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A different view of the climatic effect of CO_2 – Updated*

H. W. ELLSAESSER

Participating Guest Scientist, Atmospheric and Geophysical Sciences Division
Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94550, U. S. A.

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RESUMEN

Se presenta una versión nueva de un artículo anterior del mismo título, y se da una explicación de la forma en que gases de invernadero operan en la elevación de la temperatura superficial de un planeta. El artículo, en general, está diseñado para que sea comprendido por una gama grande de especialistas. Se adelanta el argumento de que el papel de la transferencia de radiación ha sido sobreestimado en relación a otros procesos climatológicos; en particular aquellos que se refieren a la convección profunda en los trópicos y a la evaporación en los océanos tropicales han sido subestimados e inadecuadamente modelados en nuestros cálculos del efecto climático del aumento hasta nuestros días de CO_2.

ABSTRACT

An update is given of a previous paper by the same title, an explanation is given of the way greenhouse gases operate to raise the surface temperature of a planet. The paper in general is designed to be understandable to a wide range of disciplines. The argument is advanced that the role of radiative transfer has been overemphasized relative to other climatological processes and, in particular, that the roles of deep convection in the tropics and of evaporation from tropical oceans have been underemphasized and inadequately modeled in our calculations of climatic effects of increased CO_2 to date.

Introduction

This paper is an attempt to provide a summary review of conclusions from previous studies on this subject. They have been organized under the following subject headings.

a. Conceptualization of the greenhouse effect.

b. The climatic effect of doubled CO_2.

c. Interpretation of the climatic record.

d. Diagnosis of apparent and possible model deficiencies.

e. The palaeoclimatic record.

f. Summation.

A. Conceptualization of the greenhouse effect

Sunlight, consisting of ultra violet, visible and infrared radiation reaches the Earth with a direct beam intensity of 1360 W/m^2, defined as the *solar constant.* Because of the Earth's rotation and

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* **This is an update of the paper "The climatic effect of CO_2: A different view" (Ellsaesser, 1984).**

spherical shape, the global average flux per unit area at the top of the atmosphere is only one fourth of this, or 340 W/m^2. The Earth's *albedo*, or fraction reflected, is 0.3 so that 238 W/m^2 is the average solar flux absorbed by the Earth and its atmosphere – and is the amount of energy which must be reradiated to space if the Earth's temperature is to remain unchanged.

By the empirical and theoretical Stephan-Boltzmann Law (ideal) black bodies emit radiant energy at a rate proportional to the fourth power of the Kelvin (absolute) temperature of their surfaces.

$$R = \sigma T^4 [W/m^2 T^4] \tag{1}$$

Most solids and liquids do not depart very far from the black body curve. Gases, in contrast to solids and liquids, tend to absorb and radiate energy only at discrete wave lengths or bands, but their emission remains within the T^4 limit for the wave lengths of concern.

Our sun radiates very nearly as a black body with a color temperature of 6000 K. The temperature determines not only the total energy output but also its spectral distribution and, in particular, the wave length or *color* at which the energy is a maximum. These are given by Planck's law for the distribution of radiant energy as a function of wave length and temperature and by Wien's displacement or color temperature law for the wave length of peak radiation as a function of temperature. The latter may be expressed as:

$$\lambda_m T = 2897 [\text{micron degrees } K] \tag{2}$$

The surface temperature of the Earth averaged over all latitudes and seasons is very nearly 15°C or 288 K (0° C = 273 K). A black body at this temperature would put out about 390 W/m^2 of radiant energy, i.e., 115% of the average solar flux or 165% of the absorbed solar energy, peaking at a wave length near 10.6 microns in the *IR* (infrared) part of the spectrum. However, satellite measurements confirm that the outgoing radiation from the Earth averages only 238 W/m^2, i.e., matches the amount of sunlight absorbed. This corresponds to the radiation of a black body at a temperature of 255 K or -18°C. That is, the planet Earth radiates as would a black body that is 33°C colder than the average surface temperature of the Earth. This difference is attributed to the so-called *greenhouse effect* of our atmosphere.

Figure 1 (Luther and Ellingson, 1985) shows (above) the relative intensities of sunlight reaching Earth and the Earth's outgoing "light" as functions of wave length. The sun's spectrum peaks in the visible while the Earth's radiation is all in the IR, with very little overlap of the two spectra. The lower part of the figure shows the average percentage of absorption of each wave length by the gases in the Earth's atmosphere and the gases responsible. The band of reduced absorption between 8 and 12.5 microns is the so-called *atmospheric window*. These are the only wave lengths at which IR radiation from the planet's surface can penetrate the atmosphere to outer space to any significant degree.

This representation of the atmospheric window is a global average for beams originating at the surface and directed toward the zenith. The window becomes progressively more closed as the direction of the beam departs from the zenith and as the atmosphere becomes more moist. In the moist tropics this window is completely closed by the so-called *continuum absorption* of water vapor (Kiehl and Ramanathan, 1982). One of the early explanations of surface warming due to

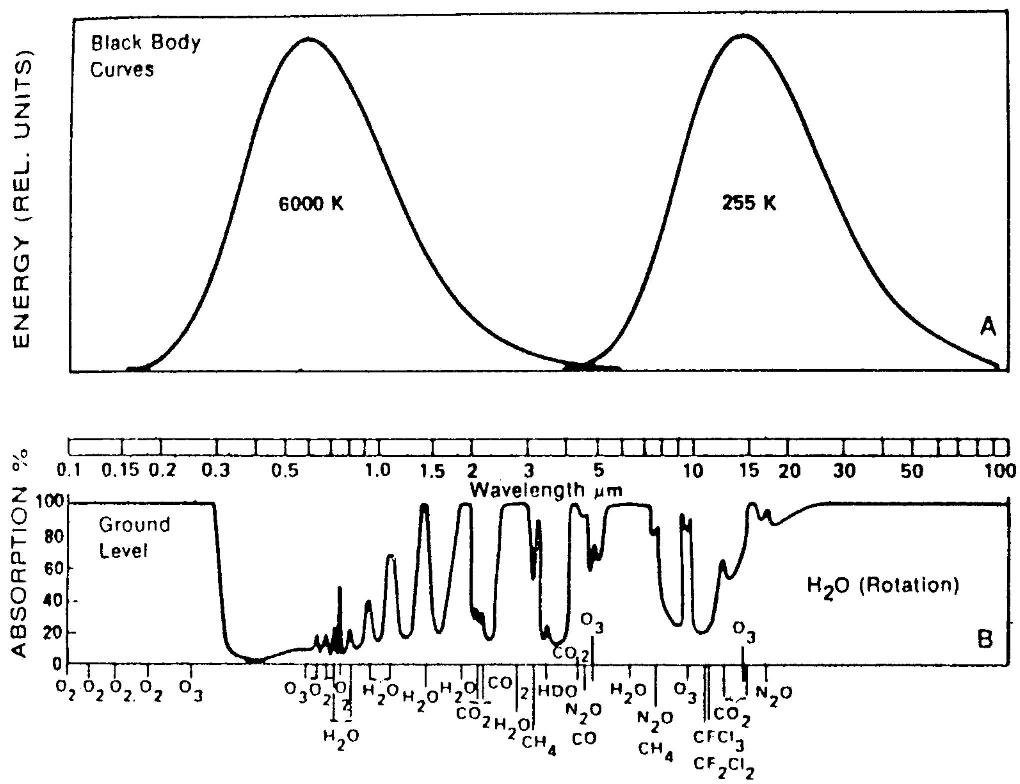

Fig. 1. Radiant energy spectra of sun (at Earth distance) and Earth (above) and absorption bands of atmospheric gases (below). Wavelengths shown on center scale (from Luther and Ellingson, 1985).

increased CO_2 was that this would cause further spreading of the 15-micron absorption band of CO_2, narrowing the atmospheric window and, as a consequence, the surface would warm until it could radiate the same amount of energy up through the narrowed window. However, current estimates are that only about 7% of the surface emitted IR escapes through the window to space without reabsorption by the overlying atmosphere (Luther and Ellingson, 1985, Fig. 2.8), so this effect must be a minor part of the greenhouse warming mechanism. But the atmosphere itself is also radiating in the IR – and in all directions, including up toward outer space and back toward the surface. At satellite altitude, most of the radiation observed coming from the planet Earth originates not from the planet's surface but from some higher level in the atmosphere.

