Real-World Constraints on Global Warming

SHERWOOD B. IDSO

Often lost in the heat of debate over global warming is the fact that the greenhouse effect of CO_2 is not in question: rising carbon dioxide concentrations, in and of themselves, do indeed have a tendency to enhance the thermal-blanketing properties of the atmosphere. Opinions diverge, however, about what happens when this phenomenon begins to operate, for practically nothing in nature happens in isolation, and numerous feedbacks—both positive and negative—severely cloud the issue.

Proponents of the theory that a dangerous level of CO_2-induced global warming is likely to occur believe that positive feedbacks that enhance the initial rise in temperature produce the major portion of whatever temperature increase ultimately occurs (or is predicted to occur). Detractors of the theory that a dangerous level of CO_2-induced global warming is likely to occur believe that negative feedbacks are capable of drastically reducing the initial impetus for warming. Some, like myself, believe that such feedbacks can negate totally the initial warming impetus; and it is the evidence for this latter position that I will discuss in this small treatise.

Negative feedbacks

There are at least three major categories of negative feedback mechanisms that are germane to the issue of CO_2-induced global warming. First—and most recognized—are the mechanisms by which rising temperatures may strengthen the cooling properties of clouds by purely physical means. Second are the mechanisms by which rising temperatures intensify biological processes that eventually lead to an enhancement of some of the same cloud-cooling properties. Third are the mechanisms by which some of these biological processes are directly enhanced by the "aerial fertilization effect" of increased concentrations of atmospheric CO_2 so that they are not dependent upon an initial warming to set the ultimate cloud-cooling processes in motion. In the following subsections, I shall describe these three types of negative feedbacks briefly and give illustrations of their great cooling power.

Feedbacks using physical processes

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 and Ekern 1988; Ramanathan *et al.* 1989). In fact, it has been calculated that a mere one percent increase in planetary albedo (i.e. the ratio of light reflected by the earth to that received by it) would be sufficient to counter totally the entire greenhouse warming that is typically predicted to result from a doubling of the atmosphere's CO_2 concentration (Ramanathan 1988).

Within this context, it has been independently demonstrated that a 10 percent increase in the amount of low-level cloud could also completely cancel the warming that is typically predicted to occur as a result of a doubling of the air's CO_2 content, again by reflecting more solar radiation back to space (Webster and Stephens 1984). In addition, Ramanathan and Collins (1991), by the use of certain "natural experiments," have shown how the warming-induced production of high-level clouds over the equatorial oceans almost totally nullifies the powerful greenhouse effect of water vapor there. In fact, Kiehl (1994) has described how the presence of high-level clouds in this area dramatically increases from close to 0 percent coverage when temperatures at the sea's surface are 26°C to fully 30 percent coverage when they are 29°C. The implication of this strong negative feedback mechanism is 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" (Ramanathan and Collins 1991: 32). They acknowledge that this estimate is a considerable departure from the predictions of most general circulation models of the atmosphere but I will shortly show it to be in complete harmony with a variety of real-world observations.

In addition to increasing their areal coverage of the planet—as they typically do in response to an increase in temperature (Henderson-Sellers 1986a, 1986b; McGuffie and Henderson-Sellers 1988; Dai *et al.* 1997)—clouds in a warmer world would likely have greater liquid-water content 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 and Harshvardhan 1987) while their reflectances for solar radiation may yet rise substantially (Roeckner *et al.* 1987), an increase in the liquid-water content of clouds would tend to counteract an impetus for warming even in the absence of an increase in cloud cover. In fact, by incorporating just this one negative feedback mechanism into a radiative-convective climate model, the warming predicted to result from a doubling of the air's CO_2 content has been shown to fall by fully 50 percent (Somerville and Remer 1984) while a 20 percent to 25 percent increase in liquid water in clouds has been shown, in a three-dimensional general circulation model of the atmosphere, to negate totally the typically predicted warming due to a doubling of the air's CO_2 content (Slingo 1990).

Feedbacks using biological processes

Charlson et al. (1987) have described another negative feedback mechanism involving clouds, which has been calculated to be of the same strength as the typically predicted greenhouse effect of CO_2 (Lovelock 1988; Turner *et al.* 1996). These investigators 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 (DMS)—will be produced in significantly greater quantities. Diffusing into the atmosphere, where it is oxidized and converted into particles that function as cloud-condensation nuclei, this augmented flux of DMS has been projected to create additional clouds and/or clouds with a higher albedo. This should 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 years (Andreae and 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 and Carpenter 1974; Rhea and Gotham 1981); this propensity is clearly evident in latitudinal distributions of marine productivity (Platt and Sathyendranath 1988; Sakshaug 1988). Second, as oceanic phytoplankton photosynthesize, they produce a substance called dimethylsulfonio propionate (Vairavamurthy *et al.* 1985), which disperses throughout the surface waters of the oceans when the phytoplankton die or are eaten by zooplankton (Nguyen *et al.* 1988; Dacey and Wakeham 1988) and 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 and Seinfeld 1988) that function as cloud-condensation nuclei (CCN) (Saxena 1983; Bates *et al.* 1987). Fourth, 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 and Warner 1967; Warner and Twomey 1967; Hudson 1983; Coakley *et al.* 1987; Charlson and Bates 1988; Durkee 1988). This latter phenomenon then 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 percent to 20 percent 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 due to a doubling of the air's CO_2 content (Slingo 1990).

Another way in which the enhanced production of CCN may retard global warming via a decrease in size of droplets in clouds 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 CCNs needed to enhance these several cooling phenomena are also produced by biological processes on land (Went 1966; Duce *et al.* 1983; Roosen and 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 two for each 5°C increase in temperature between 10°C 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 perhaps even greater importance, however, is the fact that increased concentrations of atmospheric CO_2 alone can initiate the chain of events that leads to cooling.

