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A Global Warming Primer

Introduction

The purpose of this primer is to help the reader determine whether our understanding of the Earth's climate is adequate to predict the long term effects of carbon dioxide released as a result of the continued burning of fossil fuels. The answer is not without consequence. If our understanding is adequate, and the conclusions of the Intergovernmental Panel on Climate Change (IPCC) are valid, then the 1997 Kyoto Protocol should be accepted, strengthened, and implemented.

Long term curtailment of carbon dioxide emissions will have an enormous impact on everyone, but especially on the developing world where most of the Earth's population resides. If carbon dioxide emissions are harmful, development along the Western model should be actively discouraged, if not prevented. More than two billion additional people using energy derived from fossil fuels at current Western levels of consumption would release unacceptable quantities of carbon dioxide.

Developed countries, if they are to retain anywhere near their current per capita energy consumption, must dramatically increase the use of nuclear power for electricity production. Alternative sources of energy such as solar, wind, etc. simply do not have the potential to allow consumption of energy at the current rate. That is why proponents of these energy sources couple their advocacy with energy conservation. Replacement of fossil and nuclear plants in the developed world with alternative energy sources, while not impossible, would require massive social, economic, and demographic change.

If, on the other hand, the conclusions of the IPCC are based on an over-confident assessment of the validity of climate models, then the Kyoto Protocol should be rejected because it lacks a sound scientific basis. Such over-confidence is not rare in science. One need only point to cold fusion, polywater, the fifth force and other fiascoes that are less well known. As this primer will show, the predictions of existing climate models do *not* form a sound basis for public policy decisions. With continued research and data collection, this assessment could change in the future.

Nevertheless, there may be very good reasons to curtail our burning of fossil fuels, and, in particular, the burning of coal to produce electricity. Coal is an environmental disaster. A single 1,000-megawatt plant burns more than two million tons of coal per year.[1] It is estimated that air pollution alone from coal-fired electric plants results in thousands of deaths each year.[2] This is because of the toxicity of the emissions and the scale of operations. Although the radiation levels are not dangerous to the public, coal plants also discharge greater quantities of radioactive materials into the atmosphere than nuclear plants — even when more than 95% of the fly ash is precipitated, and vastly more if it is not.[3] To be sure, oil and natural gas are far cleaner than coal, but both — unless very much larger reserves are found at a reasonable price — will be too valuable in the future as sources of energy for transportation and heating to be used for electricity generation.

This primer is organized in terms of answers to a series of fundamental questions about global warming — questions such as: How much warming has there been over the last century, and how does this warming compare to past climate variations? One of the principal sources of data is the final report[4] of Working Group 1 of the IPCC, jointly sponsored by the World Meteorological Organization and the United Nations Environment Program, first published in 1990. While additional work has been done by the IPCC since this report was published, the 1990 document is the one that formed much of the basis for negotiation of the 1997 Kyoto Protocol. Other sources used in this primer include the primary scientific literature, including research published since 1990, as well as the midterm synthesis of the Joint Global Ocean Flux Study,[5] a multi-disciplinary program that addresses the biology, chemistry, and physics of the transport and transformation of carbon within the ocean and across its boundaries to the atmosphere and land.

The principal tool for studying global warming is large scale numerical computer models that simulate the coupling between the ocean and the atmosphere. These coupled ocean-atmosphere general circulation models are used to predict the effects on climate of the rising level of carbon dioxide in the atmosphere. This rise is usually assumed to result from changing land use and the burning of fossil fuels. The impact of changing atmospheric concentrations of water vapor (the principal greenhouse gas) is treated as a feedback in climate models.

First, however, it may be useful to put the issue of climate change in historical perspective. In 1976, when carbon dioxide concentrations in the atmosphere had increased by almost 20% compared to their pre-industrial values, Lowell Ponte wrote in *The Cooling*[6] that "Our planet's climate has been cooling for the past three decades... Some monitoring stations inside the Arctic Circle report that temperature has been falling by more than 2°C *per decade* for the past thirty years." In the preface to the book, Reid A. Bryson, director of the Institute for Environmental Studies at the University of Wisconsin in Madison, wrote that "There is no agreement on whether the Earth *is* cooling. There is not unanimous agreement on whether it *has* cooled, or one hemisphere has cooled and the other warmed. One would think that there might be consensus about what data there is — but there is not. There is no agreement on the causes of climatic change, or even *why* it should not change among those who so maintain. There is certainly no agreement about what the climate will do in the next century, though there is a majority opinion that it *will* change, more or less, one way or the other. Of that majority, a majority believe that the longer trend will be downward." It was, nevertheless, clear from other scientific literature of the period that we were sliding into a new ice age.

How much warming has there been over the last century, and how does this compare to natural variations in climate over the last 10,000 years since the last ice age?

During the ice ages of the last million years global temperatures varied by about 10-12°C, and until about 10,000 years ago global temperatures averaged over the ice ages were perhaps 4°C lower than at the beginning of the 20th century. Global temperatures were higher than at the beginning of the 20th century by about 1.3°C during the Holocene Maximum, which extended from somewhat over 7,000 years ago to about four thousand years ago. Since then variations are thought to have been within a 2°C range; i.e., within a degree of the temperature at the beginning of the 20th century.

The most recent variations of significance have been the Medieval warm period from 1000 AD to 1400 AD, which was about 0.6-0.7°C warmer than the beginning of the twentieth century, and the cooling between 1400 AD and 1900 AD. This cooling period included the Little Ice Age from 1500 AD to 1700 AD when temperatures were 0.6-0.7°C cooler. From 1700 AD to 1900 AD global temperatures were about 0.3°C lower than at the beginning of the twentieth century, with a rapid rise after the turn of the century. *So since 1000 AD temperatures have varied over a range of about 1.5°C, and over almost the last 10,000 years they have varied within a range of 2°C.* This can be considered the "natural" variation over these periods. The reader should note at this point that the carbon dioxide concentration in the atmosphere is believed to have been relatively constant before 1770, and has risen steadily since then. *Therefore, none of the natural variation before 1770 was due to changes in carbon dioxide concentration.*

Relative to the average of 1951-1980, *global* temperature variations over the last century (actually between 1860 and 1990) were as follows[7]:

- 1860-1920 — Global temperature was about 0.3°C cooler than the average.
- 1920-1940 — Global temperature rose by about 0.35°C to slightly above the average.
- 1940-1975 — Global temperature shows a gradual cooling of perhaps 0.1°C.
- 1975-1990 — Global temperature rose above the average by about 0.3°C.

The total range of variation since 1860 is about 0.6°C. This is more than three times smaller than the natural range of about 2°C. The most recent report of the IPCC puts the global warming over the 20th century at 0.6°C ±0.2°C. The range of uncertainty is now pegged at the 95% confidence level, making it "very likely" that the Earth has actually warmed.[8]

Coupled ocean-atmosphere, general-circulation models must then be able to duplicate the temperature variations since 1860 and, if the rise of 0.6°C over this period is due to human activities, must prove that these changes are a result of land use changes and fossil fuel burning. It should also be kept in mind that the error in global temperature measurements over the last century is at least ±0.1°C.

