO, primed with chemical energy from ATP, cannot

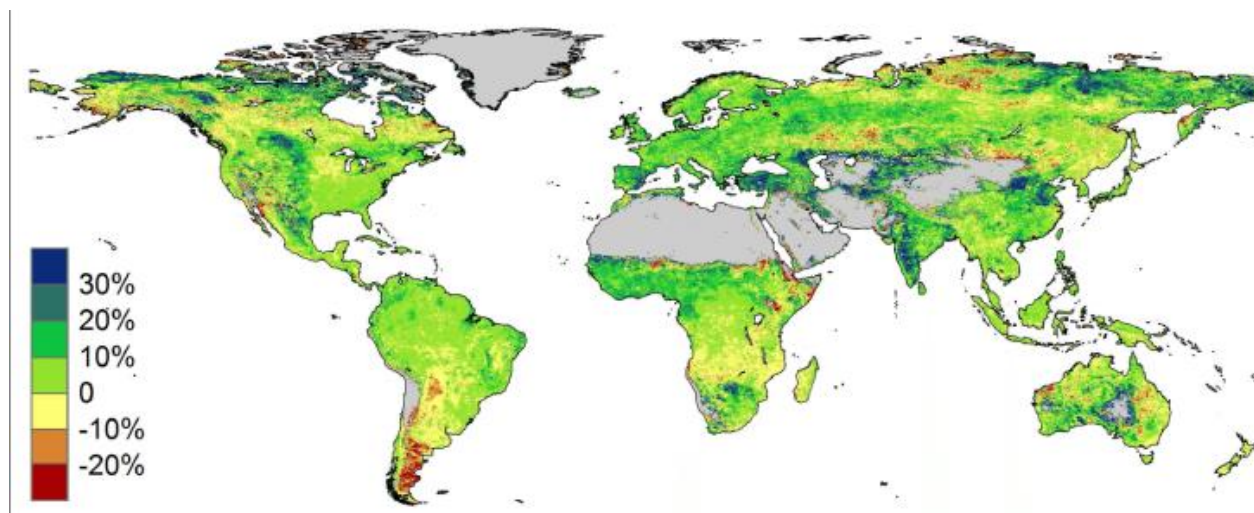
find a CO<sub>2</sub> molecule, it will grab an O<sub>2</sub> molecule instead and use its chemical energy to produce toxic byproducts like hydrogen peroxide instead of useful carbohydrates. This “photooxydation” is a serious problem. At current low CO<sub>2</sub> levels, it leads to a reduction of photosynthetic efficiency by about 25% in C<sub>3</sub> plants, which include wheat, rice, soybeans, cotton, and many others important crops. In these plants, the first molecule synthesized from CO<sub>2</sub> has three carbons, and they are said to have the C<sub>3</sub> photosynthetic pathway.

The low CO<sub>2</sub> levels of the past tens of millions of years have driven the development of C<sub>4</sub> plants (corn and sugar cane, for example) that cope with oxygen poisoning of RuBisCO by protecting it in special “bundle sheaths” from which oxygen is nearly excluded. CO<sub>2</sub> molecules are ferried into the bundle sheaths by molecules with four carbons, which give the C<sub>4</sub> pathway its name. A sketch of the C<sub>3</sub> and C<sub>4</sub> photosynthetic pathways is given in Fig. 15 of the [Interview](#). The extra biochemical energy for the more elaborate C<sub>4</sub> photosynthetic pathway comes at a cost, but one that is worth paying in times of unusually low CO<sub>2</sub> concentrations, like today. Thousands of experiments leave no doubt that all plants, both the great majority with the old-fashioned C<sub>3</sub> path, but also those with the new-fangled C<sub>4</sub> path, grow better with more CO<sub>2</sub> in the atmosphere. [\[50\]](#)