Figure 2 (Lamb, 1972, p. 9) shows an averaged profile of temperature versus altitude in the Earth's atmosphere, along with the names given to various layers of the atmosphere. The lower part of the curve in which the temperature decreases with height is called the ***troposphere***. The Earth's black body equivalent temperature of 255 K (-18°C) occurs at an altitude of about 6 km and this, in an averaged sense, is the level from which the Earth radiates to space. The ***lapse rate*** (average rate of decrease of temperature with altitude) between here and the surface is 5.5°C/km – 5.5°C/km times 6 km is 33°C, which added to the 6-km temperature of 255 K gives the surface temperature of 288 K (15°C). This is a simplistic but physically valid explanation of how the atmosphere acts as a blanket or greenhouse to keep the surface of the planet warmer than it would be without an IR absorbing atmosphere. That is, the Earth does not lose energy by IR radiation from its surface, as would a bare black body. Rather, its black body radiation to space is actually emitted from the top of its greenhouse blanket, located on average, about 6 km above

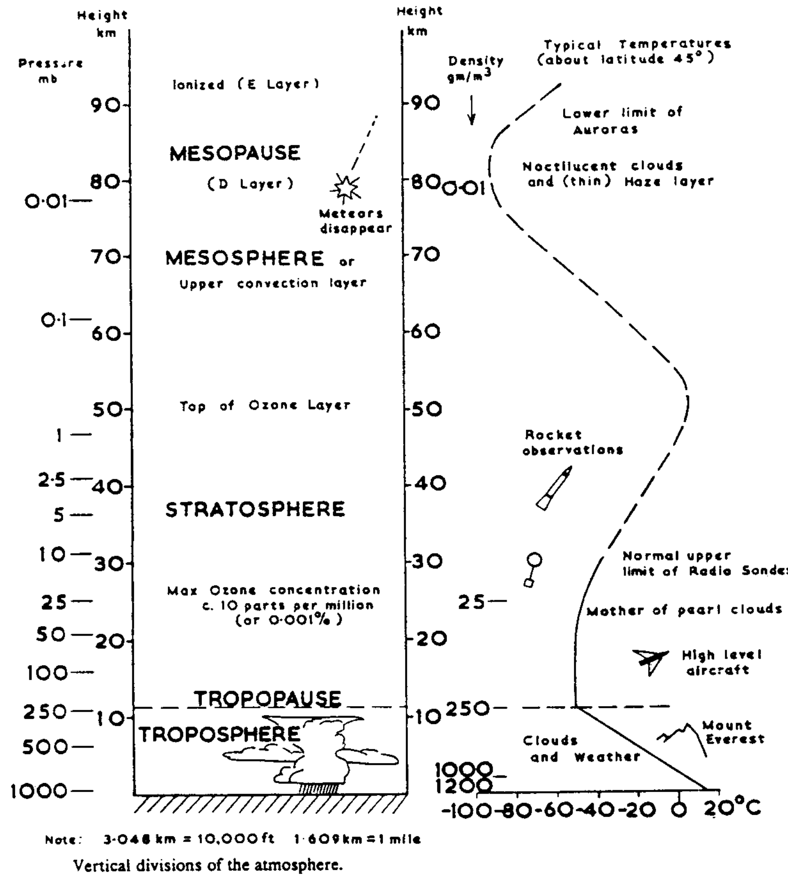

Fig. 2. Typical vertical variation of temperature within the atmosphere and nomenclature for the various levels and layers (from Lamb, 1972, p. 9).

the surface, where the average temperature is some 33°C (59°F) colder than at the surface. The IR opacity of the atmosphere, which produces this greenhouse blanket, is due to liquid and solid particles, including clouds, and the IR absorbing gases; water vapor (20.6), carbon dioxide (7.2), ozone (2.4), nitrous oxide (1.4), methane (0.8), and freons (<0.8). (The numbers in parentheses are the individual contributions in degrees C to the total greenhouse effect of each gas calculated by Kondratyev, 1986, p. 50).

If additional greenhouse gases are added to the atmosphere, it is logical to expect that the greenhouse blanket will thicken; i.e., the average altitude from which the atmosphere emits energy to space will rise above its present level of 6 km. But, since the absorbed solar energy which has to be rejected remains essentially unchanged, the radiating temperature also must remain the same. That is, the average atmospheric temperature at the new higher level of the top of the greenhouse blanket must warm to the temperature existing now at the present top of the greenhouse blanket. And if the lapse rate remains the same, then the temperature of the Earth's surface will also warm. This is a somewhat simplistic but physically valid picture of the mechanism by which increases in the greenhouse gas content of the atmosphere will lead to climatic warming.

Unfortunately, this simple picture of how the greenhouse effect operates is of little help in quantifying the amount of warming to be expected. To see why this is so, examine Fig. 3. This shows a terrestrial IR spectrum taken by Nimbus IV near Guam on 27 April 1970 on a

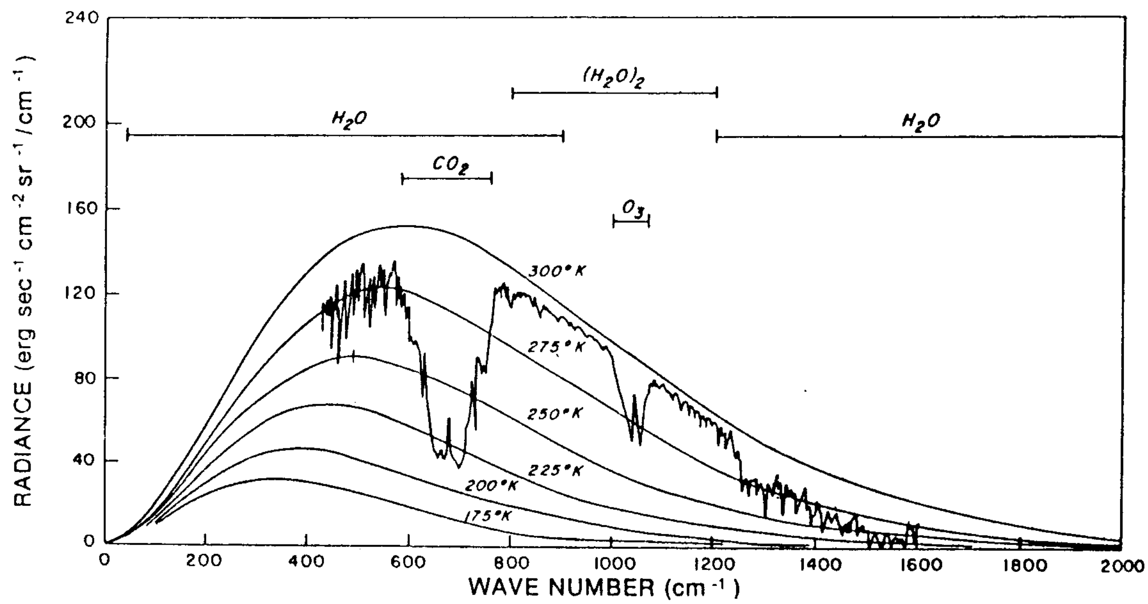

Fig. 3. Terrestrial IR emission spectra recorded by IRIS-D on Nimbus IV near Guam at 15.1°N on 27 April 1970 (from Luther and Ellingson, 1985).

background of temperature-labeled black body curves and with the wave length range of the principal atmospheric IR absorbers (emitters) indicated. It is obvious that water, including the dimer, $(H_2O)_2$ – believed to be responsible for the continuum absorption (and emission) of water vapor, is the principal emitter, without even considering the effect of clouds, which are also composed of water. And since this spectrum is taken at latitude 15.1°N, it appears quite credible that the global average temperature of this emitter is 255 K. On the other hand, the IR flux from the CO_2 band centered near 15-microns, is both a small fraction of the total and is coming from an emitter with a temperature near 220 K (-50 to -55°C). Returning to Fig. 2, this temperature range is found in the altitude range 12 to 20 km. If the top of this CO_2 greenhouse blanket were to be raised, by the addition of CO_2 and maintained at constant temperature, this would have little or no effect on the temperature at the surface and, if anything, might cause the surface to cool (i.e., if this radiating layer were pushed above 20 km without changing its temperature).

B. The climatic effect of doubled CO_2

The National Academy of Sciences in a series of reports (*NRC*, 1979, 1982 and 1983) adopted 1.5 to 4.5°C (2.7 to 8.1°F) as the mean global surface warming to be expected from a doubling of CO_2 or an equivalent increase of all greenhouse gases. At the present time the other greenhouse gases being added by man are supposed to have a warming effect about equal to that of the added CO_2 (Ramanathan, 1988). Current estimates for the time of equivalent doubling of the preindustrial CO_2 greenhouse effect range from about 2020 to 2050 AD (Wigley, 1987). The most recent experiments by our most complex models have clustered in the upper part or even exceeded this range(Mitchell, 1989). Ramanathan (1988) notes that one of the major factors contributing to this increased sensitivity in newer models has been the inclusion of interactive (i.e., model computed) clouds. He adds, that because the clouds are still computed primitively, it is premature to make reliable inferences from these more recent computations. It is my personal and professional opinion that even before these more recent results our climate models were overestimating the warming due to increasing greenhouse gases by at least a factor of 2 to 3.

Mike Schlesinger of Oregon State University has for several years been analyzing and reviewing model predictions of the climatic effect of a doubling of atmospheric carbon dioxide. Table 1, taken from his review for the US Department of Energy State-of-the-Art Reports (Schlesinger and Mitchell, 1985) gives a breakdown of the model-computed temperature changes due to the doubling of carbon dioxide alone and to the various feedbacks expected to accompany such a doubling. Note that the doubling of carbon dioxide *per se* is calculated to produce a mean global warming of only 1.2°C (29% of the total of 4.16°C; Ramanathan (1981) computed this number to be only 0.5°C) while the calculated changes in water vapor amount and distribution are calculated to cause an additional warming of 2.75°C (66%) and calculated changes in lapse rate, surface albedo and cloudiness are credited with causing an additional warming of 0.21°C (5%). That is, the doubling of carbon dioxide is now calculated to produce a mean global warming 3.46 times greater than would occur if the carbon dioxide content of the atmosphere could be doubled with no other changes. The major portion of this amplification, a factor of 3.2, coming from the changes in the amount and distribution of the water vapor in the atmosphere predicted to occur as a result of the warming initiated by the increase in CO_2.