It should also be noted that there are discrepancies between temperature measurements made at the surface of the Earth — which show a warming trend since 1979 — and from satellites, which show essentially no tropospheric trend. Climate models, contrary to the data, predict a stronger warming trend for the mid-troposphere than for the surface of the Earth.[9]

Summary: Variations in global temperatures over the last 10,000 years have been in the range of ±1°C. Because the carbon dioxide concentration in the atmosphere over this time is believed to have remained relatively constant, the range of 2°C is due to other causes and can be considered the "natural" range of temperature variations for the period. Between 1920 and 1940 temperature rose 0.3°C; from 1940 to 1975 global temperature decreased slightly while carbon dioxide concentration continued to rise; and temperature rose from 1975 to the present. The total rise in global temperature since 1860 has been about 0.6°C, more than three times smaller than natural variations over the last 10,000 years.

What is the greenhouse effect?

Disregard for a moment the exact definition of the greenhouse effect. Without this effect, the average temperature of the lower atmosphere would be about -18°C; with it, the temperature is +15°C, a difference of 33°C. The key question is: What gases in the atmosphere cause the greenhouse effect? The answer is, principally water vapor and carbon dioxide.

How much heating is due to each? As will be seen below, answers vary widely but water vapor is responsible for most of the greenhouse effect. Carbon dioxide is a minor greenhouse gas, but nevertheless an important one.

The layer of the Earth's atmosphere from the ground up to an altitude of a few miles is called the *troposphere*, and the boundary between it and the rest of the atmosphere above is called the *tropopause*. The tropopause is about 11 miles high at the equator and only about five miles high at the poles. The troposphere is the part of the atmosphere that is responsible for the greenhouse effect, since it contains essentially all of the greenhouse gases. Because the troposphere and the Earth's surface and boundary layer are closely coupled by air motions, they are considered to be a single thermodynamic system. It is for this reason that changes in radiative flux at the tropopause are used to express changes to the climate system. This is discussed in greater detail below.

The energy to warm the Earth comes from the Sun, and its flux is usually measured in watts per square meter (w/m^2). The value of this flux at the Earth's distance from the Sun is 1360 w/m^2 and is called the "solar constant." We are interested in how much of this is ultimately absorbed, and how it affects the Earth's climate.

Determining how much solar radiation is absorbed by the Earth involves some geometry. As seen from space, the Earth looks like a disk of area πr_e^2, where r_e is the radius of the Earth; so when averaged over the whole Earth, which has a surface area of $4\pi r_e^2$, the amount of radiation incident on the Earth is

$$\left(\frac{\pi r_e^2}{4\pi r_e^2}\right) \times 1367 \,\frac{w}{m^2} \;=\; 342 \,\frac{w}{m^2} \,.$$

Of this amount, the Earth *reflects* about 100 w/m^2 back into space (variations depend on cloud cover as well as atmospheric aerosol concentrations), so the net amount absorbed by the Earth is 242 w/m^2 — averaged over the whole Earth. For the Earth to be in what is known as radiative equilibrium, it must also radiate this amount into space.

Radiative equilibrium can only exist as a long-term global average, since changes in solar radiation, aerosols introduced into the upper atmosphere by large volcanic eruptions, etc., cause short-term fluctuations in the balance, and could result in a changed equilibrium temperature.

The major constituents of the atmosphere, including both water vapor and carbon dioxide, are transparent to visible light. Since sunlight peaks in the visible part of the spectrum, the atmosphere is essentially transparent to incoming radiation from the Sun. The radiation from the Earth, on the other hand, is thermal radiation (long-wavelength infrared) — the spectral region where carbon dioxide and water vapor absorb radiation. Carbon dioxide absorbs radiation primarily in a very narrow frequency band, while water vapor absorbs over a much larger spectral range. The details of carbon dioxide absorption are discussed shortly.

The oceans dominate the Earth and its radiation into space. With this understanding, the greenhouse effect, *G*, is defined as (the units are again w/m^2)

> *G= Thermal radiation emitted by the oceans — Upward thermal radiation from the tropopause*

That is, the lower atmosphere (troposphere) is assumed to be bounded by the surface of the ocean below and the tropopause above. The greenhouse effect is then the difference in long wavelength infrared radiation emitted by the surface of the ocean and that radiated into space from the top of the troposphere. It is the amount of radiation absorbed by the troposphere between the ocean's surface and the tropopause.

The value of the global mean greenhouse effect *G* is about 146 w/m^2. This value is for a clear sky. Average cloud cover adds another 33 w/m^2 for a total of about 179 w/m^2.[10] This trapping of radiation is what causes the troposphere to be 33°C warmer than it would be without the greenhouse effect. How the greenhouse effect affects surface temperature is discussed below.

How much of the greenhouse effect is due to different contributions from water vapor, carbon dioxide and other gases is difficult to determine. Section two of the IPCC report states that:

> "Of the atmospheric gases, the dominant greenhouse gas is water vapour. If H_2O was the only greenhouse gas present, then the greenhouse effect of a clear-sky mid-latitude atmosphere, as measured by the difference between the emitted thermal infrared flux at the surface and the top of the atmosphere, would be about 60-70% of the value with all gases included; by contrast, if CO_2 alone was present, the corresponding value would be about 25%."

Notice that estimates are given for a clear sky, thereby neglecting the contribution from the water vapor in clouds. As noted above, clouds add 33 w/m^2 to the clear-sky greenhouse effect of 146 w/m^2, a 23% increase.

Estimates in the literature vary widely. Barry and Chorley[11] maintain that water vapor accounts for 64% of the greenhouse effect, carbon dioxide 21%, ozone 6% and other trace gases 9%. If the 64% is for a clear sky (consistent with the IPCC estimate), it would not seem to be possible to add the contribution from water vapor in clouds since the percentages given by Barry and Chorley add up to 100%. Jacobson[12] states that water vapor is responsible for 90% of the greenhouse effect, leaving 10% for carbon dioxide and the other greenhouse gases.

Radiative forcing is defined as the change in net downward radiative flux at the tropopause resulting from any process that acts as an external agent to the climate system; it is generally measured in w/m^2. Examples are variations in the amount of solar radiation reaching the Earth and changes in the concentrations of infrared-absorbing gases in the atmosphere.

Increasing the amount of carbon dioxide in the atmosphere by, for example, a factor of two does not double the amount of infrared radiation absorbed by this gas. The reason for this is as follows: Carbon dioxide has three absorption bands at wavelengths of 4.26, 7.52, and 14.99 micrometers (microns).[13] The Earth's emission spectrum, treated as a black body (no atmospheric absorption), peaks at between 15 and 20 microns, and falls off rapidly with decreasing wavelength. As a result, the carbon dioxide absorption bands at 4.26 and 7.52 microns contribute little to the absorption of thermal radiation compared to the band at 14.99 microns.