But the nutritional value of additional CO<sub>2</sub> is only part of its benefit to plants. Of equal or greater importance, more CO<sub>2</sub> in the atmosphere makes plants more drought resistant. Plant leaves are perforated by stomata, little holes in the gas-tight surface skin that allow CO<sub>2</sub> molecules to diffuse from the outside atmosphere into the moist interior of the leaf where they are photosynthesized into carbohydrates. A leaf in full sunlight can easily reach a temperature of 30 C, where the concentration of water molecules, H<sub>2</sub>O, in the moist interior air of the leaf is about 42,000 ppm, more than one hundred times greater than the 400 ppm concentration of CO<sub>2</sub> in fresh air outside the leaf. And CO<sub>2</sub> molecules, being much heavier than H<sub>2</sub>O molecules, diffuse more slowly in air. So, depending on the relative humidity of the outside air, as many as 100 H<sub>2</sub>O molecules can diffuse out of the leaf for every CO<sub>2</sub> molecule that diffuses in, to be captured by photosynthesis. This is the reason that most land plants need at least 100 grams of water to produce one gram of carbohydrate.

In the course of evolution, land plants have developed finely tuned feedback mechanisms that allow them to grow leaves with more stomata in air that is poor in CO<sub>2</sub>, like today, or with fewer stomata for air that is richer in CO<sub>2</sub>, as has been the case over most of the geological history of land plants. [\[51\]](#) If the amount of CO<sub>2</sub> doubles in the atmosphere, plants reduce the number of stomata in newly grown leaves by about a factor of two. With half as many stomata to leak water vapor, plants need about half as much water. Satellite observations like those of Fig. 17 from R.J. Donohue, *et al.*, [\[52\]](#) have shown a very pronounced “greening” of the Earth as plants have responded to the modest increase of CO<sub>2</sub> from about 340 ppm to 400 ppm during the satellite era. More greening and greater agricultural yields can be expected as CO<sub>2</sub> concentrations increase further.





**Figure 17.** The analysis of satellite observations by Dr. Randall J. Donohue and co-workers<sup>[53]</sup> shows a clear greening of the earth from the modest increase of CO<sub>2</sub> concentrations from about 340 ppm to 400 ppm from the year 1982 to 2010. The greening is most pronounced in arid areas where increased CO<sub>2</sub> levels diminish the water requirement of plants.

