Some Coolness Concerning Global Warming

Richard S. Lindzen
Center for Meteorology and Physical Meteorology
MIT, Cambridge, MA 02139

1. Introduction

The assessment of the proper response to the possible danger of global warming depends critically on the determination of how real the danger is. There are certainly other potential problems that could be far more devastating to life on this planet (e.g., an asteroid collision), but we regard those as too unlikely to worry about.

The existence of skepticism on this issue has only recently been publicly recognized. Whatever the truth may turn out to be, there is an unusual degree of extremism associated with this issue. While environmental scares are not unheard of, few have been accompanied by recommendations that skepticism be stifled (an editorial to this effect in the *Boston Globe* [17 December 1989] is but one of a series of examples). As an admitted skeptic on this issue, I would like to discuss some aspects of the "greenhouse hypothesis" that leave me unconvinced, and leave me concerned whether unanimity on such an issue is healthy for meteorology.

2. Observations of increased CO_2 and rising temperature

The increasing concentration of CO_2 in the atmosphere is unquestionably the most substantial aspect of the warming scenario. Measurements taken at Mauna Loa Observatory since 1958 (shown in figure 1) unambiguously show an increase of CO_2 from 315 to 350 ppm, and because CO_2 is relatively well mixed in the course of a year, the increase is likely to be representative. Analysis of ice-core data further suggests that CO_2 has been increasing since the nineteenth century (Oeschger and Siegenthaler 1987). The increase is crudely described by the following equation:

$$CO_2 = 278.8\,ppm\,v + 1.17\,ppm\,v \times e^{([yr - 1800]/45\,yr)}$$

Preindustrial concentrations appear to have been 270–280 ppm. Finally, there appears to be little reason to doubt that CO_2 concentrations will continue to increase. However, the use of the above formula is unlikely to be justified in the indefinite future. Thus far, the increase in CO_2 represented by the formula is approximately half the CO_2 deposited by the burning of fossil fuel. Isotope analysis suggests that fossil fuel burning is indeed the primary source of the increase (Freyer 1979). The half that does not appear in the atmosphere is believed to be taken up by the oceans through mechanisms not completely clear. More germane, perhaps, is the expectation that the burning of all known fossil fuel will only quadruple present concentrations of CO_2. Thus, the rate of increase represented by the above formula almost certainly must go down within the next century (admittedly leaving us with the problem of fossil fuel depletion; after all such fuel is burned we may expect the gradual return of CO_2 concentrations to their preindustrial levels).[1]

It is entirely legitimate to ask whether we should be worried about increasing levels of CO_2 in the atmosphere. (The depletion of fossil fuels is another matter.) Certainly, we are dealing with significant changes in CO_2, but this alone need not be serious. CO_2 is a minor atmospheric constituent (about 0.03%), and as such, its variations might not be notably important. One can imagine some gas which is not normally present in the atmosphere. Releasing a molecule or two of such a gas would represent an enormous percentage increase without being of much concern. As it turns out, there are quite a few things that increasing levels of CO_2 *might* affect. For example, at altitudes between 25 km and 90 km, the atmosphere is cooled primarily by thermal radiation emitted to space by CO_2. Increasing CO_2 should cool these regions, and this, in turn, should lead to *increasing* concentrations of ozone at these levels.[2] Increasing

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[1] These matters are reviewed in a manner adequate for our purposes in *Changing Climate—Report of the Carbon Dioxide Assessment Panel*, a report of the Board on Atmospheric Sciences and Climate of the National Research Council (NRC) published by the National Academy Press in 1983. We shall refer to this report as *NRC 83*. More recent work includes that of Sarmiento and Toggweiler (1984), and Bolin (1986).

[2] The radiative and photochemical processes of the middle atmosphere are comprehensively reviewed in Andrews et al. (1987). The coupling of temperature and ozone is formulated in Lindzen and Goody (1965).

CO_2 might also stimulate the growth of vegetation. These possibilities are being studied, and are, on the whole, benign or even beneficial. As far as we know, there is no direct adverse effect on human beings arising from increases in CO_2 on the order of those anticipated (however uncertainly) over the next few centuries. (Certainly, much higher concentrations are found in normal indoor environments.) Our main concerns have focused on the possibility that increasing CO_2 might significantly warm our climate. Although we do not know exactly what determines CO_2 concentration, it is eminently plausible to ask what effects a doubling of present concentrations of CO_2 would have. For reasons that will be discussed later, there is general agreement that increasing CO_2 will produce warming due to its ability to absorb in the infrared radiation. As a practical matter, however, we need to know how much warming can be expected. If the expected warming is significantly less than the natural fluctuations in climate, there is little basis for concern.

Model calculations have, for at least a decade, suggested that a doubling of CO_2 will lead to increases in globally averaged temperature of 1.5° to 5°C (*NRC 83*). Although it is generally maintained that dire consequences will follow from such warming, there is substantial argument (Ellsaesser 1984; Idso 1989), and there is little question that the issue is unsettled. As will be discussed later, the models (including those running on supercomputers) are likely to be inadequate for such predictions. However, such large predictions suggest that the changes in CO_2 that have occurred over the last 150 yr should already have produced warmings of about 0.5°–2°C. The reason these numbers are so large relative to what is expected from a doubling of CO_2 is that its warming effect is logarithmic—so that continued increases in CO_2 become progressively less effective in contributing to warming (Hansen et al. 1985). The situation is exacerbated by the fact that CO_2 is by no means the only minor gas capable of absorbing infrared radiation. The contributions from methane, NO_2, and chlorofluorocarbons (taken together) are comparable to CO_2 (Hansen, et al. 1989). It is claimed, on the basis of certain observations, that the earth has warmed about 0.5°C since 1880 (Hansen and Lebedeff 1987). This would appear to be marginally consistent with only the lowest of the model estimates. However, the estimates are for changes in equilibrium temperature. As Hansen et al. (1985) have noted, ocean-heat storage can delay these temperature increases. The calculation of those delays depends critically on such