Feedback Mechanism	$(\Delta T_s)_{i-1}$, °C	f_i^*
None	1.20	0.000
Water vapor amount	1.85	0.445
Water vapor distribution	0.90	0.216
Lapse rate	−1.10	−0.264
Surface albedo	0.38	0.091
Cloud height	0.51	0.123
Cloud cover	0.42	0.101
Total	4.16	0.712

TABLE 1. RCM (radiative-convective model) analysis of the feedbacks in the GISS (Hansen *et al.*, 1984) GCM simulation of $(2 \times CO_2)$ - $(1 \times CO_2)$ temperature changes (from Schlesinger and Mitchell, 1985).

Note also that Item 4 in the table, "lapse rate", is calculated to contribute to a cooling. That is, the models are predicting doubled CO_2 to reduce the mean lapse rate of the troposphere below its present 5.5°C/km, i.e., the upper troposphere will warm more than the surface. As can be seen from Fig. 2, if the slope of the temperature curve in the troposphere is decreased, while holding the temperature near 6 km constant, then the temperature at the Earth's surface will decrease. Aside from this one small item, all of the other feedbacks listed, resulting from predicted changes in the state and distribution of water, are positive; i.e., amplify the effect of increased CO_2.

C. Interpretation of the climatic record

For a long time it was believed that the preindustrial level of CO_2 was about 290 ppm and that the burning of fossil fuels such as coal, oil and gas contributed the only significant additions to atmospheric CO_2. This is estimated to have released about 180 GtonsC to date (Rotty and Masters, 1985; 1 gigaton C = 10^{15} grams or 10^9 tonnes as carbon). In the past few years it has been realized that historical changes in land usage such as forest clearing and agriculture have probably released a cumulative total amount of CO_2 of about the same magnitude. To allow room for some fraction of this ***biospheric source*** of CO_2 to have remained in the atmosphere, the preindustrial level of CO_2 would have had to have been lower than 290 ppm. Estimates of various sorts have provided numbers from 240 to 280 ppm with about 270 ppm now appearing most widely accepted. From these numbers we derive an estimate of the atmospheric increase of CO_2 due to this biospheric source of 10-50 ppm. Biospheric releases of CO_2 to the atmosphere were most probably in the range 90-180 GtonsC according to the Department of Energy State-of-the Art Reports (Houghton *et al.*, 1985). Using 58% for the fraction remaining in the atmosphere (determined from the fossil fuel releases during the period of the Mauna Loa record of CO_2) this implies a CO_2 increase of 25-50 ppm due to the biospheric source. The extremes of these two estimates give percentage CO_2 increases of 3.5 to 21%, and assuming a warming of 3°C for a CO_2 doubling, these imply an equilibrium warming of 0.15 to 0.8°C due to the biospheric CO_2. The *NH* (Northern Hemisphere) land observations (see Fig. 4) indicate a warming of about 0.6°C between

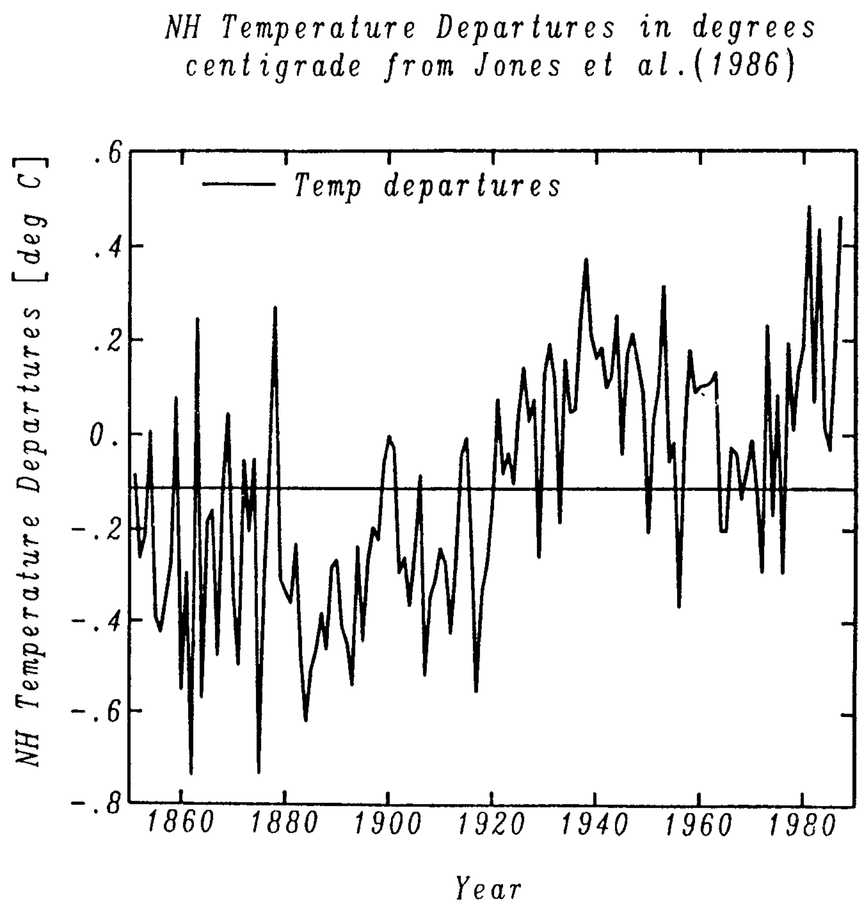

Fig. 4. Northern Hemisphere surface air temperature annual mean departures from the 1951-1970 mean (replotted from Jones *et al.*, 1986).

1881 and 1940. The data prior to 1881 are too sparse to be relied upon but mainly indicate slight progressive cooling. Thus, they mainly indicate that the historical fact that our land record of temperature data starts in 1881 will tend to exaggerate the climatic warming derived from the record for the past century. (Note: I consider the record of NH land temperatures to be our most reliable estimate of global climate change due to the unexpected and still unexplained variations shown by the more recently available SH and oceanic ship data).

If we focus on 1938, the warmest year in the NH land data record prior to 1981, the burning of fossil fuels could have added no more than 15 ppm of CO_2 to the atmosphere by then (Pearman, 1980). This would have been a percentage increase of 5.2% and for a doubled CO_2 warming of 3°C would produce an equilibrium warming of no more than 0.22°C. Thus, the warming up to 1938, if due to carbon dioxide, had to be due to the biospheric source of CO_2. If the 45 ppm of fossil fuel CO_2 added to the atmosphere since 1938 has had no effect on temperature; then it is also unlikely that the 15 ppm released before 1938 had any effect either. Therefore the total CO_2 increase due to fossil fuels of about 60 ppm or 21%, which is now calculated to produce an equilibrium warming of at least 0.83°C (assumes 3° for a CO_2 doubling), presumably still lies ahead, even if we stop burning fossil fuels today (Hansen *et al.*, 1984; Wigley and Schlesinger, 1985). (*Note:* the calculated equilibrium warming is nearly doubled if the other increasing greenhouse gases such as methane, nitrous oxide, freons and ozone are included).

Figure 5 was prepared to illustrate this problem: it is a plot of the NH temperature data from Fig. 4 versus the atmospheric concentration of CO_2 at the time of the observation. The

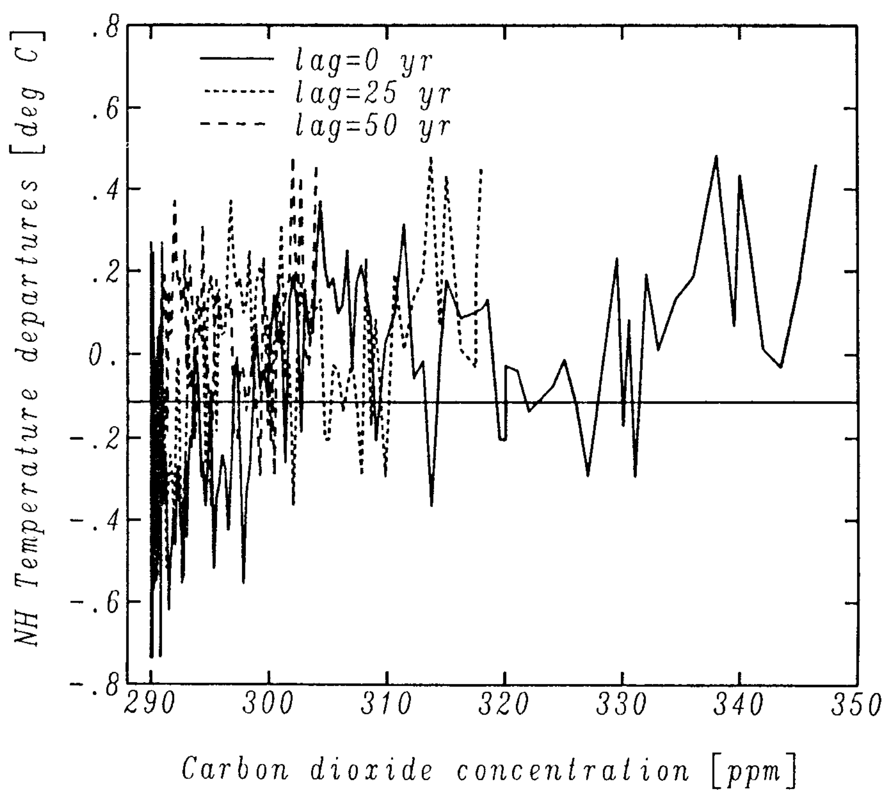

Fig. 5. Plot of NH temperature data from Fig. 4 versus the atmospheric concentration of CO_2 at the time of the observation based on Pearman's (1980) model.