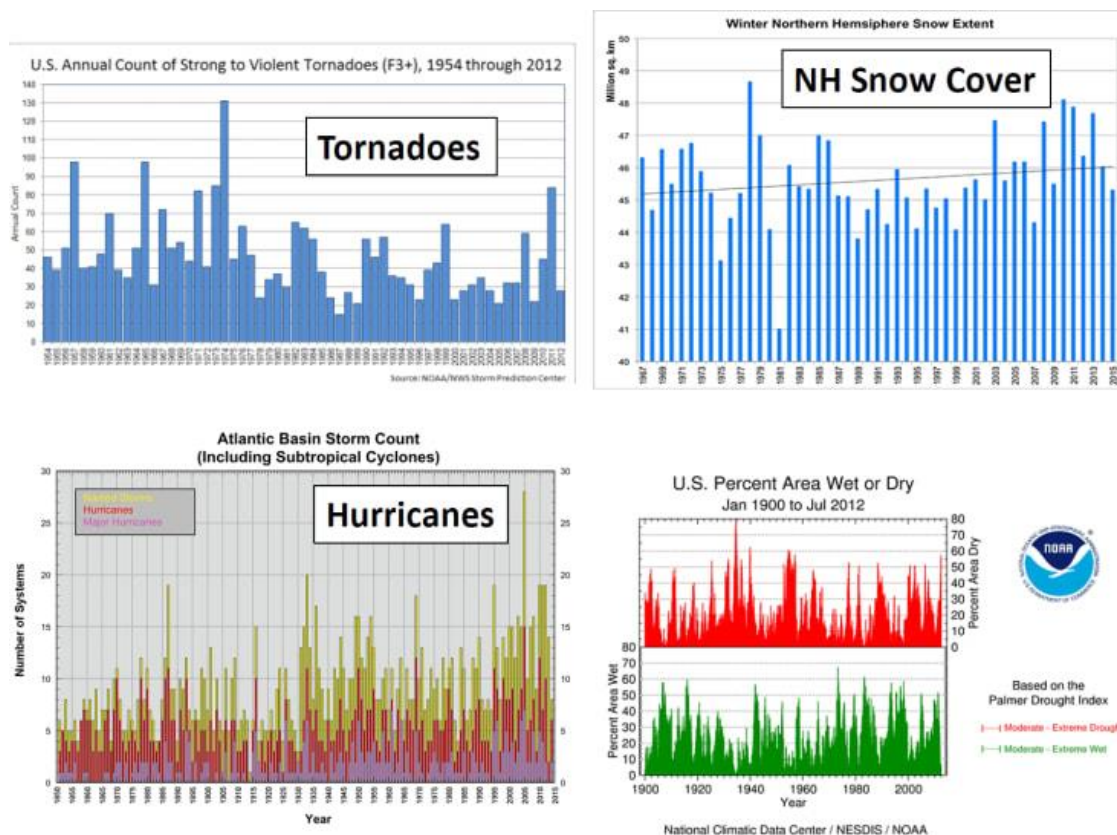
## More bogeymen

Fig. 13 and Fig. 14 show that the earth has stubbornly refused to warm nearly as much as demanded by computer models. To cope with this threat to full employment, the climate establishment has invented a host of bogeymen, other supposed threats from more CO<sub>2</sub>. It is almost comical to list them. For example, it has recently been claimed that beer supplies are threatened.<sup>[54]</sup>

The climate-alarm establishment has largely dropped the term “global warming” and replaced it by the much more flexible phrase “climate change.” The unspoken and assiduously promoted assumption is that the Earth’s climate would never change, were it not for mankind. But the Earth’s climate has always changed, and it always will. The evidence for climate change on all time scales is overwhelming. But past changes were not driven by CO<sub>2</sub>, and CO<sub>2</sub> will have little effect on future change.