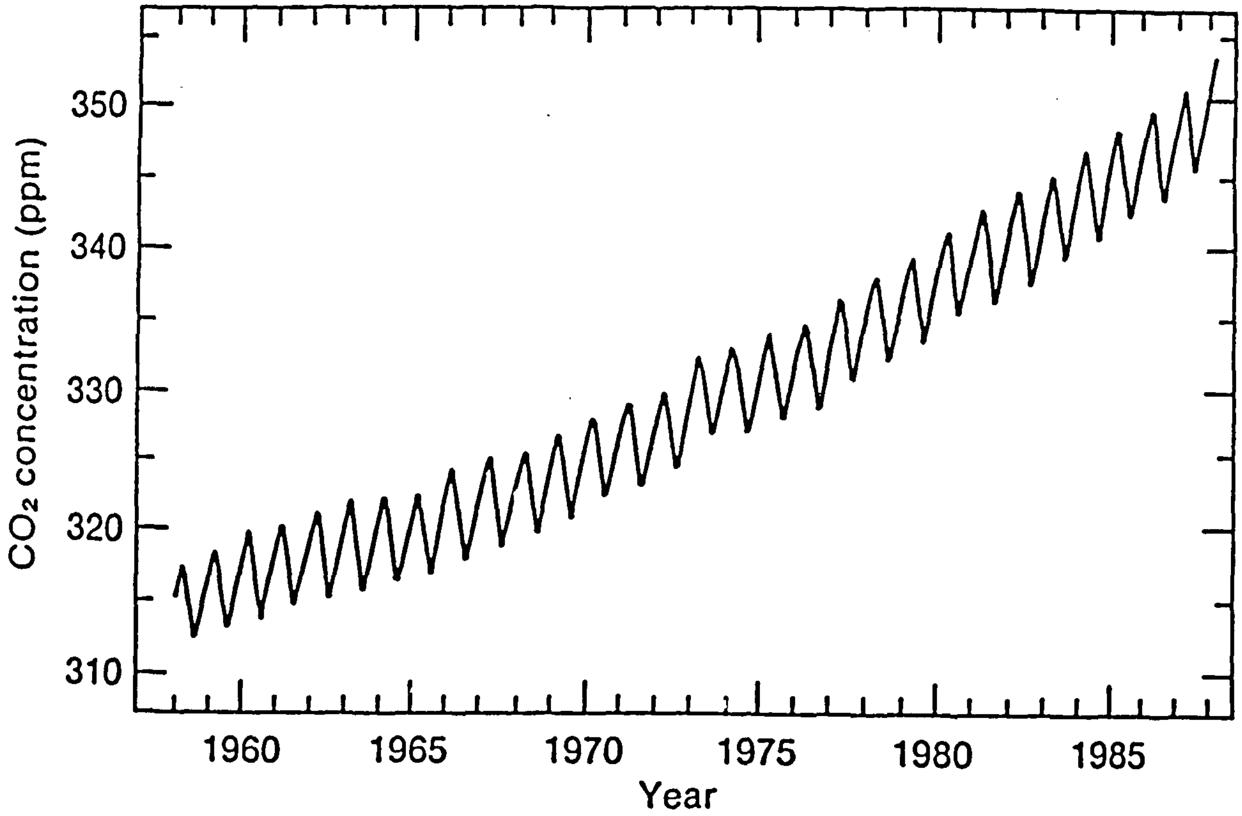

FIG. 1. Mean monthly concentrations of atmospheric CO_2 at Mauna Loa. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the Northern Hemisphere. (Source: Geophysical Monitoring for Climate Change, National Oceanic and Atmospheric Administration.)

highly uncertain matters as the distribution of eddy diffusion in the ocean (and on whether that formulation is at all appropriate). Also, the lag time for response increases with the amount of positive feedback in the system. (In the absence of positive feedbacks, models suggest about a 0.5°C increase; greater increases are due to these feedbacks, which will be discussed later in this paper.) Nevertheless, using a simple box-diffusion model, Hansen et al. (1985) found that for virtually any measure of positive feedback, the expected increase in temperature over the last century should be about 0.5°C. Smaller increases would imply net negative feedbacks. This is a matter of some importance because this is the only observational evidence for anomalous greenhouse warming available now. As we shall see, the data, although quite uncertain, do not suggest that even 0.5°C of warming has, in fact, occurred.

The determination of the globally averaged temperature of the earth's surface is a difficult task—at least at the level of accuracy we require for the present purpose. It is commonly known that temperature can vary markedly (compared to the expected global warming) over short distances; urban areas are frequently warmer than the countryside; water surfaces differ in temperature from adjacent land surfaces; temperatures vary in the course of a day, and certainly from day to day; and seasonal changes are large. Moreover, there is what is called "natural" climate variability from year to year; because it is expected to occur even in the absence of external causes.[3] It is not clear that our network of surface-temperature measurements is adequate to completely eliminate these sources of uncertainty. However, such averages as we are able to form actually show remarkable constancy from year to year. Estimated changes over the last 150 yr are less than 1°C.[4] We cannot be at all sure that these small changes are not, in significant measure, due to inadequate and/or improper sampling. For example, most of the earth's surface is covered by oceans over which we have no fixed-station records and the most commonly cited time series for globally averaged temperature is based solely on such fixed-station records. Temperatures measured at St. Helena Island are assumed, for example, to be characteristic of almost one-third of the Atlantic Ocean; this is not a sufficient assumption for the purpose of determining the small changes in global temperature. There are, many records of sea temperature taken from ships (Newell et al. 1989). These data also present problems, such as differences arising depending on whether water was sampled by bucket or through intake. Also, ship tracks in the nineteenth century did not provide adequate global coverage (Karl et al. 1989). Finally, for certain regions of the globe (i.e., the contiguous 48 states), there has been consistent and relatively dense measurement of temperature since the 1890s. Because this region is only a small portion of the earth's surface, it is a priori expected to be more variable than the globe as a whole. There is substantial difficulty in correcting land-based records for the effects of urbanization. The National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) has approached this correction with considerable care over the continental United States, but, again, the issue remains a matter of some debate—especially for the data from outside the continental United States (Karl et al. 1988a; Hansen et al. 1989; Karl et al. 1988b; Balling and Idso 1989). Because the above data are about all that are available, they are what we will have to use. However, it is important to stress that all the above records have required uncertain corrections whose magnitudes are as large as the climatic effects being sought. Under these circumstances, any scientist would intuitively regard any conclusions regarding such effects as, at best, suggestive. Only if the observed changes were substantially larger than the corrections would they be regarded as convincing, which as we shall see is not at all the case.