Feedbacks resulting from increased levels of atmospheric CO2

Consider the fact—impressively supported by literally hundreds of laboratory and field experiments (Lemon 1983; Cure and Acock 1986; Mortensen 1987; Lawlor and Mitchell 1991; Drake 1992; Poorter 1993; Idso and Idso 1994; Strain and Cure 1994)—that nearly all plants are better adapted to concentrations of atmospheric CO_2 higher than those of the present, and that the productivity of most herbaceous plants rises by 30 percent to 40 percent in the presence of a 300 ppm to 600 ppm increase in the air's CO_2 content (Kimball 1983; Idso 1992a), while the growth of many woody plants rises even more dramatically (Idso and Kimball 1993; Ceulemans and Mousseau 1994; Wullschleger *et al.* 1995, 1997). Because of this stimulatory effect on plant growth and development, the productivity of the biosphere has been rising hand in hand with the recent rise in the air's CO_2 content (Idso 1995); this is evident in (1) the ever increasing amplitude of the seasonal cycle of the air's CO_2 concentration (Pearman and 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 and Idso 1993; Idso 1995), 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 and Gentry 1994; Pimm and 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 and Sombroek 1997), where it stimulates biological activity (Curtis *et al.* 1990; Zak *et al.* 1993; O'Neill 1994; Rogers *et al.* 1994; Ineichen *et al.* 1997; Ringelberg *et al.* 1997; Godbold and Berntson 1997) that results in the enhanced emission of various sulfur gases to the atmosphere (Staubes *et al.* 1989), whereupon more CCNs 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 and Vali 1976; Vali *et al.* 1976; Bigg 1990; Novakov and Penner 1993; Saxena *et al.* 1995; Baker 1997); and the airborne presence of these materials should also be enhanced by increased concentrations of atmospheric CO_2.

Analogous CO_2-induced cooling processes likely operate at sea as well. It is well established, for example, that increased concentrations of atmospheric CO_2 stimulates the growth of both macro-aquatic plants (Titus *et al.* 1990; Sand-Jensen *et al.* 1992; Titus 1992; Madsen 1993; Madsen and Sand-Jensen 1994) and micro-aquatic plants (Raven 1991, 1993; Riebesell 1993; Shapiro 1997). In addition, it has been demonstrated in a major experimental program (Coale *et al.* 1996) that adding iron to the high-nitrate low-chlorophyll waters of the equatorial Pacific significantly stimulates the productivity of oceanic phytoplankton (Behrenfeld *et al.* 1996) and this surrogate for a CO_2-induced increase in marine productivity has been observed to increase surface-water DMS concentrations greatly (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 and Zawadzki 1997). Hence, it is clear that there exists 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 these CO_2-induced cooling forces could negate a large portion (or even all) of the primary warming effect of a rise in atmospheric CO_2, leading to little or no net change in mean global air temperature.

Evidence for muted global warming

The power of nature's negative feedbacks, like the theory of CO_2-induced global warming, must be evaluated against real-world evidence. Hence, in the subsections that follow, I make such evaluations for 4 global climatic situations that incorporate all the real-world phenomena that combine to produce the equilibrium results derived therein.

The greenhouse effect in the earth's whole atmosphere

The current greenhouse effect of earth's entire atmosphere warms the surface of the planet by approximately 33.6°C as the result of a surface-directed thermal radiation flux of approximately $348 Wm^{-2}$ (Watts per square metre) (Idso 1980, 1982). Dividing the first of these numbers by the second yields what could be called a surface air-temperature sensitivity factor, which for this particular situation has a value of $0.097°C/Wm^{-2}$. Multiplying this factor by $4Wm^{-2}$—the value by which the flux of thermal radiation to the earth's surface is expected to rise as a result of a 300 ppm to 600 ppm increase in the air's CO_2 concentration (Smagorinsky *et al.* 1982; Nierenberg *et al.* 1983; Shine *et al.* 1990)—yields a mean global warming of 0.39°C, which is but one-tenth to one-third of the warming that has been predicted for this scenario by the majority of the general-circulation models of the atmosphere that have been applied to this problem (Kacholia and Reck 1997).

Latitudinally-dependent greenhouse effect

A second evaluation of the likely warming to be expected from a doubling of the air's CO_2 content can be derived from the annually averaged equator-to-pole air-temperature gradient that is sustained by the annually averaged equator-to-pole gradient of total radiant energy absorbed at the surface (Idso 1984). Mean surface air-temperatures and water-vapor pressures required for this calculation can be obtained for each five-degree latitude increment stretching from 90°N to 90°S from information reported by Warren and Schneider (1979) and Haurwitz and Austin (1944). From these data, I calculated values of clear-sky atmospheric thermal radiation (Idso 1981) 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 19 annually averaged total surface-absorbed radiant-energy fluxes stretching from the equator to 90°N/S, against which I plotted the corresponding average values of mean surface air temperature.

This operation produced two distinct linear relationships—one of slope $0.196°C/Wm^{-2}$, which extended from 90°N/S to approximately 63°N/S, and one of slope $0.090°C/Wm^{-2}$, which extended from 63°N/S to the equator. I thus weighted the two results according to the percentages of earth's surface area to which they pertained (12 percent and 88 percent, respectively) and combined them to obtain a mean global value of $0.103°C/Wm^{-2}$. Multiplying this result, as before, by $4Wm^{-2}$ then yields a mean global warming of approximately 0.41°C, which is essentially the same amount of warming I derived from the prior whole-atmosphere calculation.

