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The Global Warming Debate Heats Up: An Analysis and Perspective*

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1. Introduction

Global warming from the increase in greenhouse gases has become a major scientific and political issue during the past decade. The facts that infrared radiation is trapped by greenhouse gases and particles in a planetary atmosphere, and that the atmospheric CO₂ level has increased by some 25% since 1850 because of fossil fuel combustion and land use (largely deforestation) are not controversial; levels of other trace greenhouse gases, such as methane or chlorofluorocarbons, have increased by even larger factors. Estimates of present and future effects, however, have significant uncertainties. Recently, there have been controversial claims that a global warming signal has been detected. Unfortunately, the media debate challenging the existence of the greenhouse effect because of the absence of temperature trends in the United States or the alleged influence of unnatural heating in cities on global trend records has been highly misleading.

Natural climate variability is sufficiently large that even the record warmth of the 1980s does not allow us to proclaim beyond a reasonable doubt detection of the greenhouse effect signal from human pollution. Another decade or two of continued warming will be required for a high degree of certainty, but waiting for this added assurance is at the risk of a larger dose of climate change than if actions to slow down greenhouse gas buildups were pursued today.

Scientific concern for a high probability of unprecedented climate change over approximately the next 50 years is not based upon the detailed fluctuations in the climate record to date, but rather on the well-validated physical processes that comprise the greenhouse effect. Results from most recent climatic models suggest that global average surface temperatures will increase by some 1.5°C-4.5°C during the next century, but future changes in greenhouse

gas concentrations, other nongreenhouse forcings (e.g., solar variability or atmospheric aerosols), and feedback processes not properly accounted for in the models could produce greater or smaller increases. Sea-level rises of 0.2-1.2 m are typically projected for the next century, but there is a small probability of greater or even negative change. Forecasts of the distribution of variables, such as soil moisture or precipitation patterns, have even greater uncertainties.

It is doubtful that more research will produce a consensus on the projection of regional climatic changes in less than one to two decades. Policy responses range from engineering countermeasures (i.e., "climate control") to passive adaptation to prevention and a "law of the atmosphere." One approach is to implement those policies now to reduce emissions of greenhouse gases and have additional societal benefits. Efficient use of energy is the most important example. Development of renewable energy supplies and lowering population growth rates are additional examples. Whether the uncertainties are large enough to suggest delaying policy responses is not a scientific question per se, but a value judgment.

2. The current global warming debate: science or media hype?

Not all knowledgeable scientists agree that global climatic changes unprecedented in the era of human civilization will occur in the 21st century. In fact, if one has followed the noisy, often polemical debate in the media recently, one might get the impression that there are but two radically opposed schools of thought about global warming: 1) that climatic changes will be so severe, so sudden, and so certain that major species extinction events will intensify, sea-level rise will create tens of millions of environmental refugees, millions to perhaps billions of people will starve, and ecosystems will be devastated; or 2) there is nothing but uncertainty about global warming, no evidence that the 20th century has done what the modelers have predicted, and the people arguing for change are just "environmental extremists"—thus there is no need for any management response to an event that is

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Bulletin

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improbable, probably would be beneficial if it did happen and in no case should any such responses interfere with the "free market" and bankrupt the nation (e.g., Brookes 1989).

Unfortunately, while such a highly charged and polarized debate makes entertaining opinion page reading or viewing for the ratings-dominated media, it provides a very poor description of the reality of the actual scientific debate or the broad consensus on basic issues within the scientific community. The "end-of-the-world" or "nothing-to-worry-about" cases are the two *least likely* possibilities, with almost any scenario in between having a higher probability of occurrence.

Figure 1 shows a projection of global warming possibilities into the 21st century drawn by an international group of scientists convened by the International Council of Scientific Unions (Jaeger 1988). It shows a further warming from a moderate 0.5°C up to a potentially catastrophic 5°C or greater warming *before* the end of the next century. The latter extreme can be labeled potentially catastrophic because that is the magnitude of global warming that occurred between about 15 000 and 5000 years ago; the end of the last ice age to our present interglacial epoch. Despite some rapid fluctuations, on average it took nature some 5000 to 10 000 years to accomplish that warming, and it was accompanied by an approximately 100-m rise in sea level, thousands-of-kilometers migration of forest species, radically altered habitats, species extinctions, species evolution, and other major environmental changes (COHMAP 1988). Indeed, the ice age-to-interglacial transition revamped the ecological systems of the planet.

If real climate changes occurred as rapidly as they are projected in the mid-to-upper part of the scenarios in figure 1, then indeed this rapid rate of temperature rise would justify the substantial concern that many scientists have over the prospect of global warming. On the other hand, the many unknown factors that make most scientists hesitant to make anything other than qualitative or intuitive probabilistic kinds of projections, could well suggest a 21st century climate in which global temperature change would be on the order of only a degree. While even that seemingly small change might be serious for certain life forms (for example, some plant or animal species living near the tops of mountains that would be driven to extinction with even a small warming), by and large, changes of less than a degree or so taking place over a century or more would clearly add less stress to natural (and certainly to human) systems than would changes of several degrees taking place in 50 years or less (e.g., Peters 1990). Indeed, the rate of change may be a most critically important factor to the adaptive capacity

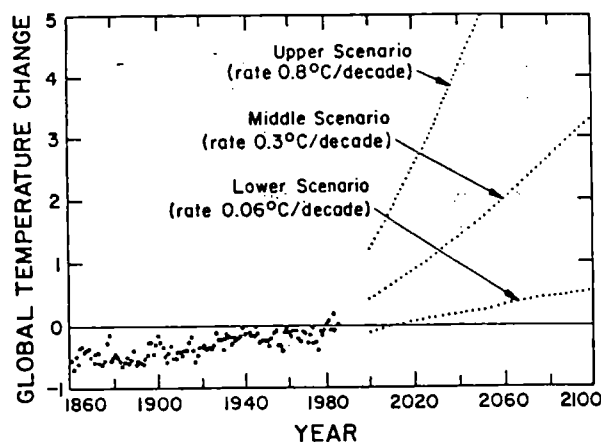


FIG. 1. Three scenarios for global surface air temperature change to the year 2100 derived from combining uncertainties in future trace greenhouse gas projections with uncertainties of modeling the climatic response to those projections. Sustained global temperature changes beyond 2°C would be unprecedented during the era of human civilization. The middle-to-upper range represents climatic change at a pace 10 to 100 times faster than typical long-term natural average rates of change. (Source: Jaeger, J. 1988, Developing Policies for Responding to Climatic Change: A Summary of the Discussions and Recommendations of the Workshops Held in Villach 28 September to 2 October 1987 [WCIP-1, WMO/TD-No. 2250].)

of both humans and other natural systems, particularly the latter, because ecosystems don't have the option of planting new seeds to match the new climate the way our farmers do (e.g., Wilson 1989).

Critics of immediate policy responses to global warming are quick to point out the many uncertainties that could reduce the average projections made by climate models (such as the middle line in figure 1). Indeed, most climate modelers include caveats to that effect in their papers. The implications of some critics are often dismaying, in that they are the ones who are responsibly pointing out these uncertainties to the public, whereas the modelers are somehow deliberately suppressing uncertainties in order to overstate the issue (e.g., see *Detroit News* 1989; Schneider 1989a). Many critiques (e.g., George C. Marshall Institute Report 1989) somehow understress that uncertainties in physical or biological processes that make it possible for the present generation of models to have overestimated future warming effects are just as likely to have caused the models to have underestimated change.

The public policy dilemma is what action to take even though we will not know in detail what will happen—the scientific community will not be able to provide much definitive information over the next decade or two about the precise timing and magnitude of century-long climate changes, especially if research efforts remain at current levels. In as much as high-resolution coupled atmosphere-ocean-biosphere models are five to ten years away, as are major

observing systems needed to validate such models, it seems obvious that statements forecasting major scientific breakthroughs in three to five years (e.g., George C. Marshall Institute 1989) are highly optimistic at best. The recent Intergovernmental Panel on Climate Changes Report (IPCC 1990, see figures 11.1 and 11.2) also project decades as the time frame for major scientific progress. Therefore, public policy makers will have to address how much information is "enough" to act on and what kinds of measures can be taken to deal with the plausible range of environmental changes long before research is likely to provide reliable projections of regional climatic change. Unfortunately, the probability of such changes cannot be estimated by definitive analytical methods. Rather, we will have to rely on the intuition of experts, which is why a highly confusing and polarized media debate can be paralyzing to anticipatory management.

Fortunately, making such scientific judgments is indeed the purpose of deliberative bodies, such as the U.S. National Academy of Sciences (NAS) or the International Council of Scientific Unions. The NAS regularly convenes a spectrum of experts to provide the best available estimates of the probabilities of various scenarios of change. These groups can deliberate to a considerable extent away from the confusion of the noisy media debates in which extreme opposites are typically pitted. Half a dozen such assessments over the past ten years have all reaffirmed the plausibility of climate change unprecedented in the 10 000-yr era of human civilization being built into the next 50-100 years (the latest, for example, NAS 1987). And in 1990, the IPCC (1990) has also reaffirmed that basic 1.5-4.5°C NAS projection for the 21st century as highly plausible (see IPCC, table 5.1).

3. The scientific debate

This section starts with a brief summary of most global warming critics, some of whom challenge these assessments. Many critics contend that the warming trend of the past century of about 0.5°C (e.g., Jones et al. 1988; Hansen and Lebedeff 1988) is suspect because the thermometer record is not very reliable (e.g., Ellsaesser 1984). Of course, the scientists who produce such records say the same thing (e.g., Karl and Jones 1989). However, given the many problems it is uncertain whether the needed corrections will necessarily reduce the 100-yr 0.5°C trend as opposed to the other direction. Some critics cite the neglect of ocean-temperature data collected from buckets dropped over the sides of schooners in the Victorian or pre-Victorian times, because some of those records suggest that the 1850s may have seen ocean

temperatures nearly as warm as the present (e.g., Newell et al., in press; Lindzen 1990). The reason that those kinds of pre-1900-ocean-temperature data are typically discounted in most assessments is that they were collected over only a few tens of percent or so of the earth's surface (see figure 2). In addition, the measurements themselves simply aren't very reliable. The most reliable statement that seems reasonable to

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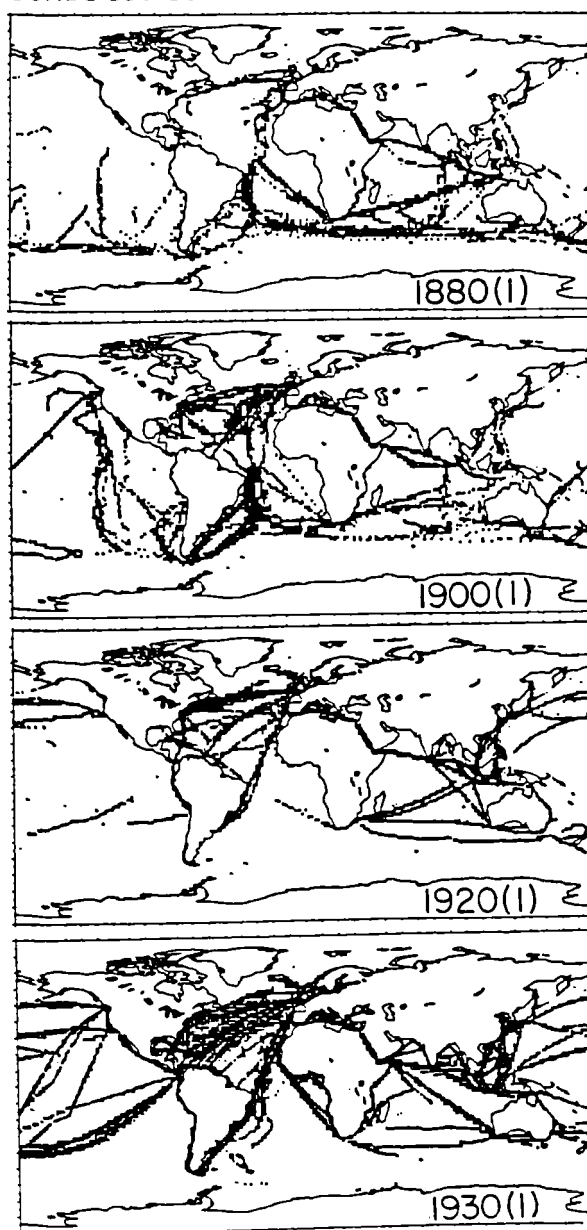


FIG. 2. Ship tracks over which one or more sea-surface temperature measurements were made during January of four different years. Coverage before 1900 is so sparse and measurement accuracy so questionable that little reliability can be attached to temperature-trend reconstructions before the 20th century (Source: Dennis Shea and Kevin Trenberth, National Center for Atmospheric Research, private communication.)

infer from the available temperature records is that a warming of some $0.5^{\circ}\text{C} \pm 0.2$ has occurred globally over the past 100 years (IPCC 1990). If greenhouse gas pollution was the only cause of that warming trend, then this is broadly consistent with the middle of the lower half of the projected range (see figure 1) of warming made by climate models. Does this mean that nature has already told us that future global warming will be half of what most models typically project? Unfortunately, we have only been accurately measuring the energy output of the sun from space over the past ten years or so and have little knowledge of the precise quantitative nature of this or other factors that could have influenced the temperature trends in this century. Without such factors being accounted for precisely, even accurate temperature data over the past century couldn't tell us very much about the sensitivity of the globally averaged surface temperature to the pollution injected since pre-industrial times (e.g., Hansen et al. 1981; Gilliland and Schneider 1984; Wigley and Raper 1990). Furthermore, although some critics have suggested that a century-long heating up of the sun by a few tenths of a percent could account for the 20th century warming of the earth (e.g., George C. Marshall Institute 1989), these critics neglected to mention that it is equally likely that the sun could have cooled down by that amount (because it was essentially unmeasured to the required accuracy), thereby having damped any enhanced greenhouse effect that otherwise would have been in the record, thus fooling us into thinking that the global warming from pollution to date is, say, half of that which existed.

Quite simply, the critics can't have it both ways. *What we don't know could increase or decrease our current estimates.* In any case, the magnitude of natural global average surface temperature fluctuations on century time scales during the 10 000 years of the present interglacial period is $1^{\circ}\text{--}2^{\circ}\text{C}$, whether solar induced or not. Thus, changes of $2^{\circ}\text{--}4^{\circ}\text{C}$, as typically projected for the next century, would swamp any solar effect, assuming there were any—*itself a highly speculative prospect* (e.g., Stuiver 1990; Foukal and Lean 1990).

Another criticism of global warming projections has been the nonperfect match between the warming of the earth and the smooth increase in greenhouse gases over the past 100 years (see bottom part of figure 3). It has been argued that because much of the warming in the 20th century took place between 1915 and the 1940s, followed by a cooling at the time the global greenhouse gases were increasing, that the decade-by-decade temperature trends in the 20th century cannot therefore be attributed to greenhouse gas buildup (e.g., Ellsaesser 1984; Solow and Broadus 1989). There are several aspects of that argument that

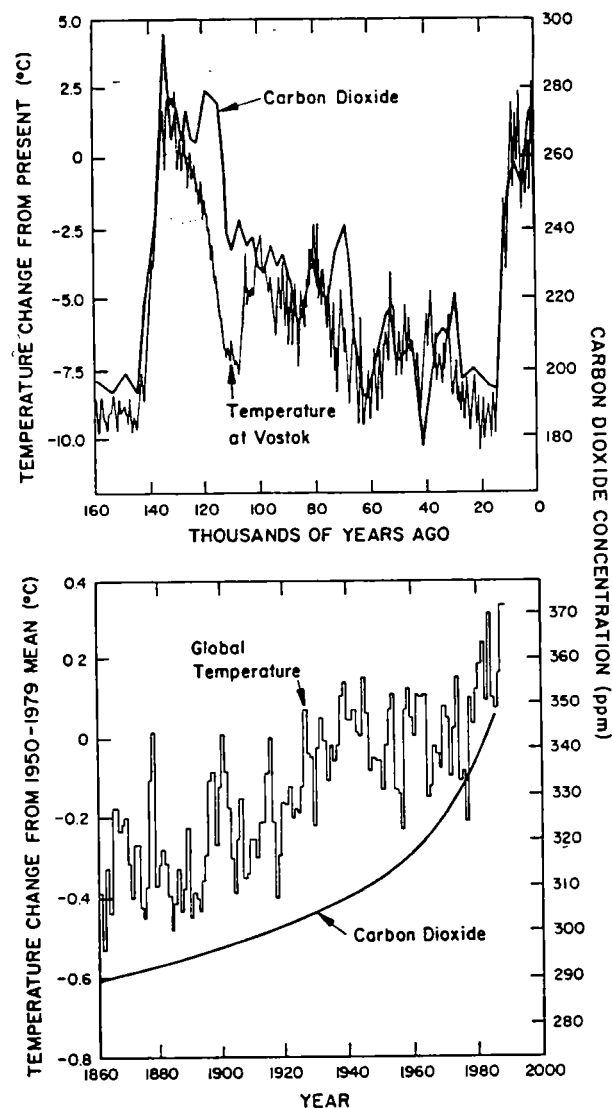


FIG. 3. Carbon dioxide and temperature are closely correlated over the past 160 000 years (top) and, to a lesser extent, over the past 100 years (bottom). The long-term record, based on evidence from a Soviet core at Vostok, Antarctica, and interpreted by the glaciology group at Grenoble, France (Barnola et al. 1987) shows how the local temperature and atmospheric carbon dioxide rose nearly in step as an ice age ended about 130 000 years ago, fell almost in synchrony at the onset of a new glacial period and rose again as the ice retreated about 10 000 years ago. The recent temperature record shows a global warming trend (0.5°C), as traced by workers at the Climatic Research Unit at the University of East Anglia. Whether the accompanying buildup of carbon dioxide and other trace greenhouse gases in the atmosphere caused the 0.5°C warming is hotly debated. (Source: Schneider, S. H., 1989b: The Changing Climate, *Scientific American*, 261: (3), September 1989, 70-79.)

need perspective. First, nature always fluctuates; several tenths of a degree Celsius warmings and coolings over decades are part of the natural record and, indeed, are normal, as figure 4 shows (Jones et al. 1988). Such fluctuations or "climatic noise," may not be predictable, particularly if they were a stochastic (e.g., Hasselmann 1976) or chaotic (Lorenz 1968)

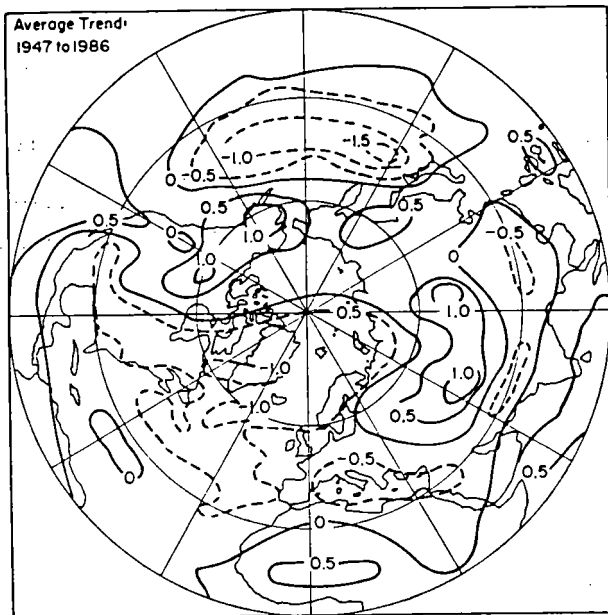


FIG. 4. Change in temperature ($^{\circ}\text{C}$) over 1947-86 accounted for by a linear trend fitted to each annual grid-point time series in the Northern Hemisphere. The statistical significance of the change in temperature depends on the interannual variability of temperature. Over oceanic areas, warming/cooling in excess of 0.5°C is significant at better than the 5% significance level. Over high-latitude (50°N) land areas, warming/cooling is significant if it exceeds 1°C . Over land at lower latitudes the trend is significant if it exceeds 0.5°C . (Source: P.D. Jones et al. 1987, Spatial patterns in recent worldwide temperature trends, *Climate Monitor*, 16: 175-185.)

response to the internal redistribution of energy among the principal reservoirs—the atmosphere, oceans, ice, biota, and land surfaces. Therefore, natural internal fluctuations could be a partial explanation of the decadal deviations from the 0.5°C 100-yr trend line (i.e., the sharp warming to the 1930s, the Northern Hemisphere's cooling to 1975, and the spectacularly rapid re-warming of the 1980s—the warmest decade of the 100-yr instrumental record). Such “noise” could have contributed to or opposed the longer-term trend that may otherwise have occurred from increased greenhouse gases. Secondly, we do not know precisely what other potential climatic forcings (i.e., processes that could force the climate to change) were doing over the past 100 years. These have been known for decades (e.g., SMIC 1971) to include energy output from the sun, stratospheric particles from volcanic eruptions, or tropospheric particles generated by human activities. For example, the very warm early 1980s were followed by a cooler few years that were coincident with the explosive volcanic eruption of El Chichon. This was followed a few years later by the warmest years in the instrumental record, 1987 and 1988 (see figure 3b). Whether it was coincidence or cause and effect is not certain. This instrumental record for the 1980s correlated well with a satellite remote-sensing technique for midtropospheric

temperature (e.g., Spencer and Christy 1990). Yet, most of the media stories following the publication of this paper ignored the correlation between the thermometer and satellite records, and instead extrapolated, out of context, a sentence of the authors to the effect that no global warming trend was evident in the ten years of their analysis. Of course, no responsible scientist would ever claim that a global warming signal could be detected above background noise from ten years of data! Nevertheless, a frequent media interpretation of this study was that there was “no global warming trend”—clearly a serious misinterpretation of the facts given the 100-yr record (figure 3b).

Arguing that climate models have been unable to predict a detailed sequence of decade-by-decade temperature fluctuations is akin to arguing that because we are unable to predict the individual rolls of a pair of dice, we therefore can't predict the odds of getting any two faces on any roll. Of course, we know the statistics for rolling any particular number, although we certainly wouldn't be expected to know what sequence of numbers might be obtained on successive rolls.

In short, those arguing that an absence of an exact match on a decade-by-decade basis between observed temperature fluctuations and greenhouse gas buildup somehow demonstrates that greenhouse effect sensitivity of models is wrong are simply off in their logic. Such time-varying agreement should not be expected in detail as long as a large degree of internally generated climatic noise continues to make up much of the decade-by-decade temperature records and as long as we haven't precise data on other nongreenhouse gas forcings. Fortunately, we are now monitoring the sun, volcanos and pollution-generated particles more accurately, and can thus better account for their effects. Thus, as greenhouse gases continue to build up in the future, if greenhouse warming isolated from other forcings does not take place at roughly the predicted rate during the 1990s and into the 2000s, then indeed it will be possible to argue on the basis of some direct evidence that the effect predicted by today's models is off base. However, waiting a decade or two for such certainty will be at the risk of committing the future to a larger dose of greenhouse gases than if actions were taken now to limit emissions. Of course, whether to cut emissions based on any amount of scientific information is a value issue, not a scientifically determinable choice (Schneider 1989c).