Natural concentrations of carbon dioxide are great enough that the atmosphere is opaque even over short distances in the center of the 14.99 micron band. As a result, at this wavelength, the radiation reaching the tropopause from above and below the tropopause is such that the net flux is close to zero.

If this were the whole story, adding more carbon dioxide to the atmosphere would contribute nothing to the greenhouse effect and consequently could not cause a rise in the Earth's temperature. However, additional carbon dioxide does have an influence at the edges of the 14.99 micron band. Because of this marginal effect, the change in forcing due to a change in carbon dioxide concentration is proportional to the natural logarithm of the fractional change in concentration of this gas. Specifically, the IPCC gives

$$\Delta F = 6.3 \ln (C/C_0) \text{ w/m}^2$$

where ΔF is the change in forcing, and C_0 and C are the initial and final carbon dioxide concentrations. This approximation breaks down for very low concentrations and for concentrations greater than 1,000 ppmv, but is valid in the range of practical interest. The Earth's temperature is therefore relatively insensitive to changes in carbon dioxide concentrations, a doubling leading to a ΔF of only 4.4 w/m^2.

The reader should not leave this section thinking that the greenhouse effect is really understood. In fact, simple, basic questions have not yet been answered. Consider what happens if the temperature of the Earth rises: this would lead to more water vapor in the atmosphere, which traps more outgoing thermal radiation, which raises the temperature of the Earth, which leads to more water vapor in the atmosphere, which... This is known as the runaway or super greenhouse effect. Worse yet, the greenhouse effect increases much faster than linearly with increasing temperature, as will be discussed below. Since the Earth shows no runaway or super greenhouse effect, there must be some negative feedback mechanism in operation. Although there have been many studies of this phenomenon, none has yielded conclusive results.[14]

The runaway greenhouse effect is often associated with the planet Venus, which has a surface temperature of some 477°C. For the Earth, the average global greenhouse effect G is about 179 w/m^2 and the absorbed solar radiation is 242 w/m^2. Note that the greenhouse effect is less than the absorbed solar radiation. Venus, although it is closer to the Sun and receives twice as much solar radiation as the Earth at the top of its atmosphere, actually absorbs less solar radiation than the Earth (only about 150 w/m^2). This is due to its high albedo: Venus reflects some 80% of incoming radiation compared with about 30% for the Earth. Venus' high surface temperature is not a result of absorbing more energy from the Sun than the Earth does, but rather is due to an enormous greenhouse effect, estimated to be 17,000 w/m^2.

Could human activities that produce carbon dioxide force the Earth into a runaway greenhouse effect that could lead to a situation similar to that found on Venus? No. The Earth and Venus have many differences, even though they are often referred to as sister planets. The lower atmosphere of the Earth is simply not massive enough to sustain a large greenhouse effect.[15] The atmosphere of Venus is 96% carbon dioxide, the rest being nitrogen and trace gases. It is 90 times as massive as that of the Earth, resulting in a surface pressure that is also ninety times that of Earth, comparable to the pressure found at a depth of one kilometer in the Earth's oceans. The length of one day on Venus is 243 Earth days, although the cloud tops on Venus rotate some sixty times as fast. Unlike the Earth, almost all of the absorption of incident solar radiation on Venus takes place at an altitude of about 60 kilometers — in the upper regions of the clouds. There are no lessons to be learned fromVenus about human activities on the Earth.

Return now to Earth, and in particular to the tropics, where absorbed solar radiation exceeds that lost from the Earth-atmosphere system. Heat is transported from the tropics to regions poleward of about 40° N and 40° S latitude, where more radiation is lost to the Earth than gained. This is achieved by a complex set of atmospheric motions driven by the heating differences between the tropics and other parts of the Earth, as well as the Earth's rotation. While radiative equilibrium exists as a global average, not every region of the Earth need be in radiative equilibrium.

To understand the greenhouse effect in the tropics it is important to realize that the effect does not vary linearly with temperature. Rather, it is the normalized greenhouse effect, defined as

$$g = \frac{G}{\sigma T_S^4},$$

that varies linearly with temperature — at least up to a sea surface temperature of 25°C, as will be discussed further below. Here G is the greenhouse effect defined above, T_S is the absolute surface temperature, and σ is Stefan-Boltzmann constant.[16] The emission of thermal radiation by the surface of the Earth (and hence the trapping of this radiation in the troposphere) varies as the fourth power of the surface temperature. This dependence on temperature is true of any object that radiates as a "black body." Dividing G by the fourth power of the temperature "normalizes" G by eliminating this dependence.

If one plots the normalized greenhouse effect (for either a clear or a cloudy sky) as a function of temperature, the relationship is seen to be linear up to a surface temperature of about 25°C.[17] Above this value, there is a rapid, non-linear increase in the normalized greenhouse effect.

Ramanathan and Collins[18] observed during the 1987 El Niño, when the equatorial Pacific warmed by as much as 3°C, that the total greenhouse effect (defined as the clear-sky atmospheric portion of the effect plus the enhancement due to clouds) increased with surface temperature at a rate that exceeded the rate of increase of radiation emitted from the ocean's surface. At a sea-surface temperature of 27°C, the greenhouse effect was measured to be about 184 w/m^2. As the sea-surface temperature increased by 3°C to 30°C, the greenhouse effect rapidly rose by 100 w/m^2. They attributed this large increase to optically thick cirrus clouds in the upper troposphere. In response to this runaway greenhouse effect it was proposed that these cirrus clouds limit sea surface temperatures to less than 32°C by shielding the ocean from solar radiation.

Ramanathan and Collins measured two parameters C_S and C_l known as the cloud short and long wavelength forcings. C_S measures the increase in albedo due to an increase in cloud cover and C_l the increase in absorption of long wavelength radiation by the clouds. Remarkably, in the tropics these generally are equal and opposite so that they cancel.

During normal periods Ramanathan and Collins found that $C_S = -0.951C_l$, so that the clouds had a slight warming effect. However, during the 1987 El Niño they found using data taken during the event that $C_S = -1.20C_l$, yielding a slight cooling, in support of their proposal. They go on to note that in the tropics "It would take more than an order-of-magnitude increase in atmospheric CO_2 to increase the maximum SST [Sea Surface Temperature] by a few degrees, in spite of a significant warming outside the equatorial regions. In this regard, the present hypothesis departs considerably from modern general circulation models."

R. T. Pierrehumbert,[19] assuming that $C_S = -C_l$, showed that cirrus clouds cannot prevent the runaway greenhouse effect in the tropics. This would not be the case if there is a substantial departure from the observed cancellation between cloud greenhouse and cloud albedo effects (so that $C_S \neq -C_l$). He also points out that: "The physical basis of the cancellation is so far unexplained, and the circumstances under which the cancellation will continue to hold in perturbed climates are unknown." While Pierrehumbert claims that the proposed mechanism of Ramanathan and Collins cannot stabilize the greenhouse effect in the tropics, he does note that "...the cloud longwave and shortwave forcing do not cancel exactly but instead sum up to a small cooling in the course of El Niño fluctuations. *Though the residual is small, it is nonetheless comparable to other small forcings driving climate, such as the radiative perturbation due to doubling* CO_2 [emphasis added]."