The greenhouse effect from an increased concentration of atmospheric CO_2 over geologic time

The same result may also be obtained from the standard resolution of the paradox of the faint early sun (Sagan and Mullen 1972; Owen *et al.* 1979; Kasting 1997), a dilemma (Sagan and

Chyba 1997; Longdoz and Francois 1997) that 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 a*l. 1957; Ezer and Cameron 1965; Bahcall and Shaviv 1968; Iben 1969), the luminosity of the sun was probably 20 percent to 30 percent less than it is now (Newman and 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 (Schopf and Barghourn 1967; Knauth and Epstein 1976; Schopf 1978; Lowe 1980; Schidlowski 1988)?

Most 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; Holland 1984; Wigley and Brimblecombe 1981; Walker 1985). Consequently, based on the standard assumption of a 25 percent reduction in solar luminosity 4.5 billion years ago, I calculated the strength of the CO_2 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 (Mojzsis *et al.* 1996; Eiler *et al.* 1997)—to the present. I plotted the results as a function of the atmospheric CO_2 concentration derived from a widely accepted atmospheric CO_2 history for that period of time (Lovelock and Whitfield 1982). Using the relationship derived from that exercise to calculate the effects of a 300 ppm to 600 ppm increase in the air's CO_2 concentration, I once again obtained a mean global warming of only 0.4°C (Idso 1988).

The greenhouse effect from increased concentration of atmospheric CO_2 on Mars and Venus

Consider, finally, 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" ((Smagorinsky *et al.* 1982: 5; Nierenberg *et al.* 1983: 274) by two select committees of the United States National Research Council, a conclusion that also appears to be accepted by the Intergovernmental Panel on Climate Change (Trenberth *et al.* 1996).

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 percent CO_2 (Kasting *et al.* 1988); 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 two points defined by these data on a log-log coordinate system of CO_2-induced global warming versus the partial pressure of atmospheric CO_2 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 ppm to 600 ppm increase in the air's CO_2 content (Idso 1988). And no other simple line that can be drawn through these real-worlds data produces any greater warming.

Summary and conclusions

Earth's climate system possesses a number of highly effective negative feedback mechanisms that tend to inhibit CO_2-induced global warming. Some of these phenomena are driven by purely physical forces and they begin to exert their cooling influence in response to an initial rise in temperature. Others have a biological origin, but also respond to increasing warmth. The scientific literature provides several demonstrations of their individual capacities to negate totally the ultimate equilibrium warming that is typically predicted to result from a doubling of the atmosphere's carbon dioxide concentration.

To this arsenal of powerful climate-stabilizing forces can be added yet a third set of real- world brakes on CO_2-induced global warming: cooling forces that have their origins in biological phenomena that are directly enhanced by the aerial fertilization by increased concentrations of atmospheric CO_2. Operating with or without an initial impetus for warming, these forces have the potential to lead to a cooling of the planet, since any of the warming-induced negative feedbacks could nullify the greenhouse effect of a rise in atmospheric CO_2, leaving the CO_2-induced cooling forces to drive temperatures down even further.

Solid support for these feedback scenarios comes from a number of real-world climatic observations. First and foremost are the empirically based evaluations that I have made of the ultimate warming likely to be produced by an increase in downward-directed thermal radiation equivalent to that expected to be received at the surface of the earth as a result of a doubling of the air's CO_2 content, warming that is only one-tenth to one-third of what has typically been predicted for this situation by most of the general-circulation models of the atmosphere that are currently in vogue. Secondary support is provided by the suite of recent observational studies that have revealed that contemporary climate models have long significantly underestimated the cooling power of clouds (Cess *et al.* 1995; Ramanathan *et al.* 1995; Pilewskie and Valero 1995; Heymsfield and McFarquhar 1996), even when demonstrating the abilities of cloud-related cooling forces to negate totally the large global warming that is generally predicted to result from a doubling of the atmosphere's CO_2 concentration.

In view of these facts, I find no compelling reason to believe that the earth will necessarily experience any global warming as a consequence of the ongoing rise in the atmosphere's carbon dioxide concentration. There could be a CO_2-induced increase in mean global air temperature, but it would have to be small—no more than 0.4°C for a 300 ppm to 600 ppm increase in the air's CO_2 content. Then, again, it is even possible that the planet could cool somewhat in response to a rise in atmospheric CO_2. Our current understanding of the planet's complex climate system is just not sufficient to draw any more detailed conclusions.

References

Adams D.F., S.O. Farwell, E. Robinson, M.R. Pack, and W.L. Bamesberger (1981). Biogenic sulfur source strengths. *Environ Sci Tech* 15: 1493–98.

Albrecht, B.A. (1988). Modulation of boundary layer cloudiness by precipitation processes. In *Proceedings: Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate* Boston, MA: American Meteorological Society): 9–13.

Andreae, M.O., and P.J. Crutzen (1997). Atmospheric aerosols: biogeochemical sources and role in atmospheric chemistry. *Science* 276: 1052–58.

Andreae, M.O., H. Berresheim, T.W. Andreae, M.A. Kritz, T.S. Bates, and J.T. Merril (1988). Vertical distribution of dimethylsulfide, sulfur dioxide, aerosol ions and radon over the northeast Pacific Ocean. J Atmos Chem 6: 149-173

Bacastow, R.B., C.D. Keeling, and T.P. Whorf (1985). Seasonal amplitude increase in atmospheric CO_2 concentration at Mauna Loa, Hawaii, 1959–1982. *J Geophys Res* 90: 10,529–40.

Bahcall, J.N., and G. Shaviv (1968). Solar models and neutrino fluxes. *Astrophys J* 153: 113–26.