4. Sensitivity and scenario analysis

Although the ultimate goal of any forecasting simulation may be to produce a single, accurate time-series

projection of some evolving variable, a lesser, useful (and certainly more realizable) goal is to specify plausible scenarios of various uncertain or unpredictable variables and then to evaluate the sensitivity of some predicted variable to either different scenarios or different model assumptions. For example, in order to predict the societal impact of climatic changes from increasing concentrations of certain trace gases, such as CO₂, it is first necessary to invoke behavioral assumptions about future population, as well as economic and technological trends. (Such factors are external to the climatic model, of course, but must be forecast nonetheless.) Although these may be impossible to forecast with confidence, a set of plausible scenarios can be derived. The differential consequences for the climatic forecast of each of these scenarios can then be evaluated.

Another type of sensitivity analysis involves building a model that incorporates important, but highly uncertain, variables into its internal structure. Key internal factors, such as the cloud feedback or vertical oceanic mixing parameters, can be varied over a plausible range of values in order to help determine which internal processes have the most importance for the sensitivity of the climate to, say, CO₂ buildup. Even though one cannot be certain which of the simulations is most realistic, sensitivity analyses can 1) help set up a priority list for further work on uncertain internal model elements, and 2) help to estimate the plausible range of climatic futures society may have to adapt to over the next several decades.

Given these plausible futures, some of us might choose to mitigate a low-to-moderate probability, high-consequence outcome associated with some specific scenario. Indeed private and public policies often seek to avoid plausible, high-cost scenarios. This is, of course, the basic assumption of insurance. On the other hand, more risk-prone people might prefer extra scientific certainty before asking society to invest present resources to hedge against uncertain, even if plausible, climatic futures. At a minimum, cross-sensitivity analyses in which the response of some forecast variables to both greenhouse gas increases and multiple variations in uncertain internal and/or external parameters allow us to examine quantitatively the differential consequences of explicit sets of plausible assumptions.

In any case, even if we cannot produce a reliable single forecast of some future variables, we might be able to provide much more credible sensitivity analyses, which can have practical applications in investigating a range of probabilities and consequences of plausible scenarios. Such predictions may simply be the best "forecasts" that scientists can provide to inform society on a plausible range of

alternative futures of complex systems. How to react to such information, again, is in the realm of values and politics.

5. Climatic model cases

a. Ancient paleoclimate

To investigate future climatic changes, let us first turn not to the present but to ancient times. If the same basic models that we use to estimate effects of greenhouse gas increases into the next century can be applied to the ancient climatic changes and a reasonable simulation is obtained, then both scientific explanation of the ancient paleoclimate and some verification of the model's ability to reproduce radically different future climatic periods can be obtained.

Three-dimensional (3-D) atmospheric circulation model studies that explicitly resolve land and sea and also explicitly calculate atmospheric motions have been applied to the sequence of climatic changes from the ice age millennium, 18 000 years ago, up to the present. One of the most successful paleoclimatic simulations to date was performed by Kutzbach and Guetter (1986). They attempted to explain the warmest period in recent climatic history, the so-called "climatic optimum" that occurred between about 5000 and 9000 years ago. It was a time when summertime northern continental temperatures were probably several degrees warmer than at present and monsoon rainfall was more intense throughout Africa and Asia. Kutzbach and Guetter found that the optimum could be explained simply by the fact that the tilt of the earth's axis (its obliquity) was slightly greater then than now. Also, the orbit was such that the earth was closer to the sun (i.e., perihelion) in June rather than in January as it is now. These orbital variations do not make substantial changes in the annual amount of solar radiation received on the earth, but do change substantially the difference between winter and summer heating periods (e.g., Berger 1984). About 5% more solar heat over much of the Northern Hemisphere in summer and a comparable amount less in winter occurred 9000 years ago compared to the present. This change was sufficient in the simulations to substantially alter midcontinental warming in the summer months, which led to enhanced monsoonal rainfall and river runoff in the models. The model results matched well with considerable amounts of paleoclimatic evidence gathered by an international team of scientists (COHMAP 1988).

b. Forecasting global warming into the 21st century

The most important question surrounding the greenhouse gas controversy is simply: What will be

the regional distribution of climatic changes associated with significant increases in CO₂ and other trace greenhouse gases? (Other trace gases, such as chlorofluorocarbons, methane, nitrogen oxides, or ozone, taken together, can have a comparable heat-trapping greenhouse effect to CO₂ (e.g., Dickinson and Cicerone 1986). To investigate such regional changes one obviously needs a model with regional resolution. It needs to include processes such as the atmospheric hydrologic cycle and the storage of moisture in the soils, because these factors are so critical to both climatic change and its impacts on agriculture and water supplies.

To investigate plausible climatic scenarios, modelers have typically run equilibrium simulations in which instantaneously increased values of carbon dioxide are imposed at an initial time and held fixed while the model is allowed to approach a new equilibrium. Syukuro Manabe and R. T. Wetherald (1986), for example, in one of the most widely quoted results, find a summer "dry zone" in the middle of North America, as well as increased summer moistness in some of the monsoon belts. All of this was from a doubling of CO₂ held fixed over time. The model was allowed to run several decades of simulated time in order to reach equilibrium, a time frame dictated by the shallow 70-m mixed-layer ocean in the model. While this shallow "sea" allows the seasonal cycle to be satisfactorily simulated, a purely mixed-layer ocean does not include the important processes whereby water is transported horizontally or vertically between the mixed layer and the abyssal depths. The latter processes slow the approach toward thermal equilibrium of the surface waters, and certainly would affect the transient evolution of the surface-temperature changes in the ocean due to the actual time-evolving increase of trace greenhouse gases. Thus, during the transient phase of warming the surface temperature increases as a function of position and the land-to-sea temperature difference could have a different pattern than at equilibrium. This, in turn, could cause significantly different climatic anomalies during the transient phase than would be inferred from equilibrium sensitivity tests to fixed increases in trace gases (e.g., Schneider and Thompson 1981; Thompson and Schneider 1982). As a result, any multivariate (so-called, "fingerprint methods") techniques of CO₂ signal detection (e.g., Wigley and Barnett 1990) attempting to match observed, evolving regional climate trends to model generated regional changes are irrelevant as a fingerprint unless transient model runs are used for the comparisons. Transient simulations are needed, of course, because the one real-world experiment is a transient, not an equilibrium situation.

To investigate the transient response question

more reliably, it is necessary that 3-D atmospheric models be coupled to 3-D oceanic models. To date, only a handful of such model experiments have been run (e.g., Washington and Meehl 1989; Stouffer et al. 1989), but none over the century-or-two time scale needed to adequately address this important issue. One reason for detailing the CO₂ transient/regional climate anomaly issue here is to exemplify the need for various sensitivity experiments across a hierarchy of models. Such methods are especially essential during the development phase of modeling. It is probably necessary to run high-resolution, synchronously coupled (e.g., Schneider and Harvey 1986) atmospheric, oceanic, cryospheric, and land surface submodel models if regional, time-evolving scenarios of climatic changes are to have credibility. On the other hand, the more complex, high-resolution, 3-D general circulation models (GCM) are not yet at an adequate phase of development to have trustworthy coupled atmosphere/ocean models that are both well verified and economical enough to be run and rerun over the 50 to 100 simulated years needed for greenhouse gas-transient simulations. Thus, simple nondynamical models or low-resolution 3-D, dynamical models can help to identify and bound potentially important problems, provide some quantitative sensitivity studies, and help set priorities for higher-resolution 3-D coupled-model research or needed observational programs over the next few decades.

Because the agricultural and other environmental impacts of increasing greenhouse gases depend on the specific regional and seasonal distribution of climatic changes, resolution of the transient debate, in particular, is critical for climate-impact assessment and adaptive responses to the advent or prospect of increasing greenhouse gases. It is unlikely that reliable projections of regional climate changes from increasing trace greenhouse gas concentrations will emerge before a decade, if then. Of course, enhanced research efforts are likely to *accelerate* the rate of progress, and perhaps could help regional planners and managers to adapt more effectively to climatic changes by anticipating potential impacts with greater reliability.

6. Validation of models

Finally, the principal reason that advocates of concern over the prospects of global warming (this author included, e.g., Schneider 1989c) stand before groups such as Congressional or Parliamentary committees and take their time with these global warming concerns is not based solely on speculative theory. Rather, such concern is based on the fact that the models which we use to foreshadow the future have already been

validated to a considerable degree, although not to the full satisfaction of any responsible scientist. At least several methods can be used, and none by itself is sufficient. First, we must check overall model-simulation skill against the real climate for today's conditions to see if the control experiment is reliable. The seasonal cycle is one good test. Manabe and Stouffer's figure 5 (1980) shows how remarkably well a 3-D global circulation model can simulate the regional distribution of the seasonal cycle of surface air temperature—a well-understood climate change that is, when averaged over the Northern Hemisphere, several times larger than globally averaged ice age-interglacial changes. The seasonal-cycle simulation is a necessary test of some processes that can be called "fast physics," but it doesn't tell us how well the model simulates slow changes in forest or ice cover or deep ocean temperatures, because these variables do not change much over a seasonal cycle, though they do influence long-term trends. A second method of verification is to test in isolation individual physical subcomponents of the model (such as its parameterizations) directly against real data and/or more highly resolved process models. This still is not a guarantee that the net effect of all interacting physical subcomponents has been properly treated, but it is an important test. For example, the upward infrared radiation emitted from the earth to space can be measured from satellites or calculated in a climate model. If this quantity is subtracted from the emitted upward infrared radiation at the earth's surface, then the difference between these quantities (G) can be identified as the "greenhouse effect," as in Raval and Ramanathan (see figure 6, 1989). Although radiative processes may not be the only ones operative in nature or in the GCM results for G , the close agreement among the satellite results (line labeled ERBE in figure 6), a GCM (labeled CCM), and line-by-line radiative transfer calculations in figure 6 gives strong evidence that this physical subcomponent is well modeled at grid scale.

Another just-emerging set of validation tests of internal model processes is to compare model-generated and observed statistics of grid-point daily variability (e.g., Mearns et al., in press; Rind et al. 1989). These have provided some examples of excellent agreements between model and observed variability as well as examples of poorer agreement.

As a third validation method, some researchers express more confidence a priori in a model whose internal makeup includes more spatial resolution or physical detail, believing that "more is better." In some cases and for some problems this is true, but by no means for all. The "optimal" level of complexity depends upon the problem we are trying to solve and the

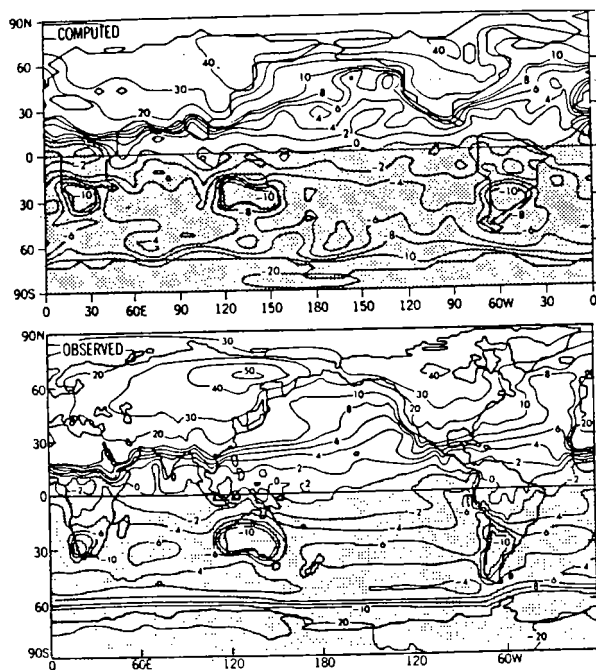


FIG. 5. A 3-D climate model has been used to compute the winter-to-summer temperature differences all over the globe. The model's performance can be verified against the observed data shown. This verification exercise shows that the model quite impressively reproduces many of the features of the seasonal cycle of surface air temperature. These seasonal temperature extremes are mostly larger than those occurring between ice ages and interglacials or for any plausible future carbon dioxide change (Source: S. Manabe and R. J. Stouffer, 1980, Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere, *J. Geophys. Res.*, **85**: 5529-5554.)

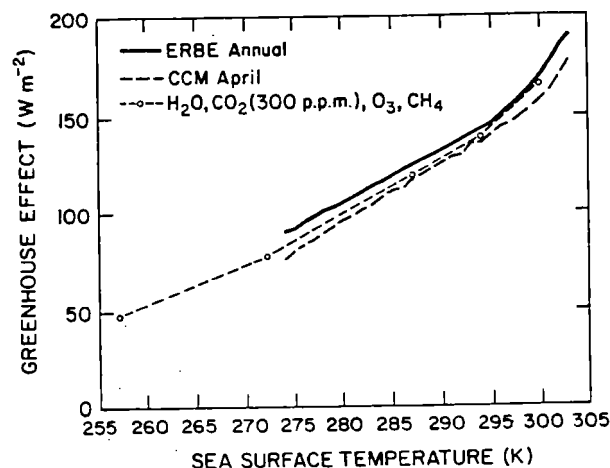


FIG. 6 Comparison of greenhouse effect, heat-trapping parameter, G , and surface temperature, obtained from three sources: bold line: ERBE annual values, obtained by averaging April, July and October 1985 and January 1986 satellite measurements; thick dashed line, 3-D climate-model simulations for a perpetual April simulation (National Center for Atmospheric Research Community Climate Model); thin dashed line, line-by-line radiation-model calculations by Dr. A. Arking using CO_2 , O_3 , and CH_4 . The line-by-line model results come close to the CCM and the ERBE values. (Source: Raval, A., and V. Ramanathan 1989, Observational determination of the greenhouse effect, *Nature*, **342**, 758.)

resources available for the task (e.g., Land and Schneider 1987). All three methods of validation must constantly be used and reused as models evolve if we are to improve the credibility of their predictions. And to these we can add a fourth method: the model's ability to simulate the very different climates of the ancient earth or even those of other planets.

As an example of the fourth method of validation, we know from observations of nature, a point neglected by some critics of global warming research, that the last ice age, which globally was about 5°C colder than the past 10 000-yr interglacial era, also had CO₂ levels about 25% less than the pre-industrial values. Methane, another important greenhouse gas, also was reduced by nearly a factor of 2 at glacial maximums relative to pre-industrial interglacial values. Ice cores in Antarctica containing gas bubbles that are records of the atmospheric composition dating back over 150 000 years, have shown that the previous interglacial age some 125 000-130 000 years ago had CO₂ and methane levels comparable to those in the present interglacial (Barnola et al. 1987). The nearly simultaneous change in these greenhouse gases and in planetary temperature over geological epochs (see figure 3a) is for a temperature change of a magnitude that one would project based on the CO₂-temperature sensitivity of today's generation of computer models. However, we still cannot assert that this greenhouse gas-temperature change coincidence is proof that our model's sensitivity is quantitatively correct, because other factors were operating during the ice age-interglacial cycles. The best that can be said is that the evidence is strong, but circumstantial.

Because of all these lines of validation, we can assume a factor of 2 to 3 confidence that the magnitude of global surface temperature change projected in figure 1 has a better than even chance of being correct—indeed, that is why, in a popular context (e.g., Schneider 1989c), the prospect for global warming in the 21st century is often referred to as “coin-flipping odds of unprecedented change,” because a sustained global change of more than 2°C would be unprecedented during the past 10 000-yr era of human civilization's development.

Raval and Ramanathan's (1989) satellite observations of the water vapor-greenhouse feedback mechanism, a process that is central to most models' estimates of some ±3°C or ±1.5°C equilibrium warming from doubling CO₂, led them to conclude that, “The greenhouse effect is found to increase significantly with sea surface temperature. The rate of increase gives compelling evidence for the positive feedback between surface temperature, water vapour and the greenhouse effect; the magnitude of the feedback is consistent with that predicted by climate models.” In

other words, the heat-trapping capacity of the atmosphere is fairly well modeled and measured on earth, and much of the sometimes polemical (e.g., Brookes 1989 or *Detroit News* 1989) debate in the media over the greenhouse effect has little reality. This empirical confirmation of the natural greenhouse effect, which is consistent with the greenhouse effect of climate models, stands in contrast to the theoretical arguments of Ellsaesser (1984) or Lindzen (1990) that negative temperature-water vapor feedback processes in parts of the tropics will reduce present model estimates of global warming by a factor of “one-half to one-fifth”; in this belief (Lindzen 1990, p. 296) asserted his belief that water is “nature's thermostat.”

6. What models can suggest

It is well known that the 25% increase in CO₂ and the 100% increase in methane (both documented since the industrial revolution) and the introduction of man-made chemicals, such as chlorofluorocarbons (also implicated for stratospheric ozone depletion), since the 1950s should all together have trapped about 2 W of infrared radiant energy over every square meter of the earth-troposphere system. However, what is less well accepted is how to translate that 2 W of heating into “X” degrees of temperature change, because this involves assumptions about how that heating will be distributed among surface temperature rises, evaporation increases, cloudiness changes, ice changes and so forth. The factor of 2 to 3 uncertainty in global temperature rise projections, as cited in typical National Academy of Sciences reports or the IPCC, reflects a legitimate estimate of uncertainty held by most in the scientific community. Indeed, recent modifications of the British Meteorological Office climate model to attempt to mimic the effects of cloud droplets roughly halved their model's sensitivity to doubled CO₂, but it is still well within the often-cited 1.5-4.5°C range. However, this model, like all current GCMs, does not yet include parameterizations for incremental (i.e. small vertical displacements at each vertical level-cloud top height feedback. This process has long been known to have the potential to substantially alter the heat-trapping efficiency of clouds (e.g., Schneider 1972), although in what direction local cloud heights would change with increased greenhouse gases remains unclear.

Lindzen suggests that, on physical grounds, “warming is also associated with deeper cumulus convection,” which would dry out the upper troposphere in the tropics and reduce the infrared heat-trapping capacity of the atmosphere.” . . . which,” Lindzen continues, “are a negative rather than a positive

feedback to CO₂ heating, and should diminish the effect of CO₂ warming rather than magnify it by a factor of approximately 3, as occurs in present models" (Lindzen 1990, p. 297). What this argument neglects is the possible positive feedback effects of incremental cloud-top height increases should this "deeper" cloud postulate prove true. Increasing cloud-top height per se (e.g., Schneider 1972) is likely to increase heat trapping, a positive feedback. Lindzen also neglects any possible radiative heat-trapping effects of cirrus cloud shields that might be generated in as a result of the postulated enhanced cumulus activity (e.g., Manabe and Wetherald 1967). In this vein, Mitchell, Senior, and Ingram (1989) wisely pointed out that although their "revised cloud scheme is more detailed, it is not necessarily more accurate than the less sophisticated scheme." This forthright and important caveat has not yet been quoted by any of the global warming critics who cite the British work as a reason to lower our concern by a factor of two or so. Finally, as stated earlier, prediction of the detailed regional distribution of climatic anomalies (i.e., where and when it will be wetter and drier, how many more floods might occur in the spring in California or forest fires in Wyoming in August) is highly speculative, although some plausible scenarios can be given. Some such scenarios are given in table 1, from the National Academy of Sciences (1987) assessment. Although climatic models are far from fully verified for future simulations, the seasonal and paleoclimatic simulations are strong evidence that state-of-the-art climatic models already have considerable skills,

particularly at larger scales and for longer averaging periods. An awareness of just what models are and what they can do is probably the best we can ask of the public and its representatives. Then, the tough policy problem is how to apply the society's values in choosing to face the future given the possible outcomes that climatic models foretell. Modelers will continue to develop and refine new models by turning to larger computers to run them and more observations to improve and verify them.

The meteorological community must ask the indulgence of society to recognize that immediate, definitive answers are not likely, as coupling of higher-resolution atmosphere, ocean, ecosystems, land-surface, and chemistry submodels will take a decade or more to fully develop, let alone validate. In essence, what climate models and their applications typify is a growing class of problems not unique to climate but also familiar in other disciplines, such as nuclear waste disposal, safety of food additives or drugs, efficacy of strategic defense technologies, etc. These are problems for which objective "scientific" probabilities and outcomes cannot be obtained, except by performing the experiment on ourselves. To deal with these complex sociotechnical problems requires a new understanding of the central role of (bounded) uncertainty and the willingness to deal with heuristic probabilistic estimation; it also calls for more modeling, provided the context of that modeling is understood and parallel observational programs for validation are concurrently pursued. Efficient functioning of society will depend upon our understanding of both the utility

TABLE 1. Possible Climate Changes from Doubling of CO₂
(Source: National Academy of Sciences 1987)

<i>Large Stratospheric Cooling</i> (virtually certain). Reduced ozone concentrations in the upper stratosphere will lead to reduced absorption of solar ultraviolet radiation and therefore less heating. Increases in the stratospheric concentration of carbon dioxide and other radiatively active trace gases will increase the radiation of heat from the stratosphere. The combination of decreased heating and increased cooling will lead to a major lowering of temperatures in the upper stratosphere.
<i>Global-Mean Surface Warming</i> (very probable). For a doubling of atmospheric carbon dioxide (or its radiative equivalent from all the greenhouse gases), the long-term global-mean surface warming is expected to be in the range of 1.5 to 4.5°C. The most significant uncertainty arises from the effects of clouds. Of course, the actual rate of warming over the next century will be governed by the growth rate of greenhouse gases, natural fluctuations in the climate system, and the detailed response of the slowly responding parts of the climate system (i.e., oceans and glacial ice).
<i>Global-Mean Precipitation Increase</i> (very probable). Increased heating of the surface will lead to increased evaporation and, therefore, to greater global mean precipitation. Despite this increase in global average precipitation, some individual regions might well experience decreases in rainfall.
<i>Reduction of Sea Ice</i> (very probable). As the climate warms, total sea ice is expected to be reduced.
<i>Polar Winter Surface Warming</i> (very probable). As the sea ice boundary is shifted poleward, the models predict a dramatically enhanced surface warming in winter polar regions. The greater fraction of open water and thinner sea ice will probably lead to warming of the polar surface air by as much as three times the global mean warming.
<i>Summer Continental Dryness/Warming</i> (likely in the long term). Several studies have predicted a marked long-term drying of the soil moisture over some mid-latitude interior continental regions during summer. This dryness is mainly caused by an earlier termination of snowmelt and rainy periods, and an earlier onset of the spring-to-summer reduction of soil wetness. Of course, these simulations of long-term equilibrium conditions may not offer a reliable guide to trends over the next few decades of changing atmospheric composition and changing climate.
<i>High-Latitude Precipitation Increase</i> (probable). As the climate warms, the increased poleward penetration of warm, moist air should increase the average annual precipitation in high latitudes.
<i>Rise in Global Mean Sea Level</i> (probable). A rise in mean sea level is generally expected due to thermal expansion of sea water in the warmer future climate. Far less certain is the contribution due to melting or calving of land ice.

and limitations of models; both natural and social scientific disciplines need to create scenarios of global change to perform impact assessments. However, in some senses, more than economic efficiency is at stake, as the very survival of some—particularly in low-lying coastal areas—will depend on present decisions we make to deal with plausible climatic futures. If the public is totally ignorant of the nature, use, or validity of climatic (or many other kinds of) models, then public-policy debates based on model results will be haphazard at best (e.g., Clark 1988). In this case, the decision-making process tends to be dominated by special interests, exaggerated media debates, or a technically trained elite.