Summary: The greenhouse effect keeps the lower atmosphere of the Earth about 33°C warmer than would otherwise be the case. Water vapour is the principal greenhouse gas and is responsible for as much as 90% of the greenhouse effect. Although carbon dioxide is a minor greenhouse gas, it is an important one. However, adding carbon dioxide to the atmosphere increases the trapping of heat from the Earth only very slowly; the forcing increasing only with the logarithm of the fractional change in carbon dioxide concentration. Particularly in the tropics, the greenhouse effect has aspects that are not yet fully understood. It would not be possible through human activity to produce a runaway greenhouse effect that could lead to conditions similar to those found on Venus.

Has the solar "constant" varied over the last few centuries, and if so by how much? What fraction of the observed surface temperature rise could be due to a brighter Sun? How well do variations in solar output and surface temperature of the Earth track?

The nominal radiation density (irradiance) from the Sun (1367 w/m^2) is called the *solar constant*. The actual irradiance from the Sun has been monitored by spacecraft since 1978, covering thus far two of the Sun's eleven year cycles. During that period, the solar output varied over a range of 0.15%. Between the twelfth century Medieval Maximum and the Maunder Minimum[20] of 1645-1715 (the time of the Little Ice Age) the brightness of the Sun is estimated to have decreased by 0.5%.[21] Solar-type stars have also been found to have variations of 0.1% to 0.4%.[22] These values seem innocuous, but in fact they have a disproportionately large impact on climate.

As is seen in a later section of this primer, proper treatment of clouds is an important factor in determining the accuracy of climate models. Clouds are composed of condensed water in the form of ice crystals and water droplets, which form around ions in the atmosphere. The principal source of such ions is cosmic rays, and the intensity of cosmic rays is strongly suppressed by solar activity[23] (measured by the number of sunspots). Cosmic rays are suppressed during active periods because the changed interplanetary magnetic field and solar wind flow shield the Earth. Thus, a more active Sun not only increases the solar "constant," but increases the amount of sunlight reaching the surface of the Earth by decreasing cloud formation. *The predictions of climate models generally do not include variations in the solar constant or its effect on the formation of clouds.* However, recent simulations — discussed below — have attempted to include changes in the solar constant.

A considerable amount of work has now been done on the connection between solar variability and climate. Cliver, et al.[24] have estimated that from 50-100% of the net global warming of 0.7-1.5°C over the last 350 years (since the Maunder Minimum) was due to an increase in solar irradiance. Crowley and Kim[25] found that solar variability may explain as much as 30% to 55% of climate variance over time scales of decades to centuries. Reid[26] estimates that the change in solar output from 1969-70 to 1979-80 was about 4 w/m^2, or 0.3% of the total output. *This value is the same as that expected from the radiative forcing resulting from a doubling of atmospheric carbon dioxide, as discussed below*. From 1890-1984, Friis-Christensen and Lassen found the change in solar output to be about one persent,[27] or more than 13 w/m^2. Notice that this is double the estimate given above for the change in solar output between the Medieval Maximum and the Maunder Minimum, although the transition then was from a warm to a cool period in contrast to 1890-1984. The IPCC estimates that the change in irradiance from the Sun between 1850 and 1990 was only 0.3 w/m^2 at the top of the atmosphere (Cliver, et al.), a value far smaller than found by the authors cited above. The value of 0.3 w/m^2 is also used in the 2001 IPCC Third Assessment Report (Shanghai Draft 21-01-2001) for changes in solar irradiance since 1750.

Using a somewhat different methodology to determine solar irradiance, Lean, et al.[28] find that changes in solar output account for only about half the surface warming since 1860 and one-third of the warming since 1970. They also found a strong correlation of surface temperature with solar irradiance from 1610 to 1800, "suggesting a predominant solar influence during this pre-industrial period." Put another way, they found that changes in solar irradiance account for 74% of the variance in northern hemisphere surface temperatures from 1610 to 1800, and 56% of the variance from 1800 to the present.

Climate models do not capture the cooling between 1940 and 1975 (an exception is discussed below). On the other hand, global temperature records closely follow the reconstruction of the Sun's brightness not only from 1940 to 1975 but also over the past 400 years.[29] It should be kept in mind that during the cooling of 1940 to 1975 carbon dioxide concentration in the atmosphere continued to increase monotonically — temperature does not simply follow increases in carbon dioxide concentration.

There is evidence that the Sun has variations in output with periodicities of ~70-90 years, ~200 years, and ~2500 years. These solar variations may enter the climate system by affecting the Quasi-biennial Oscillation and the El Niño Southern Oscillation.[30] When the historical record of

El Niño events is compared to the record of sunspot numbers, El Niño events are found to be two to three times more frequent when sunspot activity and solar irradiance are low — as during the Maunder minimum.[31]

Summary: The solar "constant" is not constant. A very significant portion of the global warming over the last century — at least half — has probably been due to an increase in solar output. Other effects of increased solar activity, such as the impact on cloud formation and El Niño events, are not yet well understood.

How much do climate models predict that the surface temperature of the Earth would change as a result of doubling the concentration of carbon dioxide in the atmosphere?

The IPCC maintains that an instantaneous doubling of carbon dioxide would lead to the Earth absorbing 4 w/m^2 more than it emits (globally), so that the temperature would have to rise to maintain radiative equilibrium. This was understood, and the value of 4 w/m^2 determined, as early as the nineteenth century.

As for errors, the IPCC states that, "climate models disagreed with detailed calculations by up to 25% for the flux change at the tropopause on doubling CO_2." It is not clear if the "detailed calculations" refer to radiative transfer calculations although they also note that radiative transfer models have uncertainties of about ±10%. In fact, there is a significant difference between measurements of energy absorption by water vapor and that predicted by the radiation transfer models used in climate modeling. As a result, "many climate models substantially underestimate the globally averaged short-wavelength absorption compared to atmospheric observations, by as much as 30% of the total atmospheric absorption in the case of clear skies."[32]

Calculation of the temperature rise at the surface of the Earth uses the following quantities:

F = Global mean infrared radiation leaving the Earth from the top of the atmosphere

S = Net downward solar radiation at the top of the atmosphere

The Earth's radiation budget is then S - F. ΔF, ΔS, ΔT_S, and ΔQ are, respectively, changes in F, S, the global mean surface temperature of the Earth and the radiative forcing of the surface-atmosphere system (4 w/m^2 for a doubling of $C0_2$).

The radiative forcing, ΔQ, is actually defined as the net downward radiative flux at the tropopause. For this to be the same as the radiative forcing at the top of the atmosphere, the response time of the stratosphere must be small compared with that of the surface-troposphere climate system. It is assumed here that this is the case.

