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REVIEW

CO_2-induced global warming: a skeptic's view of potential climate change

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ABSTRACT: Over the course of the past 2 decades, I have analyzed a number of natural phenomena that reveal how Earth's near-surface air temperature responds to surface radiative perturbations. These studies all suggest that a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration could raise the planet's mean surface air temperature by only about 0.4°C. Even this modicum of warming may never be realized, however, for it could be negated by a number of planetary cooling forces that are intensified by warmer temperatures and by the strengthening of biological processes that are enhanced by the same rise in atmospheric CO_2 concentration that drives the warming. Several of these cooling forces have individually been estimated to be of equivalent magnitude, but of opposite sign, to the typically predicted greenhouse effect of a doubling of the air's CO_2 content, which suggests to me that little net temperature change will ultimately result from the ongoing buildup of CO_2 in Earth's atmosphere. Consequently, I am skeptical of the predictions of significant CO_2-induced global warming that are being made by state-of-the-art climate models and believe that much more work on a wide variety of research fronts will be required to properly resolve the issue.

KEY WORDS: Carbon dioxide · CO_2 · Climate change · Global warming · Greenhouse effect

1. INTRODUCTION

Twenty years ago I was heavily involved in the measurement of solar and thermal radiation fluxes at the surface of the Earth, concentrating on their responses to changes in atmospheric composition that were produced by unique local weather phenomena. About the same time I also became interested in carbon dioxide-induced global warming; and I decided to see if I could learn something about the subject from the natural experiments provided by the special meteorological situations I was investigating.

My idea was to determine the magnitudes of radiative perturbations created by various climatic events and observe how the near-surface air temperature responded to the resultant changes in the surface radiation balance. From this information I sought to develop a surface air temperature sensitivity factor, defined as the rise in surface air temperature divided by the increase in surface-absorbed radiation that prompted the temperature rise. Then, by multiplying this factor by the increase in downwelling thermal radiation expected to be received at the surface of the Earth as a result of a doubling of the atmosphere's CO_2 concentration, I hoped to obtain a rough estimate of the likely magnitude of future CO_2-induced global warming.

2. DECIPHERING NATURE'S 'EXPERIMENTS'

2.1. Natural Experiment 1

The first of the unique meteorological situations I investigated was the change in atmospheric water

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vapor that typically occurs at Phoenix, Arizona, USA, with the advent of the summer monsoon (Hales 1972, 1974, Douglas et al. 1993). During the initial phases of the establishment of this more humid weather regime, atmospheric vapor pressure exhibits large day-to-day fluctuations, creating significant variations in the solar and thermal radiation fluxes received at the Earth's surface. Consequently, for all cloudless days of the 45 d period centered on the summer monsoon's mean date of arrival, I plotted the prior 30 years' daily maximum and minimum air temperatures as functions of surface vapor pressure to see to what degree these specific temperatures were influenced by fluctuations in atmospheric water vapor.

In the case of the maximum air temperature, which typically occurs in the middle of the afternoon, there was no dependence on the surface vapor pressure, due to the opposing effects of atmospheric water vapor on the fluxes of solar and thermal radiation received at the Earth's surface at that time of day. But in the case of the minimum air temperature, which typically occurs just prior to sunrise after a several hours' absence of solar radiation, there was a strong relationship, since the effect of water vapor on the flux of solar radiation is absent at that time and is thus unable to mask the effect of atmospheric moisture on the downwelling flux of thermal radiation.

Using an equation I had developed previously (Idso 1981a), which specifies the downward-directed flux of thermal radiation at the Earth's surface as a function of surface vapor pressure (e_0) and air temperature (T_0), I calculated that in going from the low-end values of this relationship (e_0 = 0.4 kPa, T_0 = 18.3°C) to its high-end values (e_0 = 2.0 kPa, T_0 = 29.4°C), the flux of thermal radiation to the Earth's surface would rise by approximately 64.1 W m^{-2}. Consequently, the surface air temperature sensitivity factor I obtained from this natural experiment was (29.4°C – 18.3°C)/64.1 W m^{-2}, or 0.173°C/(W m^{-2}) (Idso 1982).

At this stage, however, I had no reason to believe that this result applied anywhere beyond the bounds of Phoenix, Arizona, or that it was a true measure of any portion of the planet's climatic sensitivity. What bothered me most with respect to this latter point was the large size of the experiment's radiative perturbation and the short time period over which the temperature response was determined. I thought it unlikely that these experimental features would yield a surface air temperature sensitivity factor equivalent to that produced by a much smaller radiative perturbation introduced over a considerably longer time span, such as is occurring in response to the ongoing rise in the air's CO_2 content. Hence, I initiated a search for a set of meteorological circumstances that would more closely approximate this latter situation.