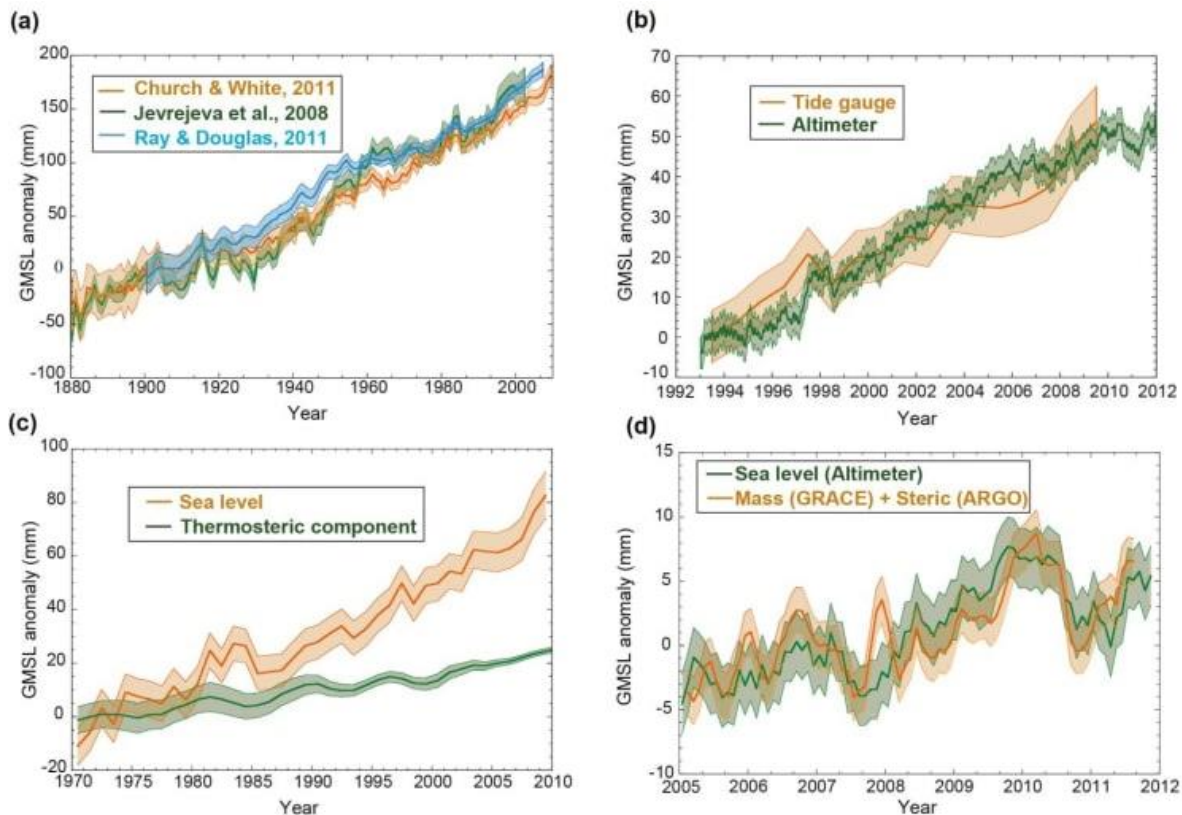
One of the bogeymen is that more CO<sub>2</sub> will lead to, and already has led to, more extreme weather, including tornadoes, hurricanes, droughts, floods, blizzards, or snowless winters. But as you can see from Fig. 18, the world has continued to produce extreme events at the same rate it always has, both long before and after there was much increase of CO<sub>2</sub> in the atmosphere. In short, extreme weather is not increasing.





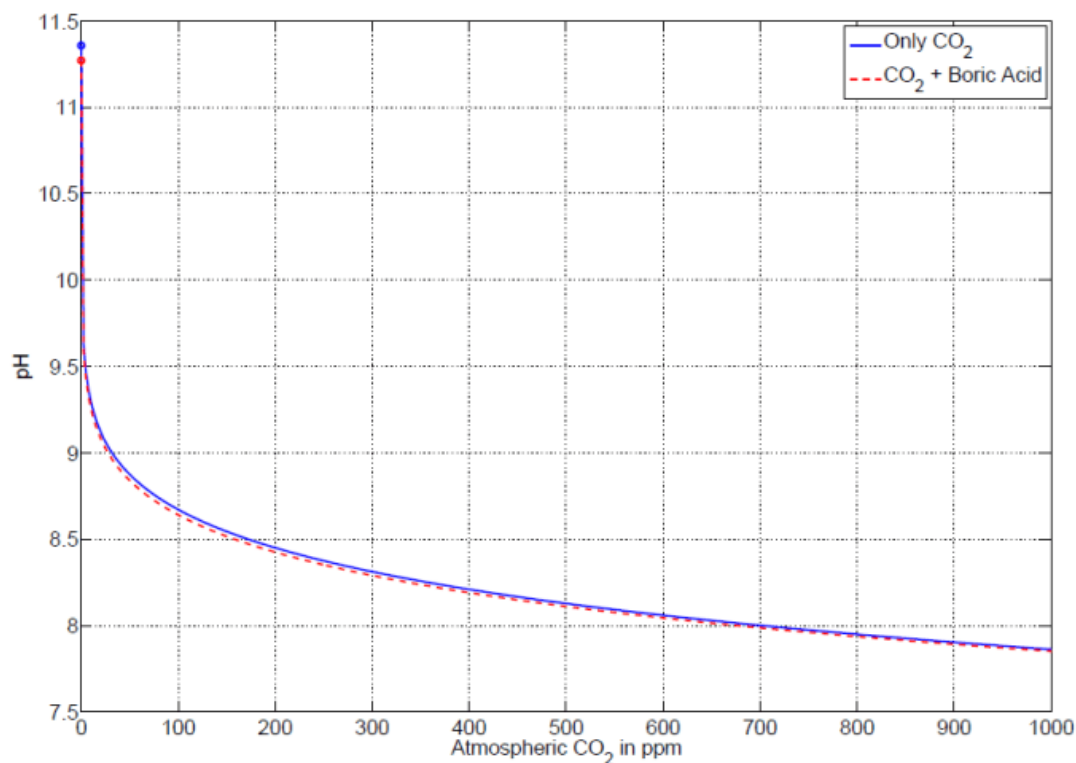
**Figure 18.** Extreme weather is not increasing. The yearly number of strong tornadoes is shown from 1954 to 2014, the yearly number of hurricanes from 1850 to 2015, the snow cover from 1967 to 2015, and the drought and flood indices from 1900 to 2012. [55]