7. Adaptation or prevention?

Public responses to the advent or prospect of global climate change typically come in two categories: adaptation and prevention. Economists, typically tend to favor adaptation (e.g., Schelling 1983). With regard to *adaptation*, flexibility of adaptive measures needs to be considered now (e.g., Glantz 1988; Waggoner 1990). Indeed, if the entire global warming debate comes out closer to the views of the present critics and only small changes occur, what would be lost, for example, by improving the flexibility of water supply systems? After all, nature will continue to give us wet and dry years. The 100-yr flood will happen sometime, as will the 100-yr drought—with or without global warming, which, of course, could change the odds of such extremes. Therefore, increasing management flexibility will pay dividends (e.g., see Waggoner 1990) even in what will be the unlikely event that global warming proves to be only 1°C or less by 2100. This situation provides a metaphor to buying insurance. Only a foolish or poor person would underinvest in insurance. However, unlike the insurance metaphor, where a premium is “wasted” if one doesn’t collect on any damages, here we actually can get benefits for our investment in flexibility at the same time we “buy insurance” against the prospect of rapid climate change at the same time. Of course, no one gets a return on investment without making an investment, and that is true not just in the private sector, but obviously in the public sector as well.

The other category of management response is *prevention*. That simply means slowing down the rate at which climate-modifying gases that are injected into the atmosphere are produced. The principal way to do that falls primarily in the jurisdiction of energy use and production managers. However, because agriculture and forestry are important components of CO₂ and CH₄ production, halting net deforestation, for example,

can help to reduce the atmospheric buildup of CO₂. Thus, prevention is also in the purview of land-management agencies. For example, domestic animals are a major source of methane, and such livestock graze extensively on public lands (e.g., Cicerone 1988). Therefore, solutions to methane emission controls will involve consideration of the use of public lands for this purpose. As another example, microbial communities in soils decompose dead organic matter into greenhouse gases, such as carbon dioxide, methane, or nitrous oxide (e.g., Andreae and Schimel 1989). Since these microbes typically increase their metabolic activity when the soil warms, deforestation or grazing, which removes vegetation cover and results in warmer soils, could enhance the production of these greenhouse gases (e.g., Lashof 1989). These issues are contentious, but nonetheless land-use changes need to be examined for their potential effectiveness as emission control strategies.

The best strategies should have high leverage—that is, help to solve more than one problem with a single investment. Such high leverage or “tie-in” strategies are the best approach to dealing with prevention, or at least delaying the rate of the buildup of greenhouse gases, and thus the prospect of rapid global warming (e.g., Schneider 1989c). It is obvious that the things to do first are the things that make the most economic and social sense, regardless of whether global warming materializes. Energy efficiency, as is often mentioned, is the single most important “tie-in” strategy; using energy efficiently will not only reduce the prospect of rapid climate change, but also will reduce acid rain (itself a threat to many natural lands), will reduce air pollution in cities (e.g., Graedel and Crutzen 1989), will reduce the balance of payment deficit of energy importing nations by reducing dependence on foreign supplies of energy, and, in the long run, can improve product competitiveness by reducing the energy components of manufactured products, which, for example, are about twice as high for the United States as for her more efficient competitors, such as Japan, Italy, or West Germany (e.g., Chandler et al. 1988).

In the value system this paper espouses, flexibility for adaptation and high-leverage strategies for prevention are not premature policy actions. If we are to manage effectively a future with increasing uncertainty in environmental conditions, then it is imperative that management flexibility be increased. *Ideology is the enemy of flexibility*. It is incumbent on all of us to rethink any of our ideologically rigid positions in order to fashion ways in which to enhance the flexibility of management. This can give us the opportunity to manage more effectively the potential consequences of serious climate change, as well as

improve the capacity of present systems to deal with the natural variability of the environment, itself a well demonstrated threat to many of our activities or resources.

Not least, and likely the least expensive, is a strategy of enhanced research in the many disciplines that constitute "global change" (e.g., NAS 1988). Regardless of whether society should wait for more knowledge before acting, itself a value tradeoff, it is obvious that more knowledge acquired sooner will put decision-making of all kinds—adaptive or preventative—on a firmer factual basis. Hopefully, the often-confusing and excessively contentious media debate surrounding global warming will not unduly delay such actions.

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References

- Andreae, M. O., and D. S. Schimel, (eds.). 1989. *Dahlem Workshop on Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere*. New York: John Wiley and Sons.
- Barnola, J. M., D. Raynaud, Y. S. Korotkevich and C. Lorius. 1987. Vostok ice core provides 160 000-year record of atmospheric CO₂. *Nature*, 329: 408-414.
- Berger, A. 1984. Accuracy and frequency stability of the Earth's orbital elements during the quaternary, Part I in *Milankovitch and Climate*, A. Berger, J. Imbrie, J. Hays, G. Kukla and B. Saltzman (eds.). Dordrecht, The Netherlands: Reidel Publishing, 3-40.
- Bottomley, M., C. K. Folland, J. Hsiung, R. E. Newell, and D. E. Parker. 1990. *Global Ocean Surface Temperature Atlas*. Bracknell, United Kingdom.
- Brookes, W. T. 1989. The Global Warming Panic. *Forbes*, 25 December 1989: 96-102.
- Chandler, W. U., H. S. Geller and M. R. Ledbetter. 1988. *Energy Efficiency: A New Agenda*. Springfield, VA: GW Press.
- Cicerone, R. J. 1988. Methane linked to warming. *Nature*, 344: 198.
- Clark, W. 1988. The Human Dimensions of Global Environmental Change. In *Toward an Understanding of Global Change: Initial Priorities for U.S. Contributions to the International Geosphere-Biosphere Program*. Washington, D.C.: National Academy Press.
- COHMAP Members, (P. M. Anderson et al.). 1988. Climatic changes of the last 18,000 years: Observations and model simulations. *Science* 241: 1043-1052.
- Detroit News*. 1989. Loads of Media Coverage. Editorial, 22 November 1989.
- Dickinson, R. E., and R. J. Cicerone. 1986. Future global warming from atmospheric trace gases. *Nature* 319: 109-115.
- Ellsaesser, H. W. 1984. The climatic effect of CO₂: A different view. *Atmos. Environ.* 18: 431-434.
- Foukal, P. and J. Lean. 1990. An empirical model of total solar irradiance variation between 1874-1988. *Science*, 6: 556-558.
- George C. Marshall Institute. 1989. *Scientific Perspectives on the Greenhouse Problem*. Washington, D.C.
- Gilliland, R. L., and S. H. Schneider. 1984. Volcanic, CO₂ and solar forcing of Northern and Southern Hemisphere surface air temperatures. *Nature* 310: 38-41.
- Glantz, M. H. (ed.). 1988. *Societal Responses to Regional Climatic Change: Forecasting by Analogy*. Boulder: Westview Press.
- Graedel, T. E., and P. J. Crutzen. 1989. The Changing Atmosphere. *Sci. Amer.* 260 No. 3: 58-68.
- Hansen, J., and S. Lebedeff. 1987. Global trends of measured surface air temperature. *J. of Geophysical Res.* 92: 13345-13372.
- _____, and _____. 1988. Global surface air temperatures: Update through 1987. *Geophys. Res. Lett.* 15: 323-326.
- _____, D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind and G. Russell. 1981. Climate impact of increasing atmospheric carbon dioxide. *Science* 213: 957-966.
- Hasselmann, K. 1976. Stochastic climate models. Part I. Theory. *Tellus XXVIII* 6: 473-485.
- Intergovernmental Panel on Climate Change (IPCC), (2nd Draft) March 1990. *Scientific Assessment of Climate Change*. Geneva, World Meteorological Organization.
- Jaeger, J. 1988. Developing Policies for Responding to Climatic Change: A Summary of the Discussions and Recommendations of the Workshops Held in Villach 28 September to 2 October 1987, (WCIP-1, WMO/TD-No. 225).
- Jones, P. D., T. M. L. Wigley, C. K. Folland and D. E. Parker. 1988. Spatial patterns in recent worldwide temperature trends. *Climate Monitor* 16: 175-185.
- Karl, T. R., and P. D. Jones. 1989. Urban bias in area-averaged surface air temperature trends. *Bull. Amer. Meteor. Soc.* 70: 265-270.
- Kutzbach, J. E., and P. J. Guetter. 1986. The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. *J. Atmos. Sci.* 43: 1726-1759.
- Land, K. C., and S. H. Schneider. 1987. Forecasting in the social and natural sciences: an overview and analysis of isomorphisms. *Climatic Change* 11: 7-31.
- Lashof, D. A. 1989. The dynamic greenhouse: Feedback processes that may influence future concentrations of atmospheric trace gases and climatic change. *Climatic Change* 14: 213-242.
- Lindzen, R. S. 1990. Some coolness concerning global warming. *Bull. Amer. Meteor. Soc.* 71: 288-299.
- Lorenz, E. N. 1968. Climate Determinism. *Meteorol. Monogr.* 8: No. 30: 1-3.
- Manabe, S., and R. J. Stouffer. 1980. Sensitivity of a global climate model to an increase in CO₂ concentration in the atmosphere. *J. Geophys. Res.* 85: 5529-5554.
- _____, and R. T. Wetherald. 1967. Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity. *J. Atmos. Sci.* 24: 241-259.
- _____, and _____. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. *Science* 232: 626-628.
- Mearns, L. O., S. H. Schneider, S. L. Thompson and L. R. McDaniel. Analysis of climate variability in general circulation models: Comparison with observations and changes in variability in 2xCO₂ experiments. *J. Geophys. Res.* (in press).
- Mitchell, J. F. B., C. A. Senior and W. J. Ingram. 1989. CO₂ and climate: A missing feedback? *Nature* 341: 132-134.
- National Academy of Sciences. 1987. *Current Issues in Atmospheric Change*. Washington, D.C.: Academy Press.
- _____. 1988. *Toward an Understanding of Global Change: Initial Priorities for U.S. Contributions to the International Geosphere-Biosphere Program*. Committee on Global Change.

- Washington, D.C.
- Peters, R. (ed.). *Proceedings of the World Wildlife Fund Conference on the Consequences of the Greenhouse Effect for Biological Diversity*, Yale University Press, New Haven. (in press).
- Raval, A., and V. Ramanathan. 1989. Observational determination of the greenhouse effect. *Nature* **342**: 758.
- Rind, D., R. Goldberg and R. Ruedy. 1989. Change in climate variability in the 21st century. *Climatic Change* **14**: 5-37.
- Report of the Study of Man's Impact on Climate (SMIC). 1971. *Inadvertent Climate Modification*. Cambridge, MIT Press.
- Schelling, T. C. 1983. Implications for Welfare and Policy. In *Changing Climate Report of the Carbon Dioxide Assessment Committee*, Washington D.C.: National Academy Press.
- Schneider, S. H. 1972. Cloudiness as a global climate feedback mechanism: The effects on the radiation balance and surface temperature of variations in cloudiness. *J. Atmos. Sci.* **29**: 1413-1422.
- _____. 1989a. News Plays Fast and Loose With the Facts. *Detroit News*, 5 December 1989.
- _____. 1989b. The Changing Climate. *Sci. Amer.* **260**, No. 3: 70-79.
- _____. 1989c. *Global Warming: Are We Entering the Greenhouse Century?* San Francisco, Sierra Club Books.
- _____, and L. D. D. Harvey. 1986. The computational efficiency and accuracy of methods for asynchronously coupling atmosphere-ocean models. Part I: Testing with a mean annual model. *J. Phys. Oceanogr.* **16**: 3-10.
- _____, and S. L. Thompson. 1981. Atmospheric CO₂ and climate: Importance of the transient response. *J. Atmos. Sci.* **37**: 895-900.
- Solow, A. R., and J. M. Broadus. 1989. On the detection of greenhouse warming. *Climatic Change* **15**: 449-453.
- Spencer, R. W., and J. R. Christy. 1990. Precise monitoring of global temperature trends from satellites. *Science* **247**: 1558-1562.
- Stouffer, R. J., S. Manabe and K. Bryan. 1989. Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO₂. *Nature* **342**: 660-662.
- Stuiver, M. 1990. Global Warming Report (letter), *Science* **247**: 15-16.
- Thompson, S. L., and S. H. Schneider. 1982. CO₂ and climate: The importance of realistic geography in estimating the transient response. *Science* **217**: 1031-1033.
- Waggoner, P. E. (ed.). 1990. *Climate Change and U.S. Water Resources*. New York: John Wiley and Sons.
- Washington, W. M., and G. A. Meehl. 1989. Climate sensitivity due to increased CO₂: Experiments with a coupled atmosphere and ocean general circulation model. *Climate Dynamics* **4**: 1-38.
- Wigley, T. M. L., and T. P. Barnett. Detection of the greenhouse effect in the observations, in *Scientific Assessment of Climate Change*, Section 8. Intergovernmental Panel on Climate Change (IPCC), WMO/UNEP Working Group I, (2nd Draft) March 1990.
- _____, and S. C. B. Raper. 1990. Natural variability of the climate system and detection of the greenhouse effect. *Nature* **344**: 324-327.
- Wilson, E. O. 1989. Threats to biodiversity. *Sci. Amer.* **260** No. 3: 108-116.

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letters to the editor

Greenhouse warming and the tropical water budget

In "Some Coolness Concerning Global Warming" (March 1990), Lindzen has raised an important climate issue: how well do we understand the water budget of the tropics? Water vapor is the major absorber in the infrared contributing to the greenhouse effect. It is not always considered a "greenhouse gas" because its concentration is controlled on timescales of order a week by convective, radiative and dynamical processes in the atmosphere; while the other greenhouse gases (such as CO_2 , CH_4 , and the CFCs) have longer timescales in the troposphere, and their concentration is steadily increasing from anthropogenic activity.

Most theoretical and modeling studies couple the water vapor content of the atmosphere to the temperature, so that atmospheric water vapor increases with increasing global temperature: this gives a major amplification of the warming produced by the more inert greenhouse gases (Ramanathan 1981). Unless there is a major decrease in the relative humidity with increasing temperature, which has not been documented at any level in the troposphere, then the Clausius-Clapyron equation dictates that water vapor increases with temperature. Lindzen (1990) argues that we should explore the possibility that deep convection might dry the upper troposphere. His argument is that as boundary layer temperature and moisture increase with increasing sea surface temperature, the tops of the deep convective clouds in the tropics will go higher to levels that are colder. If then the mean outflow is at colder temperatures, and the clouds precipitate all their cloud and ice water, then the outflow of moisture into the upper troposphere will decrease, because of the decrease of (ice) saturation mixing ratio with temperature. This is important to the greenhouse effect because decreases of moisture at high levels can offset the effect of increases at lower levels.

Clearly we must understand the processes by which water is distributed from the ocean surface into the tropical atmosphere by deep convection. Lindzen's model is a highly over-simplified one of a deep single cell circulation which transports mass between the cloud base near the surface and the upper troposphere. This model was originally proposed by Riehl and Malkus (1958) for the mean Hadley circulation, and incorporated into the simple cumulus parameterization scheme of Arakawa and Schubert (1974), which Lindzen cites. However, we have known since the GATE and MONEX experiments (Yanai 1972; Betts 1978; Houze and Betts 1981; Gamache and Houze 1983), which were designed to

study convective systems in the tropics, that this mean picture is incomplete. Tropical convective mesosystems (the so-called "cloud clusters") go through a complex life cycle. They start with a single cell circulation from low to high levels, associated with the growth of cumulonimbi, but then they develop a double cell circulation with ascent above the freezing level in a large mesoscale anvil, and with descent underneath the anvil. This double cell structure is driven by condensation and freezing above, and melting and evaporation of falling precipitation below the freezing level (which in the tropics is near 550 mb in the middle troposphere). The decay of these thick upper-level anvil ice clouds (between 550 and 150 mb) leaves large amounts of water in the upper atmosphere, so that deep convection is the major source of the upper tropospheric moisture. Gamache and Houze (1983) estimated that the water input from the anvil is roughly 10% of the precipitation. This is a water input vastly greater than ice saturation at levels close to the tropopause. Lindzen's model concept of deep tropical clouds, which detrain only near the troposphere at very cold temperatures, after precipitating virtually all their water substance, is an unrealistic oversimplification. It does not consider the life cycle of these deep mesoscale anvil clouds, which are the characteristic feature of satellite pictures of the tropics.

Another clue that the historical single cell model of the tropics is not a complete picture came from the boundary layer studies of Betts and Albrecht (1987), and Betts and Ridgway (1988). They found that the air sinking back into the top of the CBL over wide regions of the Pacific had *not* sunk unmodified from the upper troposphere, but only from near the freezing level. With radiatively driven subsidence rates of order 40 mb day^{-1} , the air sinking into the top of the CBL (near 800 mb) takes five to six days to sink from the middle troposphere. This is consistent with an advection distance of order 3500 km at 7 ms^{-1} , typical of the wavelength of disturbances in the tropics (Reed and Recker 1971; Thompson et al. 1979). At radiatively driven sinking rates of $30\text{--}40 \text{ mb day}^{-1}$, there is insufficient time between disturbances for air to sink unmodified from the upper troposphere. The single cell model may describe the mean Hadley circulation, but it does not describe the trajectories of air parcels, and of moisture associated with the transient cloud clusters.

A further important issue touched on by Lindzen (1990) is the mass and energy circulation in the mean Hadley and Walker circulations, which are primarily coupled to the vertical mass flux in deep convection. How does this change with increasing temperature? Lindzen asserts that the mass flux in the tropical convective clouds increases with warming. It is not obvious that this is correct. Indeed Betts and Ridgway (1989) in a simple model of a closed tropical circulation in energy balance found that the mass

circulation *decreases* with increasing temperature. The reason for this is simple. In this model, and probably the real atmosphere, the surface evaporation (plus the much smaller sensible heat flux), which balances the net radiative cooling of the troposphere, increases with the surface temperature at roughly the slope of the Planck function: $6 \text{ W m}^{-2} \text{ K}^{-1}$. However, the low-level moisture, which is loosely coupled to temperature through the Clausius-Clapyron equation (relative humidity near the surface changes little), increases more rapidly with surface temperature, so that the tropospheric subsidence and the corresponding ascending mass flux actually *decrease* with increasing temperature, although the upward vapor flux at cloud base increases!

Clearly we need studies in many areas. Observational studies of the dependence of upper tropospheric moisture on SST for the different ocean basins and for interannual variations could give us observational insight into the coupling of moisture to temperature. Raval and Ramanathan (1989) have shown a direct link between SST and infrared emissions to space, and by inference column moisture. However we lack good observations of upper tropospheric moisture in the tropics, as Lindzen (1990) points out. This is a key area; perhaps surface-based Raman lidar (Melfi et al, 1989) from a few stations in the tropics could give us this much needed climatology.

The link between water vapor input to the troposphere and cloud cluster lifecycle needs further study. As mentioned above, Gamache and Houze (1983) estimated that about 10% of the surface evaporation is transported into the upper troposphere by deep convection. Does this percentage increase or decrease with temperature? How might cloud precipitation efficiency and life cycle processes change with a small increase of temperature, and the height of the freezing level? Betts & Harshvardhan (1987) showed that the liquid and ice water content of *adiabatic* clouds increases with temperature, also through a link with the Clausius-Clapyron equation. However it is unclear how cloud amount or thickness will change if the climate warms. This remains a major uncertainty where the possibility of feedbacks of either sign exists.

The issue of global climate change is too important for us to wait for this experiment to be played out. There is a great deal of observational and modelling work urgently needed. However, the impact of atmospheric pollution on regional scales and the biosphere is becoming more serious annually. We will not be able to predict with any certainty for decades the impact on a global scale, because of the complexity of the whole earth system. Yet, changing the direction of our industrial society towards one which is more respectful of its impact on our global environment will take time, probably decades, even if we begin now.

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References

- Arakawa, A., and W. H. Schubert. 1974. Interaction of a cumulus cloud ensemble with the large-scale environment, part 1. *J. Atmos. Sci.* **31**: 674-701.
- Betts, A. K., and B. A. Albrecht. 1987. Conserved variable analysis of boundary layer thermodynamic structure over the tropical oceans. *J. Atmos. Sci.* **44**: 83-99.
- , and Harshvardhan, 1987: Thermodynamic constraint on the cloud liquid water feedback in climate models. *J. Geoph. Res.* **92**: 8483-8485.
- , and Ridgeway. 1988. Coupling of the radiative, convective and surface fluxes over the equatorial Pacific. *J. Atmos. Sci.* **45**: 522-536.
- , and —. 1989. Climatic equilibrium of the atmospheric convective boundary layer over a tropical ocean. *J. Atmos. Sci.* **46**: 2621-2641.
- Houze, R. A. and A. K. Betts. 1981. Convection in GATE. *Rev. Geophys. and Space Phys.* **19**: 541-576.
- Gamache, J. F., and R. A. Houze. 1983. Water budget of a meso-scale convective system in the tropics. *J. Atmos. Sci.* **40**: 1835-1850.
- Lindzen, R. S. 1990. Some coolness concerning global warming. *Bull. Amer. Meteor. Soc.* **71**: 288-299.
- Melfi, S. H., D. Whiteman and R. Ferrare. 1989. Observation of atmospheric fronts using Raman lidar moisture measurements. *J. Appl. Meteor.* **28**: 789-806.
- Ramanathan, V. 1981. The role of ocean-atmosphere interactions in the CO_2 climate problem. *J. Atmos. Sci.* **38**: 918-930.
- Raval, A., and V. Ramanathan. 1989. Observational determination of the greenhouse effect. *Nature* **342**: 758-761.
- Reed, R. J., and E. E. Recker. 1971. Structure and properties of synoptic scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.* **28**: 1117-1133.
- Riehl, H., and J. S. Malkus. 1958. On the heat balance in the equatorial trough zone. *Geophysica* **6**: 503-538.
- Thompson, R. M., Jr., S. W. Payne, E. E. Recker and R. J. Reed. 1979. Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic. *J. Atmos. Sci.* **36**: 53-72.
- Yanai, M. 1972. A review of recent studies of tropical meteorology relevant to the planning of GATE Experiment Design Proposal, *WMO-ICSU*. **2**: Annex I.

Response

I am happy that Betts concurs that the water vapor budget is a crucial part of the climate system. As Betts notes, the fact that water vapor, closely followed by water in the form of stratiform clouds, is, by far the most important greenhouse gas, is rarely stressed. Moreover, the positive feedback that arises from using convective parameterizations which tend to moisturize the atmosphere at all levels when there is warming is the most important positive feedback in current large scale climate models—despite the popular emphasis on feedbacks from cloud cover (Arking 1990). What is frequently misunderstood is the special role of water vapor in the upper troposphere. As noted in Lindzen (1990), convection carries heat away from the surface to the upper troposphere; it is at these levels that the trapping of heat by greenhouse gases assumes its greatest impor-

tance. It is easily shown that, on a molecule for molecule basis, water vapor above 6 km is much more important than water vapor near the ground in determining the surface temperature (Arking 1990). Thus, even though water vapor near the ground increases with increasing temperature, a smaller absolute decrease at upper levels can lead to a negative feedback. This point was completely misunderstood by Raval and Ramanathan (1989).

Betts suggests that this failure to stress the role of water substance may arise from the fact that these substances have short relaxation times compared to the minor greenhouse gases. I find this remark incomprehensible. The relaxation time of water substance has nothing to do with its infrared properties. Indeed, it is its short response time that peculiarly enables it to play a possible regulatory role—a role it could not play if its response time were slow.