CO_2 concentrations used are those computed by the model of Pearman (1980) which assumed a preindustrial level of 290 ppm and used the fossil fuel CO_2 emission data of Rotty (1979) and the Mauna Loa observations as controls. This figure makes it clear that essentially all of the warming of the past 135 years had occurred by the time the first quarter of the fossil fuel CO_2 had been added to the atmosphere and that the addition of the remaining three quarters of the fossil fuel CO_2 has had virtually no effect. Adding a lag for the thermal inertial of the oceans, as discussed below, simply pushes the warming farther in advance of the release of the fossil fuel CO_2. Again inclusion of the other greenhouse gases increases the discrepancy.

The current explanation as to why we cannot identify the effect of fossil fuel CO_2 in the temperature record is the thermal inertia of the oceans. It has now been recognized that the atmosphere cannot warm until the underlying surface warms. But the implication drawn is that the ocean surface cannot warm until much of the deeper ocean is warmed. The time lag required to do this is decades to centuries and this is presumed to be what is delaying the identification of a surface temperature rise due to fossil fuel CO_2 (Hansen *et al.*, 1984; Wigley and Schlesinger, 1985).

Figure 6 from Hamon and Godfrey (1975, p. 33) shows, as the typical temperature distribution in the oceans, a cross section along the 170°W meridian in the Pacific Ocean as a function of latitude and depth. Note how the warm surface water appears as a thin lens capping a very cold ocean. The thickness of the surface wind- and wave-stirred *mixed layer* varies seasonally and latitudinally and averages about 50 meters. Below it is the *thermocline* with a rapid drop in temperature to that typical of the vast bulk of the ocean. Below a few hundred meters depth the oceans are everywhere and always (relatively speaking) only a few degrees above the freezing point, which for sea water is about -2°C.

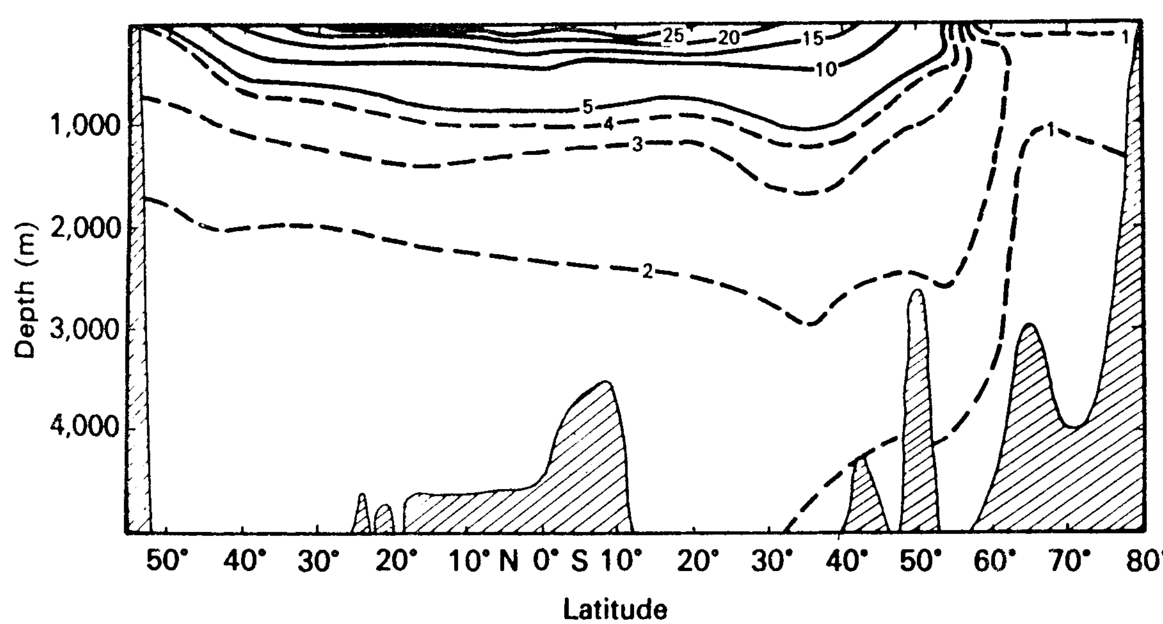

Fig. 6. North-south section of water temperature (°C) in the Pacific Ocean approximately along the 170°W meridian (from Hamon and Godfrey, 1975 p. 33).

Figure 6 makes it obvious that *the ocean surface can be warmed without warming the ocean to great depth.* Physically, warming the ocean from above is like cooling the atmosphere from below – as soon as the process begins, the affected surface layer becomes progressively decoupled from turbulent mixing with the rest of the fluid due to differences in density and, the further the process progresses, the greater the inhibition of any mixing or overturning.

Each winter as polar sea ice is formed, dense cold brine is squeezed out of the ice and, being the densest water in the ocean, sinks to the bottom–unless diluted sufficiently en route. It is this process which has filled the oceans with water near the freezing point. And this process will continue as long as sea ice forms in winter at either pole. It is currently estimated that this so-called *bottom water* is formed at a rate sufficient to push the existing waters of the oceans upward at an average rate of 4 meters per year. The water sinking at the winter pole is replaced by warm surface water moving in form lower latitudes. This constitutes the so-called *thermohaline circulation* since it is driven by density differences due to differences in both temperature and salt content.

The warm lens of surface water overlying the cold oceans is due to the absorption of solar radiation by the oceans. The surface layer of the oceans strives to balance absorbed solar radiation with energy losses in the form of sensible heat and latent heat of water vapor evaporated into the atmosphere and black body IR radiation, most of which is reabsorbed at some level within the atmosphere. The temperature of the mixed layer accordingly undergoes a seasonal cycle which lags to the sun in each hemisphere by about 30 days. The range between summer and winter temperatures is shown in Fig. 7 form Panfilova (1972). It is largest in a belt near 40° latitude and is greatest in the North Pacific where it reaches 14°C in a small area below Kamchatka. As the temperature in these bands rises in the spring, a new shallow mixed layer of only 20 to 30 meters depth forms and gradually deepens as the summer gives way to fall and winter.

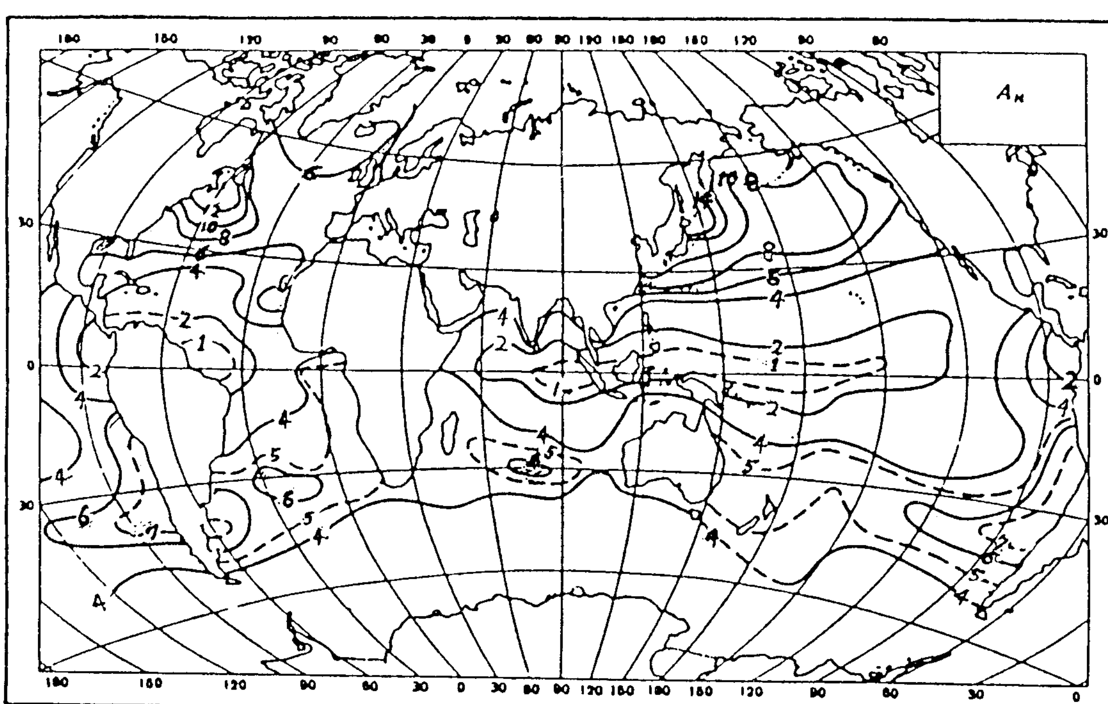

Fig. 7. Map of the seasonal range in sea surface temperature in degrees C (adapted from Panfilova, 1972).