2.2. Natural Experiment 2

I found what I sought in the naturally-occurring vertical redistribution of dust that occurs at Phoenix, Arizona, each year between summer and winter (Idso & Kangieser 1970). With respect to this phenomenon, I had previously demonstrated that the restriction of airborne dust to a much shallower depth of atmosphere during winter does not alter the transmittance of the atmosphere for the total flux of solar radiation, but that it increases the atmosphere's downwelling flux of thermal radiation at the Earth's surface by 13.9 W m^{-2} (Idso 1981b). In another study, a colleague and I had also determined that winter surface air temperatures were 2.4°C warmer than what would be expected for the vertical distribution of dust that exists in summer (Idso & Brazel 1978). Assuming that this temperature increase was a consequence of the extra thermal radiation produced by the seasonal redistribution of atmospheric dust, I divided the latter of these 2 numbers by the former to obtain a surface air temperature sensitivity factor that was identical to the result derived from my first natural experiment: 0.173°C/(W m^{-2}).

The perfect agreement of these 2 results was totally unexpected. The radiative perturbation of the second experiment was significantly less than that of the first—13.9 versus 64.1 W m^{-2}—and it unfolded over a time span of months, as opposed to a period of days. Both of these differences, I had thought, should have increased the opportunity for slower-acting secondary and tertiary feedback processes (which I had initially assumed to be predominantly positive) to manifest themselves in the second experiment, leading to a possibly very different (and presumably larger) result from that of the first experiment. Such was not the case, however, and in analyzing the situation in retrospect, I could think of no compelling reason why the net effect of all of the feedback processes that play significant roles in Earth's climatic system should be strongly positive. Indeed, it seemed more logical to me that the opposite would be true; for if strong positive feedbacks existed, the Earth would likely exhibit a radically unstable climate, significantly different from what has characterized the planet over the eons (Walker 1986).

Be that as it may, I felt that I needed more real-world evidence for the value of the surface air temperature sensitivity factor I had derived from my first and second natural experiments before I made too much of what I had found. For one thing, the perfect agreement of the 2 results could well have been coincidental; and they both were derived from data pertaining to but a single place on the planet. Consequently, I began to look for a third set of meteorological circumstances that would broaden my geographical data base and allow me to make yet another evaluation of surface air temperature response to radiative forcing.

2.3. Natural Experiment 3

The next phenomenon to attract my attention was the annual cycle of surface air temperature that is caused by the annual cycle of solar radiation absorption at the Earth's surface. To derive what I sought from this set of circumstances, I obtained values for the annual range of solar radiation reception at 81 locations within the United States (Bennett 1975), multiplied them by 1 minus the mean global albedo (Ellis et al. 1978), and plotted against the resulting values of this parameter the annual air temperature ranges of the 81 locations.

The results fell into 2 distinct groups: one for the interior of the country and one for the extreme west coast, which is greatly influenced by weather systems originating over the Pacific Ocean. Each of these data sets was thus treated separately; and the linear regressions that were run on them were forced to pass through the origin, since for no cycle of solar radiation absorption there should be no cycle of air temperature. The slopes of the 2 regressions then yielded surface air temperature sensitivity factors of 0.171°C/(W m^{-2}) for the interior of the United States—which result was essentially identical to the results of my earlier natural experiments at Phoenix—and 0.087°C/(W m^{-2}) for the extreme west coast.

Since this latter sensitivity factor was only half as great as the sensitivity factor of the rest of the country, it was clear that it was largely determined by the surface energy balance of the adjacent sea, the effects of which are advected inland and gradually diminish with distance from the coast. It was also clear, however, that this predominantly ocean-based sensitivity factor had to be somewhat elevated, due to the influence of the land over which it was determined. Consequently, assuming that it represented an upper limit for the water surfaces of the globe, which cover approximately 70% of the Earth, and assuming that the result for the interior of the United States applied to all of Earth's land surfaces, I combined the 2 results to obtain an upper-limiting global average of 0.113°C/(W m^{-2}) for the surface air temperature sensitivity factor of the entire planet (Idso 1982), recognizing, of course, that this result was probably still no more than a rough approximation of reality, for there were many climatically-significant real-world phenomena not explicitly included in the natural experiments I had analyzed.