Betts's contention, that the role of deep convection in the moisture budget of the upper troposphere is not simple, is hard to contest. However, his discussion unnecessarily confuses the situation. First, Betts misrepresents both my approach to cumulonimbus parameterization (Lindzen 1988; Geleyn et al. 1983), and that of Arakawa and Schubert (1974). He asserts that both approaches deal with clouds that originate near the ground and detrains near the tropopause. In both approaches, cumulus clouds are decomposed into infinitesimal elements, each of which is defined by its detrainment level (essentially the level where its temperature equals the environmental temperature). However, the cloud itself detrains continuously. Over how broad a region the cloud detrains depends on the moist enthalpy distribution of the air entering the cloud, but commonly the region extends from heights of 2-3 km up to the tropopause. Betts further points out that cloud detrainment is a major source of water vapor in the upper troposphere. The inference would appear to be that this is not the case in my approach. I can assure Betts that detrainment is indeed the major source of upper-level moisture in my parameterization—a point that I will return to shortly.

Betts argues that clouds should only be considered in the context of the larger scale systems that they are part of; in particular, he emphasizes clusters. My own feeling is that it is preferable to attempt to parameterize the isolated clouds, and calculate the flows that the clouds are embedded in as a response to the clouds (as well as other aspects of the forcing). In most cases, if the calculations are carried out correctly, the results should be the same. For example, if one considers the Hadley circulation generated by latent heat release in cumulonimbus clouds, then one finds that, if the heating is centered at the equator, the upward moving part of the Hadley circulation is largely occurring in the cloud updrafts themselves (Schneider and Lindzen 1977; Schneider 1977). Should one then consider the downward moving part of the Hadley circulation as part of the cloud system? One might, but there appears to be little advantage to doing so. Moreover, doing so forces one to look at clouds involved in the Hadley circulation as somehow being different from clouds embedded in squalls. This seems to me unappealing—especially since the same clouds are embedded in several systems simultaneously. In connection with the cluster systems mentioned by Betts, it might be

worth noting that Lindzen (1974) and Stevens and Lindzen (1977) anticipated the multi-cell vertical structured—though for different reasons than those suggested by Betts. Betts emphasizes the slowness of large scale subsidence; this is, in some ways, irrelevant. All subsidence, by adiabatically warming air, leads to drying.

Most of Betts's remarks concern the normal cloud balance. As he correctly notes, this does not address the real question of what happens when we have warming. What we need to know is how warming affects this balance, and how the altered balance affects upper level specific humidity. My approach to this question is relatively simple. Understanding this approach is facilitated by considering the equations for the interaction of cumulus clouds with the water vapor field (Arakawa and Schubert, 1974).

In the presence of cumulus convection—but above the trade cumulus boundary layer—the budget for specific humidity can be written

$$\rho \frac{dq}{dt} = D + M_c \frac{\partial q}{\partial z} + E - C \quad (1)$$

where

D =detrainment of water vapor,
 M_c =cumulus mass flux,
 E =reevaporation of water vapor,
 C =condensation of water vapor, and
 $\frac{dq}{dt} \approx \frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + w \frac{\partial q}{\partial z}$.

(t is time, x and y are horizontal coordinates, and z is the vertical coordinate; u , v , w are the velocity components in the x , y , z directions.) In regions of concentrated convection there is approximate compensation of cumulus heating and adiabatic cooling; i.e.,

$$\rho w \frac{\partial \theta}{\partial z} \sim M_c \frac{\partial \theta}{\partial z} \quad (2)$$

(θ is the potential temperature.) which implies that $\rho w \sim M_c$; and, therefore, in these regions the major drying term, $M_c(\partial q/\partial z)$, is approximately cancelled by $\rho w(\partial q/\partial z)$. In these regions we are left with

$$\rho \left\{ u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} \right\} \approx D + E - C \quad (3)$$

Note that in these regions there will clearly be cirrus formation limited by horizontal dispersal; if there is precipitation from these cirrus then this will contribute to net drying. Reevaporation of liquid water will, on the other hand, supplement D .

Averaged over major closed circulation systems (such as the Hadley circulation) advective terms approximately cancel. For simplicity, we will assume that the closed circulation exists in a homogeneous environment where the cancellation is complete. Upon horizontally averaging, we have the following approximate relation:

$$\bar{D} + M_c \frac{\partial \bar{q}}{\partial z} + \bar{E} - \bar{C} \approx 0 \quad (4)$$

In this average picture, warming causes D to become

smaller. The reason is that each cloud element now originates with a higher moist enthalpy, and, hence, detrains at a higher, colder level where the saturated specific humidity is less. Ongoing calculations show this to be a potentially major negative feedback factor. Betts focuses on two other terms in Equation 4. He points out that E , the reevaporation of condensed ice and water (closely related to precipitation inefficiency) might be a significant moisture source. I agree that this is a possibility. I also agree that we don't know, at this stage, whether it contributes positively or negatively to the climate feedbacks. There remains the contribution from the "drying" term, $\overline{M_c}(\partial q/\partial z)$. In our current work we find that M_c is approximately independent of warming. To be sure, M_c originates in evaporation which increases with warming; however, M_c depends on evaporation divided by the specific humidity of surface air (Lindzen 1988), and the latter quantity also increases with warming in such a manner as to largely cancel the increase in evaporation. It is possible that M_c might increase as a result of an increase in boundary layer turbulence forced by the increased evaporation (Sarachik 1985); this would produce a negative contribution to the feedback. However, preliminary estimates suggest this effect is small. I believe it is this term that Betts is referring to when he discusses the Hadley and Walker circulations. I am puzzled by his line of argument (I didn't refer to either the Hadley or Walker circulations in Lindzen, 1990). While I don't see its relevance to the present discussion, I find the contention that net cooling of the troposphere follows the Planck function at the surface peculiarly at odds with the well known near independence of outgoing longwave radiation on surface temperature (i.e., figure 24 in Lorenz 1967).

Despite the above technical disagreements, Betts and I both agree on the fundamental importance of the upper tropospheric water vapor budget to the question of global warming. I am personally more optimistic that, by keeping arguments specific, we can come to a satisfactory (even if imperfect) resolution of the question in time to rationally consider policy. Betts's wish for society sounds sufficiently noble, but is, in fact, disconcertingly vague. At least as concerns policies that purport to deal with warming, it seems only honest that these policies be required to quantitatively estimate the effect of the policies on the timing and amount of warming. Clearly, we have no accurate way of doing this at the moment. However, if such policies, even in the context of present climate models which predict substantial warming, fail to produce noticeable amelioration, we may plausibly regard it as imprudent to tie such policies

to warming. To do otherwise would render the mundane, but not unimportant, matter of governmental accountability mute. It might also endanger what might otherwise be perfectly reasonable policies.

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References

- Arakawa, A., and W.H. Schubert. 1974. Interaction of a cumulus cloud ensemble with the large-scale environment, part I. *J. Atmos. Sci.* **31**: 674-701.
- Arking, A. 1990. Feedback processes and climate response. To appear in *Proceedings of the Conference on Climate Impacts of Solar Variability*, NASA Conference Publications CP-3086.
- Betts, A.K. 1990. Greenhouse warming and the tropical water budget. *Bull. Amer. Met. Soc.* **71**.
- Geleyn, J.-F., C. Girard, and J.-F. Louis. 1982. A simple parameterization of moist convection for large-scale atmospheric models. *Beitr. Phys. Atmosph.* **55**: 325-334.
- Lindzen, R.S. 1974. Wave-CISK in the tropics. *J. Atmos. Science*, **31**: 156-179.
- Lindzen, R.S. 1988. Some remarks on cumulus parameterization, *PAGEOPH*, **16**: 123-135.
- Lindzen, R. S. 1990. Some coolness concerning global warming. *Bull. Amer. Meteor. Soc.* **71**: 288-299.
- Lorenz, E.N. 1967. The nature and theory of the general circulation of the atmosphere, WMO Monograph No. 218. TP. 115, 161 pp.
- Raval, A., and V. Ramanathan. 1989. Observational determination of the greenhouse effect. *Nature* **342**: 758-761.
- Sarachik, E. 1985. A simple theory for the vertical structure of the tropical atmosphere, *PAGEOPH*, **123**: 261-296.
- Schneider, E. 1977. Axially symmetric steady state models of the basic state of instability and climate studies. Part II: Nonlinear calculations, *J. Atmos. Sci.*, **34**: 280-296.
- Schneider, E. and R.S. Lindzen. 1977. Axially symmetric steady state models of the basic state of instability and climate studies. Part I: Linearized calculations, *J. Atmos. Sci.*, **34**: 253-279.
- Stevens, D. and R.S. Lindzen. 1978. Tropical Wave-CISK with a moisture budget and cumulus friction, *J. Atmos. Sci.*, **35**: 940-961.

Clouds and global warming

Real clouds may moderate global warming by negative feedback, or may work the other way. Comparison between observations and predictions suggests that clouds are cooling influences outside the tropics.

THE question of whether clouds would substantially change the prediction of global warming caused by the accumulation of carbon dioxide in the atmosphere has been much debated, not least because there is no simple way of answering it with precision while back-of-the-envelope calculations exist on either side and are memorable, even compelling. That is why the issue has been about for twenty years.

The simplest argument is that clouds provide negative feedback for global warming. If the surface temperature of the Earth is increased, evaporation from the ocean surface will be increased, cloud formation will be enhanced and, because clouds reflect sunlight, the net receipt of energy at the surface of the Earth will be decreased. It is true, of course, that water vapour is also in its own right a greenhouse gas (which works the other way) and that, by the same simple argument, the lower surfaces of clouds will intercept long-wavelength radiation and keep its energy in the lower atmosphere, but if surface warming is the worry, the effects of the upper surfaces of clouds must be the more important.

A second envelope-back will take the argument further. Clouds are dynamic structures, are they not, and may notoriously be a way in which water vapour and water drops are carried rapidly upwards through the height of the clouds to deposit the latent heat of ice formation near the upper surface? At the lower surface, by contrast, at least if rain is not falling from the cloud, the latent heat of evaporation is balanced by that condensation. So the right kind of cloud, a thundercloud, may be an effective means of transporting energy from low to higher altitude. The negative feedback is all the stronger.

This argument can, unfortunately, be turned around. A cloud is not just a place of high water concentration lying between a lower level at which the temperature is the dew-point and an upper level (below the freezing point) determined by the amount of water in circulation, but is driven by physical movements of the atmosphere, otherwise called winds. But how to dissipate that external energy? By making the cloud into a kind of heat-pump, transferring heat from the upper to the lower surface.

The balance between these contradictory arguments would have been settled long ago if only it had been possible to

include real clouds in the models of the general circulation of the atmosphere. Sadly, that is not even now the case, and for good reason. The most elaborate climate models may treat a dozen slices of the atmosphere between the surface of the Earth and outer space as independent, and may treat the atmosphere itself as so many vertical cells with dimensions of the order of 5° or 500 km. Whoever saw clouds that big?

In reality, the modellers have been forced to account for clouds by means of a parameter called cloudiness. Atmospheric water vapour is determined by surface temperature, and is in turn the determinant of cloudiness. And the effects of cloudiness on the state of the atmosphere, especially the radiation balance within it after allowing for the role of water vapour as a greenhouse gas, is meant to be an average between the behaviour of the atmosphere when there are no clouds and that when the surface of the Earth is obscured — an average between black and white, so to speak, almost calculated to excite suspicion. How useful is that stratagem?

Luckily, one development of the past few years makes the question almost tractable — the flow of data from the satellite observing campaign known as ERBE, for Earth Radiation Budget Experiment. There are three satellites altogether — Nimbus 9, Nimbus 10 and a dedicated ERBE satellite, all in polar orbits with different altitudes. In the long run, this is how the Earth's radiation budget will be monitored; it is a sad reflection on professional people's sense of what is important that they are not clamouring to have a better system (better coverage, more frequency channels, greater precision) launched tomorrow.

Now J. T. Kiehl from NCAR (the National Atmospheric Research Center at Boulder, Colorado) and V. Ramanathan from the University of Chicago have made the best of such data as there are by attempting to compare the behaviour of a relatively sophisticated version of the NCAR "community climate model" (CCM) with the ERBE-observed radiation from the surface of the Earth. (*J. geophys. Res.* 95, 11,679; 1990). They emphasize that, at this stage, they are not seeking to estimate the importance of whatever feedback mechanism may be operating, but to compare CCM with reality. They conclude that there is little differ-

ence between model and the observations, but luckily they leave room for argument on the backs of envelopes.

Comparison between the observations and the model calculations is possible only because the models, involving as they do the transfer of energy by radiation from one level in the atmosphere to another, allow the calculation of the radiation expected by the ERBE sensors. Are the predictions very different from the observations, and if so how and where? The comparison generally rings true in the sense that the model tends to predict greater extremes of, say, outgoing long-wave radiation as a function of latitude than the observations find, but with the same general shape; that is another way of saying that the models have still to be refined. There are a few technical difficulties also; for example, it seems that some parts of the Earth are never so free from clouds that their "clear-sky" behaviour can be observationally determined.

Broadly speaking, the discovery that matters in this painstaking comparison between prediction and observation is that the uncertainties occasioned by clouds are greatest in the tropics. In most latitudes, clouds do have the effect of cooling the Earth beneath, but in the tropics there is a difference of 4 W m⁻² between the model and observation in the amount of energy accumulated near the Earth. There is nothing seriously wrong with that difference, a mere half of a per cent of incoming radiation, even if it might make a big difference over months or even weeks.

What matters more, for the time being, is that the argument suggests a few specific modifications of the climate models. A better scheme for allowing for the effect of increased surface temperature on the transport of water vapour from the oceans is an important need. The modellers seem ready, even eager, to take that on board. A rerun of the calculations should tell whether that will, for the time being, suffice.

But further down the road, the envelope-back devotees will have to be won over by a genuine and verifiable prediction. If, for example, the models say that increased surface temperature means more water vapour, what does that mean for the frequency of cloud cover? One is bound to suspect that to be a sensitive test of the accuracy with which the feedbacks can be gauged. How does it come out?

John Maddox

fewer, allegedly because of the poorer growing conditions). Charles G. Abbot, astrophysicist and secretary of the Smithsonian Institution for a quarter of a century, directed the first systematic measurement of the solar constant. Between 1923 and 1952, daily observations, coordinated by Abbot were made at stations around the world.

More reliable data became available as soon as radiometers were rocketed into space, far above the earth's atmosphere. These satellite observations have at last

confirmed that the solar constant, perhaps better labeled the total solar irradiance, is not quite constant; it jiggles. One spaceborne radiometer, designed by Richard Willson at the Jet Propulsion Laboratory and launched in 1980 aboard *Solar Max*, the Solar Maximum Mission's satellite, has registered significant dips, lasting days to weeks, when large groups of sunspots have crossed the sun's face. "We've gone from a situation where no one really knew for sure whether the sun's total output was varying at all—

on any time scale—to seeing variations over all time scales from minutes to years," says Peter Foukal.

Herschel now appears to have been quite prescient. Willson and his collaborators reported in 1986 that solar brightness declined by about 0.1 percent from 1980 to 1984, when the sun went from a maximum to a less active mode. Foukal, in collaboration with Judith Lean of the Applied Research Corporation in Maryland, later concurred after comparing data from the *Solar Max* and *Nim-*

Clouds in the climate equations

A complete understanding of the earth's radiation budget, as well as of the way in which energy is absorbed around the globe, will not be achieved until scientists learn more about the most variable parameter in the equations—clouds. "Clouds are not the forgotten objects in climate studies, but they are certainly the neglected ones. We could be off in our assessment of the earth's energy budget by as much as 10 to 20 percent because of our uncertainty in cloud contributions to the planet's total albedo [the measure of its reflectivity]," says National Center for Atmospheric Research scientist James Coakley. "Could we be blowing long-range weather forecasts due to that uncertainty?"

It is well known that carbon dioxide and other trace gases assist in trapping more heat than escapes the earth into space, skewing the delicate balance that keeps the earth's climate in equilibrium. Over the last century, the world has warmed by nearly a degree. "If the rise continues into the twenty-second century," NCAR scientists Robert Dickinson and Ralph Cicerone have reported, "the global average temperature may reach higher values than have occurred in the past ten million years."

Clouds offer the earth a possible escape valve. Atmospheric scientists currently figure that the earth's albedo is around 30 percent, and that roughly three-quarters of that is caused by clouds. What if that fractional contribution were to increase—a conceivable effect as the global climate warms? Theorists surmise that a very small increase in the earth's cloud cover could lead to substantial decreases in global temperatures. A mere 4-percent increase in low-level stratus clouds, for example, could offset the rise of two to three degrees in global temperature produced by a doubling of carbon dioxide.

Unfortunately, these estimates are based on computer models that handle clouds in a very simplistic fashion; real data on cloud cover as it actually occurs are sparse. "Take a trip to the cliffs of Oahu, where masses of air off the Pacific Ocean rush up the precipices and form clouds within a minute," suggests Bruce Barkstrom of the National Aeronautics and Space Administration's Langley Research Center. "Trying to predict where and how that is occurring all over the globe gives you an idea of the unpredictability in this field."

The International Satellite Cloud Climatology Project (ISCCP), currently under way under the aegis of the World Climate Research Program, was organized to acquire a more realistic assessment of global cloud cover. Five geostationary and two polar-orbiting satellites are generating a five-year data set from which more reliable statistics for cloud amounts, types, and heights will be derived.

The questions that ISCCP scientists are asking are very basic ones: How many clouds are truly there? How do they change with the seasons? At the same time, intensive observations of clouds from the ground and the air are being conducted at selected sites as part of a program called FIRE—First International Satellite Cloud Climatology Project Regional Experiment.

Pollution effects

An additional concern is the effect of industrial pollution on clouds. Many scientists believe that clouds, tainted with the trace gases now spewing into the atmosphere, will absorb more solar radiation, which will speed up the global warming trend.

Sean Twomey of the University of Arizona offered a counterargument. Manufactured aerosols, he surmises, would encourage the formation of small water droplets in clouds, as well as increase the total number of water droplets in any one cloud. This, he concludes, would tend to increase a cloud's reflectivity more than it would increase its ability to absorb radiation.

A recent measurement appears to support Twomey's supposition. "It was an accident," recalls James Coakley. "I was in California on sabbatical, looking at satellite cloud images on a computer and hoping to find a way to define cloud edges." Instead, he saw a clear ship trail, the result of stack gases from a ship polluting the overlying clouds in its wake.

By comparing the radiative signal emanating from such ship trails with unpolluted clouds nearby, Coakley and several colleagues concluded that the ship trails had a noticeably higher reflectivity. "This is an important factor in the warming-versus-cooling debate," notes Coakley. Were the increase in manufactured aerosols proportional to the increase in carbon dioxide, it would lead to an

bus 7 radiometers. Variations in the two instruments matched, on time scales ranging from a few months to years.

According to a model developed by Foukal and Lean, faculae—bright solar magnetic regions that pepper the sun's surface and also surround sunspots—play the dominant role in this constant flux. "The excess radiation from the faculae during times of high activity," says Foukal, "outweighs the decrease in radiation caused by dark sunspots." Likewise, a decline in the number of faculae

during a solar minimum diminishes total solar irradiance.

Others in the field have been more cautious about this conclusion, since the apparent decline in solar radiation recorded by the radiometers is not much larger than the level of noise in the detectors themselves. Bruce Barkstrom of the National Aeronautics and Space Administration's Langley Research Center, in Virginia, team leader for the Earth Radiation Budget Experiment, which is also tracking the solar con-

stant, notes that "a degradation in the satellite detectors, which might cause the measurements to decrease over time, could be misinterpreted as a change in solar climate."

Preliminary reports, however, are suggesting that the spaceborne detectors are seeing a rise in total solar irradiance as the sun heads back toward its next maximum in 1991. If this finding holds up, it could provide some answers to some longstanding puzzles—such as that of the seventeenth- and eighteenth-



Ship trails. In infrared satellite photo, stack-gas trails from ships contrast with nearby unpolluted clouds. The higher reflectivity of polluted clouds could act to offset the greenhouse effect.

appreciable increase in cloud reflectivity, which, if extrapolated over the entire globe, could offset the warming resulting from increased carbon dioxide.

However, there is a catch: Ship trails are created over the ocean, whereas the pollution effect may well be different over land. Soviet scientists flying aircraft over polluted industrial areas even saw cloud reflectivities decline. For a more complete determination, Coakley would like to survey hundreds of square kilometers with satellites.

A complementary approach to determining the role of clouds in the earth's radiation budget is to measure the components of the radiation balance itself—the solar flux coming in and the infrared radiation emitted, in turn, at the top of the earth's atmosphere. Possible changes in this energy balance caused by disruptions in the flow of ra-

diation are the cornerstone of modern climate modeling. The Earth Radiation Budget Experiment (ERBE), now in progress, combines observations from the NASA research satellite ERBS in a low-inclination orbit with measurements from the NOAA 9 and NOAA 10 satellites in polar orbit. The ERBE program represents the most advanced attempt to measure the radiation budget since the beginning of the space age 30 years ago.

Variables

Through their measurements, the ERBE scientists—an association of NASA, NOAA, and university researchers—are seeing, in a very direct fashion, that both cloud type and height are significant. Low-level clouds emit large amounts of energy into space; clouds at higher altitudes, such as the tops of typhoons and storm cells, on the other hand, emit only half as much.

As Bruce Barkstrom points out, clouds can actually display two opposing effects. They can either reflect short-wave solar radiation back into space, keeping sunlight from being absorbed by the ocean, or they can absorb the longwave radiation the earth emits and thus act as a blanket in warming the surface. "Which wins out?" asks Barkstrom, the ERBE science team leader.

An array of maps from ERBE data, the result of 500,000 lines of code and 200 scientist-years of programming effort at NASA-Langley, are offering some initial clues. Over the oceans, especially off the west coast of South America and over the stormy North Atlantic Ocean, low-level clouds predominate and tend to reflect more radiation than they absorb. Over such regions, the earth experiences a net loss in energy, ranging from 10 to 70 watts per square meter. However, the clouds over desert landscapes tend to be high cirrus and keep heat in.

The ERBE team is far from making any final global assessments. "But," says Barkstrom, "we have a chance now of getting our first handle on cloud-forcing, the net loss and gain of heat from clouds." If low clouds increase appreciably as carbon-dioxide levels rise, a warming trend could be allayed. But if high clouds, such as cirrus or thunderstorms, prevail, then greenhouse heating of the atmosphere could accelerate. ●

M. B.

→ ↑ cloud cover over ocean, but low surface temp & more ↑ cloud, intensified heat.

Observational determination of the greenhouse effect

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Satellite measurements are used to quantify the atmospheric greenhouse effect, defined here as the infrared radiation energy trapped by atmospheric gases and clouds. The greenhouse effect is found to increase significantly with sea surface temperature. The rate of increase gives compelling evidence for the positive feedback between surface temperature, water vapour and the greenhouse effect; the magnitude of the feedback is consistent with that predicted by climate models. This study demonstrates an effective method for directly monitoring, from space, future changes in the greenhouse effect.