We also hear that more CO<sub>2</sub> will cause rising sea levels to flood coastal cities, large parts of Florida, tropical island paradises, etc. The facts, from the IPCC's Fifth Annual Report (2013), are shown in Fig. 19. [56] A representative sea level rise of about 2 mm/year would give about 20 cm or 8 in of sea level rise over a century. For comparison, at Coney Island, Brooklyn, NY, the sea level at high tide is typically 4 feet higher than that at low tide.



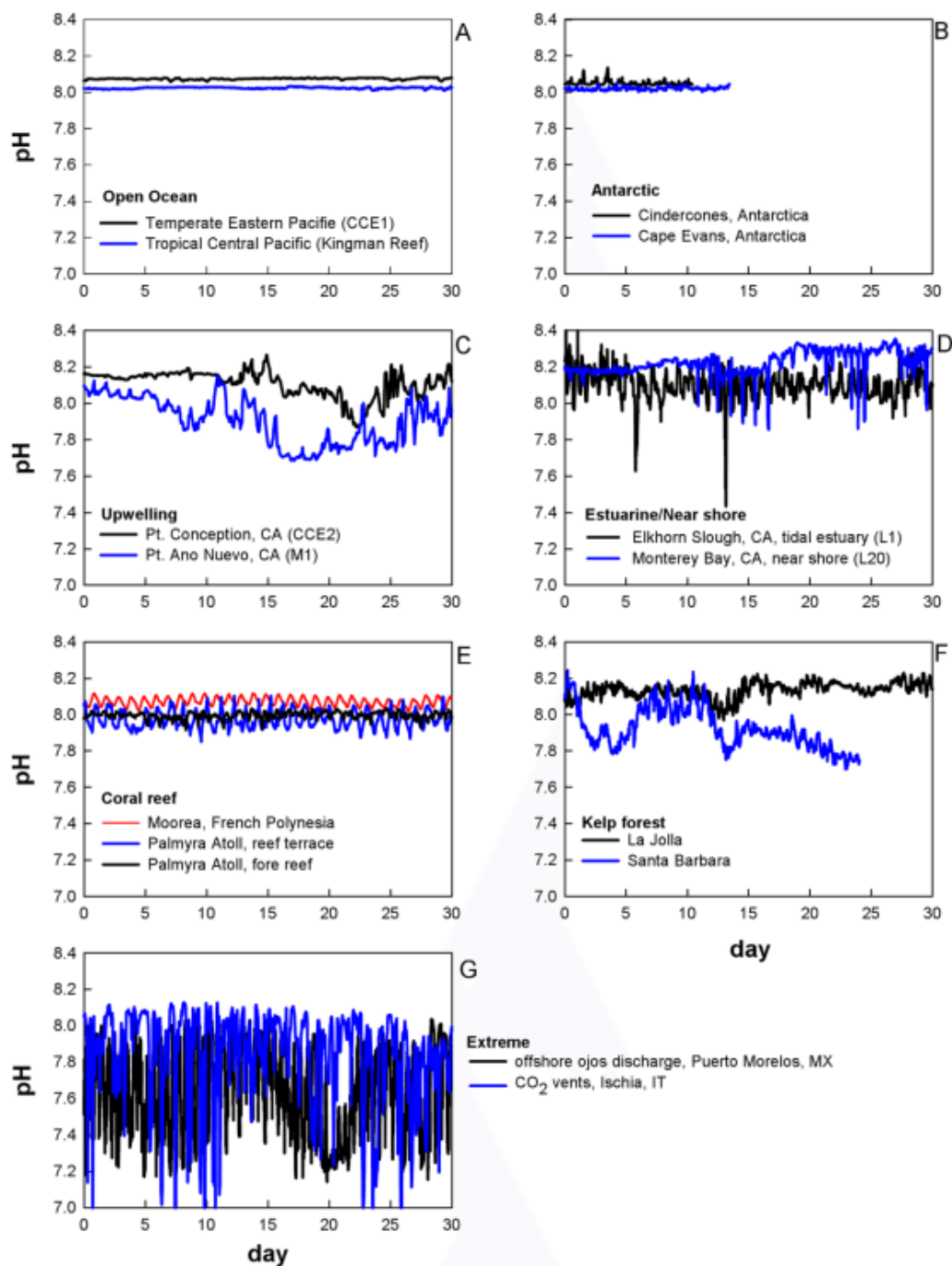
**Figure 19.** IPCC data on sea level. Since the year 1880, the sea level has been rising at an average rate of about 1.7 mm/year, but up to a factor of 2 faster or slower in shorter time intervals. GMSL means “global mean sea level.”