2.4. Initial implications

Although there was no way to prove that the results I had obtained were applicable to long-term climatic change, their consistency gave me enough confidence to pursue their implications with respect to the ongoing rise in the air's CO_2 content. Consequently, I derived a value of 2.28 W m^{-2} for the radiative perturbation likely to be expected from a 300 to 600 parts per million (ppm) doubling of the atmospheric CO_2 concentration; and multiplying this result by the upper-limiting surface air temperature sensitivity factor I had derived for the globe as a whole, I calculated that the Earth could warm by no more than 0.26°C for a doubling of the air's CO_2 content (Idso 1980). Others, however, have calculated by more sophisticated methods that the radiative perturbation for this change in CO_2 is probably closer to 4 W m^{-2} (Smagorinsky et al. 1982, Nierenberg et al. 1983, Shine et al. 1990); and this presumably more realistic result suggests that the Earth could warm by no more than 0.45°C for a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration.

Soon after the publication of these findings, and primarily on the basis of the concerns expressed above, my approaches and conclusions were both questioned (Leovy 1980, Schneider et al. 1980), as well they should have been; for there was no apparent reason why the surface air temperature sensitivity factor I had derived should necessarily describe the long-term climatic response of the Earth to the impetus for warming produced by the atmosphere's rising CO_2 concentration. Hence, I began to look for a situation where the surface air temperature of the entire planet had achieved unquestioned equilibrium in response to a change in surface-absorbed radiant energy in a natural experiment that implicitly included all processes that combine to determine the climatic state of the Earth; and I ultimately identified 2 such situations.

2.5. Natural Experiment 4

The first of these 2 global-equilibrium natural experiments consisted of simply identifying the mean global warming effect of the entire atmosphere and dividing it by the mean flux of thermal radiation received at the surface of the Earth that originates with the atmosphere and which would be non-existent in its absence (Idso 1984). Calculation of both of these numbers is straightforward (Idso 1980, 1982), and there is no controversy surrounding either of the results: a total greenhouse warming of approximately 33.6°C sustained by a thermal radiative flux of approximately 348 W m^{-2}. Hence, the equilibrium surface air temperature sensitivity factor of the entire planet, as defined by this fourth approach to the problem, is 0.097°C/(W m^{-2}).

2.6. Natural Experiment 5

My second global-equilibrium experiment made use of the annually-averaged equator-to-pole air temperature gradient that is sustained by the annually-averaged equator-to-pole gradient of total surface-absorbed radiant energy (Idso 1984). Mean surface air temperatures (Warren & Schneider 1979) and water vapor pressures (Haurwitz & Austin 1944) for this situation were obtained for each 5° latitude increment stretching from 90° N to 90° S. From these data I calculated values of clear-sky atmospheric thermal radiation (Idso 1981a) incident upon the surface of the Earth at the midpoints of each of the specified latitude belts. Then, from information about the latitudinal distribution of cloud cover (Sellers 1965) and the ways in which clouds modify the clear-sky flux of downwelling thermal radiation at the Earth's surface (Kimball et al. 1982), I appropriately modified the clear-sky thermal radiation fluxes and averaged the results over both hemispheres. Similarly-averaged fluxes of surface-absorbed solar radiation (Sellers 1965) were then added to the thermal radiation results to produce 18 annually-averaged total surface-absorbed radiant energy fluxes stretching from the equator to 90° NS, against which I plotted corresponding average values of surface air temperature.

This operation produced 2 distinct linear relationships—one of slope 0.196°C/(W m^{-2}), which extended from 90° NS to approximately 63° NS, and one of slope 0.090°C/(W m^{-2}), which extended from 63° NS to the equator. Hence, I weighted the 2 results according to the percentages of Earth's surface area to which they pertained (12 and 88%, respectively) and combined them to obtain a mean global value of 0.103°C/(W m^{-2}). Averaging this result with the preceding analogous result of 0.097°C/(W m^{-2}) then produced a value of 0.100°C/(W m^{-2}) for what I truly believe is Earth's long-term climatic sensitivity to radiative perturbations of the surface energy balance. And this value is just slightly less than the upper-limiting value I had obtained from my first 3 experiments, as indeed it should be.

2.7. Intermediate implications

In light of the exceptional agreement of the 2 preceding results, as well as their appropriate relationship to the results of my first 3 natural experiments (which relationship may still be argued to be largely coincidental, however), I began to think that my observationally-derived value of 0.1°C/(W m^{-2}) may be much more than a rough approximation of Earth's climatic sensitivity to surface radiative forcing. Indeed, I began to think that it may be a very good representation of it; and to assess its implications I multiplied it by 4 W m^{-2}, which is the radiative perturbation likely to be produced by a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration, to obtain a mean global temperature increase of 0.4°C (Idso 1984), which is but a tenth to a third of the warming that has historically been predicted for this scenario by most general circulation models of the atmosphere (Kacholia & Reck 1997).