IN its normal state, the Earth-atmosphere system absorbs solar radiation and maintains global energy balance by re-radiating this energy to space as infrared or longwave radiation. The intervening atmosphere absorbs and emits the longwave radiation, but as the atmosphere is colder than the surface, it absorbs more energy than it emits upward to space. The energy that escapes to space is significantly smaller than that emitted by the surface. The difference, the energy trapped in the atmosphere, is popularly referred to as the greenhouse effect, G . Some very interesting questions about the greenhouse effect involve feedbacks between the various elements of the climate system¹. These feedbacks tend to enhance or diminish small external perturbations in the radiation balance. One of the most important is the water-vapour feedback². Consider an initial increase in the global temperature because of the direct infrared trapping resulting from, say, an increase in carbon dioxide. As the surface and the atmosphere warm, the saturation vapour pressure increases exponentially with temperature, and more H_2O can evaporate into the atmosphere. Because water vapour is a strong greenhouse gas, the extra water vapour traps more longwave radiation and drives the temperature even higher. This feedback can amplify the original perturbation by as much as a factor of two^{1,2}.

The greenhouse effect and its feedback on the climate have been explored by hundreds of theoretical and model studies. Satellite radiation-budget measurements have also been used to examine the radiative feedbacks in the climate system³. Yet to our knowledge the radiative trapping by the atmosphere has not been examined in depth with observed data (with the exception of unpublished work by R. D. Cess). Here we address three critical issues: (1) the magnitude of G in the present atmosphere; (2) the quantitative nature of the feedback between surface temperature and G ; (3) the change in G with time. We provide observational estimates for the former two and discuss how our findings bear on the third issue. A possible change in G is of urgent concern because of the rate at which human activities have been adding greenhouse gases to the atmosphere.

We obtain G by subtracting longwave radiation escaping to space from estimates of the radiation emitted by the ocean surface. The radiation escaping to space has been measured since 1985 by the spaceborne Earth Radiation Budget Experiment (ERBE). Under cloudless skies, the atmosphere traps

146 W m^{-2} whereas clouds increase G by 33 W m^{-2} . G increases significantly with surface temperature (T_s), even when it is normalized by the surface emission. The rate of increase of G , $3.3 \text{ W m}^{-2} \text{ K}^{-1}$, is consistent with the magnitude of the H_2O greenhouse feedback inferred from climate models and line-by-line radiative-transfer calculations. Furthermore, the observed variation of total atmospheric water content (W) with T_s indicates that the normalized greenhouse effect (g) is strongly correlated with W . The observations are compelling evidence for the H_2O feedback. The data also reveal a rapid rise in G at the higher temperatures ($T_s > 298 \text{ K}$), the cause(s) of which are not apparent.

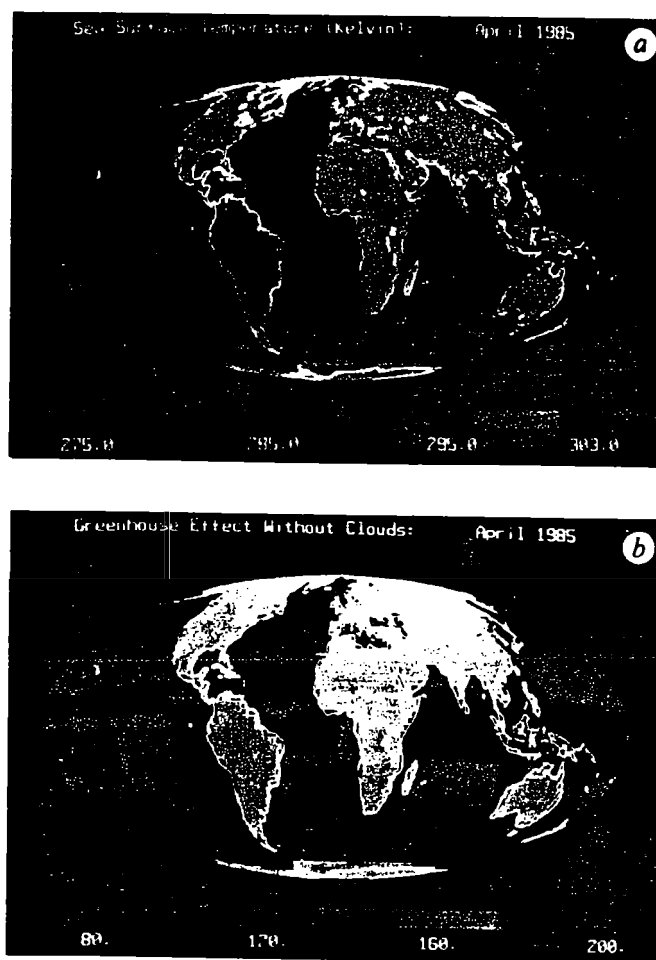


FIG. 1 a. Monthly-mean map of observed sea surface temperature (K) for April 1985. b. Same as in a but for the greenhouse effect (G) of atmosphere under clear skies. Values are in W m^{-2} . The major inference from these figures is that the greenhouse effect of the atmosphere is strongly correlated with surface temperature. This correlation can explain the Equator to pole decrease in G as well as the east to west variations. For example, G is maximum over the relatively warm western equatorial Pacific Ocean (Indonesian region) and is very low over the cold oceanic upwelling regions in the central and eastern equatorial Pacific and off the west coasts of Africa and South America.

Determination of the greenhouse effect

If E is the longwave flux emitted by the surface at a certain location, and F is the flux leaving the top of the atmosphere (TOA) directly above that location, then the greenhouse effect G for that location can be defined as $G = E - F$.

The TOA fluxes F have been measured with good accuracy by scanning radiometers on board the spaceborne ERBE⁴. ERBE consists of three satellites carrying identical scanners that detect both longwave (infrared) and shortwave (solar) radiation. The ERBE scanners, when viewing directly down, can resolve an area of $\sim 35 \times 35$ -km. The scanners have in-flight calibration which assures an accuracy of 1% for the satellite-altitude readings. Those readings are converted to TOA fluxes on a global grid of $2.5^\circ \times 2.5^\circ$ (latitude $\times$ longitude). So far, we have processed data for the months of April, July and October 1985 and January 1986. A unique feature of ERBE is that it separates the fluxes for clear skies (cloudless conditions) from fluxes for cloudy skies (mixture of clear and overcast areas). Hence we can obtain the greenhouse effect of the atmosphere and that of clouds separately.

We estimate the emission from the surface using the Stefan-Boltzmann black-body law ($E = \sigma T_s^4$) and the observed surface temperature. Because, in the infrared, the ocean surface approximates a blackbody to within 1% (ref. 6), and because the diurnal surface temperature variation is small in the ocean's mixed layer (less than a few degrees K), the uncertainties in the calculated values of E are minimum over oceans. We restrict this study to the open oceans; that is, we ignore continents and ocean regions covered with sea ice.

We obtained surface temperatures (SSTs) from the National Meteorological Center daily data sets archived at the National Center for Atmospheric Research (NCAR). The SST values are derived by blending *in situ* (ship and buoy) data with satellite temperature retrievals.

The SSTs used during the period of this study have an estimated error of about ± 1.0 K (ref. 7). The error in the surface emitted flux is simply $\Delta E = 4\sigma T_s^3 \Delta T$, or about ± 5 W m⁻². ERBE TOA longwave fluxes have an estimated error of about ± 5 W m⁻² for monthly averaged values^{4,5}. Because the errors in E and F are uncorrelated, the error in the monthly averaged greenhouse effect for a single location is ± 7 W m⁻². When these values are averaged around a latitude belt, the random error will diminish significantly. Clear-sky fluxes, however, can have systematic errors that are due to cloud contamination. The magnitude of this error was examined⁵ by sorting out homogeneous cloudless regions, that is cloudless regions that are surrounded by other cloudless regions and for which the spatial standard deviation of the longwave flux is $< 1\%$ of the clear-sky flux. This stringent homogeneity criterion gave fluxes that were smaller than the operational values used here by only 4 W m⁻², indicating minimal cloud contamination⁵. In addition, the clear-sky fluxes when compared with state-of-the-art radiation models agreed within 1% (ref. 5). Overall, we expect the error (systematic plus random) in the monthly and regional mean values of G to be 5 to 10 W m⁻².

Global greenhouse effect of atmosphere and clouds

Estimates of G over the open oceans for a cloudless atmosphere (clear sky) reveal significant regional variations (Fig. 1b). Globally, for April 1985, the surface emission is 421 W m⁻² whereas the TOA emission is 243 W m⁻², resulting in a total trapping of 178 W m⁻². Of this, the atmospheric gases (H₂O, CO₂ and O₃ among others) trap 146 W m⁻², whereas clouds trap the remaining 33 W m⁻². The greenhouse effect for each of the months studied is given in Table 1.

As the months are taken from the four seasons, we will assume the four month mean to be representative of the annual average. Then the annual average value of G (179 W m⁻²) is comparable to the global mean solar absorption, ~ 237 W m⁻². The global

mean latent heat released in the atmosphere is ~ 100 W m⁻². The greenhouse effect of a doubling of CO₂ is 4 W m⁻² and that of human activities during the past century⁸ is ~ 2 W m⁻². The greenhouse effect of the atmosphere, next to solar absorption, is the largest factor in maintaining the present climate.

The TOA flux is given by the radiation transfer equation

$$F = B(T_s) - \int_0^1 A(x) [dB/dx] dx \quad (1)$$

This equation is written in a normalized pressure coordinate, $x = p/p_s$, where p_s is the surface pressure. The blackbody emission B is simply $\sigma T^4 = \int B_\lambda(T) d\lambda$, where B_λ is the monochromatic Planck function evaluated at atmospheric temperature T . The effective absorptivity A is the integral of the monochromatic absorptivity A_λ weighted with dB_λ , and normalized by dB (ref. 2). Thus $A(x)$ is the absorptivity between the TOA ($x = 0.0$) and the pressure level x . T_s is the surface temperature. Because $G = E - F$ and $E = B(T_s)$, we obtain

$$G = 4\sigma \int_0^1 A(x) T^3 [dT/dx] dx \quad (2)$$

where we have let $(dB/dx) = 4\sigma T^3 (dT/dx)$. Most of the contribution to A comes from the troposphere (the bottom 10 km) which contains the bulk of the absorber mass. (Although CO₂ is uniformly mixed in the atmosphere, the major absorbers—water vapour and clouds—are almost entirely restricted to the troposphere.) In the troposphere temperature generally decreases with height. Hence $(dT/dx) > 0.0$ and G is positive. This reveals that for G to be positive, the temperature must decrease with altitude in the region of the absorbing gas.

Evidence of water vapour feedback

The clear-sky G (Fig. 1b) generally decreases from Equator to pole with some exceptions. The trapping that is due to clouds (not shown here) does not vary systematically with latitude, but peaks in the convectively disturbed regions of low latitudes and in the vicinity of the mid-latitude jet-stream regions. We find that the clear-sky G has a strong positive correlation with sea surface temperature (compare Fig. 1a with b). Here we show that this correlation gives direct evidence of the H₂O feedback.

We do this in three steps. First, we show the correlation of G with T_s implies that the longwave absorptivity of the atmosphere increases with surface temperature. Second, the variation of water vapour in the atmosphere is determined largely by the increase in the saturation vapour pressure with temperature, as shown by other observational⁹ and modelling¹⁰ studies. Third, if the observed variation of water vapour causes the sort of G - T_s coupling revealed by the data, the atmosphere absorptivity must scale logarithmically with the water content. This is not only indicated by the observations but is also consistent with theories of radiative transfer.

Step 1. Because the surface emission increases as the fourth power of T_s , the trapping should also increase with T_s . To remove the T_s^4 dependence, we define a normalized trapping $g = G/\sigma T_s^4$. Both the clear-sky g (Fig. 2) and the cloudy g (not shown) increase nonlinearly at warm temperatures ($T_s > 298$ K), but otherwise g increases smoothly with T_s . The grid-point

TABLE 1 Monthly- and global-mean greenhouse effect (W m⁻²)

Month	Clear sky	Clouds	Cloudy sky*
April 1985	146.3	32.1	178.4
July 1985	147.7	31.3	179.0
October 1985	146.9	32.9	179.8
January 1986	143.7	34.1	177.8
Four-month mean	146	33	179

* Cloudy sky is the sum of clear sky and clouds.

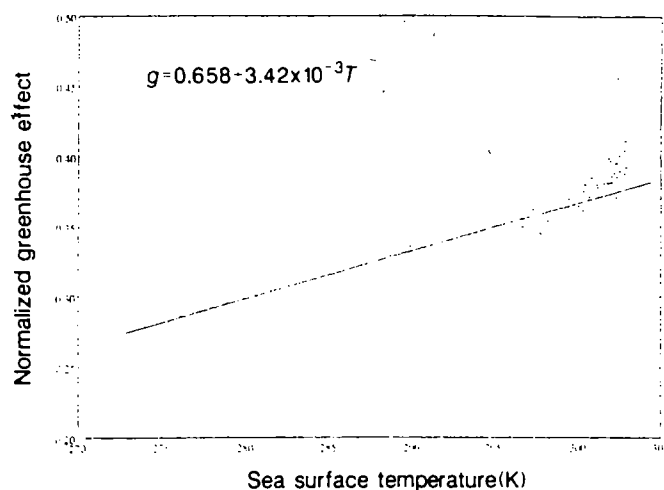


FIG. 2 Clear-sky greenhouse effect normalized by infrared emission (g) as a function of surface temperature. April 1985. Values are monthly averages for each $2.5^\circ \times 2.5^\circ$ region. The solid line indicates a least-squares fit through all the points. Fits done individually through Northern and Southern Hemisphere points do not deviate by more than 3%.

values of g for the individual months and the two hemispheres reveal similar dependencies on T_s . Because of the robustness of this feature, we conclude that g and the surface temperatures are strongly coupled.

The increase in g is primarily because of the increase in the absorptivity with T_s . In the troposphere the lapse rate $\Gamma = -dT/dz$ is approximately constant with pressure. We can then express the atmospheric temperature as $(T/T_s) = x^\alpha$, where $\alpha = \Gamma R/g_a$, where g_a is the gravitational acceleration. Inserting this in equation (2)

$$g = G/\sigma T_s^4 = 4\alpha \int_0^1 A(x)x^\beta dx \quad (3)$$

where $\beta = (4\alpha - 1)$. We first see that g does not explicitly depend on T_s . The g - T_s coupling must arise because either the lapse rate (and hence α) or A depend on T_s . The observed change in lapse rate¹¹ over the range of T_s considered here can affect g by at most 10% (based on flux sensitivities to lapse rates given in ref. 12). The only other variable is A . For a fixed amount of H_2O , A varies by only 5% (ref. 2) for the range of T_s considered here. The temperature dependence of A also cannot explain the rate of increase of g with T_s . Therefore, the amount of water vapour must increase with surface temperature.

Step 2. The increase in water vapour with T_s , which in turn causes an increase in A , is sufficient to explain the g - T_s coupling. The saturation vapour pressure e_s of H_2O is given by the Clausius-Clapeyron equation $C \exp\{-(LR^{-1})/T\}$. Here, C is a constant, L is the latent heat of vaporization and R is the gas constant for water vapour; LR^{-1} , at the global mean temperature, is $\sim 5,400$ K. Using the observed global mean lapse rate and relative humidity profile² we numerically calculate the total water content W in a vertical column in the troposphere for a range of values of T_s . W increases exponentially with a rate of increase $d(\ln W)/dT_s = 6.7 \times 10^{-2} \text{ K}^{-1}$. Compare this to the actual rate of increase ($5.5 \times 10^{-2} \text{ K}^{-1}$), obtained by satellite microwave observations¹³ of W (Fig. 3a). They agree to within 20%, hence W is largely determined by the surface temperature, in agreement with the findings of Prabhakara *et al.*⁹ and Stephens¹⁴. This coupling between W and T_s arises from the temperature dependence of the saturation vapour pressure.

Step 3. Because we are ignoring variations in the lapse rate or in spectroscopic parameters with temperature, we can write dg/dT_s as a product of a partial and a total derivative:

$$\frac{dg}{dT_s} = \frac{\partial g}{\partial \ln W} \frac{d \ln W}{dT_s} \quad (4)$$

The first term is the observed coupling of the normalized greenhouse effect with T_s . The last term represents the fundamental source of the H_2O feedback—the water content increases with T_s . The second term represents the 'return loop' in the feedback—the absorptivity increases with water content. We infer from equation (4) that if g varies linearly with T_s (which it does for $T_s < 298$ K in Fig. 2), and if $\ln W$ also varies linearly with T_s (as suggested from theory and from the satellite microwave data in Fig. 3a), then g should increase logarithmically with W . In fact, theoretical calculations² (see ref. 15) have shown that, for the range of W considered in Fig. 3, the absorptivity scales logarithmically with the absorber amount. A plot of g against $\ln W$ (Fig. 3b) shows this scaling. Our analysis is consistent, because dg/dT_s (from Fig. 2) is $3.4 \times 10^{-3} \text{ K}^{-1}$, on a global average, whereas the product of $\partial g/\partial(\ln W)$ (from Fig. 3b) and $d(\ln W)/dT_s$ (from Fig. 3a) is $3.2 \times 10^{-3} \text{ K}^{-1}$. This comparison may be used in an illustrative sense only, because the microwave soundings of W are only available for the period 1979–83, and the ERBE measurements are not available before 1985. However, a comparison of zonal averages (as shown in the plot of g against $\ln W$ in Fig. 3b) minimizes the variation across these two time periods.

The analysis strongly indicates the presence of the H_2O feedback. Three further points can be made in favour of this interpretation. First, the clear-sky greenhouse effect and its temperature

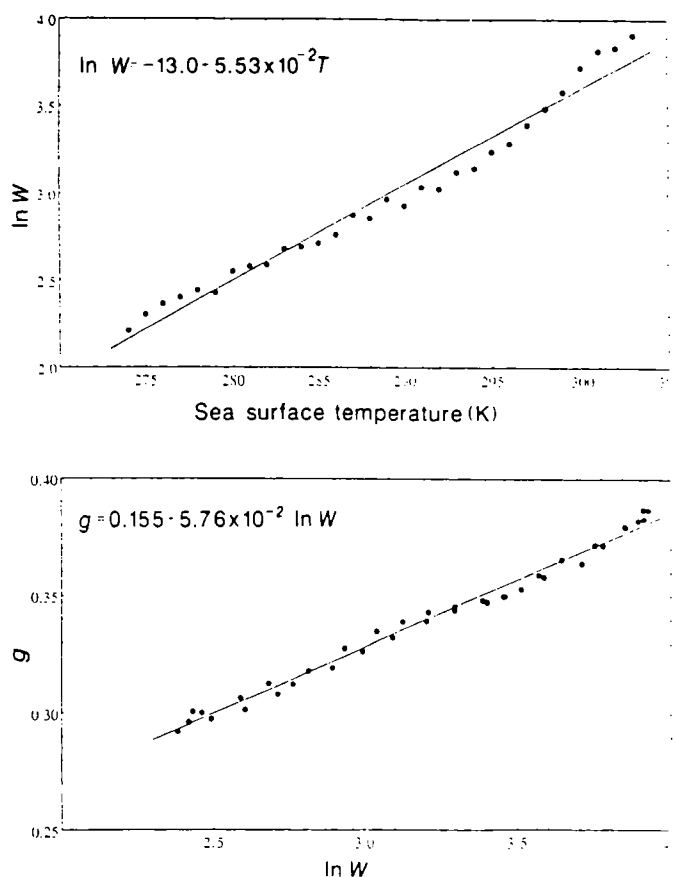


FIG. 3 a. Natural logarithm of the atmospheric water content (W , kg m^{-2}) as a function of surface temperature. April 1982, monthly averages for $3^\circ \times 5^\circ$ regions. The water content was derived from microwave satellite soundings¹³ available for 1979–1983. The error in W is $\sim 10\%$ (ref. 13). The strong positive correlation indicates that the behaviour of W follows simple thermodynamic laws; the slight upward and then downward deviations are consistent with the latitudinal variations in relative humidity² and lapse rate¹¹ which are governed by the dynamics of the atmosphere. b. Normalized clear-sky greenhouse effect (g) for April 1985 plotted against $\ln W$ for April 1982. ERBE data is not available before 1985 whereas W is not available after 1983. To minimize the effect of year to year variations in W , we have used zonally averaged values.

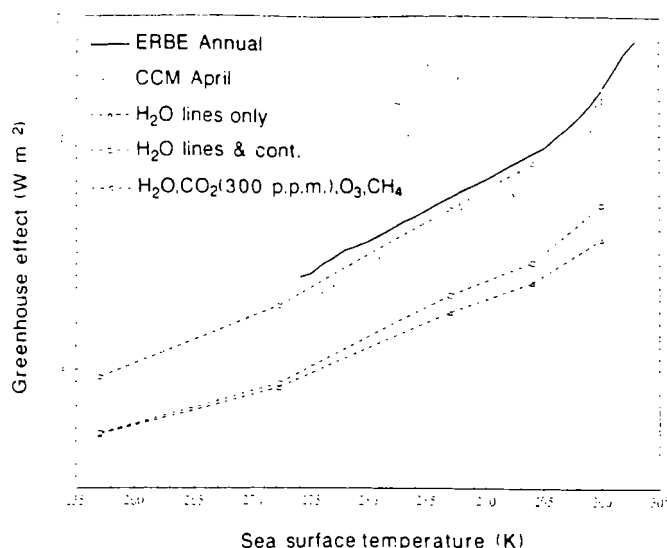


FIG. 4 Comparison of G and surface temperature, retrieved from three sources: bold line, ERBE annual values, obtained by averaging April, July and October 1985 and January 1986; thin line, three-dimensional climate-model simulations for a perpetual April (National Center for Atmospheric Research, Community Climate Model); dashed lines, line-by-line radiation-model calculations by Dr A. Arking (cited in ref. 16) for individual H_2O spectral lines, as well as the continuum absorption. The five points use climatological winter and summer atmospheric profiles for subarctic and mid-latitude conditions, and a tropical profile. A comparison of the calculated G with and without the continuum absorption (bottom two dashed lines) indicates a nonlinear contribution from the continuum. This may in part account for the nonlinear rise at the highest temperatures in the ERBE-derived G . When CO_2 , O_3 and CH_4 are added (the top dashed line) the line-by-line model results come close to ERBE values.

dependence is consistent with state-of-the-art radiative-transfer calculations¹⁶ (Fig. 4). These calculations use observed humidity and temperature profiles for each climate type (subpolar winter, midlatitude summer, for example). Hence, their agreement with the observed G indicates that the 'return loop' in the H_2O feedback, $\partial g / \partial (\ln W)$, behaves as expected from theory. Second, the sensitivity dG/dT_s of the NCAR Community Climate Model (CCM)¹⁷ agrees closely with the observed sensitivity (Fig. 4). The CCM is a three-dimensional general circulation model. The model ignores the radiative effects of trace gases such as CH_4 and N_2O (which contribute $\sim 5\text{--}7\text{ W m}^{-2}$ to the clear-sky G) and is also drier than the observed climate¹⁸. Hence it systematically underestimates G by $10\text{--}15\text{ W m}^{-2}$. It has, however, a latitudinal sensitivity dG/dT_s of $3.1\text{ W m}^{-2}\text{ K}^{-1}$, which compares well with the value of $3.3\text{ W m}^{-2}\text{ K}^{-1}$ obtained from ERBE, averaged annually and over the whole range of sea surface temperatures.