The formula for the change in global mean surface temperature of the Earth is then

$$\Delta T_S = \left[\frac{\Delta F}{\Delta T_S} - \frac{\Delta S}{\Delta T_S}\right]^{-1} \Delta Q.$$

We consider now the simplest case where the warming due to a doubling of CO_2 causes no change in the climate system other than temperature (in particular, no increase in the amount of water vapor). For this case, there is no additional downward flux from the tropopause so that $\Delta S = 0$. The IPCC gives the value of $\Delta F/\Delta T_S$ as 3.3 w/m^2 per °C; so for a radiative forcing of 4 w/m^2 we have

$$\Delta T_S = \left[\frac{\Delta F}{\Delta T_S}\right]^{-1} \Delta Q = \frac{1}{3.3}\left(\frac{m^2\ {}^oC}{watts}\right) \times 4 \left(\frac{watts}{m^2}\right) = 1.2\ {}^oC.$$

Now $\Delta F/\Delta T_S$ is the change in the upward radiation at the top of the atmosphere for a change ΔT_S in surface temperature. If water vapor is present the IPCC claims this flow change is reduced from 3.3 w/m^2 per °C to 2.3 w/m^2 per °C. In addition, since water vapor is now present, ΔS is not really zero and the IPCC gives the value of $\Delta S/\Delta T_S$ as 0.2 w/m^2 per °C. With these corrections, the change in surface temperature for a doubling of CO_2 becomes

$$\Delta T_S = 1.9\ ^{o}C.$$

This is comparable to the change of 1.5°C between the Medieval warm period and the beginning of the 20th century. It does not, however, include the effect of additional cloud cover, which is discussed below.

One cannot ask the question that heads this section without considering water vapor, as we have done above. But there is another form of water that has a major impact on the response of the climate system to a change in carbon dioxide concentration, and this is clouds. Clouds not only contribute to greenhouse warming by absorbing outgoing thermal radiation, but also contribute to cooling by reflecting incoming sunlight and reducing the amount of solar radiation absorbed (as is discussed earlier when considering the runaway greenhouse effect).

The IPCC estimates the amount of outward bound thermal radiation absorbed globally by clouds as 31 w/m^2 and the amount of short-wavelength solar radiation reflected as 44 w/m^2. This means that clouds cause a net *cooling* of the annual global climate system of -13 w/m^2 (the minus sign designates a cooling). Harries[33] gives the net global, time-averaged cooling as -20 w/m^2, with a range of –140w/m^2 to +50 w/m^2. Other models give values in the range of 0 w/m^2 to –30 w/m^2. The question is: If the amount of carbon dioxide in the atmosphere is doubled, how much will this cooling (the -13 w/m^2) change due to the consequent change in cloud cover? Remember, the radiative forcing due to an instantaneous doubling of carbon dioxide is estimated to be 4 w/m^2, so the effect of altered cloud cover must be known to much better than this value.

In fact, not even the sign of the change is known! This is not the only problem. Even the basic physics of clouds is not understood. Climate models generally assume that clouds reflect some incident solar radiation but absorb no more than a clear sky would. Recent measurements show that clouds absorb more solar radiation than calculated by the models used to simulate the Earth's climate.[34] The difference is about 22 w/m^2, more than five times larger than 4 w/m^2. The point is, there are very large uncertainties in current knowledge of the effect that a doubling of carbon dioxide would have on cloud cover, and in turn on climate.

As Harries, referred to above, puts it: "High ice clouds almost certainly have a very significant effect on the cooling of the Earth to space. However, at present, we are almost completely unaware of the true magnitude of this effect, and especially of whether or not climate models correctly predict how this emission might change as a result of global warming."

Summary: If the concentration of carbon dioxide in the atmosphere is doubled the global surface temperature, including the feedback effect of water vapor, is expected to rise by about 1.9°C. However, the uncertainties having to do with clouds are so great as to render this figure meaningless.

Over geological time scales that include the ice ages, is there a causal relationship between increased carbon dioxide concentration in the atmosphere and temperature rise?

Carbon dioxide concentrations in the atmosphere are taken by most climatologists to be the cause of changes from glacial to interglacial periods in the Earth's history.[35] But some do not believe this is the case, and give primary responsibility to Milankovich orbital cycles which vary the eccentricity of the Earth's orbit, the distance of the Earth from the Sun and the angle of the Earth's tilt with respect to the plane of the ecliptic (obliquity). The axis of rotation of the Earth also precesses, thereby changing its direction in space. The Milankovich cycles have periodicities of 100,000 and 400,000 years for the eccentricity, 40,000 years for variation of the tilt between 22° and 24.5° and 22,000 years for the precession of the Earth's axis of rotation. The IPCC does acknowledge that geological and astronomical mechanisms may be the *ultimate* cause of the transitions from glacial to interglacial conditions. They note that the

Milankovich orbital variations "appear to be correlated with the glacial-interglacial cycle since glacials arise when solar radiation is least in the extratropical Northern Hemisphere summer." In fact, it has been commonly accepted that subtle changes in the seasonal distribution of solar radiation resulting from Milankovich orbital variations, with virtually no change in net radiation, was sufficient to initiate the climate cycles of the Pleistocene.[36] Rare orbital congruences involving obliquity and eccentricity correspond to major transient glaciations.[37]

The orbits of the planets are known to be inherently chaotic — meaning that they depend sensitively (exponentially) on differences in initial conditions. As a result, over tens of millions of years it is not possible to predict the exact locations of the planets. In particular, the tilt of the Earth with respect to its orbital plane is expected to increase in the distant future and could increase to as much as 90°, with drastic effects on climate. Other planets in the solar system also display such behavior. For example, the tilt of Mars varies chaotically by ± 13.6° around its average of 24° over millions of years.[38]

The IPCC also recognizes that rapid changes in climate can occur on time scales of a century, which cannot be related to changes in the Earth's orbit or atmospheric concentration of carbon dioxide. The Younger Dryas event of about 10,500 years ago (where the temperature dropped some 4°C) was the last global event of this type, and it lasted 500 years before ending very suddenly. The Younger Dryas event is not understood, although there is speculation that changes in the North Atlantic currents could have been a factor.

Recent research by other climatologists has cast a great deal of doubt on the causal relation between climate swings over the last 550 million years and the concentration of carbon dioxide in the atmosphere. Veizer, et al.[39] have shown that climate changes over this period were global in nature, but their results also show that *carbon dioxide concentrations were probably not the principal driver*. Consistent with this, Indermühle, et al.[40] have found that over the last 11,000 years most of the variability in atmospheric carbon dioxide concentration was caused by changes in the amount of land biomass and sea surface temperatures. These changes are driven by geological and astronomical mechanisms. The relationship between sea surface temperatures and the partial pressure of carbon dioxide in the atmosphere is exponential,[41] meaning that the concentration of carbon dioxide in the atmosphere increases much faster than linearly with increasing sea surface temperature (we will see below that the ocean is the principal reservoir of carbon dioxide).