In order to resolve the discrepancy between the predictions of these 2 approaches to the CO_2-climate problem, major changes need to be made to one or both of them. If the discrepancy were to be totally resolved in the realm of my natural experiments, for example, it is clear that my estimate of Earth's climatic sensitivity would have to be increased by a factor of 3.3 to 10. However, I can conceive of no way that an adjustment of this magnitude could be made to the analyses of my 2 global-equilibrium natural experiments, which I believe are the best founded analyses of the 5 situations discussed thus far. In addition, the results of still other natural experiments I have identified and analyzed suggest—at least to me—that the value I have derived for Earth's climatic sensitivity is indeed correct.

2.8. Natural Experiment 6

Consider what we can learn from our nearest planetary neighbors, Mars and Venus. In spite of the tremendous differences that exist between them, and between them and the Earth, their observed surface temperatures have been said to confirm 'the existence, nature, and magnitude of the greenhouse effect' by 2 select committees of the U.S. National Research Council (Smagorinsky et al. 1982, Nierenberg et al. 1983), which conclusion appears also to be accepted by the Intergovernmental Panel on Climate Change (Trenberth et al. 1996). So what can these planets tell us about CO_2-induced warming on Earth?

Venus exhibits a greenhouse warming of approximately 500°C (Oyama et al. 1979, Pollack et al. 1980) that is produced by a 93-bar atmosphere of approximately 96% CO_2 (Kasting et al. 1988); while Mars exhibits a greenhouse warming of 5 to 6°C (Pollack 1979, Kasting et al. 1988) that is produced by an almost pure CO_2 atmosphere that fluctuates over the Martian year between 0.007 and 0.010 bar (McKay 1983). Plotting the 2 points defined by these data on a log-log coordinate system of CO_2-induced global warming versus atmospheric CO_2 partial pressure and connecting them by a straight line produces a relationship that, when extrapolated to CO_2 partial pressures characteristic of present-day Earth, once again yields a mean global warming of only 0.4°C for a 300 to 600 ppm doubling of the air's CO_2 content (Idso 1988a).

2.9. Natural Experiment 7

The same result may also be obtained from the standard resolution of the paradox of the faint early sun (Sagan & Mullen 1972, Owen et al. 1979, Kasting 1997), which dilemma (Longdoz & Francois 1997, Sagan & Chyba 1997) is most often posed by the following question. How could Earth have supported life nearly 4 billion years ago, when according to well-established concepts of stellar evolution (Schwarzchild et al. 1957, Ezer & Cameron 1965, Bahcall & Shaviv 1968, Iben 1969), the luminosity of the sun was probably 20 to 30% less at that time than it is now (Newman & Rood 1977, Gough 1981), so that, all else being equal, nearly all of Earth's water should have been frozen and unavailable for sustaining life?

Most of the people who have studied the problem feel that the answer to this question resides primarily in the large greenhouse effect of Earth's early atmosphere—which is believed to have contained much more CO_2 than it does today (Hart 1978, Wigley & Brimblecombe 1981, Holland 1984, Walker 1985)—with a secondary contribution coming from the near-global extent of the early ocean (Henderson-Sellers & Cogley 1982, Henderson-Sellers & Henderson-Sellers 1988, Jenkins 1995). Consequently, based on the standard assumption of a 25% reduction in solar luminosity 4.5 billion years ago, I calculated the strength of the greenhouse effect required to compensate for the effects of reduced solar luminosity at half-billion year intervals from 3.5 billion years ago — when we are confident of the widespread existence of life (Schopf & Barghourn 1967, Schopf 1978, Schidlowski 1988, Mojzsis et al. 1996, Eiler et al. 1997) — to the present; and I plotted the results as a function of atmospheric CO_2 concentration derived from a widely accepted atmospheric CO_2 history for that period of time (Lovelock & Whitfield 1982). The relationship derived from that exercise (Idso 1988a) is nearly identical to the one derived from the preceding comparative planetary climatology study, once again implying a mean global warming of only 0.4°C for a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration. And it is the essentially perfect agreement of the results of these last 4 global equilibrium natural experiments that leads me to believe that I have indeed obtained the proper answer to the question of potential CO_2-induced climate change. There is, nevertheless, yet another natural phenomenon that warrents consideration within this context.