Finally, the general circulation model (GCM) designed by S. Manabe shows a climate sensitivity consistent with the analysis of ERBE flux observations. Wetherald and Manabe calculated¹⁹ that a 2% increase in the solar constant increased the GCMs

outgoing longwave flux by 6.3 W m^{-2} , and the surface temperature increased by 3.0 K. Thus the longwave trapping of the GCM has a sensitivity to the global mean temperature of $dG/dT_s = 4\sigma T_s^3 - dF/dT_s$, or $3.7\text{ W m}^{-2}\text{ K}^{-1}$. A 2% decrease in the solar constant results in a higher sensitivity, $4.0\text{ W m}^{-2}\text{ K}^{-1}$. The cloud cover is held constant in this model, hence the cloud-cover feedback is zero. The observed sensitivity is within 15% of the GCM values. This implies that the climatological sensitivity of this GCM is in good agreement with the latitudinal sensitivity of the present atmosphere. Such behaviour is necessary if the change in the equilibrium climate is determined largely by the H_2O greenhouse feedback.

The analysis up to this point is very encouraging—the independent climate data sets show an overall consistency that can be explained in terms of thermodynamics and radiation physics. This is perhaps one of the best indicators of the accuracy of satellite data. We find compelling evidence that the H_2O feedback is detectable from ERBE observations and that it can account for most (at least 80%) of the observed variation of G with surface temperature. Other atmospheric processes, such as the variation of relative humidity or lapse rate with latitude, are needed to explain the remaining variation.

Implications to the global warming problem

The coupling between surface temperature and the greenhouse effect will lead to a strong positive feedback on any perturbations to the present climate. One significant implication is that we might detect the greenhouse effect of human activities. The increase in trace gases, if it continues unabated, will directly increase G by about 0.5 W m^{-2} per decade. The cumulative increase in G for the next 50 years will then be $\sim 2.5\text{ W m}^{-2}$. In the same period, the globe is expected to warm by 2–4 K (ref. 8). Because of the coupling between T_s and g , the global G will actually increase by a further $6.5\text{--}13\text{ W m}^{-2}$, leading to a total increase of $9\text{--}15.5\text{ W m}^{-2}$. Such an increase should be clearly detectable if we continue ERBE-type observations into the next century. If the tropical regions exhibit the nonlinear increase revealed by the ERBE data (Fig. 2), the effect should be most prominent in the tropics.

Both the cloudy and clear-sky greenhouse effect increases rapidly at temperatures characteristic of the tropics. It is at present not known whether this nonlinear rise is simply a climatological feature of low latitudes, unrelated to temperature variations. For example, the relatively dry regions found in the subtropics ($290 < T_s < 298\text{ K}$) may slightly suppress the rate of increase of g with T_s and hence change the slope.

The nonlinearity might, on the other hand, be due to the nonlinear dependence of the H_2O continuum opacity¹⁶ or a temperature threshold for deep convection²⁰. Because deep convection is a source for the ice content of cirrus clouds, the greenhouse effect of cirrus clouds can increase with T_s when T_s exceeds a certain threshold value. If so, the magnitude of the positive feedback is so large that we should look for a compensating negative feedback elsewhere in the system to explain the relative stability of the tropical climate during the last great ice age.

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- Hansen, J. et al. *Climate Processes and Climate Sensitivity* (eds Hansen, J. & Takahashi, T.) 130–163 (Am. Geophys. Un., Washington, DC, 1984).
- Manabe S. & Wetherald, R. T. *J. Atmos. Sci.* **24**, 241–259 (1967).
- Cess, R. D. *J. Atmos. Sci.* **33**, 1831–1843 (1976).
- Barkstrom, B. R. *Bull. Am. Met. Soc.* **65**, 1170–1185 (1984).
- Ramanathan, V. et al. *Science* **243**, 57–62 (1989).
- Beutner, K. J. K. & Kern, C. D. *J. Geophys. Res.* **70**, 1329–1337 (1965).
- Reynolds, R. W. *J. clim.* **1**, 75–86 (1988).
- Dickinson, R. E. & Cicerone, R. J. *Nature* **319**, 109–114 (1986).
- Prabhakara, C., Short, D. A. & Volmer, B. E. *J. Clim. appl. Met.* **24**, 1311–1324 (1985).
- Mitchell, J. F. B., Wilson, C. A. & Cunningham, W. M. Q. *J. R. met. Soc.* **113**, 293–322 (1987).
- Stone, P. H. & Carlson, J. H. *J. Atmos. Sci.* **36**, 415–423 (1979).

- Coakley, J. A. *J. Atmos. Sci.* **34**, 465–470 (1977).
- Prabhakara, C., Chang, H. D. & Chang, A. T. C. *J. appl. Met.* **21**, 59–68 (1982).
- Stephens, G. *J. Clim.* (in the press).
- Goody, R. M. *Atmospheric Radiation* Vol. 1, Ch. 9 (Oxford University Press, 1964).
- Luther, F. M. *World Climate Programme* Vol. 93 (WMO Geneva 1984).
- Williamson, et al. *NCAR Technical Note NCAR/TN-285-STR* (NCAR, Boulder, Colorado 1987).
- Kiehl, J. T. & Ramanathan, V. *J. Geophys. Res.* (in the press).
- Wetherald, R. T. & Manabe, S. *J. Atmos. Sci.* **32**, 2044–2059 (1975).
- Gadgil, S., Joseph, P. V. & Joshi, N. V. *Nature* **312**, 142–143 (1984).

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Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño

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Observations made during the 1987 El Niño show that in the upper range of sea surface temperatures, the greenhouse effect increases with surface temperature at a rate which exceeds the rate at which radiation is being emitted from the surface. In response to this 'super greenhouse effect', highly reflective cirrus clouds are produced which act like a thermostat, shielding the ocean from solar radiation. The regulatory effect of these cirrus clouds may limit sea surface temperatures to less than 305 K.

WATER vapour and clouds are the dominant regulators of the radiative heating of the planet. General circulation model studies have identified the complex effects of the various cloud and water vapour feedbacks and their importance to climate change¹⁻³. We do not understand how these radiative effects respond to a climate change, nor do we understand their feedback effects. What we need is a natural climate-change experiment in a region that exhibits a strong coupling between surface temperatures and radiative fluxes. The tropical Pacific shows such behaviour. In particular, during the El Niño events which occur once every 2-6 years⁴, the equatorial Pacific warms by as much as 2-4 K, and the warming is accompanied by marked variations in the radiation fluxes at the top of the atmosphere⁵. Accurate data on the radiation budget from the Earth radiation budget experiment (ERBE)⁶ and sea-surface-temperature (SST) data from weather satellites and ships⁷ are available for the 1987 El Niño⁸. We use this data set to explore the link between ocean warming and the radiative feedbacks. Relevant definitions are given next.

The total greenhouse effect of the atmosphere and clouds, G , is defined⁹ as $G = E - F$, where F is the radiation emitted to space, and $E = \sigma T^4$ is the energy emitted by the ocean surface, with $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ and $T = \text{SST}$. Observations of F over the clear-sky regions, F_c , are employed to obtain the atmospheric portion of the greenhouse effect, $G_a = E - F_c$. The difference between G and G_a gives the enhancement of the greenhouse effect caused by clouds, or 'cloud long-wave forcing', $C_1 = G - G_a = F_c - F$. Clouds also enhance the albedo (reflectivity) of the planet, thereby decreasing the planetary solar heating. This effect, the 'cloud short-wave forcing' (ref. 6), C_s , is estimated by subtracting the solar energy absorbed by a region from that over just the clear-sky portion of that region. Hence, the absorbed solar energy can be expanded as $S(1 - A) = S_c + C_s$, where S is the solar radiation at the top of the atmosphere, A is the column albedo, and S_c is the clear-sky solar absorption. ERBE measurements yield the fluxes for the top of the atmosphere of F , F_c , S and S_c together with the albedo A . Thus we have observable definitions for the various feedback terms.

During the El Niño of 1987, the equatorial Pacific warmed by as much as 3 K (Fig. 1a). The warming was accompanied by a significant increase in the greenhouse effect of the atmo-

sphere (Fig. 1b) and that of the clouds (Fig. 1d). These positive feedback effects are offset by a significant decrease in the absorbed solar energy (Fig. 1c). We show that this cirrus regulation of ocean warming is triggered primarily when SSTs exceed 300 K. Results of past studies⁹⁻¹³ enable us to conclude that the interactions between SST, deep convection, large-scale transport of moisture and cirrus formation are responsible for the observed negative feedback effect of cirrus.

Analyses of the interactions

We begin with the net radiative heating of the surface-atmosphere system, $H = S(1 - A) - F$. Adopting the previous definitions for $F = \sigma T^4 - G_a - C_1$ and $S(1 - A) = S_c + C_s$, we have

$$H = S_c - \sigma T^4 + G_a + C_1 + C_s \quad (1)$$

The absorbed solar radiation, S_c , heats the surface, which emits the energy as long-wave radiation, σT^4 . An amount G_a is

TABLE 1 Summary of feedback terms

a. Experiment 1: spatial and seasonal

Domain	Period (month/year)	dG_a/dT ($\text{W m}^{-2} \text{ K}^{-1}$)	dC_s/dC_1
25°N-25°S	4/85	5.6†	-1.07*
	4/87	6.5†	-1.03†
	2/87	6.9†	-0.96*
	2/88	6.3†	-0.94*
	4/85	7.2†	-1.13*
10°N-10°S	4/87	8.1*	-1.12*
	2/87	8.2*	-0.9†
	2/88	8.5†	-0.9†
	2/85	4.6*	-1.01*
	4/85	5.2†	-1.26*
0-25°N	2/85	7.4†	-1.03†
0-25°S	4/85	6.5†	-0.87*
10°N-10°S	4/85; 2/87; 2/88; 4/89	7.7*	-0.95†
Atlantic	Same	7.9*	-1.03†
Indian Ocean	Same	8.1†	-1.03†

b. Experiment 2: El Niño

Domain	Period (month/year)	dG_a/dT ($\text{W m}^{-2} \text{ K}^{-1}$)	dC_s/dC_1	dC_s/dG	a_s ($\text{W m}^{-2} \text{ K}^{-1}$)	a_l
10°N-10°S	{4/87-4/85; 4/89-4/87; 2/88-2/87}	6.8*	-1.2*	-0.92†	-22†	18*
	4/87-4/85	9.2*	-1.33†	-0.97*	-20*	16*
	4/89-4/87	8.5*	-1.23†	-0.95†	-19†	17*
	2/87-2/85	6.4†	-1.09†	-0.97†		
	2/88-2/87		-1.11*	-0.97*		
	5/87-5/85	8.0*	-1.22†	-0.92†		
	7/87-7/85	5.7*	-1.17†	-0.79†		
	10/87-10/85	6.0*	-1.32†	-0.99*		

Unless otherwise stated, the domain is the Pacific Ocean stretching from 140°E (western Pacific) to 90°W (eastern Pacific). SST is denoted by T ; the atmospheric greenhouse effect by G_a ; the cloud long-wave forcing is C_1 ; the total greenhouse effect is $G = G_a + C_1$; the cloud modulation of absorbed solar energy is the cloud short-wave forcing C_s ; and the cloud-forcing slopes a_s (short-wave) and a_l (long-wave) are obtained from Fig. 4a and b, respectively.

* Correlation coefficient $|r|$ for least-squares linear fit is in range $0.9 > |r| > 0.8$

† $|r| > 0.9$

‡ $0.8 > |r| > 0.7$. When $|r| < 0.7$, the correlation is considered insignificant and is omitted from the table.

trapped in the atmosphere, thus reducing the cooling to space. The long-wave energy flow out of the system is further reduced by the flux C_1 trapped in clouds. But this heating effect is offset by the reduction C_s of solar absorption by clouds with $C_s < 0$. We wish to examine how G_a , C_1 and C_s vary with T . These dependences are obtained both from the spatial and seasonal variations in T and from the 1987 El Niño, which began during late 1986.

We use ERBE measurements for 1985–89. The SSTs are obtained from combined analyses from the National Oceanic and Atmospheric Administration and the National Meteorological Center⁷ of satellite and *in situ* data. The data are monthly averaged values with a spatial resolution of 2.5° (latitude) $\times$ 2.5° (longitude). The analyses will focus primarily on April, but we will briefly review results for the months of February, May, July and October. April is preferred for several reasons. Because of the near-hemispherical symmetry of solar radiation and of meteorological features in the equatorial regions, we can safely ignore hemispherical asymmetries in the dependence on the solar zenith angle before comparing the albedos of the different oceans. Around April, equatorial SSTs reach peak seasonal values and exceed 300 K over most of the Pacific⁴, the minimum SST necessary to initiate deep convection. Finally, the 1987 El Niño warming stabilized at near-maximum values around April 1987.

Experiment 1

In this experiment, we examined spatial variations in the greenhouse effect and cloud forcing for different seasons. The total

greenhouse effect $G = G_a + C_1$ increases sharply when the SST exceeds ~ 300 K (Fig. 2a), a feature that is present in all the months and can also be inferred from earlier studies^{14,15}. Optically thick cirrus clouds in the upper troposphere are needed to account for the large increase in G of ~ 100 W m^{-2} as the temperature increases from 300 to 303 K. The slope, dG_a/dT , for the tropical Pacific (10° N to 10° S) is $\sim 6\text{--}9$ $\text{W m}^{-2} \text{K}^{-1}$ (Fig. 2b, and Table 1), whereas it is ~ 3.4 $\text{W m}^{-2} \text{K}^{-1}$ for the entire Pacific (60° N to 60° S). About half of the 3.4 $\text{W m}^{-2} \text{K}^{-1}$ is due to atmospheric trapping of the increased black-body emission. The balance is due to water vapour feedback⁹: the warmer atmosphere contains more water vapour which in turn traps more radiation. The fact that $dG_a/dT > 6$ $\text{W m}^{-2} \text{K}^{-1}$ has important climate implications.

The surface emission increases at a rate close to $dE/dT = 4\sigma T^3 \approx 6.1$ $\text{W m}^{-2} \text{K}^{-1}$ at $T = 300$ K. But as $dG_a/dT \geq dE/dT$, the energy cannot escape to space but instead is trapped in the atmosphere. Indeed, the slightly larger slope of G_a suggests that the trapping increases faster than the surface emission. The main deduction is that the warmer tropical-ocean/atmosphere system has lost the fundamental negative feedback between temperature and infrared emission which expels excess heat by radiating to space. This tropical 'super greenhouse effect' is caused by a combination of several mutually reinforcing factors, including increases in total-column H_2O ^{9,10,16}, H_2O continuum absorption¹⁷ which scales quadratically with H_2O partial pressure; higher middle- and upper-troposphere H_2O concentrations¹⁹, and changes in the lapse rate^{18,19}. The system is potentially unstable unless another negative feedback exists to stabilize it,

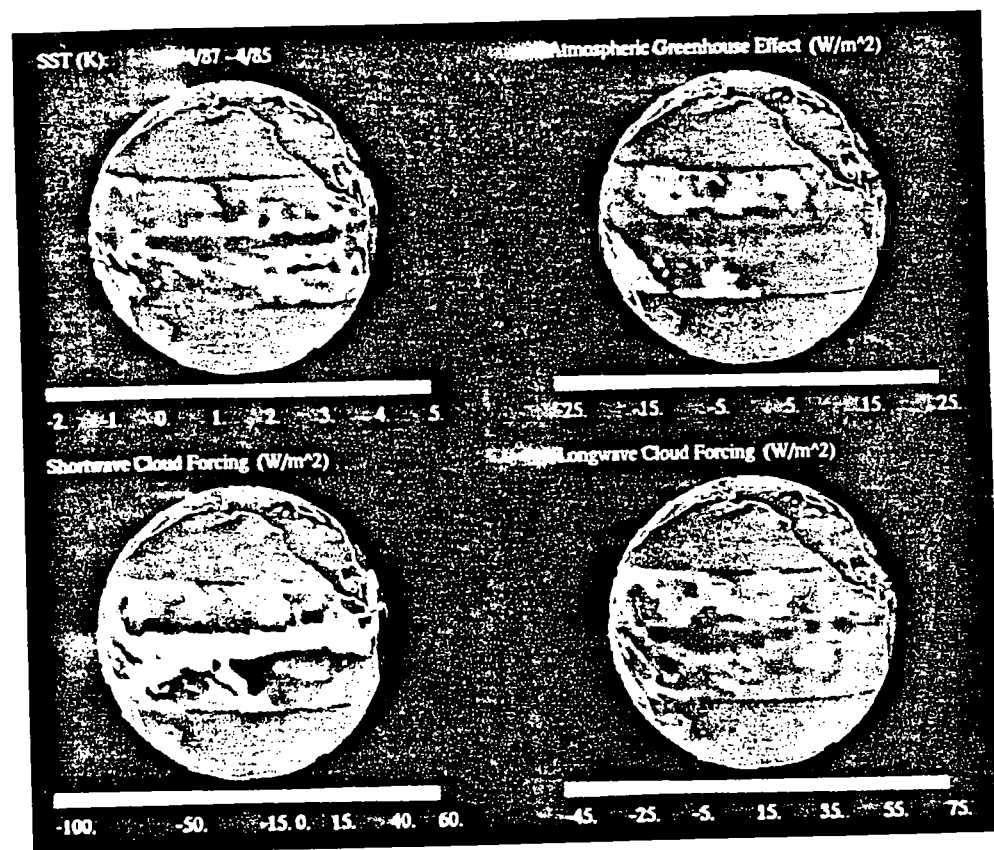


FIG. 1 Changes in the SST, the greenhouse effect and the cloud forcing accompanying the 1987 El Niño. Top left panel (a), April 1987 minus April 1985 monthly mean SSTs for 25° N to 25° S. Outside this region changes are much smaller. SST data are obtained from ref. 7. The equatorial warming began during late 1986 and was well established by April of 1987 (ref. 8). Top right panel (b), April 1987 minus April 1985 atmospheric greenhouse effect. Bottom left panel (c), April 1987 minus April 1985 cloud short-wave

forcing. The El Niño warming leads to highly reflective clouds which reduce (as $C_s < 0$) the solar energy absorbed by the oceans by as much as 100 W m^{-2} . Bottom right panel (d), April 1987 minus April 1985 cloud long-wave forcing, C_1 . The greenhouse effect of clouds increases significantly over the regions subject to the surface warming. Increased cirrus cloudiness in the upper troposphere is needed to account for changes in C_1 larger than 30 W m^{-2} .

and this brings us to the changes in the cloud forcing. The cloud-forcing terms C_1 (Fig. 1d) and C_s (Fig. 1c) also increase in magnitude for warmer oceans (Fig. 1a). A closer examination of the relationship between C_1 and C_s (Fig. 2c), reveals the strong degree of anti-correlation between the two, which can also be deduced from results published earlier²⁰⁻²². The generality of this finding is shown in Table 1. This remarkable correlation and the fact that large negative values of C_s are correlated with warmer waters (Fig. 1d) lead to the following conjecture: as the tropical oceans warm, the rapid rise of G_a with SST leads to an unstable feedback. The warming continues until the clouds become thick enough to shield the ocean from the solar radiation and arrest further warming. This thermostat effect of the cirrus anvils controls the maximum value of SSTs. The validity of this inference is examined next.

Experiment 2

In this experiment, we examined the flux changes that occurred during the 1987 El Niño. The observed changes are very similar to those inferred above. First, G_a increases with SST (Fig. 3a) at a rate of $6-9 \text{ W m}^{-2} \text{ K}^{-1}$. The plot of dC_s against dC_1 (Fig. 3b) confirms that clouds with large C_1 are also very reflective. As $dC_s/dG \approx -1$, the decrease in the absorbed solar energy nearly balances the increase in the total greenhouse effect (Fig. 3c). These results support the inference from experiment 1 that G increases significantly with a warming of the ocean, and this unstable increase is effectively offset by the brighter clouds resulting from the warming. Similar results are obtained for the months of February, May, July and October (Table 1), but results for February and July should be viewed with caution as we have not accounted for seasonal changes in the incoming solar radiation and the solar zenith angle, both of which have complex and largely unknown effects on the cloud-forcing terms.

To probe further into the link between the warming and the absorbed solar energy, we plot the product of dT and dC_s

against $(dT)^2$ for each $2.5^\circ \times 2.5^\circ$ region (Fig. 4). If the relationship is linear, we can obtain the rate of decrease of C_s with increase in SST from the slope, a_s . A statistically significant relationship does exist for April (Fig. 4 and the column under a_s in Table 1), although it is weaker for the other months; for example, for February 1987 minus February 1985 and for May 1987 minus May 1985, a_s is $\sim -15 \text{ W m}^{-2} \text{ K}^{-1}$. The correlation coefficient $|r|$ is only ~ 0.6 and is almost zero for July and October. But we may obtain a better picture by examining the relationship on a larger scale.