Data from the last 250,000 years, covering the last three glacial terminations, show that carbon dioxide concentrations in the atmosphere increased some 400 to 1,000 years *after* the termination of an ice age,[42] a time lag that is on the order of the ocean mixing time (the time needed to mix surface and deeper waters of the ocean). This implies that the carbon dioxide was put into the atmosphere by a warming ocean, and was *not* the cause of the warming.

Summary: Transitions from glacial to interglacial periods in the Earth's history are not driven by increases in carbon dioxide concentration in the atmosphere. Rather, carbon dioxide levels increase some 400 to 1,000 years after the transition, consistent with releases from warming oceans. Major temperature changes in the relatively recent past are not understood: one such is the Younger Dryas event of 10,500 years ago, which had a temperature drop of 4°C and lasted for 500 years.

How much has the concentration of carbon dioxide in the atmosphere risen, and is the cause of the rise known?

The position of the IPCC on the buildup of carbon dioxide in the atmosphere is that, "For thousands of years prior to the industrial revolution, abundances of the greenhouse gases were relatively constant. However, as the world's population increased, as the world became more industrialized and as agriculture developed, the abundances of greenhouse gases increased markedly."

However, Indermühle, et al. (referred to under the last question) found that the global carbon cycle has not been in a steady state during the past 11,000 years. There has been a steady rise in the concentration of carbon dioxide from about 260 parts per million by volume (ppmv) 8,000 years ago to about 285 ppmv in 1900 (other sources give 290 ppmv for 1900). Interestingly enough, there was a dip in carbon dioxide concentration from about 285 ppmv to 275 ppmv during the Little Ice Age.[43] Although the transitions are not sharply defined, it can be said that the level of carbon dioxide fell after the initiation of the Little Ice Age and rose again after its termination. The fall occurred between about 1600 AD and 1700 AD while the rise began in about 1800 AD and has continued until today. The fall and rise time of about 100 years is the time it takes for the atmosphere to respond to a change in sea surface temperatures.[44] If changes in sea surface temperatures were indeed responsible for the 10 ppmv dip in carbon dioxide concentration during the Little Ice Age, that would correspond to a reduction in sea surface temperatures of about 0.8°C. Variation in carbon dioxide concentration over the last 1,000 years (up to 1900 AD) has been between 275 ppmv and 287 ppmv — about 12 ppmv, or 4.3%.

Since the mid-19th century, a time that corresponds to the average carbon dioxide concentration in the atmosphere over the last 1,000 years, the concentration of this gas has risen from about 280 ppmv to about 350 ppmv, or about 25%. This is a very large increase, comparable to changes that occurred during the ice ages. Sea surface temperature changes alone cannot be responsible for this increase — they would have had to increase by roughly 5.5°C since the end of the 18th century. While sea surface temperatures have indeed increased over this period, they have only gone up at most some 0.5°C. The rise in sea surface temperatures has not been gradual; most of it occurred from 1910 to 1940, and after 1975. *Between 1940 and 1975 sea surface temperatures were relatively constant, and globally the Earth experienced a slight cooling*. Climate simulations do not show this cooling. An exception is the recent work of Stott, et al.,[45] who included changes in solar irradiance (from Lean, et al.) as well as the effects of aerosols in their simulations. They conclude that although there are significant uncertainties, natural forcings (solar changes, etc.) were relatively more important in the warming of the early 20th century, and anthropogenic forcing (carbon dioxide production) the dominant factor in recent decades.

Because the results of Stott, et al. are reproduced in the IPCC 2001 Third Assessment Report (Shanghai Draft 21-01-2001), it is important to describe this work in a little more detail. These authors used estimates of various forcings in a coupled ocean-atmosphere general-circulation model to simulate the changes in annual-mean global surface temperatures. These forcings, such as solar irradiance variations, increases in carbon dioxide and changes in sulfate aerosols (which reflect incoming solar radiation), correspond to the influence of different factors altering the balance of incoming and outgoing radiation in the Earth-atmosphere system. By adjusting these factors, the authors were able to match 30-year observed surface temperature trends starting in 1910, 1940 and 1970.

Stott, et al. were, however, careful to caveat their results: "Given the uncertainties in historical forcing, climate sensitivity, and the rate of heat uptake by the ocean, the good agreement between model simulation and observations could be due in part to a cancellation of errors... Hence, our result does not remove the need to reduce uncertainty in these factors, particularly as these might not cancel in the future." North[46] is far stronger in his reservations about climate models: "There are so many adjustables in the models, and there is a limited amount of observational data, so we can always bring the models into agreement with the data."

Although changes in land use and the burning of fossil fuels are generally thought to be responsible for the exponential increase in atmospheric carbon dioxide, in order to prove this one must understand the global carbon cycle to an accuracy better than the fraction of carbon dioxide produced by these activities.[47]

The oceans contain about 50-65 times as much carbon dioxide as the atmosphere, while soils and land plants contain about three times as much. Carbon fluxes are measured in gigatons of carbon (GtC), where 1 Gt = 10^9 metric tons = 10^{12} kg. One ppmv of carbon dioxide in the atmosphere corresponds to 2.23 GtC or 8.2 Gt of carbon dioxide.

The IPCC estimates that the ocean surface absorbs 92 GtC per year and releases 90 GtC. Both plants and soils are estimated to release about 100 GtC per year while plants absorb some 102 GtC per year. These figures lead to a net sequestering of 4 GtC per year. The flux is then roughly 200 GtC released per year and slightly more absorbed. Now fossil fuel burning is estimated to release 5 GtC per year and deforestation another 2 GtC per year for a total of 7 GtC per year. *So, in order to show that the buildup of carbon dioxide in the atmosphere is due to these sources, one must understand the carbon cycle (or at least the net fluxes of carbon dioxide between the ocean, land, and atmosphere) to an accuracy better than 7 GtC/200 GtC = 3.5%.*

In comparison with actual measurements, atmospheric models overestimate the increase in atmospheric carbon dioxide due to emissions from the burning of fossil fuels, cement production, and deforestation. Post, et al. state that, "Since the ranges of predicted and observed increases in atmospheric carbon do not even overlap, many scientists remain skeptical that we can analyze the impact of fossil-fuel burning on the global carbon cycle."