2.10. Natural Experiment 8

A final set of empirical evidence that may be brought to bear upon the issue of CO_2-induced climate change pertains to the greenhouse effect of water vapor over the tropical oceans (Raval & Ramanathan 1989, Ramanathan & Collins 1991, Lubin 1994). This phenomenon has recently been quantified by Valero et al. (1997), who used airborne radiometric measurements and sea surface temperature data to evaluate its magnitude over the equatorial Pacific. Their direct measurements reveal that a 14.0 W m^{-2} increase in downward-directed thermal radiation at the surface of the sea increases surface water temperatures by 1.0°C; and dividing the latter of these 2 numbers by the former yields a surface water temperature sensitivity factor of 0.071°C/(W m^{-2}), which would imply a similar surface air temperature sensitivity factor at equilibrium. By comparison, if I equate my best estimate of the surface air temperature sensitivity factor of the world as a whole [0.100°C/(W m^{-2})] with the sum of the appropriately-weighted land and water surface factors [0.3×0.172°C/(W m^{-2}) + $0.7 \times W$, where W is the surface air temperature sensitivity factor over the open ocean], I obtain a value of 0.069°C/(W m^{-2}) for the ocean-based component of the whole-Earth surface air temperature sensitivity factor, in close agreement with the results of Valero et al.

Of course, there is no compelling reason why the results of these 2 evaluations should necessarily agree so well; for different portions of the planet can clearly exhibit different surface air temperature sensitivity factors, as I have shown herein to be the case for land versus water (Natural Experiment 3) and for high latitudes versus low latitudes (Natural Experiment 5). Indeed, it is only when the planet is treated in its entirety that one should expect the same result, such as is obtained from Natural Experiments 4, 6 and 7. Nevertheless, the good agreement between the results of this last natural experiment and all of my prior evaluations is still gratifying, although a significant disagreement would not have been all that discouraging.

3. RISING CO_2 AND THE GLOBAL WARMING OF THE PAST CENTURY

As demonstrated by the results of the several natural experiments described above, a large body of real-world evidence points to the likelihood of a future CO_2-induced global warming of but a tenth to a third of what is currently predicted by theoretical numerical models of the Earth-ocean-atmosphere system. However, the observed global warming of the past century, which has occurred in concert with a 75 ppm rise in the air's CO_2 content, has already exceeded the 0.4°C increase in temperature that my analyses suggest would require an atmospheric CO_2 increase of fully 300 ppm; and it is only natural to wonder if this relatively large warming of the last hundred years was produced by the relatively small concurrent rise in the air's CO_2 content. This question is of crucial importance, for if the global warming of the past century was wholly the result of the concurrent rise in atmospheric CO_2, it would imply that the primary conclusion derived from my natural experiments is incorrect.

Although the question cannot be unequivocally resolved at the present time, it is possible that the warming of the Earth over the last hundred years may well have been wholly unrelated to the concurrent rise in atmospheric CO_2; for the observed temperature increase may have been produced by changes in a number of other climatically-important factors, such as the energy output of the sun, for example, which is looking more and more like a major determinant of Earth's climate each year (Baliunas & Jastrow 1990, Foukal & Lean 1990, Friis-Christensen & Lassen 1991, Lockwood et al. 1992, Scuderi 1993, Charvatova & Strestik 1995, Lean et al. 1995, Baliunas & Soon 1996, 1998, Soon et al. 1996, Hoyt & Schatten 1997). Indeed, it is even possible that the global warming of the past century may have been nothing more than a random climatic fluctuation.

That some alternative explanation of the observed warming is, in fact, quite plausible is readily evident when the temperature increase of the past century is viewed from the broader perspective of the past millennium. From this improved vantage point, the warming of the last hundred years is seen to be basically a recovery (Idso 1988b, Reid 1993) from the global chill of the Little Ice Age, which was a several-hundred-year period of significantly cooler temperatures than those of the present that persisted until the end of the nineteenth century (Grove 1988, Whyte 1995). And as ice-core data give no indication of any drop in atmospheric CO_2 over the period of the Little Ice Age's induction (Friedli et al. 1984, 1986), something other than CO_2 had to have initiated it, implying that the inverse of that something—or even something else (or nothing at all, in the case of a random climatic fluctuation)—is likely to have been the cause of its demise.

But what if temperatures were to rise even higher in the future? Here, again, the long historical perspective proves invaluable; for it reveals that the Little Ice Age was preceded by a several-centuries-long period of significantly warmer temperatures than those of the present (Le Roy Ladurie 1971, Lamb 1977, 1984, 1988, Keigwin 1996). And while the Earth was traversing the entire temperature range from the maximum warmth of this Little Climatic Optimum (Dean 1994, Petersen 1994, Serre-Bachet 1994, Villalba 1994) to the coolest point of the Little Ice Age, the CO_2 content of the atmosphere, as inferred from ice-core data, varied not at all (Idso 1988b). Consequently, the Earth can clearly warm even more than it has already warmed over the last century without any change in atmospheric CO_2, suggesting that even continued global warming—which appears to have peaked (Hurrell & Trenberth 1997, Spencer 1997)—would imply very little (and possibly nothing at all) about the potential for future CO_2-induced climatic change.