We focus on the region of maximum warming, the central and eastern Pacific from 180° (the date line) to 90° W and 5° N to 5° S . During April, for example, the average SST for this region increased from 300.1 in 1985 to 301.9 K in 1987 and the average C_s changed from -29 in 1985 to -63 W m^{-2} in 1987 ($dC_s = -34 \text{ W m}^{-2}$); for February, SST increases from 299.2 to 301 K and $dC_s = -32 \text{ W m}^{-2}$; for May, SST increases from 300 to 301.7 K and $dC_s = -34 \text{ W m}^{-2}$; for July, the changes are from 299 to 301 K and $dC_s = -12 \text{ W m}^{-2}$; and finally for October, SST increases from 298.6 to 300.3 K and $dC_s = -6 \text{ W m}^{-2}$. Several inferences can be made. First, on the larger scale the warming is accompanied by a decrease in solar absorption without exception. This is reassuring as the processes that link SST with C_s involve cooperative interaction between deep convection and the large-scale circulation which transports moisture into the region of warming from the rest of the tropical Pacific (details given later). Second, if we exclude the colder eastern Pacific from 90° W to 120° W , which is mostly devoid of deep convection, dC_s for October decreases from -6 to -13 W m^{-2} with similar decreases (ranging from -5 to -9 W m^{-2}) during other months. This is another indication of the role of deep convection in triggering the negative feedback between SST and C_s . Finally, the marked decrease of $-dC_s$ towards October, which roughly marks the final phase of the El Niño, is a reminder of the transient nature of the event. As the El Niño warming is

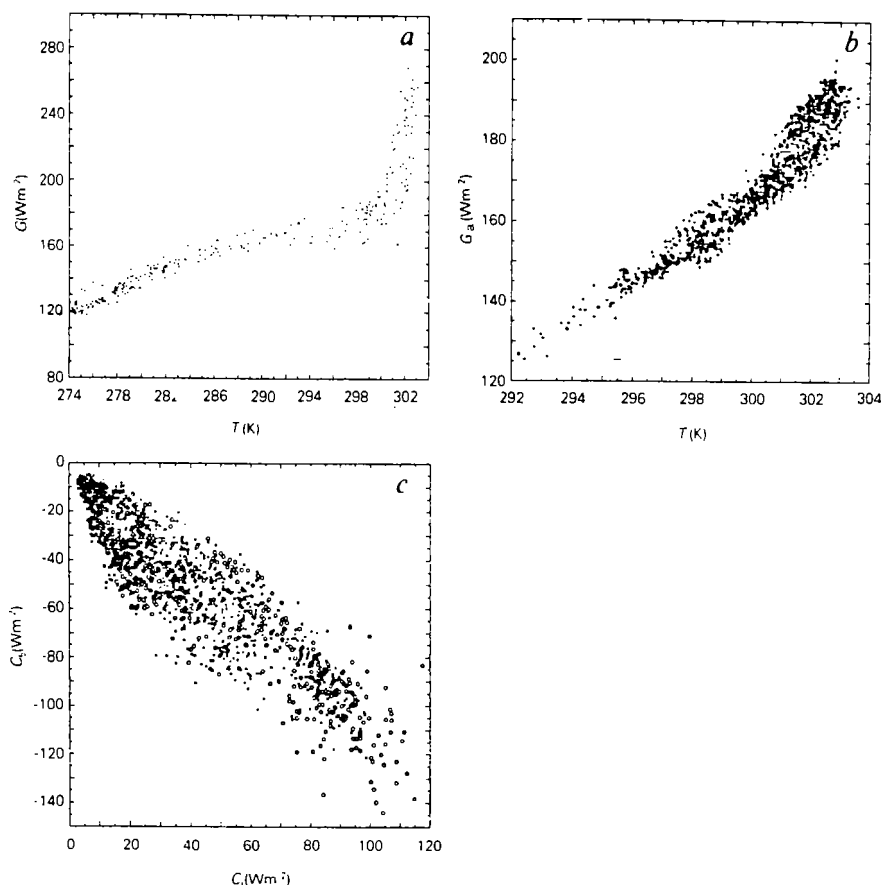
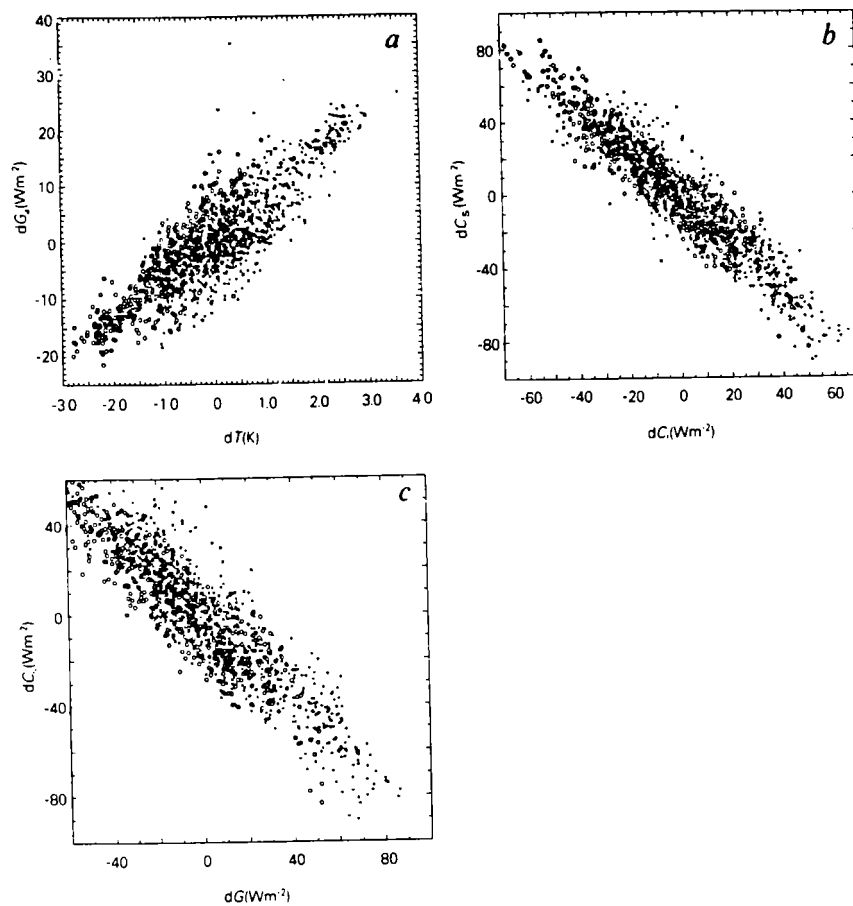


FIG. 2 Monthly mean greenhouse effect and cloud-forcing terms for the Pacific extending from 140° E to 90° W . Each point in this and other figures represents a monthly averaged value for a 2.5° (latitude) $\times 2.5^\circ$ (longitude) region. a, Total greenhouse effect, G , plotted as a function of SST for April 1987 from 85° N to 85° S . Regions with $\text{SST} < 274 \text{ K}$ are excluded. b, Atmospheric greenhouse effect G_a against SST for the tropical Pacific from 25° N to 25° S for April 1987. The least-squares linear slope is $dG_a/dT = 6.5 \text{ W m}^{-2} \text{ K}^{-1}$ with a correlation coefficient of $r = 0.96$. c, Cloud short-wave forcing against cloud long-wave forcing for the region 10° N to 10° S for 4/85(+), 2/87(O), 2/88(x), and 4/87(·). The linear correlation is $dC_s/dC_1 = -0.951$ ($r = -0.9$).

FIG. 3 Changes induced by 1987 El Niño in monthly mean greenhouse effect, cloud-forcing terms and SST for the Pacific ocean (140° E to 90° W) from 10° N to 10° S. The points represent the differences for 4/87 minus 4/85(+), 4/89 minus 4/87(○), and 2/88 minus 2/87(×). *a*, dG_a against dT where d denotes difference between two years. The linear fit is $dG_a/dT = 6.80 \text{ W m}^{-2} \text{ K}^{-1}$ ($r = 0.85$). *b*, Change in cloud short-wave forcing against change in cloud long-wave forcing. The linear fit is $dC_s/dC_l = -1.20$ ($r = -0.93$). As $dC_s/dC_l < -1$, clouds have a net cooling effect. *c*, Change in cloud short-wave forcing against change in total greenhouse effect $G = G_a + C_l$. The linear fit is $dC_s/dG = -0.92$ ($r = -0.92$), which indicates that the increase in the greenhouse effect is slightly larger than the decrease in solar absorption.



a transient phenomenon which started to revert back to 'normal' conditions around November 1987, considerable changes in the equatorial dynamics during the terminal phase of the El Niño¹³ can be expected to modify the radiative feedbacks.

To explore additional climate implications, we estimate the change of C_l with SST, although acknowledging that this is a hazardous task given the nonlinear nature of the coupling between SST, ocean-atmosphere dynamics and radiation physics. We can use two independent methods: (1) From Fig. 3a, $dG_a/dT \approx 6.8 \text{ W m}^{-2} \text{ K}^{-1}$. As $dC_s = -0.92 (dC_l + dG_a)$ (Fig. 3c) with the further constraint that $dC_s = -1.20 dC_l$ (Fig. 3b), we obtain $dC_s/dT \approx -27 \text{ W m}^{-2} \text{ K}^{-1}$ and $dC_l/dT \approx 23 \text{ W m}^{-2} \text{ K}^{-1}$. (2) The covariance plot (Fig. 4a) of dC_s and dT with $(dT)^2$ and the corresponding plot for dC_l (Fig. 4b) yield $dC_s/dT \approx -22$ and $dC_l/dT \approx 18$, where because of uncertainties in the SST data, regions with $dT < 1 \text{ K}$ are excluded.

Thermodynamics and dynamics of the feedbacks

In what follows, we describe the fundamental principles that govern the observed correlations described above. In the warm climate regimes of interest to this study, the thermodynamics of H_2O have a dominant influence on the radiative feedbacks. The saturation humidity, q_s , depends exponentially on temperature as $\{e^{(-5,400/T)}\}/T$ (T in kelvin). As a result, a 1% increase in T from $T = 300 \text{ K}$, for example, increases q_s by 17%. Indeed, satellite observations^{9,10} reveal that total atmospheric water vapour increases by $\sim 17\%$ per 1% increase in SST. Hence G_a increases with SST.

The latent energy of a parcel of air also grows by 17% per 1% increment in T . When $T > 300 \text{ K}$, a parcel of moist air near the surface has sufficient latent energy that if it is forcibly lifted until it reaches saturation, it can overcome the gravitational potential energy and rise to the upper troposphere as a cumulonimbus cloud^{11,12}. The ice crystals detrained by these deep clouds spread thousands of kilometres downwind in the

form of cirrus anvils^{22,23} and also moisten the upper troposphere¹⁸. The maxima in the cloud-forcing fields (Fig. 1) are caused by the cirrus anvils¹² and not by the cumulonimbus clouds, which are two orders of magnitude smaller²³. When SST drops below 300 K, the latent energy in the surface layer is generally not sufficient to form deep convection²⁴. Hence G increases rapidly when $T > 300 \text{ K}$.

Consider next the total static energy of the atmosphere, $h = C_p T + gZ + Lq$, where the first term is the thermal energy, the second is the gravitational potential energy and the third is the latent energy, with Z the altitude and q the H_2O mass mixing ratio. We rewrite it in the form $h/C_p = T + (g/C_p)Z + (L/C_p)q$ where $g/C_p = 9.8 \text{ K km}^{-1}$ and $L/C_p = 2,500 \text{ K}$. At $T = 303 \text{ K}$, the saturation q at the surface is 0.026, and assuming a reasonable value of 75% for the relative humidity, the latent energy is $\sim 50 \text{ K}$ and $h/C_p = 353 \text{ K}$. If we adopt the observed equatorial temperature and humidity profiles²⁵, h/C_p decreases from 353 K at $Z = 0 \text{ km}$ to 330 K at $Z = 6 \text{ km}$. Above 6 km it increases with Z to $\sim 350 \text{ K}$ at 16 km because of the dominance of the potential energy term. As a result, a surface parcel with SST = 303 K can penetrate to $\sim 16 \text{ km}$. When the SST drops to 297 K, the surface parcel has a static energy of only 330 K and can barely reach the middle troposphere.

The warmer ocean thus produces clouds at higher altitudes. As cloud-top temperature and emission of radiation to space decrease with altitude, these clouds trap more long-wave radiation and have a larger greenhouse effect²⁶. As a result C_l can increase with SST. Why does the solar reflection increase with SST? Deeper penetration by clouds is not sufficient to account for the enhanced solar reflection; in addition, the extent of cloudiness and the optical thickness of the clouds have to increase with SST. The required moisture for sustaining cirrus is not necessarily provided by local evaporation²⁷ but instead by large-scale transport within the lower troposphere into the region of convection^{27,28}. These large circulation systems are the

'Hadley' and 'Walker' circulations⁴. The sources of energy for these large-scale motions are the latent heat released by convection²⁹, the cirrus long-wave cloud forcing and the spatial gradients in SST³⁰. Therefore this convective large-scale system is self-sustaining. The large-scale convergence of moisture into the warm oceanic regions amplifies the warming through the enhanced atmospheric greenhouse effect, further driving the circulation. This continues until the cirrus clouds, which accumulate during this process, reflect enough sunlight to arrest further warming. Thus the anvils act like a thermostat.

Predictions of the thermostat hypothesis

The independent natural experiments support this hypothesis: the feedback between SST, convection and cloud reflection of solar radiation prevents a runaway greenhouse effect on the SST and acts as a thermostat to regulate the maximum ocean temperatures on the planet. The climate implications of this hypothesis are now developed in more detail.

Maximum ocean temperature. Let us consider an ocean region where dynamical transport of heat in the surface layers is negligible so that it can reach the maximum value imposed by the solar absorption. The equatorial western Pacific nearly satisfies this criterion because the net heat flux into the ocean is very small ($0\text{--}20\text{ W m}^{-2}$)^{31,32}. We can therefore apply equation (1) with a correction for atmospheric transport which is discussed next. An examination of the equatorial temperature gradients²⁵ reveals that the mid-to-upper troposphere has negligible east-west and north-south gradients in spite of the fact that the latent heating ($200\text{--}300\text{ W m}^{-2}$)^{4,31} and cloud greenhouse effect add as much as $300\text{--}400\text{ W m}^{-2}$ heat flux in the western portions of the Pacific. Seasonal and longitudinal average temperatures in the upper troposphere differ by less than 2 K between 25° N to 25° S . Likewise, the upper troposphere in the equatorial western Pacific is less than 2 K warmer than that of the eastern Pacific 10^4 km away. This homogeneity follows from the balancing of latent and radiative heating in the tropical atmosphere by adiabatic cooling resulting from convective and large-scale overturning³³. In particular, adding energy to the upper troposphere is very effective in driving the Walker and the Hadley cell circulation²⁹. Recent general circulation model studies^{34,35} also suggest that the radiative energy converging in the anvils does not cause localized warming over the anvil regions. Instead, the warming is uniformly distributed over the entire tropical region.

We therefore assume that the C_1 term, which is largely heat trapped in the troposphere, is transported out of the western Pacific, and only a small fraction contributes to warming the ocean locally. This fraction, f , ranges between 0 and 0.2. The upper bound is related to the fraction of the long-wave emission from the base of cirrus clouds that can reach the ocean surface directly. Incidentally, C_1 ($\sim 60\text{--}80\text{ W m}^{-2}$) is nearly equal to the net annual mean radiative heating of 80 W m^{-2} (ref. 36) at the

top of the atmosphere minus the oceanic heat transport³² of $\sim 0\text{--}20\text{ W m}^{-2}$ in the western Pacific region. This implies that 60 W m^{-2} is being transported out of the region by advection within the atmosphere, which is consistent with the assumed range for f .

On the other hand, the C_s term represents a direct loss of solar energy to the ocean surface³⁴. With the above inferences, equation (1) can be rephrased as follows:

$$\text{SST}_{\text{max}} = T_0 + \{(S_c + G_0 - \sigma T_0^4)/\beta\} \quad (2)$$

$$\text{where } \beta = 4\sigma T_0^3 - dG_a/dT - f dC_1/dT - dC_s/dT$$

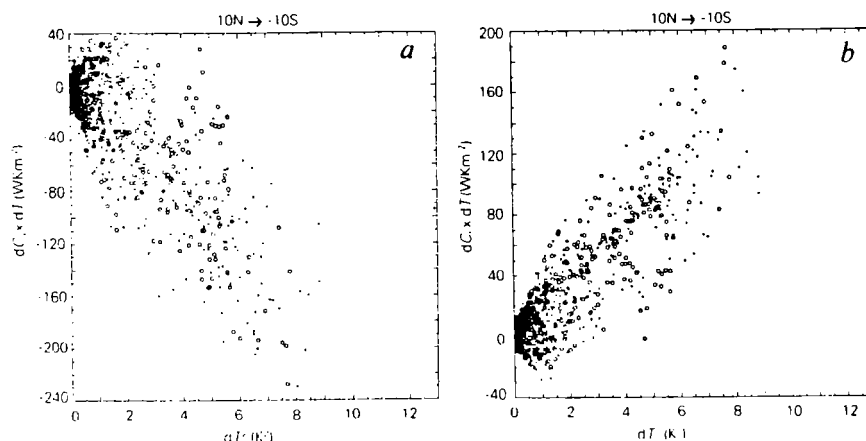
The net radiative feedback is denoted by β . The variables have been expanded about a reference temperature T_0 ; for example, $G_a = G_0 + dG_a/dT$, where $G_0 = 165\text{ W m}^{-2}$ is the value of G_a at T_0 , assumed to be 300 K. It is safe to assume an uncertainty of $\sim \pm 15\text{ W m}^{-2}$ in the radiative flux terms. The clear-sky solar absorption is $S_c = S(1 - A_c) = 370\text{ W m}^{-2}$, where $S = 424\text{ W m}^{-2}$ is the annual mean equatorial solar radiation and $A_c = 0.1$ is the clear-sky albedo, and we subtract 12 W m^{-2} for stratospheric solar absorption³⁷. Similarly, the stratospheric contribution of 5 W m^{-2} to G_a has been subtracted from G_0 . The values derived from Figs 3 and 4 are adopted for the various feedback terms in β . Changes in the equatorial atmospheric temperature and humidity profiles in response to SST changes are implicitly included in the long-wave feedback terms, as dG_a and dC_1 are obtained directly from observed changes. The cloud feedback terms arising from convection will be zero when $T < T_0$, and the black-body term is $4\sigma T_0^3 = 6.1\text{ W m}^{-2}\text{ K}^{-1}$. Note first that in the absence of the cloud feedback terms, the black-body negative feedback (the first term in the denominator) is dominated by the positive feedback effect of dG_a/dT ($6.8\text{ W m}^{-2}\text{ K}^{-1}$), creating a potentially unstable state. Substitution of $-27 < dC_s/dT < -22$ and $18 < dC_1/dT < 23$ yields:

$$303 < \text{SST}_{\text{max}} < 305\text{ K}$$

The lower limit is for $f = 0.0$ and $dC_s/dT = -27$, and the upper limit of 305 K is for $f = 0.2$ and $dC_s/dT = 22\text{ W m}^{-2}\text{ K}^{-1}$ (from Fig. 3). If we allow 20 W m^{-2} for oceanic heat transport, the 305 K value drops to $\sim 304\text{ K}$ and the 303 K value drops to 302 K in agreement with observed western Pacific SSTs (Fig. 2a). For the above example, the feedback value ranges between $15 < \beta < 26\text{ W m}^{-2}\text{ K}^{-1}$. This large damping should tend to minimize the seasonal variations of the SST in the western Pacific.

Evaporative cooling of the warm oceans is another possible mechanism^{15,25} for limiting SSTs, but this cannot be a limiting factor for several reasons: (1) the added moisture to the boundary layer will enhance G_a ; and (2) observed precipitation exceeds evaporation by nearly a factor of 2 in the western Pacific^{4,25,31} (the western Pacific ocean imports rather than

FIG. 4 a, Change induced by 1987 El Niño in solar absorption by the ocean-atmosphere system. Product of dC_s and dT against $(dT)^2$ for the Pacific, 10° N to 10° S . The points represent the differences between 4/87 and 4/85(+) and 4/89 and 4/87(○). A negative value for the product indicates a decrease (increase) in absorbed solar energy with a warming (cooling) of the ocean. The linear fit is $dC_s/dT = -19\text{ W m}^{-2}\text{ K}^{-1}$ ($r = -0.80$). The error in SST data is 1 K, and when regions with $dT < 1\text{ K}$ are excluded the fit is $dC_s/dT = -22\text{ W m}^{-2}\text{ K}^{-1}$ ($r = -0.73$). b, Same as (a) but for cloud long-wave forcing. The linear fit is $dC_1/dT = 16$ and increases to $17.5\text{ W m}^{-2}\text{ K}^{-1}$ when points with $dT < 1\text{ K}$ are excluded.



exports water vapour). This inference, albeit based on imprecise observations, is also substantiated by the low salinity of the surface water³¹. What is needed is a permanent loss of energy, and reflection of sunlight back to space is the most efficient mechanism to accomplish this task.

El Niño warming. The basic hypothesis should apply during an El Niño as well. Indeed, during both the 1987 El Niño and the more severe 1983 El Niño⁴, the maximum SST did not exceed 303 K. In the central and eastern Pacific, upwelling of colder water from below and advection of cold water from the eastern coast causes SSTs to drop below 303 K (refs 4, 31). When the dynamical cooling effects abate during periods such as an El Niño year, the SST approaches the maximum value permitted by the anvil thermostat. Thus the El Niño year constitutes the equilibrium state of the Pacific, whereas the non El Niño years are the periods when the central and east Pacific is pulled away from equilibrium by the ocean dynamics.

Greenhouse and solar-dominated climate regimes

For the oceans⁹, the globally averaged greenhouse effect (G) is 175 W m^{-2} and the absorbed solar radiation is 240 W m^{-2} . For the warmest equatorial oceans, the maximum values are $G \approx 280$ (Fig. 2a) and solar absorption $\sim 300 \text{ W m}^{-2}$ (ref. 36). In the absence of clouds, S can be as large as 380 W m^{-2} (ref. 6). Thus as the planet gets warmer, it shifts from a solar-energy-dominated regime to a regime in which the greenhouse effect becomes comparable to the solar absorption. The extreme example of this convective response to warming is Venus, with a convectively driven deep troposphere of $\sim 60 \text{ km}$, overcast conditions

and a high planetary albedo of 80% (compared with 30% for Earth). As a result, although Venus receives twice as much solar radiation as Earth at the top of the atmosphere, the absorbed solar radiation is smaller ($\sim 150 \text{ W m}^{-2}$). But in spite of this brightening effect, the planet is hotter (750 K) because its atmospheric greenhouse effect exceeds $17,000 \text{ W m}^{-2}$.

The feedback between convection, greenhouse effect and planetary brightness limits the temperatures in the warmest regions of the Earth to less than 305 K. What is the implication of this negative feedback if its validity extends to a perturbed atmosphere? It would take more than an order-of-magnitude increase in atmospheric CO_2 to increase the maximum SST by a few degrees, in spite of a significant warming outside the equatorial regions. In this regard, the present hypothesis departs considerably from modern general circulation models. It is encouraging, however, that some model studies^{1,16} are finding a marked feedback in the thermodynamic link between SST and cirrus properties. More significantly, a recent coupled ocean-atmosphere/general circulation model study²⁸ has suggested that the interaction between SST and solar radiation at the ocean surface is an important negative feedback in the El Niño dynamics. This result was also indicated qualitatively by earlier studies^{15,38}. For the hypothesis to become a validated theory, we need to establish the link between convection dynamics, large-scale moisture convergence into the warm regions and the brightness of those regions. Three-dimensional climate models in conjunction with detailed field and satellite observations can provide that link, but first the models must pass the test posed by the El Niño observations. $\square$

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- Mitchell, J. F. B., Senior, C. A. & Ingram, W. J. *Nature* **341**, 132-134 (1989).
- IPCC *Climate Change* (Cambridge University Press, 1990).
- Cess, R. D. et al. *Science* **245**, 513-516 (1989).
- Philander, S. G. *El Niño, La Niña & the Southern Oscillation* (Academic, London, 1990).
- Ardanuy, P. E. & Kyle, H. L. *Mon. Weath. Rev.* **114**, 415-433 (1986).
- Harrison, E. F. et al. *J. geophys. Res.* **95**, 18687-18703 (1990).
- Reynolds, R. W. *J. Clim.* **1**, 75-86 (1988).
- WMO Report: *The Global Climate System 1986-1988 3rd Biennial Rev.* (CSMR 89/86 Geneva).
- Raval, A. & Ramanathan, V. *Nature* **342**, 758-761 (1989).
- Stephens, G. L. *J. Clim.* **3**, 634-645 (1990).
- Betts, A. K. & Ridgway, W. J. *atmos. Sci.* **46**, 2621-2641 (1989).
- Houze, R. A. & Betts, A. K. *Rev. Geophys. Space Phys.* **19**, 541-576 (1981).
- Cane, M. A. & Zebiak, S. E. *Science* **228**, 1085-1087 (1985).
- Gadgil, S., Joseph, P. V. & Joshi, N. V. *Nature* **312**, 141-143 (1984).
- Graham, N. E. & Barnett, T. P. *Science* **238**, 657-659 (1987).
- Somerville, R. C. & Remer, L. J. *geophys. Res.* **89**, 9668-9672 (1984).
- Hallberg, R. thesis Univ. of Chicago (1990).
- Rind, D. et al. *Nature* **349**, 500-503 (1991).
- Hallberg, R. Eureka Conf. Abstr. ENV1.1K CALTECH (Calif. Inst. Technol., Pasadena, California, 1991).
- Cess, R. D., Briegleb, B. P. & Lian, M. S. *J. atmos. Sci.* **39**, 53-59 (1982).
- Randel, D. L. & von der Haar, T. H. *J. Clim.* **3**, 1168-1173 (1990).
- Liou, K. *Mon. weath. Rev.* **114**, 1167-1199 (1986).
- Houze, R. A. & Hobbs, P. V. *Adv. Geophys.* **24**, 225-314 (1982).
- Fu, R., Del Genio, A. D. & Rossow, W. J. *J. Clim.* **3**, 1129-1152 (1990).
- Newell, R. E. et al. *The General Circulation of the Tropical Atmosphere* Vol. 1 (MIT Press, Massachusetts, 1974).
- Ramanathan, V. *J. atmos. Sci.* **34**, 1886-1897 (1977).
- Cornejo-Garrido, A. G. & Stone, P. H. *J. atmos. Sci.* **34**, 1155-1162 (1977).
- Barnett, T. P. et al. *J. Clim.* (in press).
- Hartmann, D. L. et al. *J. atmos. Sci.* **41**, 113-121 (1984).
- Lindzen, R. S. & Nigam, S. *J. atmos. Sci.* **44**, 2418-2428 (1987).
- Pickard, G. L. & Emery, W. J. *Descriptive Physical Oceanography* (Pergamon, Oxford, 1982).
- Gent, P. R. *J. geophys. Res.* **96**, 3323-3330 (1991).
- Holton, J. *Introduction to Dynamic Meteorology* (Academic, 1972).
- Slingo, A. & Slingo, J. M. *Q. J. R. met. Soc.* **114**, 1027-1062 (1988).
- Ramaswamy, V. & Ramanathan, V. *J. atmos. Sci.* **46**, 2293-2310 (1989).
- Stephens, G. et al. *J. geophys. Res.* **86**, 9739-9760 (1981).
- Ramanathan, V. & Dickinson, R. E. *J. atmos. Sci.* **36**, 1084-1104 (1979).
- Ramanathan, V. *J. met. Soc. Japan spec. vol. Short- and Medium-Range Numerical Weather Prediction* 151-176 (1987).