Baker, M.B. (1997). Cloud microphysics and climate. *Science* 276: 1072–78.

Barkstrom, B.R. (1984). The Earth Radiation Budget Experiment (ERBE). *Bull Amer Meteorol Soc* 65: 1170–85.

Bates, T.S., R.J. Charlson, and R.H. Gammon (1987). Evidence for the climatic role of marine biogenic sulphur. *Nature* 329: 319–21.

Batjes, N.H., and W.G. Sombroek (1997). Possibilities for carbon sequestration in tropical and subtropical soils. *Global Change Biol* 3: 161–73.

Behrenfeld, M.J., A.J. Bale, Z.S. Kolber, J. Aiken, and P. Falkowski (1996). Confirmation of iron limitation of phytoplankton photosynthesis in the equatorial Pacific Ocean. *Nature* 383: 508–11.

Betts, A.K., and Harshvardhan (1987). Thermodynamic constraint on the cloud liquid water feedback in climate models. *J Geophys Res* 92: 8483–85.

Bigg, E.K. (1973). Ice nucleus concentrations in remote areas. *J Atmos Sci* 30: 1153–57.

——— (1990). Measurement of concentrations of natural ice nuclei. *Atmos Res* 25: 397–408.

——— (1996). Ice forming nuclei in the high Arctic. *Tellus* 48B: 223–33.

Bonsang, B., B.C. Nguyen, A. Gaudry, and G. Lambert (1980). Sulfate enhancement in marine aerosols owing to biogenic sulfur compounds. *J Geophys Res* 85: 7410–16.

Brost, R.A., D.H. Lenschow, and J.C. Wyngaard (1982) Marine stratocumulus layers. Part II. Turbulence budgets. *J Atmos Sci* 39: 818–36.

Cess, R.D., M.H. Zhang, P. Minnis, L. Corsetti, E.G. Dutton, B.W. Forgan, D.P. Garber, W.L. Gates, J.J. Hack, E.F. Harrison, X. Jing, J.T. Kiehl, C.N. Long, J.-J. Morcrette, G.L. Potter, V. Ramanathan,B. Subasilar, C.H. Whitlock, D.F. Young, and Y. Zhou (1995). Absorption of solar radiation by clouds: observations versus models. *Science* 267: 496–99.

Ceulemans, R., and M. Mousseau (1994). Effects of elevated atmospheric CO_2 on woody plants. *New Phytol* 127: 425–46.

Charlock, T.P. (1981). Cloud optics as a possible stabilizing factor in climate change. J A*tmos Sci* 38: 661–63.

——— (1982) Cloud optical feedback and climate stability in a radiative-convective model. *Tellus* 34: 245–54.

Charlson, R.J., and T.S. Bates (1988). The role of the sulfur cycle in cloud microphysics, cloud albedo, and climate. In *Proceedings: Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate* (Boston, MA: American Meteorological Society): 1–3.

Charlson, R.J., J.E. Lovelock, M.O. Andreae, and S.G. Warren (1987) Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. *Nature* 326: 655–61.

Cleveland, W.S., A.E. Frenny, and T.E. Graedel (1983). The seasonal component of atmospheric CO_2: information from new approaches to the decomposition of seasonal time-series. *J Geophys Res* 88: 10,934–40.

Coakley, J.A., R.l. Bernstein, and R.A. Durkee (1987). Effect of ship-stack effluents on cloud reflectivity. *Science* 237: 1020–22.

Coale, K.H., K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S. Tanner, F.P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W.P. Cochlan, M.R. Landry, J. Constantinou, G. Rollwagen, A. Trasvina, and R. Kudela (1996). A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383: 495–501.

Cure, J.D., and B. Acock (1986). Crop responses to carbon dioxide doubling: A literature survey. *Agric For Meteorol* 8: 127–45.

Curtis, P.S., L.M. Balduman, B.G. Drake, and D.F. Whigham (1990). Elevated atmospheric CO_2 effects on below ground processes in C_3 and C_4 estuarine marsh communities. *Ecology* 71: 2001–06.

Dacey, J.W.H., and S.G. Wakeham (1988) Oceanic dimethylsulfide: production during zooplankton grazing on phytoplankton. *Science* 233: 1314–16.

Dai, A., A.D. Del Genio, and I.Y. Fung (1997). Clouds, precipitation and temperature range. *Nature* 386: 665–66.

Drake, B.G. (1992). The impact of rising CO_2 on ecosystem production. *Water Air Soil Poll* 64: 25–44.

Duce, R.A., V.A. Mohnen, P.R. Zimmerman, D. Grosjean, W. Cautreels, R. Chatfield, R. Jaenicke, J.A. Ogsen, E.D. Pillizzari, and G.T. Wallace (1983). Organic material in the global troposphere. *Rev Geophys Space Phys* 21: 921–52.

Durkee, P.A. (1988). Observations of aerosol-cloud interactions in satellite-detected visible and near-infrared radiance. In *Proceedings: Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate* (Boston: American Meteorological Society): 157–60.

Eiler, J.M., S.J. Mojzsis, and G. Arrhenius (1997) Carbon isotope evidence for early life. *Nature* 386: 665.

Eppley, R.W. (1972). Temperature and phytoplankton growth in the sea. *Fish Bull* 70: 1063–85.

ERBE Science Team (1986). First data from the Earth Radiation Budget Experiment (ERBE). *Bull Amer Meteorol Soc* 67: 818–24.

Ezer, D., A.G.W. Cameron (1965). A study of solar evolution. *Can J Phys* 43: 1497–517.

Godbold, D.L., and G.M. Berntson (1997). Elevated atmospheric CO_2 concentration changes ectomycorrhizal morphotype assemblages in *Betula papyrifera*. *Tree Physiol* 17: 347–50.