4. COOLING THE GLOBAL GREENHOUSE

Although the evidence I have presented suggests that a doubling of the air's CO_2 content could raise Earth's mean surface air temperature by only about 0.4°C, there are a number of reasons to question whether even this minor warming will ever occur. There are, for example, a variety of ways by which rising temperatures may strengthen the cooling properties of clouds and thereby retard global warming. In addition, several biological processes that are enhanced by the aerial fertilization effect of atmospheric CO_2 enrichment can directly intensify these climate-cooling forces.

With respect to the first of these subjects, it has long been recognized that the presence of clouds has a strong cooling effect on Earth's climate (Barkstrom 1984, ERBE Science Team 1986, Nullet 1987, Nullet & Ekern 1988, Ramanathan et al. 1989). In fact, it has been calculated that a mere 1% increase in planetary albedo would be sufficient to totally counter the entire greenhouse warming that is typically predicted to result from a doubling of the atmosphere's CO_2 concentration (Ramanathan 1988). And as the typically-predicted warming may be 3 to 10 times larger than what could actually occur, according to my interpretation of the real-world evidence I have presented herein, it is possible that but a tenth to a third of a 1% increase in planetary albedo may be sufficient to accomplish this feat.

Within this context, it has been shown that a 10% increase in the amount of low-level clouds could completely cancel the typically-predicted warming of a doubling of the air's CO_2 content by reflecting more solar radiation back to space (Webster & Stephens 1984). In addition, Ramanathan & Collins (1991), by the use of their own natural experiments, have shown how the warming-induced production of high-level clouds over the equatorial oceans totally nullifies the greenhouse effect of water vapor there, with high clouds dramatically increasing from close to 0% coverage at sea surface temperatures of 26°C to fully 30% coverage at 29°C (Kiehl 1994). And in describing the implications of this strong negative feedback mechanism, Ramanathan & Collins state that 'it would take more than an order-of-magnitude increase in atmospheric CO_2 to increase the maximum sea surface temperature by a few degrees,' which they acknowledge is a considerable departure from the predictions of most general circulation models of the atmosphere.

In addition to increasing their coverage of the planet, as they appear to do in response to an increase in temperature (Henderson-Sellers 1986a, b, McGuffie & Henderson-Sellers 1988, Dai et al. 1997), clouds in a warmer world would also have greater liquid water contents than they do now (Paltridge 1980, Charlock 1981, 1982, Roeckner 1988). And as the heat-conserving greenhouse properties of low- to mid-level clouds are already close to the maximum they can attain (Betts & Harshvardhan 1987), while their reflectances for solar radiation may yet rise substantially (Roeckner et al. 1987), an increase in cloud liquid water content would tend to counteract an initial impetus for warming even in the absence of an increase in cloud cover. By incorporating just this one negative feedback mechanism into a radiative-convective climate model, for example, the warming predicted to result from a doubling of the air's CO_2 content has been shown to fall by fully 50% (Somerville & Remer 1984); while a 20 to 25% increase in cloud liquid water path has been shown to totally negate the typically-predicted warming of a doubling of the air's CO_2 content in a 3-dimensional general circulation model of the atmosphere (Slingo 1990).

Another negative feedback mechanism involving clouds, which is estimated to be of the same strength as the typically-predicted greenhouse effect of CO_2 (Lovelock 1988, Turner et al. 1996), has been described by Charlson et al. (1987). They suggest that the productivity of oceanic phytoplankton will increase in response to an initial impetus for warming, with the result that one of the ultimate by-products of the enhanced algal metabolism—dimethyl sulfide, or DMS—will be produced in more copious quantities. Diffusing into the atmosphere where it is oxidized and converted into particles that function as cloud condensation nuclei, this augmented flux of DMS is projected to create additional and/or higher-albedo clouds, which will thus reflect more solar radiation back to space, thereby cooling the Earth and countering the initial impetus for warming (Shaw 1983, 1987).