The following estimates (in GtC per year) were given by the IPCC for the decade 1980-1989:

Emissions	
Fossil fuel burning	5.4 ± 0.5
Deforestation and land use	1.6 ± 1.0
Total emissions of CO_2	7.0 ± 1.1
Reservoir Uptake	
Total accumulation of CO_2 in the atmosphere	3.4 ± 0.2
Uptake of CO_2 by the ocean[48]	2.0 ± 0.8
Total uptake of CO_2	5.4 ± 0.8

Except for disturbances such as deforestation, the exchange of carbon between the atmosphere and terrestrial ecosystems is assumed to be in balance over the time scale of several years. For this reason the uptake of land plants is not included in the above table. The difference or net imbalance of 1.6 ± 1.4 GtC corresponds to a lack of understanding of the disposition of 1.6/7 = 23% of the carbon. Similarly, from 1850-1986 the total carbon released by these processes is estimated to be 312 ± 40 GtC, while for the same period the increase in carbon dioxide in the atmosphere is 60 ppmv or 127 GtC, which is only 41% of the estimated release. The missing carbon sink (where the excess carbon dioxide goes) corresponds to an enormous error in the net flux of carbon dioxide between the ocean, land, biosphere and the atmosphere.

According to Post et al., the inability to balance the carbon fluxes over the period from 1800 to the present may be due to overlooking dynamic responses from land plants and the ocean. Increased carbon dioxide levels in the atmosphere may stimulate land plants and phytoplankton (small ocean plants) to take up additional carbon dioxide.

The response of land plants is complex, but some 95% of the Earth's plants show an increase in biomass when exposed to elevated carbon dioxide levels. The IPCC noted that "Net primary production could be enhanced by increased CO_2 in a variety of ways," although they listed a number of caveats.

Plants fall into two broad categories known as C_3 plants or C_4 plants, depending on whether one of the main early products of photosynthesis is one of the three-carbon intermediates — phosphoglyceraldehyde — of the Calvin cycle (used by all plants for the synthesis of carbohydrates) or a four-carbon compound instead. C_4 plants have the advantage over C_3 plants under conditions of high temperature and intense light, when stomatal closure results in low carbon dioxide and high oxygen concentrations in the air spaces within their leaves.

Optimal carbon dioxide uptake from the atmosphere per unit of leaf weight takes place in C_4 plants like maize (corn) — which originated in the tropics — in the range of atmospheric carbon dioxide concentration of 200 ppmv to 800 ppmv (The uptake of carbon dioxide is essentially constant over this range of concentration). C_3 plants reach their optimum carbon dioxide uptake for atmospheric carbon dioxide concentrations of 500 ppmv to 800 ppmv (a range over which the uptake is again constant). However, the efficiency of C_3 plants (the amount of carbon dioxide taken up per unit of light energy absorbed) is greater than that of C_4 plants up to a leaf temperature of a little less than 30°C. The efficiency of C_4 plants is constant over the temperature range of 10°C to 40°C, and greater than that of C_3 plants above 30°C.

In summary, C_4 plants cannot be expected to increase their uptake of carbon dioxide with rising atmospheric concentrations of this gas. C_3 plants, which have the advantage in temperate climates, will increase carbon dioxide uptake up to a concentration of about 500 ppmv.

In the case of the ocean, it is known that climate change will affect marine ecosystems, but there is inadequate data to predict how these ecosystems will respond. The response of marine ecosystems is important not only from the perspective of global warming: it is the plants in the ocean that produce essentially all of the oxygen in the Earth's atmosphere. There is, however, some understanding of how carbon dioxide is absorbed by the ocean. Phytoplankton are extremely important in this process, since photosynthesis by these plants is what reduces carbon dioxide (releasing oxygen) in a shallow surface layer of the ocean. The amount of carbon dioxide in this layer is dependent on the relationship between wind speed and the value of what is called the *gas transfer coefficient*, which is only known to ±30%. Biologically produced debris (containing carbon) from these surface layers sinks into the deep ocean where it is decomposed (oxidized) by microbes. This process is known as the biological pump.

The biological pump is important because it allows the removal of far more carbon dioxide from the atmosphere than would otherwise occur. It maintains the carbon profile of the ocean, where deep ocean water (below about 500 m) is supersaturated with carbon dioxide compared to atmospheric carbon dioxide (if this deep water were warmed to the mean surface temperature of 18°C it would result in an atmospheric partial pressure of carbon dioxide two to three times its present value). The surface layers of the oceans are generally within ±40% of saturation with atmospheric carbon dioxide; i.e., within ±40% of that concentration the surface layers would have dissolved in them if they were in equilibrium with atmospheric carbon dioxide.

For every carbon atom fixed by photosynthesis, a molecule of carbon dioxide (the source of the carbon atom) is removed from the ocean surface layer. Call the amount removed this way $C_{organic}$. On the other hand, for every carbon atom fixed into the calcium carbonate of sea creatures (mostly coccoliths, foraminifera and pteropods), one molecule of carbon dioxide is released into the surface layer.[49] Call the amount released this way $C_{carbonate}$. The ratio $C_{organic} : C_{carbonate}$ is known as the 'rain ratio.' This ratio represents the net carbon dioxide removed from the surface layer of the ocean: if it is 1:1, the biological pump releases as much carbon dioxide to the surface layer through calcium carbonate formation as it removes through the formation of organic molecules containing carbon. The rain ratio is generally around 4:1, but varies over a very wide range of perhaps just over one to 20.

The point to be emphasized is that without the biological pump, the partial pressure of carbon dioxide in the surface layer of the ocean would be much greater than it is, and atmospheric concentrations would consequently also be much greater. Various simulations starting with the pre-industrial atmospheric concentration of carbon dioxide of 280 ppmv indicate that if the biological pump were able to utilize all available surface nitrate it would have resulted in a current value of 160 ppmv (compared to the actual value of about 350 ppmv); if the biological pump did not exist, the result would be 450 ppmv.[50] Despite the wide potential variation in the performance of the biological pump in response to changing conditions in the ocean's surface layer, it is generally assumed to have remained in essentially a steady state during the buildup of carbon dioxide in the atmosphere over the last century. This assumption is presumably built into the climate models used to predict the response of the Earth to rising carbon dioxide concentration.

The biological pump is estimated to be responsible for the uptake of about 5 GtC per year, of which 1 GtC per year, or 20%, is at the continental margins, which are the most susceptible to changes resulting from human activity. The 5 GtC per year should be compared to the 7 GtC per year estimated to be produced by the burning of fossil fuels and land use changes.[51]

Summary: The carbon cycle is not well understood and current estimates of carbon fluxes have very large errors. Dynamic responses of the ocean and land plants are generally not included in coupled ocean-atmosphere general-circulation models. Although the buildup of carbon dioxide in the atmosphere may be due to increased burning of fossil fuels and changes in land use, it is difficult to determine how much of this buildup may be due to changes in the performance of the biological pump for reasons that may be unrelated to the burning of fossil fuels.

How good are the predictions of coupled ocean-atmosphere climate models?