Goldman, J.C., E.J. Carpenter (1974). A kinetic approach to the effect of temperature on algal growth. *Limnol Oceanogr* 19: 756–66.

Gough, D.O. (1981). Solar interior structure and luminosity variations. *Sol Phys* 74: 21–34.

Graybill, D.A., and S.B. Idso (1993) Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies. *Global Biogeochem Cycles* 7: 81–95.

Hart, M.H. (1978). The evolution of the atmosphere of the Earth. *Icarus* 33: 23–29.

Hatakeyama, S.D., M. Okuda, and H. Akimoto (1982). Formation of sulfur dioxide and methane sulfonic acid in the photo-oxidation of dimethylsulfide in the air. *Geophys Res Lett* 9: 583–86.

Haurwitz, B., and J. M. Austin (1944) *Climatology*. New York: McGraw-Hill.

Henderson-Sellers, A. (1986a). Cloud changes in a warmer Europe. *Clim Change* 8: 25–52.

——— (1986b). Increasing cloud in a warming world. *Clim Change* 9: 267–309.

Heymsfield, A.J., and G.M. McFarquhar (1996). High albedos of cirrus in the tropical Pacific warm pool: Microphysical interpretations from CEPEX and from Kwajalein, Marshall Islands. *J Atmos Sci* 53: 2424–51.

Hill, F.B., V.P. Aneja, and R.M. Felder (1978). A technique for measurement of biogenic sulfur emission fluxes. *Environ Sci Health* 13: 199–225.

Holland, H.D. (1984). *The Chemical Evolution of the Atmosphere and Oceans*. Princeton, NJ: Princeton University Press.

Hudson, J.D. (1983). Effects of CCN concentrations on stratus clouds. *J Atmos Sci* 40: 480–86.

Iben, I. (1969). The Cl^{37} solar neutrino experiment and the solar helium abundance. *Ann Phys* 54: 164–203.

Idso, K.E. (1992a). *Plant Responses to Rising Levels of Atmospheric Carbon Dioxide: A Compilation and Analysis of the Results of a Decade of International Research into the Direct Biological Effects of Atmospheric CO_2 Enrichment*. Tempe, AZ: Office of Climatology, Arizona State University.

Idso, K.E., and S.B. Idso (1994). Plant responses to atmospheric CO_2 enrichment in the face of environmental constraints: a review of the past 10 years' research. *Agric For Meteorol* 69: 153–203.

Idso, S.B. (1980). The climatological significance of a doubling of earth's atmospheric carbon dioxide concentration. *Science* 207: 1462–63.

——— (1981). A set of equations for full spectrum and 8-14 μm and 10.5-12.5 μm thermal radiation from cloudless skies. *Water Resources Res* 18: 295–304.

——— (1982). A surface air temperature response function for earth's atmosphere. *Boundary-Layer Meteorol* 22: 227–32.

——— (1984). An empirical evaluation of earth's surface air temperature response to radiative forcing, including feedback, as applied to the CO_2-climate problem. *Arch Meteorol Geophys Bioclimatol*, Ser. B, 34: 1–19.

——— (1988). The CO_2 greenhouse effect on Mars, Earth, and Venus. *Sci Total Environ* 77: 291–94.

——— (1990). A role for soil microbes in moderating the carbon dioxide greenhouse effect? *Soil Sci* 149: 179–80.

——— (1992b). The DMS-cloud albedo feedback effect: greatly underestimated? *Clim Change* 21: 429–33.

——— (1995). *CO_2 and the Biosphere: The Incredible Legacy of the Industrial Revolution*. St. Paul, MN: Department of Soil, Water and Climate, University of Minnesota.

Idso, S.B., and B.A. Kimball (1993). Tree growth in carbon dioxide enriched air and its implications for global carbon cycling and maximum levels of atmospheric CO_2. *Global Biogeochem Cycles* 7: 537–55.

Ineichen, K., V. Wiemken, and A. Wiemken (1997). Shoots, roots and ectomycorrhiza formation of pine seedlings at elevated atmospheric carbon dioxide. *Plant Cell Environ* 18: 703–07.

Jongen, M., M.B. Jones, T. Hebeisen, H. Blum, and G. Hendrey (1995). The effects of elevated CO_2 concentration on the root growth of *Lolium perenne* and *Trifolium repens* grown in a FACE system. *Global Change Biol* 1: 361–71.

Kacholia, K., and R.A. Reck (1997). Comparison of global climate change simulations for 2 x CO_2-induced warming: an intercomparison of 108 temperature change predictions published between 1980 and 1995. *Clim Change* 35: 53–69.

Kasting, J.F. (1997). Warming early Earth and Mars. *Science* 276: 1213–15.

Kasting, J.F., O.B. Toon, and J.B. Pollack (1988). How climate evolved on the terrestrial planets. *Sci Amer* 258, 2: 90–97.

Kauppi, P.E., K. Mielikainen, and K. Kuusela (1992). Biomass and carbon budget of European forests, 1971–1990. *Science* 256: 70–74.

Keeling, C.D., J.F.S. Chin, and T.P. Whorf (1996). Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Nature* 382: 146–49.

Keeling, C.D., T.P. Whorf, M. Wahlen, and J. van der Pilcht (1995). Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature* 375: 666–70.

Keeling, C.D., T.P. Whorf, C.S. Wong, and R.D. Bellagay (1985). The concentration of carbon dioxide at ocean weather station P from 1969–1981. *J Geophys Res* 90: 10,511–28.

Kiehl, J.T. (1994). On the observed near cancellation between longwave and shortwave cloud forcing in tropical regions. *J Clim* 7: 559–65.