This warm mixed layer is less dense than the water below. Thus they can be mixed only by mechanical force such as wind stirring. If the surface layer were to be made warmer, as from increased CO_2, it would resist mixing with the colder water below even more strongly. There appears to be no mechanism here to delay the heating of the mixed layer of the ocean much beyond the 30 days by which the temperature of the mixed layer is observed to lag the sun.

Even if there is such a lag mechanism, unless it exceeds a century, it should not have prevented warming from the biospheric pulse of CO_2 from becoming apparent by now. Thus, if the model estimates are correct, then the warming of 0.3 to 0.5°C since The Little Ice Age (1430-1850 AD) must have been due to the biospheric pulse of CO_2 from forest clearing. So far as I am aware, only Wilson (1978) of New Zealand has so far suggested such a connection. However, you can be certain that more and more people will jump on this band wagon unless they can somehow make the biospheric pulse of CO_2 go away. Why? Because, unless a warming due to the biospheric CO_2 pulse of 90-180 GtonsC (Houghton *et al.*, 1985) can be identified, there is very little reason to believe what our climate models are now telling us about the effect of the fossil fuel pulse of CO_2 which has now reached about 180 GtonsC (Rotty and Masters, 1985).

Is the warming since The Little Ice Age due to the biospheric pulse of CO_2? I don't know. And I have so far been unable to think of a way in which the question can be answered definitively. I do not believe that it was due to CO_2, or at least not entirely due to CO_2, for at least three reasons:

1) I see no reason for ocean surface warming to lag more than a few years behind a flux increment and thus, if the warming we have detected was due to the biospheric CO_2, why have we been unable to detect any warming from the fossil fuel CO_2?

2) Warming of the present climate appears to be possible without increased CO_2. Both the Medieval or Little Optimum centered about 1,000 YBP, and the Climatic Optimum, centered about 6,000 YBP, are believed to have had mean surface temperatures 0.5 (Lamb, 1965) to 2°C (*WMO-ICSU,* 1982, p. 114) warmer than that of today. While we do not know what caused these warmer periods, there is at present no reason to believe that the levels of CO_2 in the atmosphere then were different from its preindustrial value.

3) Perhaps the most persuasive reason is the drastic differences between the predicted and observed patterns of temperature change. The warming up to 1940 was a minimum near the equator and a maximum near the poles but in most other respects differed from what present models predict for increased CO_2. All observed patterns of surface temperature change, including that of 1881 to 1940, display cellular patterns of both warming and cooling; with very few exceptions the models predict uniform monotonic warming for increasing CO_2. According to the land observations the NH warmed much more rapidly than the SH from 1881 to 1940; the models indicate no such hemispheric asymmetry. The major fraction of the NH land data warming occurred in a discrete step of about 0.4°C between 1919 and 1921 (Ellsaesser *et al.*, 1986). A 7-year running average of the data from Fig. 4, presented in Fig. 8, illustrates this point. This is not at all the type of warming the models have led us to expect from a steadily increasing concentration of a greenhouse gas.

There is another point to be made from Fig. 8. We have heard much recently of how the climatic change predicted from increased CO_2 will be so rapid that both man and the natural biosphere will have trouble adjusting. Has anyone heard of any particular hardships caused by the apparent 0.4°C jump in NH land temperatures essentially between 1919 and 1921? To my knowledge, only a few of the specialists who have pored over the data are even aware of this abrupt "climate change" of this century.

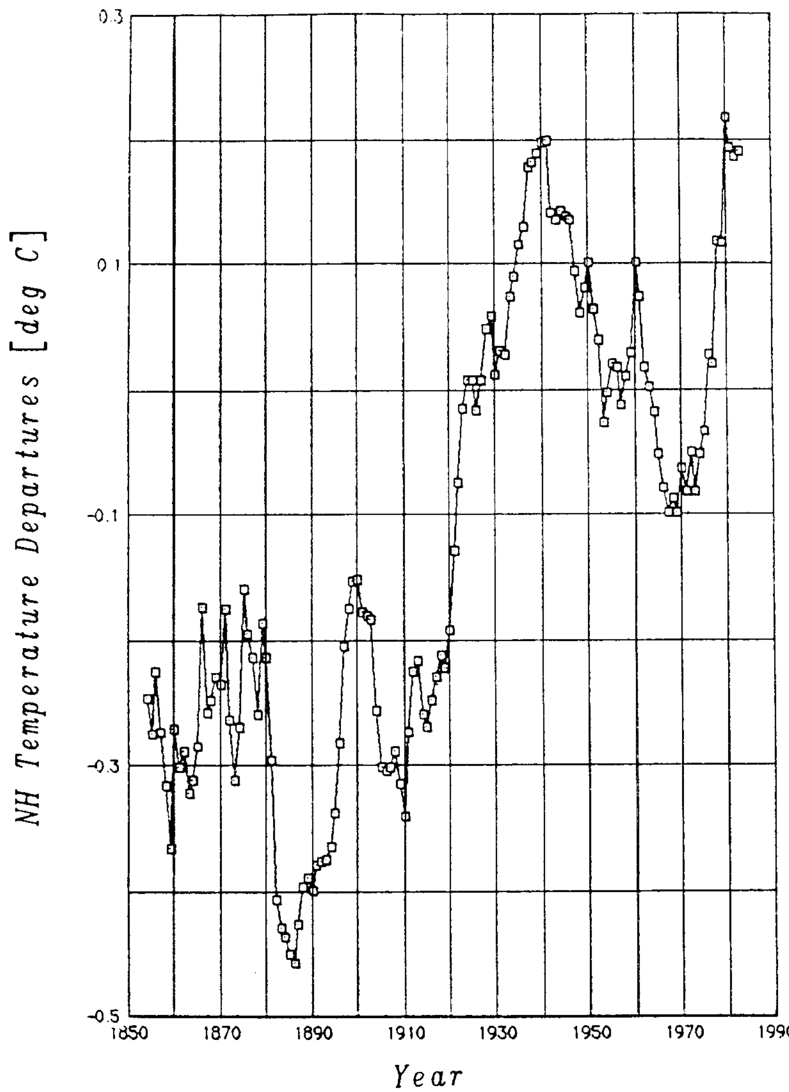

Fig. 8. Plot of 7-year running average of the data in Fig. 4.

While I am on this subject, I fell I should point out that one of the strongest supporters of the contention that the warming of the past century has been due to man-produced CO_2, Mikhail Ivanovich Budyko of the USSR State Hydrological Institute of Leningrad, has broken with most of his colleagues. While he still believes that doubled CO_2 will lead to a global warming of 3°C, he no longer believes this will be a climatic catastrophe. It is his view, that while global warming will initially be accompanied by some drying in mid latitudes, as the warming progresses, continental rainfall will increase almost everywhere and the planet will be a better place to live and produce crops for all of us. Rather than slowing the release of CO_2, he proposes that we speed up the process to hurry over the possibly unfavorable transition period (Budyko and Sedunov, 1988; Budyko, 1988).

D. Diagnosis of the apparent and possible model deficiencies

I believe there are many reasons to be skeptical of the magnitude of the warming now being computed for the climatic effect of doubled CO_2. The most important ones are related to specific deficiencies which I see in the models and which I will discuss individually. Later I will summarize some more general problems which have been noted in the models.

1. *Incorrect handling of tropical convection*

Over the approximately half of the Earth's surface constituting the tropics – roughly between 30°N and 30°S latitude – essentially all precipitation occurs in deep convection cells such as occur in the *ITCZs* (Intertropical Convergence Zones), monsoons, tropical cyclones (hurricanes, typhoons, etc.), easterly waves and orographically induced thunderstorms. The first two of these, the ITCZs and monsoons, constitute the updraft leg of the *Hadley* circulation which is a zonally symmetric planetary scale circulation with strong rising motion concentrated in relatively narrow bands near, but displaced from, the equator and slow broad scale sinking motion or *subsidence* on either side covering the trade wind regions of both hemispheres and concentrated in the eastern and equatorward portions of the so-called subtropical anticyclones.

Each of the above types of deep convection, on their own space scales, sweeps the warm moist air from the atmospheric boundary layer covering the tropical oceans and concentrates it into single cells or narrow bands of ascending air. If dry, the ascending air would cool at the so-called *adiabatic lapse rate* of 10°C/km (lapse rates any greater than this are statically unstable and will automatically cause overturning, like a layer of water on top of oil). But when saturated with water vapor, this cooling leads to condensation of the water vapor and release of latent heat reducing the rate of cooling to an average of 6.5°C/km. Over tropical oceans it can be as low as 2°C/km. This so-called *moist adiabatic* ascent is at very nearly the average lapse rate observed in the atmosphere – which in turn provides evidence that this is the mechanism that leads to the lapse rate which we observe throughout most of the troposphere.

In deep convection, however, the latent heat which is released when water vapor is condensed and precipitated back to the surface, is not mixed into the atmosphere at the level at which condensation occurs. Instead, this latent heat merely supplies the buoyancy which keeps the convective bubble or plume rising until it reaches a level in the atmosphere at which it is gravitationally stable, that is, that has the same density as the rising plume. While inertia may cause some overshooting of this level, the plume will soon settle back and spread out at its equilibrium level. The spreading tops of the convection cells or thunderstorms are visible as the so called *anvils* of the thunderstorms. Around the convective updraft there will be volume conserving descent or subsidence, extending from the level at which the plume ceases to rise and spreads out horizontally all the way down to the level from which the updraft started. This descent will occur under dry adiabatic conditions; that is, it will warm at the rate of 10°C/km, unless there are water drops present which can be evaporated. It is this mechanism which actually warms the atmosphere in regions of convection. Since the area of downdraft is very much larger than the area of ascent, the downward displacement for each individual convective plume is quite small. However, the process is cumulative. Each convection cell adds to the process, so eventually, most of the tropical troposphere above the trade wind inversion is filled by air that has subsided from the altitude of the anvil tops of the deep convective cells. Since temperatures at that level are very low, -50 to -90°C, this subsided air is very dry.