At this point in this series of questions, readers may judge for themselves the answer to this question.[52] Perhaps the most contentious summary of the status of climate models has been given by the preeminent physicist Freeman Dyson in a talk to the American Physical Society in March of 1999.[53]

After discussing a Department of Energy program known as ARM (for Atmospheric Radiation Measurements), and pointing out that measured carbon dioxide uptake by some mature forests was far higher than expected (or modeled), Dyson summarized his findings as follows:

“The bad news is that the climate models on which so much effort is expended are unreliable. The models are unreliable because they still use fudge-factors rather than physics to represent processes occurring on scales smaller than the grid-size. Besides the general prevalence of fudge-factors, the climate models have other more specific defects that make them unreliable. First, with one exception, they do not predict the existence of El Niño. Since El Niño is a major and important feature of the observed climate, any model that fails to predict it is clearly deficient. Second, the models fail to predict the marine stratus clouds that often cover large areas of ocean. Marine stratus clouds have a large effect on climate in the oceans and in coastal regions on their eastern margins. Third, the climate models do not take into account the anomalous absorption of radiation revealed by the ARM measurements. This is not a small error. If the ARM measurements are correct, the error in the atmospheric absorption of sunlight calculated by the climate models is about 28 watts per square meter, averaged over the whole Earth, day and night, summer and winter. The entire effect of doubling the present abundance of carbon dioxide is calculated to be about four watts per square meter. So the error in the models is much larger than the global warming effect that the models are supposed to predict. Until the ARM measurements were done, the error was not detected, because it was compensated by fudge-factors that forced the models to agree with the existing climate. Other equally large errors may still be hiding in the models, concealed by other fudge-factors. Until the fudge-factors are eliminated and the computer programs are solidly based on local observations and on the laws of physics, we have no

> good reason to believe the predictions of the models. [This does not mean that climate models are worthless, but] they are not yet adequate tools for predicting climate. If we persevere patiently with observing the real world and improving the models, the time will come when we are able both to understand and to predict. Until then, we must continue to warn the politicians and the public, don't believe the numbers just because they come out of a supercomputer."

The well known solar physicist Eugene Parker (referred to above) summarized our general state of knowledge as follows: "The inescapable conclusion is that we will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate. We expect that burning fossil fuel at the extravagant rate to which we have become accustomed is a contributing factor, but so are the increased solar brightness and the increased sea water temperatures. In our present state of ignorance it is not possible to assess the importance of individual factors. The biggest mistake that we could make would be to think that we know the answers when we do not."[54]

As put by Ahilleas Maurellis of the Space Research Organization Netherlands in the February 2001 issue of *Physics World*, "Ultimately, it is too simplistic to blame global warming on a particular gas or process... Perhaps the real villain is not carbon dioxide or even water vapour, but simply a mixture of inertia, hysteria and misinformation. Until we understand the full picture, perhaps the best reaction to global warming is for everybody to just keep their cool."

Conclusion

Perhaps the most important indicator that human activities could be affecting the global environment is the 25% rise in atmospheric carbon dioxide concentration since the end of the eighteenth century. However, our understanding of the carbon cycle is such that it cannot be said with certainty that this buildup is due to human activity, and in particular to the burning of fossil fuels and deforestation, although such activity (which, on a yearly basis, comprises some 3.5% of the two-way exchange of carbon between the Earth and its atmosphere) must certainly contribute to the increased concentration of this gas. A 25% increase may appear large, but because carbon dioxide is a *minor* greenhouse gas, and increased carbon dioxide concentration in the atmosphere does not proportionately increase its greenhouse effect, this has had only a minimal impact on the Earth's temperature.

Using the methodology of the IPCC to find the increase in radiative forcing due to the 25% increase in atmospheric carbon dioxide concentrations, as well as the formula given earlier for determining the rise in the Earth's average surface temperature (including the effects of water vapor), this increase corresponds to a 0.6°C temperature rise. This number is the same as the global temperature increase over the last century and a half — a striking correspondence. However, it is three times smaller than the 2°C variations one could consider to be natural. The correspondence becomes even less striking if one considers other factors affecting the Earth's temperature.

Solar output varies by at least 0.1% to 0.4% (or 1.4 w/m^2 to 5.5 w/m^2). The radiative forcing due to the 25% rise in carbon dioxide concentration is 1.4 w/m^2 (including the water vapor feedback). Solar variation since1978 alone has been *measured* to be in the range of 0.15% or 2 w/m^2. Thus, the radiative forcing due to the 25% increase in carbon dioxide concentration is comparable to the solar variation over the last twenty years, and could well be much smaller than solar variations over the last century. Many researchers now believe that a very significant portion of the global warming over the last century — at least half — has probably been due to an increase in solar output. Other effects of increased solar activity, such as the impact on cloud formation and El Niño events, are not yet well understood, and are not factored into the predictions of climate change.

The IPCC, based on the predictions of climate models, estimates that doubling the concentration of carbon dioxide in the atmosphere would lead to a rise in global surface temperature, including the feedback effect of water vapor, of about 1.9°C. However, the uncertainties having to do with clouds are so great as to render this figure meaningless.

Over longer periods of the Earth's history, the record shows that transitions from glacial to interglacial periods are not driven by increases in carbon dioxide concentration in the atmosphere. Rather, carbon dioxide levels increase some 400 to 1,000 years after the transition, consistent with releases from warming oceans. Thus, it is difficult to maintain that the role of carbon dioxide in climate change is really understood.

Given the uncertainties described above, and the current state of coupled ocean-atmosphere general-circulation models, the predictions of these models cannot and do not form a sound basis for public policy decisions.

What should be done? Perhaps the most important single action would be to de-politicize the issue of climate change. Funding should be maintained for continued research, modeling, and data collection. In time it may be possible to develop an understanding of the Earth's climate that is good enough to contribute meaningfully to policy decisions.

by Gerald E. Marsh
Physicist
National Advisory Board
The National Center for Public Policy Research

Note: Gerald Marsh is a physicist at Argonne National Laboratory. Opinions expressed in the Primer are his own. Mr. Marsh can be reached at gmarsh@anl.gov.

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[49] Carbon dioxide has a high solubility in water through the reactions: $CO_2(\mathrm{gas}) + H_2O\ (\leftrightarrow H_2CO_3) \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$ which, because of the relative reaction rates, can be summerized as $CO_2(\mathrm{gas}) + H_2O + CO_3^{2-} \leftrightarrow 2HCO_3^{2-}$. The bicarbonate ions ($2HCO_3^{2-}$) can then interact via the calcification equation $Ca^{2+} + 2HCO_3^- \longrightarrow CaCO_3 + CO_2 + H_2O$ to release carbon dioxide.

[50] R.B. Hanson, et al, eds.

[51] K. K. Liu, et al., “Continental Margin Carbon Fluxes,” in R. B. Hanson, et al., eds.

[52] The reader may also be interested in the article by Gerald Westbrook, titled “Global Warming: Are Society’s Attitudes and Actions Based on an Over-Simplistic View of a Highly Complex System,” in the December, 1997 *Dialogue* published by the United States Association for Energy Economics.

[53] Freeman J. Dyson, *The Science and Politics of Climate*, talk given at the American Physical Society Centennial Meeting in Atlanta, GA, March 25, 1999.

[54] E. N. Parker, *Nature* **399**, 416 (1999).