Figure 2 shows three time series for annually averaged surface temperature. The top record is an area-weighted average (i.e., records weighted in proportion to the area they represent) of fixed surface measurements from all over the globe; dating back to 1855. The center record is derived from millions of ship records, and also dates from approximately 1855. The bottom curve is for the contiguous 48 states, and dates back to 1900. All these records begin before the bulk of industrial CO_2 deposition into the atmosphere. Although all three series differ in detail, none indicates significant variability in excess of 1°C. None indicates *any* significant temperature change between the start of the record and the present. Finally, the best record (that for the 48 contiguous states), and the record expected to show the greatest varia-

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[3] The issue of "natural" variability is far more serious than is commonly stated. In a review of the recent Workshop on Greenhouse-Gas-Induced Climatic Change (Kerr 1989), a discussion of one of the most interesting findings was that almost all models, when run for periods of about 100 yr, exhibited variability unrelated to greenhouse warming that was as large or larger than the greenhouse-induced warming itself. The variability found in nature seems to be smaller than that found in the models, but still may mask anticipated greenhouse effects. The precise origin of natural variability is still uncertain, but it is not that surprising. Although the solar energy received by the earth-ocean-atmosphere system is relatively constant, the degree to which this energy is stored and released by the oceans is not. As a result, the energy available to the atmosphere alone is also not constant.

[4] An excellent review of global-climate data is given in Ellsaesser et al. (1986).

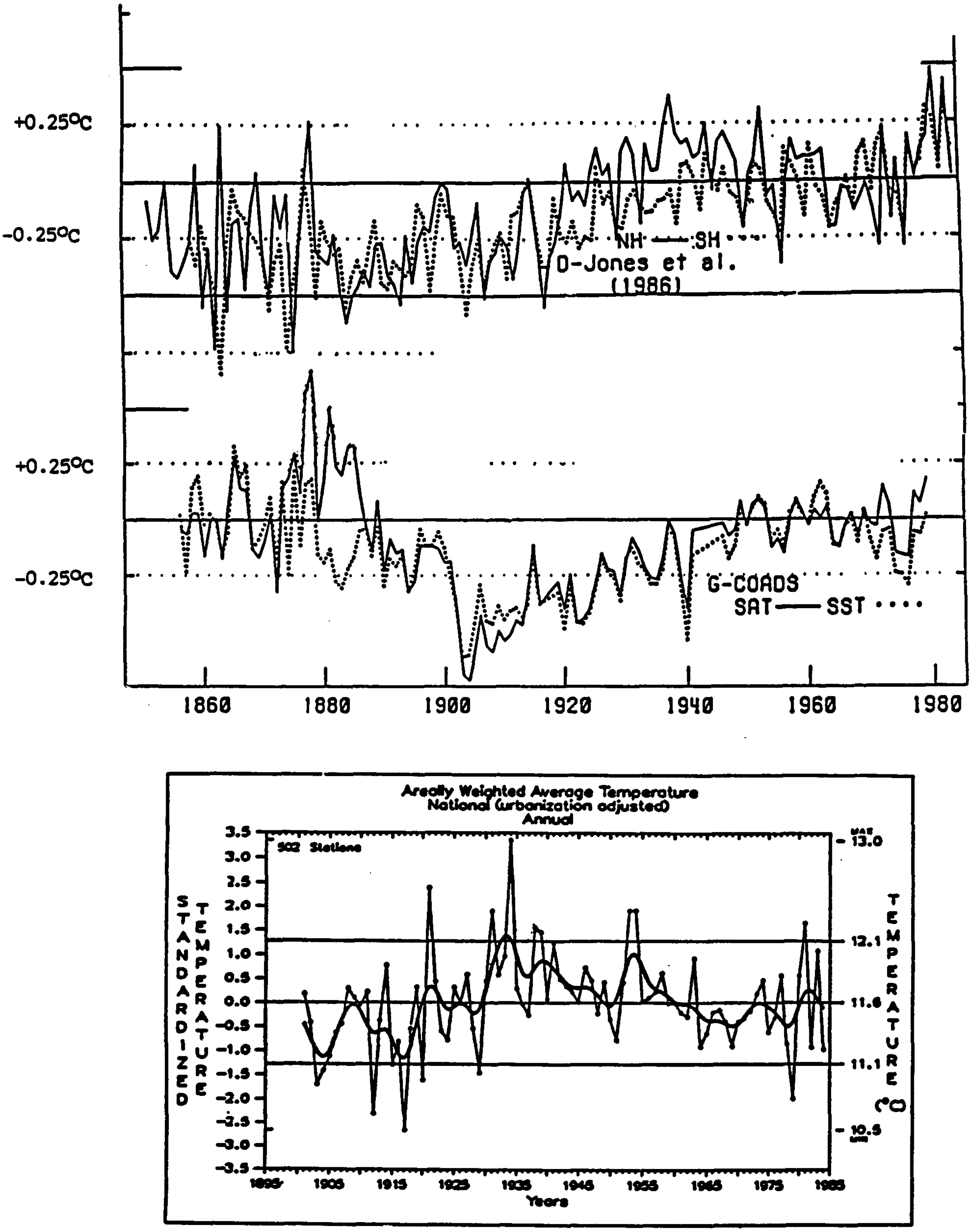

FIG. 2. Annual mean temperature departures (top) from 1951–70 normals derived from station data. The solid curve represents Northern Hemisphere data; the dotted curve represents Southern Hemisphere data. The average between the two tends to be somewhat smoother than either curve. (Reproduced from Ellsaesser et al. 1986, who used analyses from Jones et al. 1986a,b.) Annual mean temperature departures (center) from 1951–70 normal derived from ship data for air temperature (solid line) and sea-surface temperature (dotted line). (Reproduced from Ellsaesser et al. 1986 based on analyses of Slutz, et al. 1985; Ramage 1984; and Folland et al. 1984.) Annual mean temperature (bottom) areally weighted over the contiguous 48 states. The solid curve represents a 9-yr running smoother. (Reproduced from Karl et al. 1988.)