There is much evidence—700 papers in the past 10 yr (Andreae & Crutzen 1997)—to support the validity of each link in this conceptual chain of events. First, there is the demonstrated propensity for oceanic phytoplankton to increase their productivity in response to an increase in temperature (Eppley 1972, Goldman & Carpenter 1974, Rhea & Gotham 1981), which fact is clearly evident in latitudinal distributions of marine productivity (Platt & Sathyendranath 1988, Sakshaug 1988). Second, as oceanic phytoplankton photosynthesize, they are known to produce a substance called dimethylsulfonio propionate (Vairavamurthy et al. 1985), which disperses throughout the surface waters of the oceans when the phytoplankton either die or are eaten by zooplankton (Dacey & Wakeham 1988, Nguyen et al. 1988) and which decomposes to produce DMS (Turner et al. 1988). Third, it has been shown that part of the DMS thus released to the Earth's oceans diffuses into the atmosphere, where it is oxidized and converted into sulfuric and methanesulfonic acid particles (Bonsang et al. 1980, Hatakeyama et al. 1982, Saltzman et al. 1983, Andreae et al. 1988, Kreidenweis & Seinfeld 1988) that function as cloud condensation nuclei or CCN (Saxena 1983, Bates et al. 1987). And more CCN can clearly stimulate the production of new clouds and dramatically increase the albedos of pre-existent clouds by decreasing the sizes of the clouds' component droplets (Twomey & Warner 1967, Warner & Twomey 1967, Hudson 1983, Coakley et al. 1987, Charlson & Bates 1988, Durkee 1988), which phenomenon tends to cool the planet by enabling clouds to reflect more solar radiation back to space (Idso 1992b, Saxena et al. 1996). In fact, it has been calculated that a 15 to 20% reduction in the mean droplet radius of Earth's boundary-layer clouds would produce a cooling influence that could completely cancel the typically-predicted warming influence of a doubling of the air's CO_2 content (Slingo 1990).

Another way in which the enhanced production of CCN may retard warming via a decrease in cloud droplet size is by reducing drizzle from low-level marine clouds, which lengthens their life-span and thereby expands their coverage of the planet (Albrecht 1988). In addition, since drizzle from stratus clouds tends to stabilize the atmospheric boundary layer by cooling the sub-cloud layer as a portion of the drizzle evaporates (Brost et al. 1982, Nicholls 1984), a CCN-induced reduction in drizzle tends to weaken the stable stratification of the boundary layer, enhancing the transport of water vapor from ocean to cloud. As a result, clouds containing extra CCN tend to persist longer and perform their cooling function for a longer period of time.

The greater numbers of CCN needed to enhance these several cooling phenomena are also produced by biological processes on land (Went 1966, Duce et al. 1983, Roosen & Angione 1984, Meszaros 1988); and in the terrestrial environment the volatilization of reduced sulfur gases from soils is particularly important in this regard (Idso 1990). Here, too, one of the ways in which the ultimate cooling effect is set in motion is by an initial impetus for warming. It has been reported, for example, that soil DMS emissions rise by a factor of 2 for each 5°C increase in temperature between 10 and 25°C (Staubes et al. 1989); and as a result of the enhanced microbial activity produced by increasing warmth (Hill et al. 1978, MacTaggart et al. 1987), there is a 25-fold increase in soil-to-air sulfur flux between 25°N and the equator (Adams et al. 1981). Of even greater importance, however, is the fact that atmospheric CO_2 enrichment alone can initiate the chain of events that leads to cooling.

Consider the fact, impressively supported by literally hundreds of laboratory and field experiments (Lemon 1983, Cure & Acock 1986, Mortensen 1987, Lawlor & Mitchell 1991, Drake 1992, Poorter 1993, Idso & Idso 1994, Strain & Cure 1994), that nearly all plants are better adapted to higher atmospheric CO_2 concentrations than those of the present, and that the productivity of most herbaceous plants rises by 30 to 50% for a 300 to 600 ppm doubling of the air's CO_2 content (Kimball 1983, Idso 1992a), while the growth of many woody plants rises even more dramatically (Idso & Kimball 1993, Ceulemans & Mousseau 1994, Wullschleger et al. 1995, 1997). Because of this stimulatory effect of elevated carbon dioxide on plant growth and development, the productivity of the biosphere has been rising hand-in-hand with the recent historical rise in the air's CO_2 content (Idso 1995), as is evident in (1) the ever-increasing amplitude of the seasonal cycle of the air's CO_2 concentration (Pearman & Hyson 1981, Cleveland et al. 1983, Bacastow et al. 1985, Keeling et al. 1985, 1995, 1996, Myneni et al. 1997), (2) the upward trends in a number of long tree-ring records that mirror the progression of the Industrial Revolution (LaMarche et al. 1984, Graybill & Idso 1993), and (3) the accelerating growth rates of numerous forests on nearly every continent of the globe over the past several decades (Kauppi et al. 1992, Phillips & Gentry 1994, Pimm & Sugden 1994, Idso 1995).