Kimball, B.A. (1983). *Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 770 Prior Observations*. Phoenix, AZ: United States Water Conservation Laboratory.

Kimball, B.A., S.B. Idso, and J.K. Aase (1982). A model of thermal radiation from partly cloudy and overcast skies. *Water Resources Res* 18: 931–36.

Knauth, L.P., and S. Epstein (1976). Hydrogen and oxygen isotope ratios in modular and bedded cherts. *Geochim Cosmochim Acta* 40: 1095–108.

Kreidenweis, S.M., and J.H. Seinfeld (1988). Nucleation of sulfuric acid-water and methanesulfonic acid- water solution particles: implications for the atmospheric chemistry of organosulfur species. *Atmos Environ* 22: 283–96.

LaMarche, V.C., Jr., D.A. Graybill, H.C. Fritts, and M.R. Rose (1984). Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation. *Science* 223: 1019–21.

Lawlor, D.W., R.A.C. Mitchell (1991). The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. *Plant Cell Environ* 14: 807–18.

Leavitt, S.W., E.A. Paul, B.A. Kimball, G.R. Hendrey, J.R. Mauney, R. Rauschkolb, H. Rogers, K.F. Lewin, J. Nagy, P.J. Pinter Jr., and H.B. Johnson (1994). Carbon isotope dynamics of free-air CO_2-enriched cotton and soils. *Agric For Meteorol* 70: 87–101.

Lemon, E.R. (1983). *CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*. Boulder, CO: Westview Press.

Longdoz, B., L.M. François (1997). The faint young sun climatic paradox: influence of the continental configuration and of the seasonal cycle on the climatic stability. *Global Planet Change* 14: 97–112.

Lovelock, J.E. (1988). *The Ages of Gaia: A Biography of Our Living Earth.* New York: Norton.

Lovelock, J.E., and M. Whitfield (1982). Life span of the biosphere. *Nature* 296: 561–63.

MacTaggart, D.L., D.F. Adams, and S.O. Farwell (1987). Measurement of biogenic sulfur emissions from soils and vegetation using dynamic enclosure methods: total sulfur gas emissions via MFC/FD/FPD determinations. *J Atmos Chem* 5: 417–37.

Madsen, T.V. (1993). Growth and photosynthetic acclimation by *Ranunculus aquatilis* L. in response to inorganic carbon availability. *New Phytol* 125: 707–15.

Madsen, T.V., and K. Sand-Jensen (1994). The interactive effects of light and inorganic carbon on aquatic plant growth. *Plant Cell Environ* 17: 955–62.

McGuffie, K., and A. Henderson-Sellers (1988). Is Canadian cloudiness increasing? *Atmos Ocean* 26: 608–33.

McKay, C. (1983). Section 6. Mars. In R.E. Smith and G.S. West (eds), *Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development*. Huntsville, AL: Marshall Space Flight Center.

Meszaros, E. (1988). On the possible role of the biosphere in the control of atmospheric clouds and precipitation. *Atmos Environ* 22: 423–24.

Mojzsis, S.J., G. Arrhenius, K.D. McKeegan, T.M. Harrison, A.P. Nutman, and C.R.L. Friend (1996). Evidence for life on Earth before 3,800 million years ago. *Nature* 384: 55–59.

Mortensen, L.M. (1987). Review: CO_2 enrichment in greenhouses. Crop responses. *Sci Hort* 33: 1–25.

Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698–702.

Newman, M.J., and R.T. Rood (1977). Implication of the solar evolution for the Earth's early atmosphere. *Science* 198: 1035–37.

Nguyen, B.C., S. Belviso, N. Mihalopoulos, J. Gostan, and P. Nival (1988). Dimethyl sulfide production during natural phytoplanktonic blooms. *Marine Chem* 24: 133–41.

Nicholls, S. (1984). The dynamics of stratocumulus: aircraft observations and comparisons with a mixed layer model. *Quart J Roy Meteorol Soc* 110: 783–820.

Nierenberg, W.A., P.G. Brewer, L. Machta, W.D. Nordhaus, R.R. Revelle, T.C. Schelling, J. Smagorinsky, P.E. Waggoner, and G.M. Woodwell (1983) Synthesis. In *Changing Climate: Report of the Carbon Dioxide Assessment Committee* (Washington, DC: National Academy Press): 5–86.

Novakov, T., and J.E. Penner (1993). Large contribution of organic aerosols to cloud-condensation-nuclei concentrations. *Nature* 365: 823–26.

Nullet, D. (1987). Sources of energy for evaporation on tropical islands. *Phys Geogr* 8: 36-45.

Nullet, D., and P.C. Ekern (1988). Temperature and insolation trends in Hawaii. *Theoret Appl Climatol* 39: 90–92.

O'Neill, E.G. (1994). Responses of soil biota to elevated atmospheric carbon dioxide. *Plant Soil* 165: 55–65.

Owen, T., R.D. Cess, and V. Ramanathan (1979). Enhanced CO_2 greenhouse to compensate for reduced solar luminosity on early earth. *Nature* 277: 640–42.

Oyama, Y.I., G.C. Carle, F. Woeller, and J.B. Pollack (1979). Venus lower atmospheric composition: analysis by gas chromatography. *Science* 203: 802–05.

Paltridge, G.W. (1980). Cloud-radiation feedback to climate. *Quart J Roy Meteorol Soc* 106: 895–99.

Pearman, G.I., and P. Hyson (1981). The annual variation of atmospheric CO_2 concentration observed in the northern hemisphere. *J Geophys Res* 86: 9839–43.

Phillips, O.L., and A.H. Gentry (1994) Increasing turnover through time in tropical forests. *Science* 263: 954–58.