bility because of the small area covered, shows almost no significant trend at all; nor does the ocean data. On the basis of the records available, the best estimate for the global temperature change that has occurred over the industrial period does not significantly vary from 0, suggesting that current models are probably exaggerating expected warming. The contention that temperature has increased about 0.5°C in the past century comes from assuming that the top curve in figure 2 begins around 1880 (Hansen and Lebedeff 1987). There is, in fact, a good reason to begin with 1880. Before this date there was little attempt to systematically organize and collect global-climate data. However, earlier—albeit more sparse—data exists suggesting that earlier temperatures were warmer. Even beginning at the 1880 minimum, the record is hardly one of uniform increase. The major, sharp increase occurred by 1940. This increase antedated the much greater increase in CO_2 deposition after this date, and might reasonably be interpreted as a return of the global temperature to its value before the anomalous 1880 minimum. From 1940 until the 1960s the record suggested global cooling (leading to the suggestions in the 1960s that an ice age was coming). Beginning in the 1960s there is evidence of a reversal of the earlier cooling trend (leading to the current suggestions of global warming). There is clearly variance in the record on all times scales (including time scales that are probably longer than the instrumental record), and the magnitude of this variance is entirely comparable with the trend being sought. The interpretation of this record, in terms of a linear trend, seems highly inappropriate. Finally, it should be emphasized that even the purported trend in this record is, at best, suggestive. The absence of any significant trend in the record for the contiguous 48 states leads to the suspicion that all the trends in the global record may, in fact, be spurious. The absence of any net change in the ocean record between the nineteenth century and the present one also supports this possibility. Spencer et al. (1989) have recently used satellite-microwave soundings to study temperature trends beginning in 1978. Satellite coverage eliminates sampling problems. Over this period they find that satellite-observed trends over the continental United States correlate excellently with the land-based thermometric record. However, the correlation with the land-based record for the globe is poor—suggesting that the land-based global record is inadequate for measuring global trends. We certainly cannot assert that no warming occurred; however, it cannot be said the data show it.

The difficulty with detecting trends was clearly recognized in *NRC 83*. They suggested that this difficulty might be circumvented by a technique they referred to as "fingerprinting." The idea behind this approach is simply that models predict a detailed distribution of temperature and not simply a globally averaged temperature. Perhaps the data might confirm patterns of regional change more clearly than it could detect trends in globally averaged temperature. The trouble with this approach arises because existing models differ greatly (sometimes even in sign) in their predictions of regional variations. The models do not even accurately simulate present-day regional variations. About the only thing existing climate models agree on is that warming will be greatly exaggerated in polar regions—especially during winter. These predictions are shown in figure 3. Unfortunately, observations show that exactly the opposite has occurred in the Arctic; as we see in figure 4, the Arctic is not warming, but, instead, appears to be cooling, which is particularly pronounced in winter (Rogers 1989).[5]

3. The greenhouse effect

Given the data alone, we would have little basis for alarm. The alarm arises instead from theoretical considerations—namely the so-called "greenhouse effect." The idea here is deceptively simple. Averaged over several years, the surface of the earth is in a state of approximate thermal balance. In particular, cooling balances heating. If the earth had no atmosphere at all, this balance would be achieved by radiation alone. The heating would be due to the absorption of sunlight, and the cooling would be due to thermal (infrared) radiation, which increases as temperatures increase. The temperature would rise (or sink) until heating and cooling balanced. It can be shown that such a balance would lead to an average surface temperature of about −18°C—a value much lower than that actually found (close to 15°C). The difference arises because the earth has an atmosphere containing infrared absorbers known as "greenhouse gases." These gases absorb some of the infrared radiation cooling the earth and re-emit that radiation both upward and downward. The downward component supplements the radiation from the sun. Thus the earth must warm up so that the total radiation incident on the earth can be balanced by cooling, i.e., the greenhouse effect.[6] The process is schematically illustrated in figure 5. The most important infrared absorbers are water vapor and liquid water in the form of cloud

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[5] According to Kerr (1989), a model being run by Washington and Meehl is displaying Arctic cooling. The observed cooling amounts to about 0.5°C between 1960 and the present. In terms of climate, this is a fairly significant cooling—especially in comparison with the expected warming.

[6] A relatively simple treatment of traditional greenhouse ideas is given in Houghton (1977).