In consequence of this CO_2-induced increase in plant productivity, more organic matter is returned to the soil (Leavitt et al. 1994, Jongen et al. 1995, Batjes & Sombroek 1997), where it stimulates biological activity (Curtis et al. 1990, Zak et al. 1993, O'Neill 1994, Rogers et al. 1994, Godbold & Berntson 1997, Ineichen et al. 1997, Ringelberg et al. 1997) that results in the enhanced emission of various sulfur gases to the atmosphere (Staubes et al. 1989), whereupon more CCN are created (as described above), which tend to cool the planet by altering cloud properties in ways that result in the reflection of more solar radiation back to space. In addition, many non-sulfur biogenic materials of the terrestrial environment play major roles as both water- and ice-nucleating aerosols (Schnell & Vali 1976, Vali et al. 1976, Bigg 1990, Novakov & Penner 1993, Saxena et al. 1995, Baker 1997); and the airborne presence of these materials should also be enhanced by atmospheric CO_2 enrichment.

That analogous CO_2-induced cooling processes operate at sea is implied by the facts that (1) atmospheric CO_2 enrichment stimulates the growth of both macro- (Titus et al. 1990, Sand-Jensen et al. 1992, Titus 1992, Madsen 1993, Madsen & Sand-Jensen 1994) and micro- (Raven 1991, 1993, Riebesell 1993, Shapiro 1997) aquatic plants, and (2) experimental iron-induced (Coale et al. 1996) increases (acting as surrogates for CO_2-induced increases) in the productivity of oceanic phytoplankton in high-nitrate low-chlorophyll waters of the equatorial Pacific (Behrenfeld et al. 1996) have been observed to greatly increase surface-water DMS concentrations (Turner et al. 1996). There is also evidence to suggest that a significant fraction of the ice-forming nuclei of maritime origin are composed of organic matter (Rosinski et al. 1986, 1987); and the distribution of these nuclei over the oceans (Bigg 1973) has been shown to be strongly correlated with surface patterns of biological productivity (Bigg 1996, Szyrmer & Zawadzki 1997). Hence, there may well exist an entire suite of powerful planetary cooling forces that can respond directly to the rising carbon dioxide content of the atmosphere over both land and sea. And in view of the relative weakness of the CO_2 greenhouse effect at current atmospheric CO_2 partial pressures, as revealed by the natural experiments I have described herein—a likely warming of only 0.4°C for a 300 to 600 ppm doubling of the air's CO_2 content—these CO_2-induced cooling forces could potentially negate a large portion (or even all) of the primary warming effect of a rise in atmospheric CO_2, leading to little net change in mean global air temperature.

5. SUMMARY AND CONCLUSIONS

There is no controversy surrounding the claim that atmospheric CO_2 concentrations are on the rise; direct measurements demonstrate that fact. The basic concept of the greenhouse effect is also not in question; rising carbon dioxide concentrations, in and of themselves, clearly enhance the thermal blanketing properties of the atmosphere. What is debatable, however, is the magnitude of any warming that might result from a rise in the air's CO_2 concentration. While admittedly incomplete and highly approximate general circulation models of the atmosphere predict that a 300 to 600 ppm doubling of the air's CO_2 content will raise mean global air temperature a few degrees Celsius, natural experiments based upon real-world observations suggest that a global warming of no more than a few tenths of a degree could result from such a CO_2 increase. Which conclusion is correct?

Several complexities of Earth's climate system make accurate predictions of global climate change very difficult for general circulation models of the atmosphere and probably account for the deviations of their predictions from those of the natural experiments I have described herein. First, there are a number of planetary cooling forces that are intensified by increases in temperature and which therefore tend to dampen any impetus for warming; and many of these phenomena are only now beginning to be fully appreciated, much less adequately incorporated into the models. Second, nearly all of these cooling forces can be amplified by increases in biological processes that are directly enhanced by the aerial fertilization effect of atmospheric CO_2 enrichment; and most of these phenomena are also not included in general circulation model studies of potential CO_2-induced climate change. Third, many of these cooling forces have individually been estimated to have the capacity to totally thwart the typically-predicted (and likely overestimated) warming of a doubling of the atmosphere's CO_2 concentration. Fourth, real-world measurements have revealed that contemporary climate models have long significantly underestimated the cooling power of clouds (Cess et al. 1995, Pilewskie & Valero 1995, Ramanathan et al. 1995, Heymsfield & McFarquhar 1996), even when demonstrating their ability to completely negate the likely overestimated global warming that is typically predicted to result from a doubling of the air's CO_2 content.

In light of these observations, it is my belief that it will still be a very long time before any general circulation model of the atmosphere will be able to accurately determine the ultimate consequences of the many opposing climatic forces that are both directly and indirectly affected by the rising CO_2 content of Earth's atmosphere. Consequently, although many equally sincere and thoughtful scientists may feel otherwise, I believe that these models do not yet constitute an adequate basis for developing rational real-world policies related to potential climate change.

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