Yet another bogeyman is “ocean acidification.” The ocean is mildly alkaline with a representative pH of 8, compared to a pH of 7 for neutral water (neither acid nor alkaline) at a temperature of 25 C. Fig. 20 shows the pH of ocean surface water in contact with the atmosphere with various concentrations of CO<sub>2</sub>.[\[57\]](#)



**Figure 20.** pH of ocean surface water at a temperature of 25 C versus the concentration of CO<sub>2</sub> in the atmosphere. An ocean alkalinity of 2.3 mM was assumed, and a boron concentration of 0.42 mM. If there were no CO<sub>2</sub> in the atmosphere, the ocean pH would be about 11.3, close to that of household ammonia and much too caustic for most life. Boric acid, the second most abundant weak acid after CO<sub>2</sub>, lowers this caustic pH only slightly. It is CO<sub>2</sub> that gets the ocean pH down to values hospitable to life. Doubling the atmospheric CO<sub>2</sub> level from the present value of 400 ppm to 800 ppm would reduce the pH from 8.2 to 7.9, a change comparable to normal variations of pH with position and time in the oceans today, as shown in Fig. 21.

Measured variations of pH in the ocean today are shown in Fig. 21.[\[58\]](#) In biologically productive areas, photosynthesizing organisms remove so much CO<sub>2</sub> during the day that the pH can increase by 0.2 to 0.3 units, with similar decreases at night when respiring organisms return CO<sub>2</sub> to the water.



**Figure 21.** The natural, day-by-day variations in pH of biologically productive areas of the oceans are larger than those that would be caused by doubling CO<sub>2</sub> concentrations. Doubling would take a century or more.

## Climate Science

Droughts, floods, heat waves, cold snaps, hurricanes, tornadoes, blizzards, and other weather- and climate-related events will complicate our life on Earth, no matter how many laws governments pass to “stop climate change.” But if we understand these phenomena, and are able to predict them, they

will be much less damaging to human society. So, I strongly support high-quality research on climate and related fields like oceanography, geology, solar physics, etc. Especially important are good measurement programs like the various satellite measurements of atmospheric temperature<sup>[59]</sup> or the Argo<sup>[60]</sup> system of floating buoys that is revolutionizing our understanding of ocean currents, temperature, salinity, and other important properties.