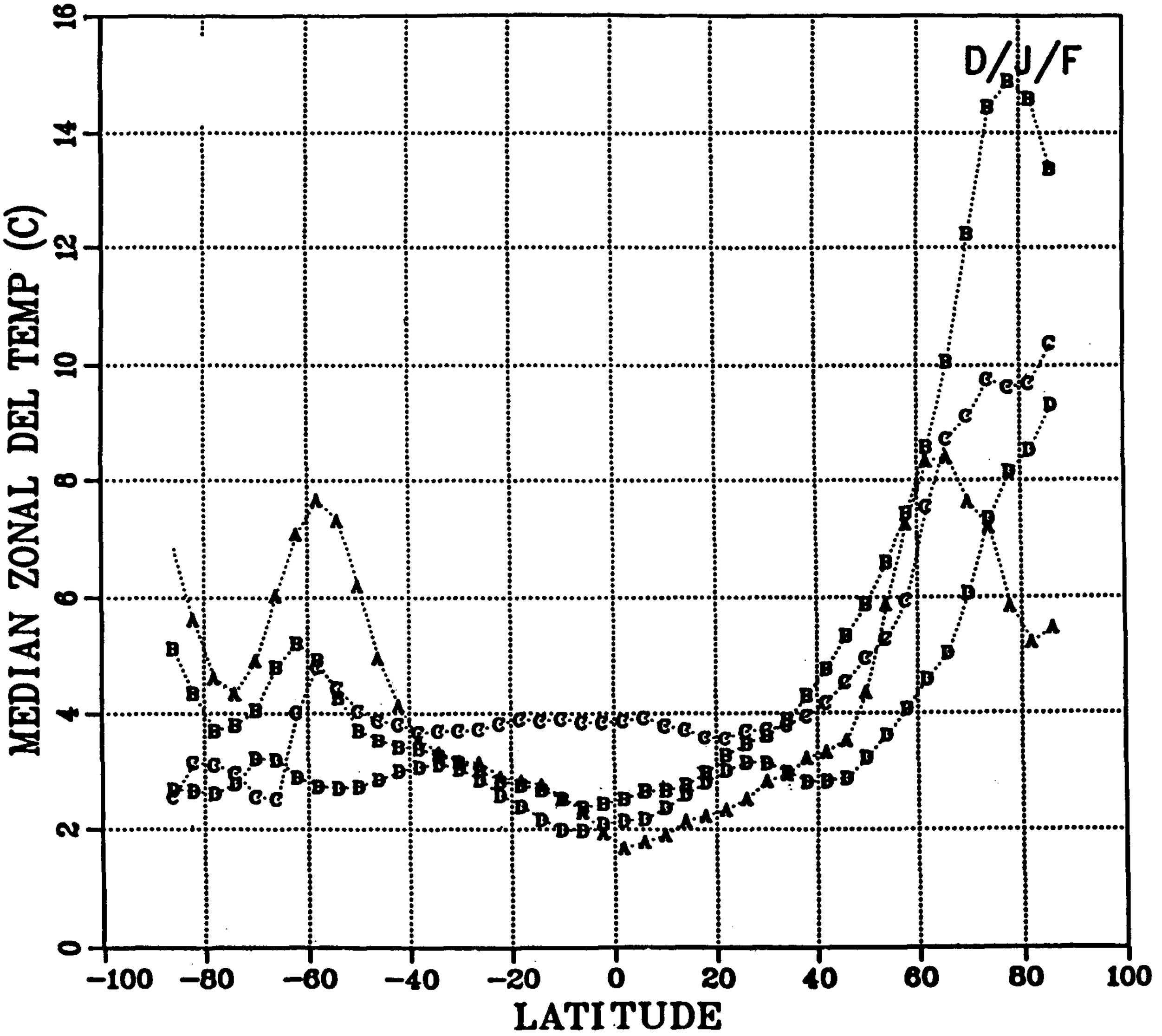

FIG. 3. Superposed medians for four GCMs of the zonal distributions for the predicted change in surface-air temperature due to a doubling of CO_2 for the period December–February (DJF) (A is the NCAR Community Climate Model; B, GFDL; C, Goddard Institute for Space Studies; and D, Oregon State University). (After Grotch [1988].)

droplets arrayed in stratiform clouds. (The latter also acts to reflect sunlight, which is a cooling effect; the heating and cooling effects almost balance.) It is currently believed, however, that the cooling effect slightly exceeds the warming effect (Ramanathan et al. 1989). Additional minor absorbers, such as CO_2, ozone, nitrous oxide, chlorofluorocarbons, and methane contribute slightly to this effect, and all other things being equal, we may expect increasing absorber amounts will lead to increased surface temperature. However, it should be pointed out that *the contributions of the expected additions of minor greenhouse gases to warming are small, even compared to the estimated slight difference between the warming and cooling properties of stratiform clouds*. The above picture is hardly new; it was reasonably understood by the early part of this century. It was also known that the above picture, as applied to the earth's surface, is too simple. The surface of the earth does *not* cool primarily by infrared radiation. It cools mainly through evaporation.[7] Most of the evaporated moisture ends up in convective clouds (clouds with strong vertical currents carrying the air and its contents upward, as op-

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[7] This fact is not always clear in schematic depictions of the earth's surface-energy budget. Figure 6 (from MacCracken and Luther 1985) would suggest that the surface cools primarily by infrared emission. The diagram shows an outward infrared flux from the surface greatly exceeding the latent heat flux (i.e., the cooling due to evaporation). However, the same figure shows the atmosphere re-emitting a large infrared flux back to the surface. It is the difference between these fluxes that represents the actual surface cooling due to infrared emission. In the limiting case where the atmosphere is totally opaque to infrared radiation this difference goes to zero. This is almost the situation in the tropics.

posed to layered clouds, which form and stay at a particular level) where the moisture condenses into rain. Just as evaporation cools, the condensation of water vapor heats, and the atmosphere realizes most of this heat at altitudes >5 km. It is at these heights that the atmosphere must balance the heat deposited by convection from the surface through cooling by thermal radiation. It is worth noting that, in the absence of convection, pure greenhouse warming would lead to a globally averaged surface temperature of