What does this have to do with the climatic effect of increased CO_2? The climate models predict that increased CO_2 will lead to surface warming and since warmer air can hold more water vapor, they predict a faster evaporation of water vapor, an acceleration of the hydrological cycle leading to more precipitation and a general increase in the amount of water vapor in the atmosphere; that is, a deepening of the greenhouse blanket due to water vapor. As pointed out above, this is expected to amplify the greenhouse effect of increased CO_2 alone by a factor of 3.2. But over the tropics, which is the warmest and most moist half of the total area of the globe and where essentially all precipitation occurs in deep convection, acceleration of the hydrological cycle also means acceleration of the subsidence surrounding the deep convection cells – possibly including the global scale Hadley circulation. Any increase in water vapor in this part of the atmosphere will be restricted to the boundary layer and that small part of the area occupied by the ascending convective plumes. Over the vast bulk of the tropics the stronger subsidence is more likely to lead to a drier tropical troposphere or a thinner, rather than thicker, greenhouse blanket due to water vapor. Thus, over this half of the globe, the warmest and most moist half, the *feedback from water vapor* is likely to be *negative* rather than positive. It certainly does not appear likely that the expected more than 3-fold amplification by water vapor of the added CO_2 greenhouse effect will occur here.

Figure 9 (Prahakara *et al.,* 1985) presents observational data from satellite showing that the

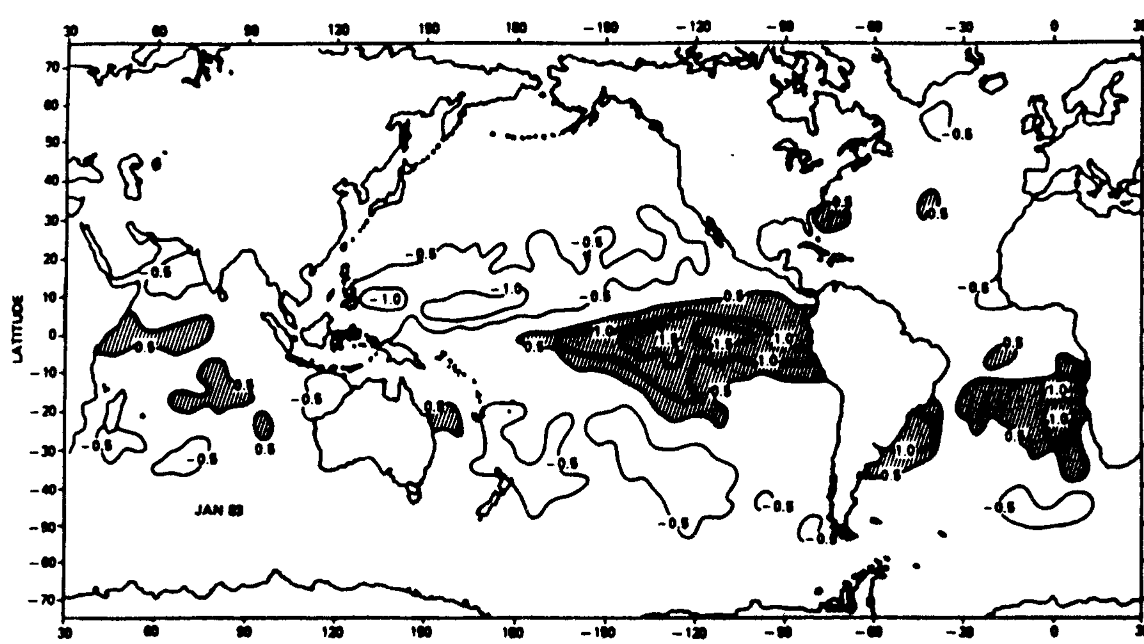

Fig. 9. Map of January 1983 anomalies in precipitable water (g/cm²) with respect to the 3-yr mean 1979-81. Positive areas hatched (from Probhakara and Short, 1985).

acceleration of the hydrological cycle and/or Hadley circulation in the eastern tropical Pacific during the El Niño of 1982/83 produced exactly the moisture distribution changes I have described – i.e., a deeper moist layer (increase in precipitable water) in the enhanced ITCZ area near the equator and shallower moist layers (decreases in precipitable water) over the remaining tropical latitudes of both hemispheres. Such a distribution of vertical motion and precipitation anomalies was also found by Nicholson (1986) over Africa in those years which she classified as "stronger Hadley-type".

It is also of interest to note that the integrated upward IR flux at the top of the atmosphere, particularly in winter, peaks in the subtropics rather than at the equator. That is, IR emission can escape to space from lower and warmer altitudes because of the reduced optical thickness of the overlying column of water vapor which occurs in the Hadley downwelling region of the subtropics compared to that near the equator (Charlock, 1984). Any strengthening of this subtropical downwelling would result in enhance emission to space from an even lower and warmer top of the moist layer in these latitudes.

As the above analysis indicates, any acceleration of the hydrological cycle in the tropics should augment the already sharp contrasts in precipitation observed there. That is, the wet regions should become wetter and the dry regions drier. However, any decrease in the precipitation in the dry regions should be far more noticeable than slight increase in precipitation in the wet regions. This analysis leads to the conclusion that climatic changes such as the present Sahelian drought may be the first detectable evidence of climatic changes induced by increased CO_2 (Ellsaesser, 1987). Current climate model results tend to support this. They show generally an acceleration of both the hydrological cycle and the Hadley circulation for a doubling of CO_2 and they all produce quite similar latitudinal profiles of percentage change in precipitation versus latitude (Schlesinger and Mitchell., 1985). In the annual mean, the latter are peaked at the equator, show minima or even negative changes in subtropical latitudes of both hemispheres and then increasing percentage increases toward the poles. Thus, the climate models compute at least part of the expected climatic change from increased CO_2 by accelerating the intertropical convergence of the ITCZs even though they do not handle the convection within these circulation systems very well.

However, since the Hadley circulation is presumably driven by surface frictional drag on the trade winds; if increased CO_2 reduces zonal winds, as most models predict, the Hadley circulation itself will more likely decrease than increase as predicted by the models, even if the hydrological cycle is accelerated. Available evidence seems to indicate that the Hadley circulation was stronger during the period of stronger zonal winds of the last ice age and weaker during the warmer than present Altithermal of 6,000 YBP (Janecek and Rea, 1985). Separation of the separate driving mechanisms of deep tropical convection and the Hadley cell is a problem which there is no hope of resolving until models are able to handle deep convection in a physically realistic manner. However, in two published studies of the energy balance of the equatorial trough, Riehl and Malkus (1958, 1979) concluded that the mass updraft in deep convection is at least twice that of the mean flow or Hadley updraft and that the excess is compensated by broadscale dry adiabatic descent and by near-cloud down drafts which are, at least in part, moist adiabatic.

This argument, that through inadequate representation of deep convection, the climate models are overestimating the surface warming to be expected from the doubling of CO_2, in now also supported by Professor Richard S. Lindzen (1989) of MIT. In fact he estimates the warming to be overestimated "by a factor of about six".

2. Overestimation of the warming of the tropical oceans

In their analyses of recent doubled CO_2 experiments with GCMs (General Circulation Models), Schlesinger and Mitchell (1985) noted that most of the models computed a warming of $\sim 2^{\circ}C$ over the tropical oceans but that the GISS model (Hansen *et al.*, 1984) computed a warming there nearly twice as great. I believe the problem is far more serious than the mere disagreement among the models, which in itself is adequate reason for concern on this point.

The important point to remember is that the atmosphere cannot be warmed unless the underlying surface is warmed first. The present tropospheric lapse rate is much less steep than can be maintained by radiation transport alone. This means that each layer of the troposphere is now emitting more IR radiation than it absorbs from the overlying and underlying layers, including sunlight, and would therefore cool if radiation were the only process operating. All models since that of Manabe and Strickler (1964) compute a net radiative loss of energy from the lower atmosphere due to the three principal radiatively active gases in the atmosphere; water vapor (H_2O), carbon dioxide (CO_2) and ozone (O_3). The net radiation (solar plus IR) tends to show cooling throughout the troposphere, except below surface inversions in high latitudes, ranging up to $2.5^{\circ}C$/day and averaging $1.2^{\circ}C$/day for the whole troposphere per Dopplick (1979). This cooling is not uniform but shows a maximum in a 2-km thick warm moist tropical surface layer extending over 30 to 50 degrees of latitude which migrates seasonally with the sun and another maximum in a nearly continuous layer near 11 km which is relatively uniform but does show a maximun at the summer pole and a minimum at the winter pole (Charlock, 1984). The apparent global mean radiating layer near 6 km and a temperature of 255 K mentioned earlier is, obviously, in reality more structured.