Pilewskie P, Valero FPJ (1995) Direct observations of excess solar absorption by clouds. Science 267: 1626-1629

Pimm, S.L., and A.M. Sugden (1994). Tropical diversity and global change. *Science* 263: 933–34.

Platt, T., and S. Sathyendranath (1988). Oceanic primary production: estimation by remote sensing at local and regional scales. *Science* 241: 1613–20.

Pollack, J.B. (1979). Climate change on terrestrial planets. *Icarus* 37: 479–553.

Pollack, J.B., O.B. Toon, and R. Boese (1980). Greenhouse models of Venus' high surface temperature, as constrained by Pioneer Venus measurements. *J Geophys Res* 85: 8223–31.

Poorter, H. (1993). Interspecific variation in the growth response of plants to an elevated ambient CO_2 concentration. *Vegetatio* 104/105: 77–97.

Ramanathan, V. (1988). The greenhouse theory of climate change: a test by an inadvertent global experiment. Science 240: 293–99.

Ramanathan, V., and W. Collins (1991). Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. *Nature* 351: 27–32.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmed, and D. Hartmann (1989). Cloud-radiative forcing and climate: results from the Earth Radiation Budget Experiment. *Science* 243: 57–63.

Ramanathan, V., B. Subasilar, G.J. Zhang, W. Conant, R.D. Cess, J.T. Kiehl, H. Grassl, and L. Shi (1995). Warm pool heat budget and shortwave cloud forcing: a missing physics? *Science* 267: 499–503.

Raven, J.A. (1991). Physiology of inorganic C acquisition and implications for resource use efficiency by marine phytoplankton: relation to increased CO_2 and temperature. *Plant Cell Environ* 14: 779–94.

——— (1993). Phytoplankton: limits on growth rates. *Nature* 361: 209–10.

Rhea, G.-Y., and I.J. Gotham (1981). The effect of environmental factors on phytoplankton growth: temperature and the interactions of temperature with nutrient limitation. *Limnol Oceanogr* 26: 635–48.

Riebesell, U., D.A. Wolf-Gladrow, and V. Smetacek (1993). Carbon dioxide limitation of marine phytoplankton growth rates. *Nature* 361: 249–51.

Ringelberg, D.B., J.O. Stair, J. Almeida, R.J. Norby, E.G. O'Neill, and D. White (1997). Consequences of rising atmospheric carbon dioxide levels for the belowground microbiota associated with white oak. *J Environ Qual* 26: 495–503.

Roeckner, E. (1988). A GCM analysis of the cloud optical depth feedback. In *Proceedings: Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate* (Boston, MA: American Meteorological Society): 67–68.

Roeckner, E., U. Schlese, J. Biercamp, and P. Loewe (1987). Cloud optical depth feedbacks and climate modeling. *Nature* 329: 138–40.

Rogers, H.H., G.B. Runion, and S.V. Krupa (1994). Plant responses to atmospheric CO_2 enrichment with emphasis on roots and the rhizosphere. *Environ Poll* 83: 155–89.

Roosen, R.G., and R.J. Angione (1984). Atmospheric transmission and climate: results from Smithsonian measurements. *Bull Amer Meteorol Soc* 65: 950–57.

Rosinski, J., P.L. Haagenson, C.T. Nagamoto, and F. Parungo (1986). Ice-forming nuclei of maritime origin. *J Aerosol Sci* 17: 23–46.

——— (1987). Nature of ice-forming nuclei in marine air masses. *J Aerosol Sci* 18: 291–309.

Sagan, C., and C. Chyba (1997). The early faint sun paradox: organic shielding of ultraviolet-labile greenhouse gases. *Science* 276: 1217–21.

Sagan, C., and G. Mullen (1972). Earth and Mars: evolution of atmospheres and surface temperatures. *Science* 177: 52–56.

Sakshaug, E. (1988). Light and temperature as controlling factors of phytoplankton growth rate in temperate and polar regions. *EOS: Trans Amer Geophys Union* 69: 1081.

Saltzman, E.S., D.L. Savoie, R.G. Zika, and J.M. Prospero (1983). Methane-sulfonic acid in the marine atmosphere. *J Geophys Res* 88: 10,897–902.

Sand-Jensen, K., M.F. Pedersen, and S. Laurentius (1992). Photosynthetic use of inorganic carbon among primary and secondary water plants in streams. *Freshwater Biol* 27: 283–93.

Saxena, P., L.M. Hildemann, P.H. McMurry, J.H. Seinfeld (1995). Organics alter hygroscopic behavior of atmospheric particles. *J Geophys Res* 100: 18,755–70.

Saxena, V.K. (1983). Evidence of the biogenic nuclei involvement in Antarctic coastal clouds. *J Phys Chem* 87: 4130.

Saxena, V.K., P.A. Durkee, S. Menon, J. Anderson, K.L. Burns, and K.E. Nielsen (1996). Physico-chemical measurements to investigate regional cloud-climate feedback mechanisms. *Atmos Environ* 30: 1573–79.

Schidlowski, M. (1988). A 3,800-million-year isotopic record of life from carbon in sedimentary rocks. *Nature* 333: 313–18.

Schnell, R.C., and G. Vali (1976). Biogenic ice nuclei. Part I. Terrestrial and marine sources. *J Atmos Sci* 33: 1554–64.

Schopf, J.W. (1978). The evolution of the earliest cells. *Sci Amer* 239, 3: 110–38.

Schopf, J.W., and E.S. Barghourn (1967). Alga-like fossils from the early Precambrian of South Africa. *Science* 156: 507–12.

Schwarzchild, M., R. Howard, and R. Harm (1957). Inhomogeneous stellar models. V. A solar model with convective envelope and inhomogeneous interior. *Astrophys J* 125: 233–41.