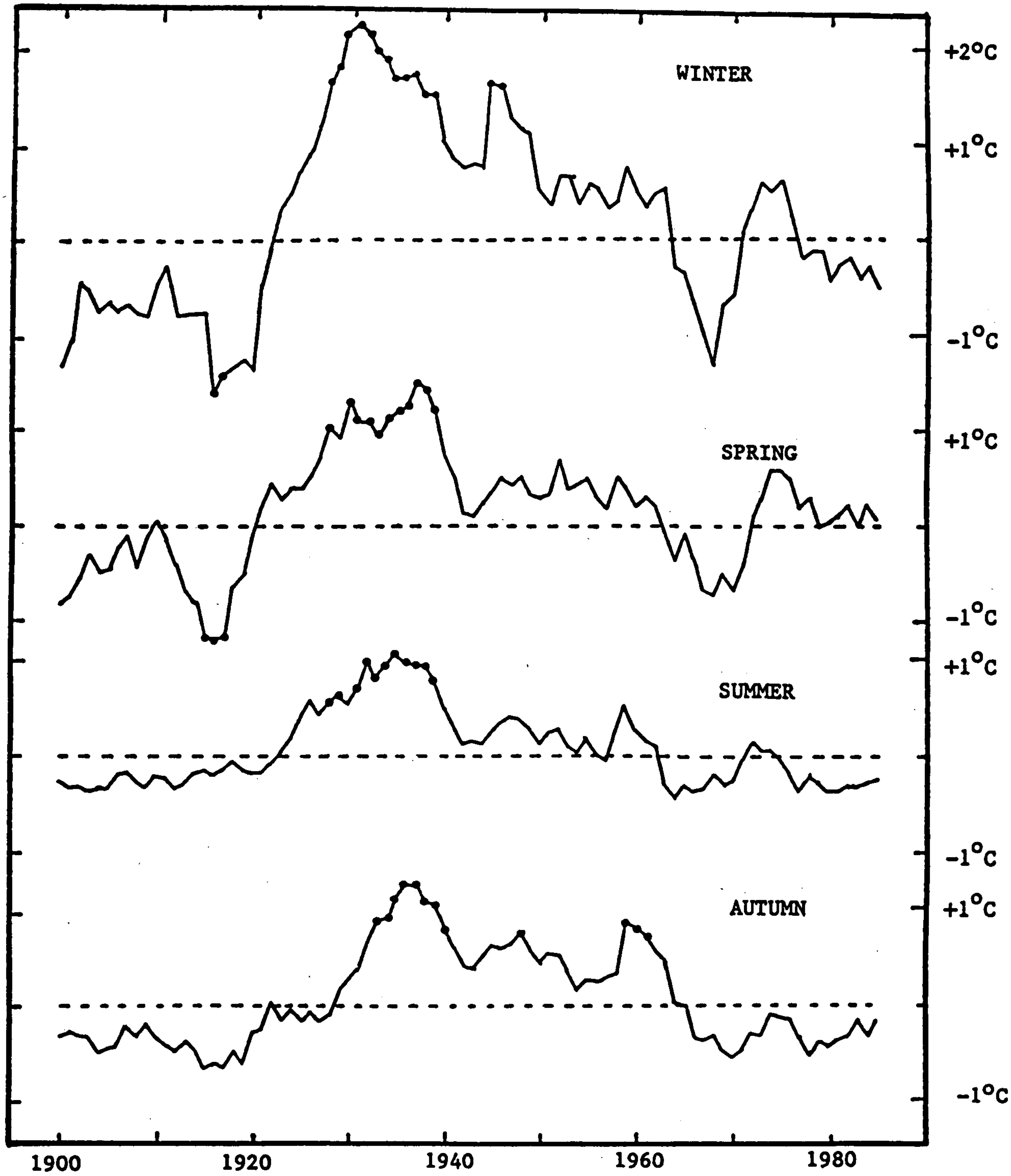
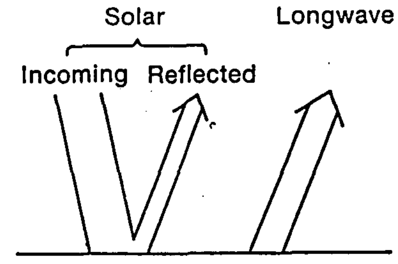


FIG. 4. 5-yr averages of seasonal temperature anomalies over the Atlantic Arctic since 1900. Dots indicate 5-yr mean temperature anomalies which are significantly above or below the 1881–1987 mean using the Cramer *t*-test. Temperatures are plotted on the middle year of the 5-yr means. (After Rogers 1989.)

72°C given current conditions (Möller and Manabe 1961). Our current average temperature, 15°C, is actually much closer to the black body temperature (temperature without any greenhouse warming), −18°C, than to the pure greenhouse result.[8] The relative ineffectiveness of the greenhouse effect is due to convection which carries heat past the bulk of the water vapor (which has a characteristic scale height of about 2 km), and to large-scale meridional heat transport which carries heat from the moist tropics to the less moist higher latitudes. Because of this transport, it is primarily the distribution of infrared absorbers above 5 km (rather than below 5 km) that is important for containing the heat carried away from the earth's surface (Lindzen et al. 1982). Some infrared radiation in the water-vapor continuum does originate from below this height; however, it seems possible that this radiation may contribute to the net cooling of the atmosphere. However, this is only a minor gloss on the simple model of the purely radiative greenhouse. It may, nonetheless, have major implications for current predictions. In the mean time the greenhouse effect is not nearly as straightforward as is commonly stated.

The physics described in the above few paragraphs is characteristic of all current models used to estimate the effect of doubling CO_2. These include simple models readily evaluated on a personal computer, and gigantic codes requiring supercomputers. Not surprisingly, results differ relatively little among these various models. Such differences are not due to differences in the model size, but rather from identifiable differences in physical assumptions. Moreover, at present there is little reason to trust the larger models more than the smaller ones. All such models (at least in the current literature) predict that a doubling of CO_2 will lead to a global warming of between 1.5°C and 5°C.[9] They also suggest that a warming of at least 0.5°C should already have occurred over the last 100 yr. We have seen that the data hardly support even this claim. Finally, the model result—that the warming predicted to have occurred over the last 100 yr should be strongest in the Arctic—is directly contradicted by the observed cooling trend in this region.



(a) No atmosphere

(b) With atmosphere

FIG. 5. Schematic illustration of the greenhouse effect showing (a) no atmosphere, where longwave radiation escapes directly to space, and (b) an absorbing atmosphere, where longwave radiation from the surface is absorbed and reemitted both downward, and upward, maintaining radiative balance at the top of the atmosphere.

4. Problems

At this point, there would normally be a strong impetus toward discovering what was wrong with our models. Indeed, efforts along these lines are in progress. The notion that there are likely to be serious problems in existing computer simulations of the climate is not at all surprising within the meteorological and oceanographic communities. Models commonly have difficulty reproducing well-observed major features of the current climate (e.g., mean global temperature, pole-to-equator temperature difference, intensity and position of the jet stream, seasonally averaged regional variations of climate, etc.) without what is euphemistically referred to as "tuning." In tuning, processes not resolved by the model are parameterized to bring the model into agreement with what are believed to be the observations. Even such seemingly basic quantities as the solar irradiation of the earth are subjected to adjustment. These adjustments are considerably larger than the 4 W/m^2 increase in downward radiation at the earth's surface that is expected to result from a doubling of CO_2.[10] Models used for climate predictions are usually somewhat primitive versions of the models used for weather prediction. Problems have also been observed with weather-prediction models, though the situation has certainly been improving.[11] The most likely area to search for severe problems is in the interaction of climate with water (in all its phases).

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[8] This is especially clear when one considers that surface infrared emission varies as T^4.

[9] Reasonably current reviews of climate modeling may be found in papers by Schlesinger, and Schlesinger and Mitchell in MacCracken and Luther (1985).

[10] For purposes of comparison, the current downward flux is about 327 W m^2.

[11] Grotch (1988) reviews differences among models, and between models and observations.