But too much “climate research” money is pouring into very questionable efforts, like mitigation of the made-up horrors mentioned above. It reminds me of Gresham’s Law: “Bad money drives out good.”<sup>[61]</sup> The torrent of money showered on scientists willing to provide rationales, however shoddy, for the war on fossil fuels, and cockamamie mitigation schemes for non-existent problems, has left insufficient funding for honest climate science.

The *Philosophical Transactions of the Royal Society of London* — once edited by John Tyndall, who discovered greenhouse gases — is one of the most prestigious scientific journals in the world. Every issue of this journal used to include an “Advertisement,” which contained the statement:<sup>[62]</sup>

It is an established rule of the Society, to which they will always adhere, never to give their opinion, as a Body, upon any subject, either of Nature or Art, that comes before them.

Alas, recent leaders of the Royal Society have ignored this precept. Explaining the politically correct view on climate, former President of the Royal Society, Lord Robert May, told BBC reporter Roger Harrabin:<sup>[63]</sup>

I am the President of the Royal Society, and I am telling you the debate on climate change is over.

These are the tactics of a religious cult or a pseudoscience like Lysenkosim.<sup>[64]</sup> It is not traditional science, where everything is supposed to be open to question.

## Summary

The Earth is in no danger from increasing levels of CO<sub>2</sub>. More CO<sub>2</sub> will be a major benefit to the biosphere and to humanity. Some of the reasons are:

- As shown in Fig. 1, much higher CO<sub>2</sub> levels than today's prevailed over most last 550 million years of higher life forms on Earth. Geological history shows that the biosphere does better with more CO<sub>2</sub>.
- As shown in Fig. 13 and Fig. 14, observations over the past two decades show that the warming predicted by climate models has been greatly exaggerated. The temperature increase for doubling CO<sub>2</sub> levels appears to be close to the feedback-free doubling sensitivity of  $S = 1$  K, and much less than the "most likely" value  $S = 3$  K promoted by the IPCC and assumed in most climate models.
- As shown in Fig. 12, if CO<sub>2</sub> emissions continue at levels comparable to those today, centuries will be needed for the added CO<sub>2</sub> to warm the Earth's surface by 2 K, generally considered to be a safe and even beneficial amount.
- Over the past tens of millions of years, the Earth has been in a CO<sub>2</sub> famine with respect to the optimal levels for plants, the levels that have prevailed over most of the geological history of land plants. There was probably CO<sub>2</sub> starvation of some plants during the coldest periods of recent ice ages. As shown in Fig. 15–17, more atmospheric CO<sub>2</sub> will substantially increase plant growth rates and drought resistance.
- There is no reason to limit the use of fossil fuels because they release CO<sub>2</sub> to the atmosphere. However, fossil fuels do need to be mined, transported, and burned with cost-effective controls of real environmental problems — for example, fly ash, oxides of sulfur and nitrogen, volatile organic compounds, groundwater contamination, etc.

Sometime in the future, perhaps by the year 2050 when most of the original climate crusaders will have passed away, historians will write learned papers on how it was possible for a seemingly enlightened civilization of the early 21<sup>st</sup> century to demonize CO<sub>2</sub>, much as the most "Godly" members of society executed unfortunate "witches" in earlier centuries.

The global warming crusade has been driven by many forces: political imperatives, huge amounts of research funds for scientists willing to support politicians, crony capitalists getting rich from "saving the planet," the puzzling need by so many people to feel a sense of guilt, anxieties about overpopulation of the world, etc.

But genuine science has not been one of the drivers. Widespread scientific illiteracy — alas, even in the scientific community — has facilitated this latest episode of human folly. I hope very much that this Focused Civil Dialogue contributes to increased scientific literacy.



## Acknowledgement

My son, James W. Happer, read several drafts of this manuscript and made many helpful suggestions on how to improve it.

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