Sellers, W.D. (1965). *Physical climatology.* Chicago, IL: University of Chicago Press.

Shapiro, J. (1997). The role of carbon dioxide in the initiation and maintenance of blue-green dominance in lakes. *Freshwater Biol* 37: 307–23.

Shaw, G.E. (1983). Bio-controlled thermostasis involving the sulfur cycle. *Clim Change* 5: 297–303.

——— (1987). Aerosols as climate regulators: a climate-biosphere linkage? *Atmos Environ* 21: 985–86.

Shine, K.P., R.G. Derwent, D.J. Wuebbles, and J.-J. Morcrette (1990). Radiative forcing of climate. In J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds), *Climate Change: The IPCC Scientific Assessment* (Cambridge: Cambridge University Press): 41–68.

Slingo, A. (1990). Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature* 343: 49–51.

Smagorinsky, J., L. Armi, F.P. Bretherton, K. Bryan, R.D. Cess, W.L. Gates, J. Hansen, J.E. Kutzbach, and S. Manabe (1982). *Carbon Dioxide and Climate: A Second Assessment*. Washington, DC: National Academy Press.

Somerville, R.C.J., and L.A. Remer (1984). Cloud optical thickness feedbacks in the CO_2 climate problem. *J Geophys Res* 89: 9668–72.

Staubes, R., H.-W. Georgii, and G. Ockelmann (1989). Flux of COS, DMS and CS_2 from various soils in Germany. *Tellus* 41B: 305–13.

Strain, B.R., and J.D. Cure (1994). Direct effects of atmospheric CO_2 enrichment on plants and ecosystems: an updated bibliographic data base. Oak Ridge, CA: Oak Ridge National Laboratory.

Szyrmer, W., and I. Zawadzki (1997). Biogenic and anthropogenic sources of ice-forming nuclei: a review. *Bull Amer Meteorol Soc* 78: 209–28.

Titus, J.E. (1992). Submersed macrophyte growth at low pH. II. CO_2 sediment interactions. *Oecologia* 92: 391–98.

Titus, J.E., R.S. Feldman, and D. Grise (1990). Submersed macrophyte growth at low pH. I. CO_2 enrichment effects with fertile sediment. *Oecologia* 84: 307–13.

Trenberth, K.E., J.T. Houghton, L.G. Meira Filho (1996). The climate system: an overview. In J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds). *Climate Change 1995: The Science of Climate Change* (Cambridge: Cambridge University Press): 51–64.

Turner, S.M., G. Malin, P.S. Liss, D.S. Harbour, and P.M. Holligan (1988). The seasonal variation of dimethyl sulfide and dimethylsulfoniopropionate concentrations in nearshore waters. *Limnol Oceanogr* 33: 364–75.

Turner, S.M., P.D. Nightingale, L.J. Spokes, M.I. Liddicoat, and P.S. Liss (1996). Increased dimethyl sulphide concentrations in sea water from *in situ* iron enrichment. *Nature* 383: 513–17.

Twomey, S.A., and J. Warner (1967). Comparison of measurements of cloud droplets and cloud nuclei. *J Atmos Sci* 24: 702–03.

Vairavamurthy, A., M.O. Andreae, and R.L. Iverson (1985). Biosynthesis of dimethylsulfide and dimethylpropiothetin by *Hymenomonas carterae* in relation to sulfur source and salinity variations. *Limnol Oceanogr* 30: 59–70.

Vali, G., M. Christensen, R.W. Fresh, E.L. Galyan, L.R. Maki, and R.C. Schnell (1976). Biogenic ice nuclei. Part II: Bacterial sources. *J Atmos Sci* 33: 1565–70.

Walker, J.C.G. (1985). Carbon dioxide on the early Earth. *Origins Life* 16: 117–27.

Warner, J., and S.A. Twomey (1967). The production of cloud nuclei by cane fires and the effect on cloud droplet concentration. *J Atmos Sci* 24: 704–06.

Warren, S.G., and S.H. Schneider (1979). Seasonal simulation as a test for uncertainties in the parameterizations of a Budyko-Sellers zonal climate model. *J Atmos Sci* 36: 1377–91.

Webster, P.J., and G.L. Stephens (1984). Cloud-radiation interaction and the climate problem. In J.T. Houghton (ed), *The Global Climate* (Cambridge: Cambridge University Press): 63–78.

Went, F.W. (1966). On the nature of Aitken condensation nuclei. *Tellus* 18: 549–55.

Wigley, T.M.L., and P. Brimblecombe (1981). Carbon dioxide, ammonia and the origin of life. *Nature* 291: 213–15.

Wullschleger, S.D., W.M. Post, and A.W. King (1995). On the potential for a CO_2 fertilization effect in forests: estimates of the biotic growth factor based on 58 controlled-exposure studies. In G.M. Woodwell, and F.T. Mackenzie (eds), *Biotic Feedbacks in the Global Climatic System* (New York: Oxford University Press): 85–107.

Wullschleger, S.D., R.J. Norby, and C.A. Gunderson (1997). Forest trees and their response to atmospheric CO_2 enrichment: a compilation of results. In L.H. Allen Jr., M.B. Kirkham, D.M. Olszyk, and C.E. Whitman (eds), *Advances in CO_2 Effects Research* (Madison, WI: American Society of Agronomy): 79–100.

Zak, D.R., K.S. Pregitzer, P.S. Curtis, J.A. Teeri, R. Fogel, D.L. Randlett (1993). Elevated Atmospheric CO_2 and feedback between carbon and nitrogen cycles. *Plant Soil* 151: 105–17.