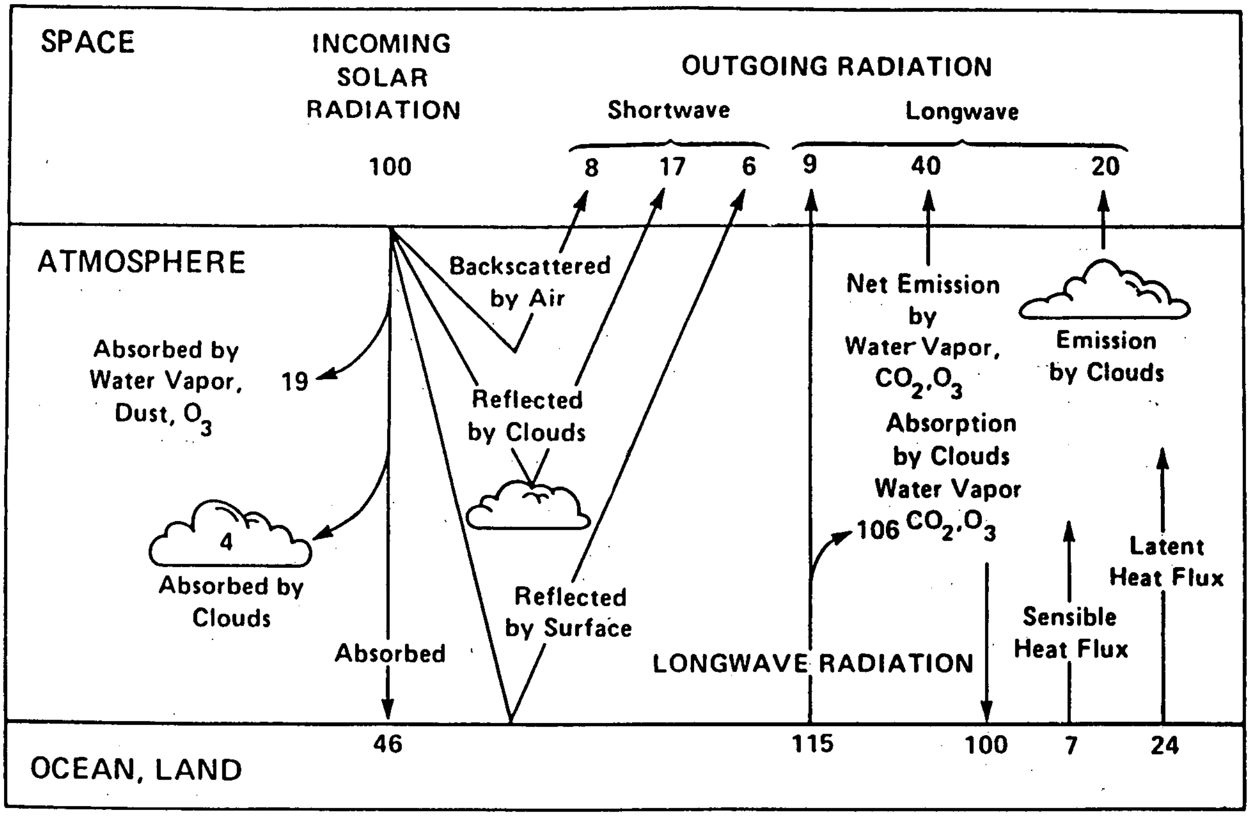

FIG. 6. Schematic representation of the atmospheric heat balance. The units are percent of incoming solar radiation. The solar fluxes shown on the left-hand side, and the longwave (thermal IR) fluxes are on the right-hand side (from MacCracken and Luther 1985).

The remarkable thermodynamic properties of water almost certainly lead to its acting as nature's thermostat. Yet in the major numerical models, all feedbacks between warming and water are *positive*. In the absence of these positive feedbacks, these same models would yield warmings (due to doubling of CO_2) only one-half to one-fifth of those cited above. When it is recognized that at least some of these feedbacks may be *negative* rather than positive, it is easy to see that the actual response to a doubling of CO_2 may be much less. These are by no means idle or eccentric suggestions. For example, in models, warming leads to increased high-level cloud cover, the net effect of which is to amplify the warming. The modeling of cloud cover is a delicate and uncertain effort. Still, modest changes can lead to dramatic results. The British Meteorological Office climate model had predicted a 5°C warming accompanying a doubling of CO_2. Very recently they reported that the simple matter of changing the ice content of layer clouds had reduced this value to under 2°C—a reduction of 60% (Mitchell et al. 1989)!

The positive feedbacks from increasing upper-level clouds are not the largest in current models. A much higher rate of feedback in all large numerical models is due to the fact that warming is associated with increasing water vapor at all levels in the models (Manabe and Wetherald 1980). Recall that water vapor is a far more important greenhouse gas than CO_2 and that convection significantly short circuits the greenhouse absorption below about 5 km. Greenhouse absorption is primarily important above 5 km. The existing climate models have considerable difficulty predicting upper-level water vapor. Although, in nature, warming increases water vapor near the ground, warming is also associated with more and deeper cumulus convection. This leads to drying of the upper troposphere[12] (above 5 km). The nature of this drying effect, which is questionably dealt with in current climate models (Geleyn et al. 1982), is illustrated in figure 7. This cumulus convection occurs in deep towers of rapidly rising air. The air cools as it rises, and the water vapor in the air condenses and falls out as rain. By the time these clouds top out (at altitudes as great as 16 km), they are relatively drained of water vapor. Of course, these rapidly rising towers of air cannot exist without compensating air subsidence almost everywhere else; this subsidence acts to fill the atmosphere above about 3–5 km with dry air.

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[12] The drying effect of cumulonimbus convection is well known to specialists in the field, viz., Arakawa and Schubert (1974), and Geleyn et al. (1982). Hugh Elssaeser has long advocated the importance of this process to the problem of global warming.

Figure 8 illustrates the effects of warming on this process.[13] Warming leads to drying of the atmosphere above 5 km (as opposed to the moistening which occurs in current models), and leads to the elevation of the altitude at which convected heat is deposited. The latter effect increases the extent to which convection short circuits greenhouse absorption. Both effects are negative rather than positive feedbacks to CO_2 heating, and should diminish the effect of CO_2 warming, rather than magnifying it by a factor of approximately 3, as occurs in present models. Careful studies of this matter will probably not be completed for another year or so.