For our principal greenhouse gas, water vapor, Doherty and Newell (1984) computed that the rate of radiative cooling increases throughout the troposphere as water vapor is increased to about 1.5 times the present level and, above 850 mb, the rate of cooling continued to increase up to the highest water contents tested, even though the changes were quite modest for a range of precipitable water content of 0.2 to 2.2 times the present. The only reason that additional CO_2 does not also increase the tropospheric cooling rate is that increased CO_2 is uniformly mixed up into the stratosphere where there is a ***temperature inversion***, i.e., where temperature increases with altitude. While the increased CO_2 causes a cooling at these levels, it still results in an increase in the downward IR flux to the troposphere.

This analysis clarifies why the surface air cannot be warmed until the underlying surface is warmed. It also implies that, in contrast to current practice, climate models designed to compute surface air temperature changes should focus their attention on the lower boundary, particularly the surface or mixed layer of the oceans.

On a global bases, doubling the atmospheric content of CO_2 alone leads to an increase in IR flux to the surface of 1 to 1.5 W/m^2. (As pointed out above, this is actually only a decrease in net outgoing flux from the surface). In the tropics, Kiehl and Ramanathan (1982) computed almost no increase because the moist surface layer is already essentially opaque to IR radiation due to the continuum absorption by water vapor. In addition, as temperatures rise, an increasing fraction of any enhanced flux to the surface will be used to evaporate more water from the oceans as opposed to raising the temperature of the water (Flohn, 1982).

From a study of maximum temperatures attained by plant foliage and the surface waters of tropical oceans, Priestley (1976) deduced that there should be a "rather sharply defined upper limit to which air temperature will rise above a well watered surface". Using monthly average of daily maximum temperatures he identified the limiting temperature for land stations which had no exhausted their soil moisture as about 92°F (33.3°C). Priestley and Taylor (1972) found that the *Bowen ratio* (ratio of sensible to latent heat flux from the surface to the atmosphere) decreased monotonically with increasing temperature, suggesting that sensible heat flux became negative (flows from the atmosphere to the surface) at temperatures above about 32°C. A reversal of the heat transfer between plant leaves and the air in the vicinity of 33°C (i.e., heat moving from the air to the plant at temperatures above 33°C) was reported earlier by Linacre (1964). A review of the Bowen ratio data by Brutsaert (1982, Fig. 10.3) placed the apparent sign reversal near 30°C. Newell and Doplick (1979) sought to illustrate the physics of this situation. Holding the surface atmospheric conditions fixed at 27°C and 65% relative humidity, they computed a requirement of 30 W/m^2 incremental flux to warm the oceans surface 1°C. This paper has been widely and vehemently condemned as unrealistic for not allowing the air to warm and to increase its water vapour content. Since then, two papers have come to my attention which estimated the thermal inertia of the surface waters of the eastern Mediterranean (Assaf, 1983) and of the Tropical Pacific (Niiler, 1981) to be 40 W/m^2 per degree C. (Professor Newell told me that, since the cited paper appeared, he and his colleagues have been essentially blackballed by those alloting climate research funds. It is my impression that the paper aroused great animosity in the climate research community - almost as great as that aroused by the papers of Idso (Luther and Cess, 1985)).

Flohn (1982) stated: "Above warm heated waters, the air is heated from below and thus unstable, water vapour is transported rapidly upward with atmospheric turbulence and the relative humidity cannot increase above a certain threshold (near 78 percent)", and that due to "the exponential increase of saturation vapour pressure with SST: above about 29°C (at a maximum 29.5°C) the available net radiation- see Hastenrath and Lamb (1978, 19[79]) - is no longer sufficient to maintain the process of evaporation".

The palaeoclimatologists, Matthews and Poor (1980), proposed the working hypothesis that the surface temperatures of the tropical oceans are tied to the solar constant and have maintained their present values back even through the Cretaceous - the period of warmest terrestrial climate yet documented (Barron *et al.*, 1981). In their reconstruction of the climate of 18,000 YBP CLIMAP (1976, 1981) found very little change in tropical ocean surface temperatures other than that attributed to stronger Chile and Benguela ocean currents and stronger equatorial upwelling.

Of all the types of information available to us at present - including the palaeoclimatic data from the Cretaceous when CO_2 levels were several times higher than now, only the climate models suggest that tropical ocean temperatures will warm as a result of doubled CO_2. Thus, from present knowledge, the fact that the climate models predict that tropical ocean SSTs will warm by as much as 2°C, much less the 4°C predicted by the GISS model (Hansen *et al.*, 1984), is more a reason to question the models than to be concerned about the warming they predict.

3. General climate model deficiencies

Below is offered a general diagnosis of the causes of some of the problems with the models cited above. These are at best educated guesses and could only by substantiated, if at all, by substantial additional model experiments. They are offered primarily as a stimulus to attract additional attention to this important problem. They are based primarily on comparative analyses of the four principal GCM models analyzed by Grotch (1988); i.e., the GCMs of the modeling groups at NCAR (Washington and Meehl, 1984), GFDL (Manabe and Wetherald, 1986; Manabe *et al.,* 1981), GISS (Hansen *et al.*, 1984) and OSU (Schlesinger, 1982).

a. Convection and summer precipitation.

One rather broad generalization is that the models, as noted above, do not handle atmospheric convection, particularly deep convection at all well. This shows up in the mainly convective precipitation of summer. To varying degrees (OSU most, GISS least) the models underestimate convective precipitation generally as in the South Pacific Convergence Zone (which if Jaeger (1976) and Schutz and Gates (1971, 1972) can be believed, is even stronger in the SH winter than in summer) but particularly over small land areas. Outstanding example of deficits in summer precipitation occur over Central America and north and central South America, over the Caribbean in general and along the Antarctic Convergence. On the other hand, the models tend to overestimate summer rain over continental interiors. In their diagnoses of the GISS models, Strauss and Shukla (1988a, b) and Rind (1988) frequently note that the discrepances with observations are greater in summer and that continental precipitation is excessive in summer by a factor of 2. After experiments with models of different space resolutions, Rind (1988) reported: "Our true uncertainty in climate sensitivity is probably of the order of 100%,..."

b. Radiation errors suggested by continental summer temperatures.

A second broad generalization is that the models are quite diverse in their handling of radiative transport and in so far as they disagree in this respect they are probably all in error since no single model stands out as better than the others in this respect. The strongest evidence here is the poor agreement in computed land temperatures in summer (see Grotch, 1988). In as much as the model agreements in sea surface temperature and in land surface temperatures in winter are more or less imposed by the essentially prescribed (or tuned) ocean temperatures on the one hand and the strong latitudinal temperature gradients in the winter hemisphere on the other, the above weakness of the models is particularly discouraging. Hansen *et al.* (1988) pointed out, that despite the overall lesser variability of the models compared to observations – particularly in the upper troposphere and stratosphere, the models show unrealistically large surface temperature variability over the continents in summer. "The largest discrepancy in the [GISS] model is the overestimate of variability in continental areas during summer, with the model yielding a variability about twice as large as in the observations" (Hansen and Lebedeff, 1987; Hansen *et al.,* 1988).

Additonal evidence for this particular type of error is provided by the positions and intensities of the continental summer heat lows. Both the NCAR and GFDL models compute excessively strong continental heat lows, particularly over Australia (the smallest continent) and they also place the N. American heat low in the eastern rather than the southwestern US (far east and north of its observed position). This latter error, in particular, would appear to be clearly due to errors in the radiation calculations, possibly mediated by errors in water vapor and soil moisture distributions.

This comparative analysis of the results of the four principal GCM models tends to cast doubt on the validity of the GFDL (Manabe *et al.,* 1981) prediction of reduced soil moisture in mid-latitudes as a result of doubled CO_2. As shown in Grotch (1988, Figs. 6-7, 6-8 and 6-9), for the land areas of Africa, Western Europe and the US, only GFDL computed a decrease of precipitation in summer for doubled CO_2. But as shown in Grotch (1988, Fig. 5-17), GFDL also predicted the largest warming of NH land areas in summer and particularly over N. America and the US. These higher summer temperatures will strongly affect soil moisture levels as well as vice versa. However, there is little room for complacency here. That is, while the predicted decreases in soil moisture in mid-latitudes may not be believable, both the models and theoretical analysis suggest greater aridity in the already dry subtropics with increased CO_2 (Ellsaesser, 1987). It should be noted that in discussions of soil moisture, few of the contributers on this subject have discussed, or even mentioned, the tendency of enhanced CO_2 to reduce the degree or daily period that plant stomata are open and thus to reduce evapotranspiration and the plant's water needs. This is particularly surprising since the theoretical basis for this effect is just as strong as that for enhancement of the greenhouse effect and the supporting experimental evidence is far greater (Idso, 1988). There are even suggestions that this will lead to increased run off – river flow (Idso and Brazel, 1984; Wigley and Jones, 1985).

The OSU model appears to stand out in placing the subtropical anticyclones, or at least the areas of minimum precipitation usually associated with them, over, rather than to the west of the subtropical continents. The cause of this is not apparent but may again be a result of the improper calculation of radiative transport as suggested above.

c. Strong band of warming at 65°S.