The above hardly exhaust the possible sources of error in present models.[14] However, it suffices to show that the *possibility* of large overestimates exists. Consistent with past data, corrected models may very well end up predicting greenhouse warmings of only a few tenths of a degree centigrade. Such changes have already occurred (viz. the period 1915–1935 in figure 2) without disastrous consequences.

These, then, are my (and other people's) reasons for believing that greenhouse warming may be much smaller than currently publicized estimates. It should be noted that neither I nor anyone else is in a position to guarantee that the earth will not get significantly warmer or cooler; it certainly has done so in the past. Indeed, our climate has been both warmer and colder than at present, due solely to the natural variability of the system. External influences are hardly required for such variability to occur.

5. Remarks

The current state of our understanding of climate hardly justifies a consensus over the response of climate to the small increase in downward flux caused by a doubling of CO_2. It is not clear that models will ever be able to deal with this issue with great certainty. Nonetheless, it is clear that much can be done to significantly reduce uncertainty. For example, data from El Niño and non–El Niño periods might be used to study the response of water vapor and clouds to warming. Detailed studies of the oceans' seasonal thermocline could yield information that would enable us to better estimate the lag from ocean-heat storage. More broadly, a decade should permit us to sufficiently improve our understanding of convection, cloud cover, ocean chemistry, ocean dynamics, etc., so as to make our predictions more meaningful. If there is any single, major impediment to progress, it may very well

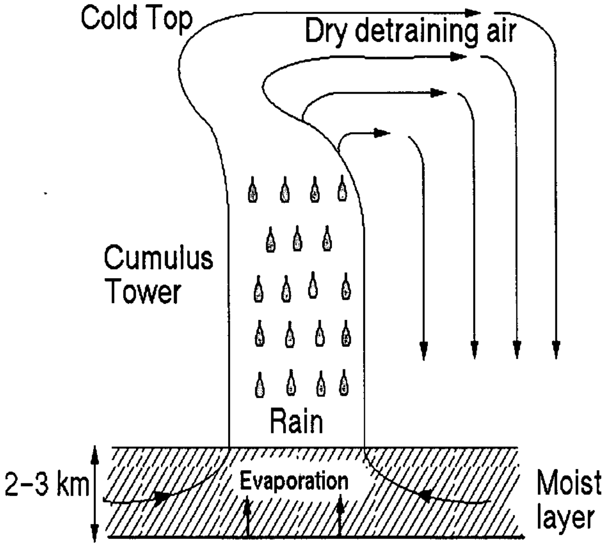

FIG. 7. Schematic illustration of cumulus tower wherein moisture evaporated from the surface and converged into cumulus convection is rained out, leaving dry air to detrain into the environment.

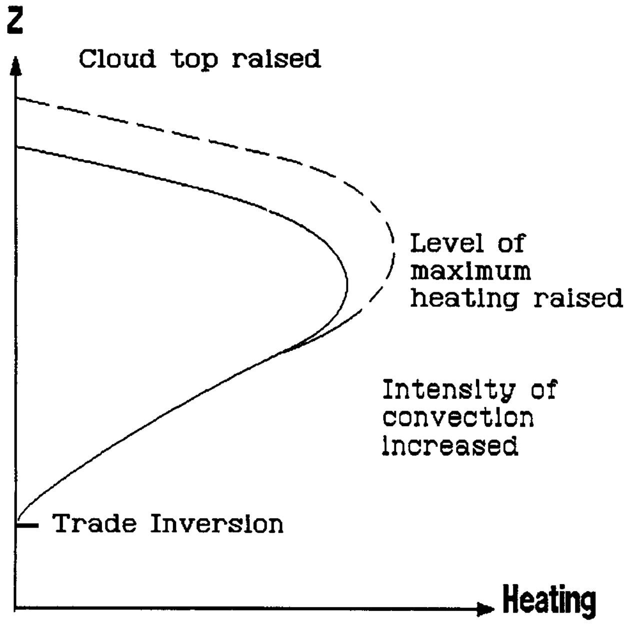

FIG. 8. Schematic illustration of cumulus heating distribution under (solid line) normal conditions, and (dashed line) under conditions of anomalous warming. Warming leads the following effects: 1) cloud tops are raised leading to dryer detrained air; 2) convective intensity increases which leads to the dryer air being pushed down more effectively; and 3) there is an increase in the height at which there is maximum cumulus heating, thus bypassing more infrared absorbers in the atmosphere.

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[13] Globally, cumulus mass flux is proportional to the integrated surface evaporation of water vapor, which increases as surface temperature increases. Locally, the relation is less clear due to low-level convergence of water vapor.

[14] Even the frequently cited ice/snow albedo feedback is not free of question; clearly, for very cold temperatures, snow is reduced. Also, as mentioned earlier, increased water vapor in the boundary layer—which is expected to accompany warming—may also lead to cooling since its greenhouse effect is short circuited by convection. Suggestions have even been made that increasing CO_2 may increase oceanic albedo.

be a lack of an adequate number of capable scientists.

Where does this leave us? Certainly, the possibility of a significant greenhouse warming remains for the present. Since the more extreme forecasts predict warming in excess of the normal variance seen in figure 2, observations over the next decade or two should begin to restrict the possibilities. Theoretical and observational process studies should reveal whether present models suffer from certain explicit defects. Oddly enough, though, despite all the uncertainty, there is one thing that is surprisingly clear right now; it is difficult to envision any practical action that will make much difference to the final outcome. As a pollutant, CO_2 is peculiarly associated with population and standard of living. If no significant warming is expected to accompany increasing CO_2 then there is little that needs to be done—at least regarding warming. However, according to the most pessimistic models, much of the predicted warming is already in the pipeline—delayed only by ocean heat absorption. Because of the logarithmic dependence of warming on CO_2, large changes in CO_2 emission (20%–40%) will, at most, reduce warming by a fraction of a degree. Even such reductions are likely to be nullified in a relatively short period. This is a situation that demands more careful thought than it has hitherto received.

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