A third serious and general problem is revealed by the strong band of warming – even in summer – computed for a doubling of CO_2 at approximately 65°S by all of the models except OSU. For the NH summer all models computed a doubled CO_2 warming of less than 2°C at the North Pole (see Grotch, 1988, Fig. 5-4), yet in the SH summer (DJF) they computed warmings of 4 to 8°C at 60 to 70°S (see Grotch, 1988, Fig. 5-3) a region were the current annual range in temperature is held to about 1°C due to the deep oceanic overturning in this area. This error suggests that the control models computed excess ice cover which melted with doubled CO_2.

d. Disagreement with observations.

In addition to the differences in predicted and observed changes pointed out above, the more detailed observations of changes in atmospheric structure observed since 1957 show even stronger departures from the uniform monotonic polar-amplified type of warming suggested by the models. This is perhaps most apparent from Angell's (1988) analyses of upper air sounding data. During this later period, the SH warmed more than the NH at the surface. However, most of the warming has been in low latitudes and Antarctica such that the equator-to-pole temperature gradient *increased* in the NH while decreasing in the SH. In the mid to lower troposphere (850-300 mb) the meridional temperature gradient also increased in the NH while remaining essentially unchanged in the SH. During the most recent 15 years, 1973-1987, Angell's (1988) data indicate surface warming in all climatic zones except the two polar zones, i.e., cooling occurred in those zones where "greenhouse" warming is computed to be a maximum. This resulted in an increase in meridional temperature gradients in both hemispheres in this significant layer of the troposphere, again contrary to the expected effect of increased greenhouse gas.

Even more troubling is Angell's (1988) finding of cooling in the 300-100 mb layer, particularly in the tropics where this layer in within the upper troposphere and where the models generally compute greater warming than at the surface. This has been cited as a "significant discrepancy" by several researchers even though Angell (1988) himself called it a "neutral finding".

4. *The turf factor*

You are all no doubt aware of the tendency for each profession to find the solution to problems to lie within its own area of expertise, i.e., within its own turf. The CO_2 problem has actually been taken over by a specialty within a specialty – the specialists in radiation transport.

This is not particularly surprising. Radiation transport is a complex subject requiring a huge volume of detailed physical data of various types and specialized mathematical methods. Even now there are comparatively few specialists capable of reworking the CO_2 problem from first principles. Those who were able to do so were given major roles in climate model development and for the most part emerged as the spokesmen of the climate modeling effort. This in itself would not be bad except that the training requirements for excelling in the field and the demand for their special talents in most cases left little time for becoming comparably familiar with the other important meteorological and climatic processes. As a corollary, many meteorologists, even though they have strong reservations about the model predictions, have remained silent rather than reveal, or be accused of ignorance with regard to radiation transport. This combination of circumstances has led to a tendency for all climatic processes to be interpreted in terms of radiation transport and, in particular, in the on-going climatic debate, to exaggerate the role of radiative transport compared to other processes of equal or even greater importance in climatogenesis.

5. *Use of an erroneous standard*

Weather, particularly as measured by temperature, is an extremely variable quantity; night-to-day, winter-to-summer and pole-to-equator. Climate, on the other hand, is an extremely stable quantity; 30-year mean temperatures for any given location vary by no more than a few degrees C, hemispheric and global mean temperatures are even more stable– varying at most by about 3°C over the past 10,000 years and by about 0.5°C over the last 135 years for which we have instrumental records.

Our so-called climate models do quite well at reproducing the large night-to-day, winter-to-summer and pole-to-equator temperature differences which we associate with *weather* but fail miserably in reproducing the modern *climate* when judge against the minute variability of climate. This was early recognized but since forgotten, under the unprovable assumption that the perturbation in a model-predicted climate (as from the doubling of CO_2) is believable even though there are obvious errors in the normal or unperturbed climate predicted by the model. In view of the large model-to-model differences in such predicted climatic perturbations, I believe there is strong reason to question this assumption.

In any case, this unproven assumption, which underlies all our current climate predictions, needs to be considered by those who would make multi-trillion dollar decisions as to what we should do to protect ourselves from the hazards predicted by such models.

E. The palaeoclimatic record

Based on several types of evidence, but mainly on variations in the isotope Oxygen-18 in drilling cores from the ocean floor, the climatic history of the Earth has been reconstructed in considerable detail (Crowley, 1983; Berger, 1988).

1. The last 100 million years

Other than the estimated 6°C cooling from the Cretaceous warmth of about 100 million years ago (Barron *et al.,* 1981), the outstanding feature of this history is the waxing and waning of continental glaciers over cycles approximately 100 thousand years in duration during the most recent part of this period. These cycles have been asymmetric, involving long periods of staged, multi-step temperature decline and glacial buildup – called the *glacials*, which last about 90 thousand years each and are terminated abruptly by rapid transitions to warm periods – the *interglacials*, which last about 10 thousand years each. Over the past 2 to 3 million years there have been at least 17 such cycles, with a further abrupt cooling about 900,000 YBP accompanied by a 10% increase in ice volume and 3.5°C cooling of N. Atlantic SSTs (Maasch, 1988). The periods and phasing of the more regular records of the past 7 of these cycles have appeared (until recently Winograd *et al.,* 1988) to be related to changes in received solar radiation due to the periodic variations in the Earth's orbit around the sun. But the quantitative relationships as to how such weak changes, mostly in the seasonal and latitudinal distribution of solar flux, can cause such large climate variations remain a puzzle (Berger, 1988). These cycles have been accompanied by oscillations in the average surface air temperature of the globe from values near the present to a global average 3 to 5°C colder than present (Crowley, 1983). Even if our present Pleistocene interglacial climate occurred a similar 10% of the time during the previous Ice Ages cited by Berger (1988), it would still have existed during no more than 1% of the Earth's 4.5 billion-year history, and therefore, cannot be regarded as an immutable or inviolable norm simply because it is all we have ever known. The present interglacial, called the Holocene, is believed to have begun approximately 11,000 YBP (Crowley, 1983). Thus, the available evidence suggests that the onset of the next glacial is, if anything, overdue. In fact, it may already have been underway for 6,000 years (Berger, 1988).

2. The last 10,000 years

The oceanic sediments from which the above climatic record was derived accumulated at rates of millimeters to centimeters per thousand years, so the records are greatly smoothed by the creatures living on the ocean floor and burrowing in the bottom ooze. Polar glaciers, buildup ten to a thousand times more rapidly than ocean sediments, have few borrowing life forms and also have a temperature-indicative variation of Oxygen-18 about 5 times larger than that of ocean sediments. However, they are subject to other sources of confusion of the record – melting and glacial flow. Still, if cores are drilled at points perennially below freezing and forming a summit of the glacier, any flow should be outward in all directions so the layers below should be subject only to thinning with no relative displacement from one layer to the next.

Ice cores from such sites in both the Greenland and Antarctic Glaciers have given us an even more detailed reconstruction of climatic history back through the last interglacial, or approximately the last 120 thousand years. In addition to the temperature changes indicated by Oxygen-18, the ice layers record past atmospheric levels of dust, radioactive tracers, chemicals such as sulphate, and even the greenhouse gases, such as CO_2 and methane. While the CO_2 levels appear to have varied from about 200 ppm during the glacials to 265 to 280 ppm during the interglacials, the evidence suggests this is as much a result of the temperature changes as a cause of them.

Such reconstructions of the history of past temperature also show superimposed oscillations about 2,500 years in duration; with warmer periods centered about 1,000, 3,500 and 6,000 YBP and colder periods centered in between them (Crowley, 1983; Berger, 1988). It was during the Medieval Little Optimum, centered about 1,000 YBP, that the sea ice melted back in the North Atlantic and the Norsemen were able to settle Iceland and Greenland and may even have reached Labrador. Similarly, it was during the following cold part of the cycle, the Little Ice Age (usually assigned to 1430 to 1850 AD), that the Greenland colony died out and history recorded glacier advances and abandonment of farms and villages in parts of Europe. The Medieval Little Optimum (1,000 YBP) and the Climatic Optimum (6,000 YBP) apparently had mean temperatures 0.5 (Lamb, 1965) to 2°C (*WMO-ICSU*, 1974, P. 114) warmer than today. Since current evidence indicates that CO_2 was at the preindustrial level during those periods, higher levels of CO_2 are apparently not needed for the temperature to rise at least 2°C above the present level.

F. Summation

As noted above, in the present Pleistocene Ice Age or climatic epoch, there have been some seventeen glacial/interglacial cycles and the present interglacial is believed to have begun approximately 11,000 YBP. Thus, by present knowledge, there is no reason not to anticipate the onset of the next cycle of 90 thousand years of glaciation beginning at any time. In this context, I find it remarkable that one rarely if ever hears the suggestion that increased carbon dioxide in the atmosphere is just what is needed to prevent or delay the onset of the next period of glaciation which, if anything, is apparently already overdue, or already in progress! Also, on the longer time scale (100 million years), the Earth has been cooling and the atmosphere has been losing carbon dioxide. Most C-3 plants are not expected to be able to survive at CO_2 concentrations below about 100 ppm, about half the levels reached during the most recent glacials. Both Lovelock and Watson (1982), and Budyko (1984) have voiced the opinion that our planet is evolving toward a state in which the atmosphere will have too little CO_2 to support plant life – and if the plants go, so will the animals. Yet no one seems to dare to suggest that man might be *fertilizing* rather than *fouling* his nest, or that turning to the consumption of fossil fuels was an act of such providential foresight for the preservation of the biosphere that it could only have been ***divinely inspired*** !

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