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ERBE

Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment

V. RAMANATHAN, R. D. CESS, E. F. HARRISON, P. MINNIS, B. R. BARKSTROM, E. AHMAD, D. HARTMANN

→ overall, global
feedback from clouds → ⊖ in N. Hem; ⊕ in tropics

The study of climate and climate change is hindered by a lack of information on the effect of clouds on the radiation balance of the earth, referred to as the cloud-radiative forcing. Quantitative estimates of the global distributions of cloud-radiative forcing have been obtained from the spaceborne Earth Radiation Budget Experiment (ERBE) launched in 1984. For the April 1985 period, the global shortwave cloud forcing [-44.5 watts per square meter (W/m^2)] due to the enhancement of planetary albedo, exceeded in magnitude the longwave cloud forcing (31.3 W/m^2) resulting from the greenhouse effect of clouds. (Thus) clouds had a net cooling effect on the earth. This cooling effect is large over the mid- and high-latitude oceans, with values reaching -100 W/m^2 . The monthly averaged longwave cloud forcing reached maximum values of 50 to 100 W/m^2 over the convectively disturbed regions of the tropics. However, this heating effect is nearly canceled by a correspondingly large negative shortwave cloud forcing, which indicates the delicately balanced state of the tropics. The size of the observed net cloud forcing is about four times as large as the expected value of radiative forcing from a doubling of CO_2 . The shortwave and longwave components of cloud forcing are about ten times as large as those for a CO_2 doubling. Hence, small changes in the cloud-radiative forcing fields can play a significant role as a climate feedback mechanism. For example, during past glaciations a migration toward the equator of the field of strong, negative cloud-radiative forcing, in response to a similar migration of cooler waters, could have significantly amplified oceanic cooling and continental glaciation.

CLOUDS ARE REGULATORS OF THE RADIATIVE HEATING OF the planet. They reflect a large part of the incoming solar radiation, causing the albedo of the entire earth to be about twice what it would be in the absence of clouds (1). Clouds also absorb the longwave (LW) radiation (also known as infrared or thermal radiation) emitted by the warmer earth and emit energy to space at the colder temperatures of the cloud tops. Cloud LW absorption and emission are, in a sense, similar to the radiative effects of atmospheric gases. The combined effect of LW absorption and emission—that is, the greenhouse effect—is a reduction in the LW radiation emitted to space. The greenhouse effect of clouds may be larger than that resulting from a hundredfold increase in the CO_2 concentration of the atmosphere (2).

How these two competing effects of clouds vary with time, geography, or cloud type and structure is not well understood; nor do we know how clouds modulate meridional and regional radiative heating. Such heating drives the general circulation of the atmosphere and oceans. Significantly different estimates of cloud radiative effects have been used in models of past and future climates. In short, the fundamental question, whether clouds cool or warm the climate, has remained unanswered.

Cloud-radiative interactions represent a large source of uncertainty in several areas including: (i) the prediction of climate changes associated with an anthropogenic increase in trace gases, and (ii) the understanding of past and future climate changes caused by variations in the solar constant or the orbital parameters of the earth (3, 4). General circulation model (GCM) studies (4) have contributed to our understanding of cloud-climate feedback, and limited observational studies (5) have aided the identification of complex mechanisms of cloud-climate interaction. However, a global perspective on cloud-radiative interactions based on observations has been lacking.

Observations of the modulation of the solar and LW radiation fluxes by clouds can provide needed insights into the cloud-climate interaction. Such modulations are called the shortwave (SW) and longwave cloud-radiative forcing (6). We have obtained quantitative estimates of the global distributions of SW and LW forcing from the Earth Radiation Budget Experiment (ERBE), a system of satellites that provides data on incoming and emitted radiation (7). In this article, we develop the cloud-radiative forcing concept, describe global variations in the forcing on the basis of the ERBE data, and, finally, discuss the implications of these data for understanding past and future climate changes.

Description of ERBE. The ERBE includes three satellites in different orbits, a system that improves temporal sampling and can provide data on diurnal variations. The Space Shuttle Challenger launched the first of three satellites, the Earth Radiation Budget Satellite (ERBS), in October 1984. The second satellite (National Oceans and Atmospheric Agency, NOAA-9) was launched in December 1984. The third (NOAA-10) was launched in July 1986 (8). In our study, we used data gathered by the ERBS and NOAA-9 satellites. Each satellite contained a pair of instrument packages: a scanner and a nonscanner; we used the scanner measurements only. The scanner footprint at nadir, that is, looking down, was about 35

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km. During flight, observations of internal black bodies and the sun were used to calibrate the measurements. Independently monitored tungsten lamps also provided a relative check of the SW calibration. A solar monitor on the nonscanner instrument measures solar irradiance. We use this measurement to calculate the geographic distribution of incident sunlight. The instruments on the scanner measure the reflected SW and the emitted LW fluxes at the top of the atmosphere. The difference between the incident flux and the reflected SW flux gives the solar energy absorbed by the surface-atmosphere column. The emitted LW flux is the energy radiated away by the column. The difference between the absorbed and emitted flux is the net radiative heating of the surface-atmosphere column. We combined the radiation budget data from ERBS and NOAA-9 satellites to produce diurnal average fluxes on a daily basis. Then, we averaged these daily fluxes over the days in the month to produce the data presented. We discuss below the completed analyses for April 1985. Our initial analyses of data available for other months support the conclusions based on the April 1985 data.

The cloud-radiative forcing concept. Let us consider a domain of an area large enough to contain regions of overcast skies and

regions of clear skies. In the overcast regions, water vapor occurs with condensed water or ice, or both; in the clear sky regions, water occurs only in the vapor phase. The domain can be the whole earth, an entire latitude belt, or a specific region on the globe. Typically, such a domain would be a composite of overcast and clear skies and is referred to, usually, by meteorologists as cloudy. The term cloudy should not be confused with the term overcast. A cloudy domain is overcast only when it is completely covered with clouds.

The net radiative heating, H , for the entire surface-to-atmosphere column of a cloudy domain is

$$H = S(1 - \alpha) - F \quad (1)$$

where S is the solar irradiance and α is the albedo; hence $S(1 - \alpha)$ is the absorbed solar radiation. F is the LW flux emitted to space.

To describe the effects of clouds on H from observations, we first define the cloud forcing C

$$C = H - H_{\text{clr}} \quad (2)$$

where H_{clr} is the clear-sky net heating. If a domain has no clouds, $H = H_{\text{clr}}$ and $C = 0$. Thus, clouds should cause any difference between the net radiative heating averaged over the domain and the

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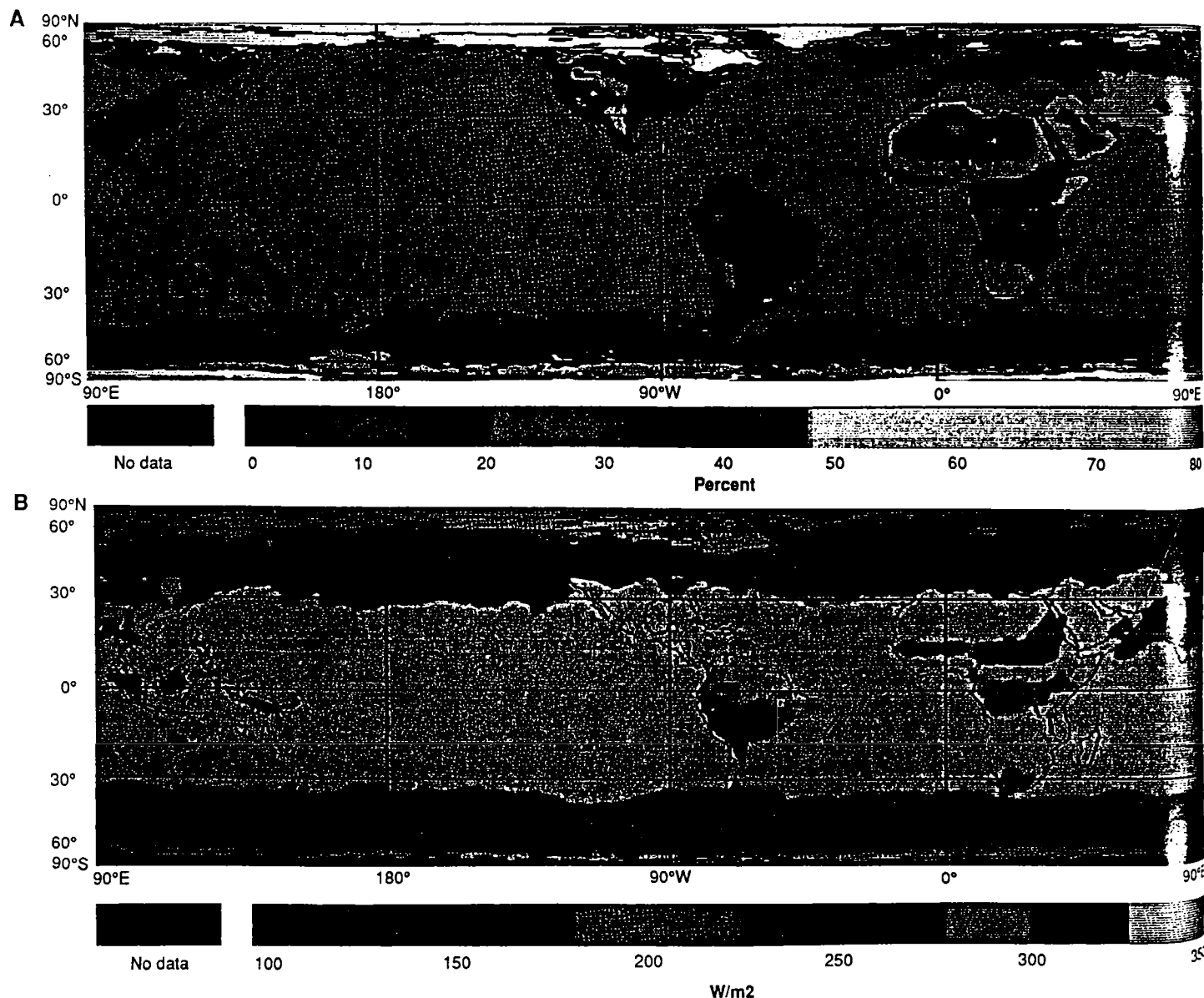


Fig. 1. (A) Clear-sky albedo; monthly averages for April 1985. Data from the scanners on-board ERBS and NOAA-9 satellites have been combined; **(B)** same as (A), but for clear-sky LW flux.

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heating averaged only over the clear-sky regions in that domain. From Eqs. 1 and 2, we can write C as

$$C = C_{SW} + C_{LW} \quad (3)$$

where $C_{SW} = S(\alpha_{clr} - \alpha)$ and $C_{LW} = F_{clr} - F$; α_{clr} is the clear-sky albedo and F_{clr} is the clear-sky LW radiation flux.

Clouds are almost always more reflective than the ocean surface and land, except where there is snow. Thus, when clouds are present, they reflect more solar energy into space than would clear skies. The SW cloud forcing, C_{SW} , gives a quantitative estimate of this effect. C_{SW} is simply the difference between the clear-sky and cloudy-sky reflected solar fluxes. When clouds are present, the atmospheric column radiates less thermal energy into space than it would if the skies were clear. The LW cloud forcing (C_{LW}) measures this effect. The net effect of clouds is simply the sum of the LW and SW cloud forcing (Eq. 3). Equations 1 to 3 can also be derived in a slightly different way (6), which leads to a cloud forcing expression in cloud fraction and radiative fluxes from overcast skies. For example, $C_{SW} = S(\alpha_{clr} - \alpha)$ is equal to

$$S(\alpha_{clr} - \alpha) = S \sum_i f_i (\alpha_{clr,i} - \alpha_{o,i}) \quad (4)$$

In Eq. 4, the domain is subdivided into i subregions; f_i is the cloud fraction and $\alpha_{o,i}$ is the overcast albedo for region i .

Obtaining the forcing from the expression on the left-hand side of Eq. 4 is simpler and more effective than obtaining it from the right-hand side. First, the clear-sky fluxes are significantly more homogeneous than overcast sky fluxes. As a result, the extension of clear-sky fluxes to the entire domain minimizes the errors caused by poor spatial and temporal sampling. Second, estimation of poorly constrained quantities, such as cloud fractions, is not necessary. Thus, obtaining the cloud-radiative forcing reduces to the relatively simple (but still difficult) problem of measuring the clear-sky fluxes (9).

The spatial resolution of meteorological scanners is not small enough to allow identification of all the clear-sky areas in a region, but this is not a problem because we do not anticipate systematic variations in the clear-sky fluxes as a function of resolution. Clear scenes that are larger than the resolution of the telescope should have the same fluxes as smaller clear scenes. Observations for periods longer than a week should average variations caused by random scene-to-scene differences. Another potential problem occurs where an entire region is overcast. In such regions, we can still infer a cloud forcing by enlarging the size of the region so that it includes some clear skies. An equivalent procedure is the adoption of an average of the clear-sky fluxes estimated for the surrounding regions. The uncertainty in the estimates increases with the spatial inhomogeneity of regional-scale clear-sky fluxes. Our results show that the clear-sky fluxes among adjacent regions are significantly more homogeneous than the fluxes for average cloudy conditions.

ERBE observations of clear-sky albedo and LW flux. The distribution of clear-sky albedo (Fig. 1A) reveals that the oceans are the darkest regions of the globe. They have albedos that range from 6 to 10 percent in the low latitudes to 15 to 20 percent near the poles. Ocean albedo increases toward high latitudes because the albedo of the surface increases as the sun lowers in the sky (10). The brightest parts of the globe are the snow-covered Arctic and Antarctic. Next in brightness to the snow-covered regions are the major deserts. The Saharan and Saudi Arabian deserts reflect as much as 40 percent of the incident solar radiation. The other major deserts, the Gobi and Gibson deserts, reflect about 25 to 35 percent. The tropical rain forests in South America and Central Africa have albedos from 10 to 15 percent. They are the darkest land surfaces on the earth.

The clear-sky LW radiation data (Fig. 1B) show a more systematic

pattern. Emission decreases from a maximum of 330 W/m² in the tropics to about 150 W/m² in the polar regions. Although the clear-sky observations contain no major surprises, they do provide quantitative estimates of the distribution of clear-sky radiative heating.

Statistics of clear-sky fluxes and uncertainties. The accuracy of the estimates for regional and time-averaged clear-sky fluxes depends on the homogeneity of the clear region fluxes. The spatial resolution of the scanner is not sufficient to detect all of the clear regions in the domain of interest. The error attributed to this poor sampling depends on the spatial and temporal variability of the clear-sky fluxes. To demonstrate that the clear-sky flux estimates were accurate, we computed their standard deviation (σ) for several spatial

Table 1. Standard deviation of clear-sky LW and SW fluxes (in parentheses) in watts per meter squared. Four overlapping scans were used to estimate the pixel scale σ 's. Each scan contains 62 pixels. All of the clear-sky pixels in the four-scan set entered the computation of a mean and a standard deviation. The pixels were also sorted into 2.5° by 2.5° regions. The clear-sky data for 1 day then yield regional σ values. The 1-day σ 's for each 2.5° latitude belt were averaged. For the daily average, the σ of 30 daily mean values was computed for each region and the σ 's were averaged over a latitude belt.

Latitude zone	Pixel scale	Regional scale	Daily (regional scale)
42.5°N to 47.5°N	3.9 (8.3)	7.7 (3.1)	4.3 (3.5)
27.5°N to 32.5°N	2.7 (8.9)	4.1 (2.0)	6.5 (4.2)
2.5°N to 2.5°S	3.2 (6.3)	2.5 (1.8)	3.9 (3.2)
27.5°S to 32.5°S	4.0 (9.3)	2.4 (1.5)	5.5 (5.5)
42.5°N to 47.5°S	1.8 (4.5)	3.9 (2.0)	5.4 (4.6)

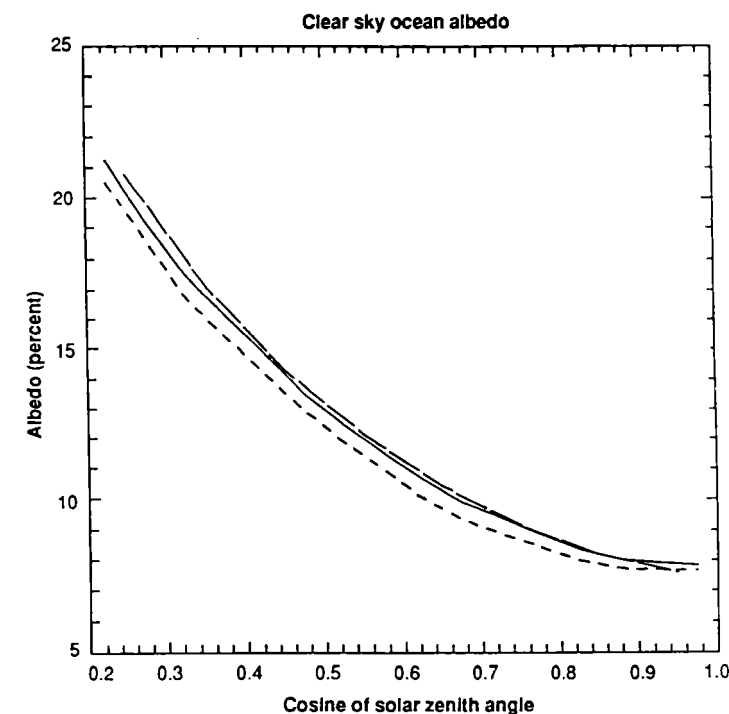


Fig. 2. Clear-sky ocean albedos. (solid line) Observed albedos for April 1985. The albedos were inferred from the scanner pixel data with the use of the operational ERBE algorithm for identifying clear-sky scenes. A total of 1,280,047 scanner pixels covering the global oceans was included. (Short dash) Same as the solid curve but, in addition to the operational algorithm, a stringent homogeneity criterion was used; a total of 50,640 pixels was included. (Long dash) Computed albedos from the model described in (10). In this model, observed ocean surface reflectivities are used in a multiple-scattering model that accounts for Rayleigh and aerosol scattering and absorption by O₃, H₂O, and CO₂.

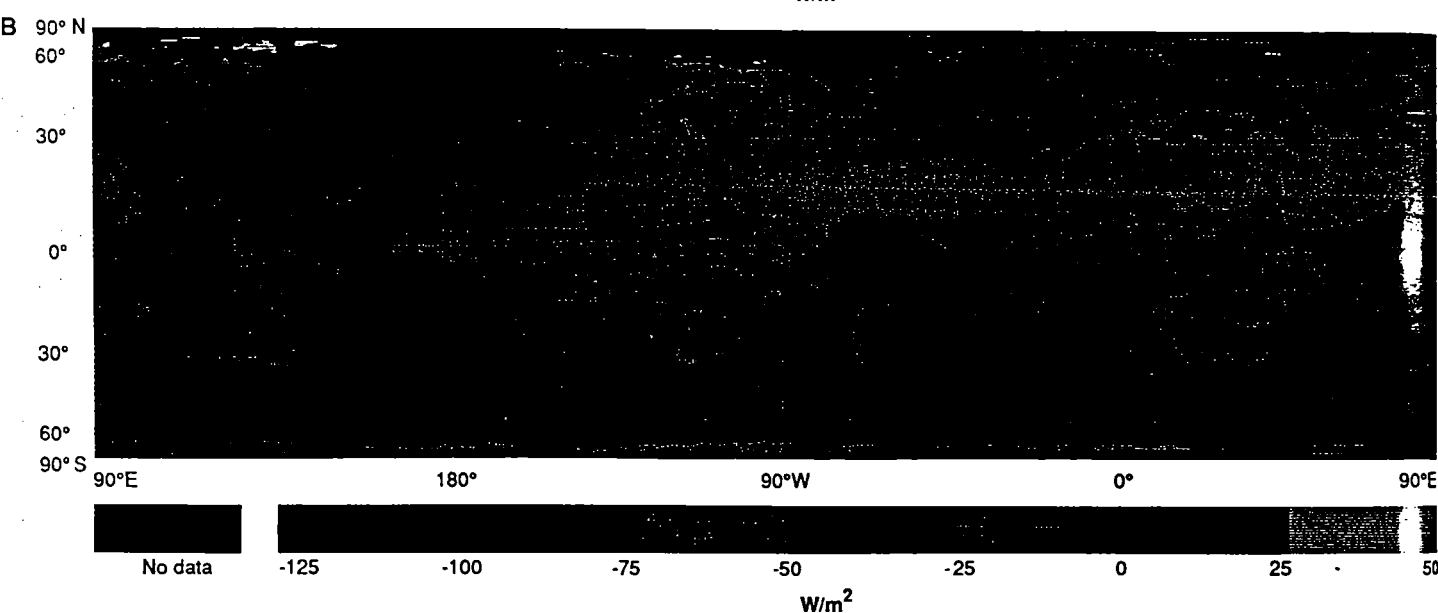
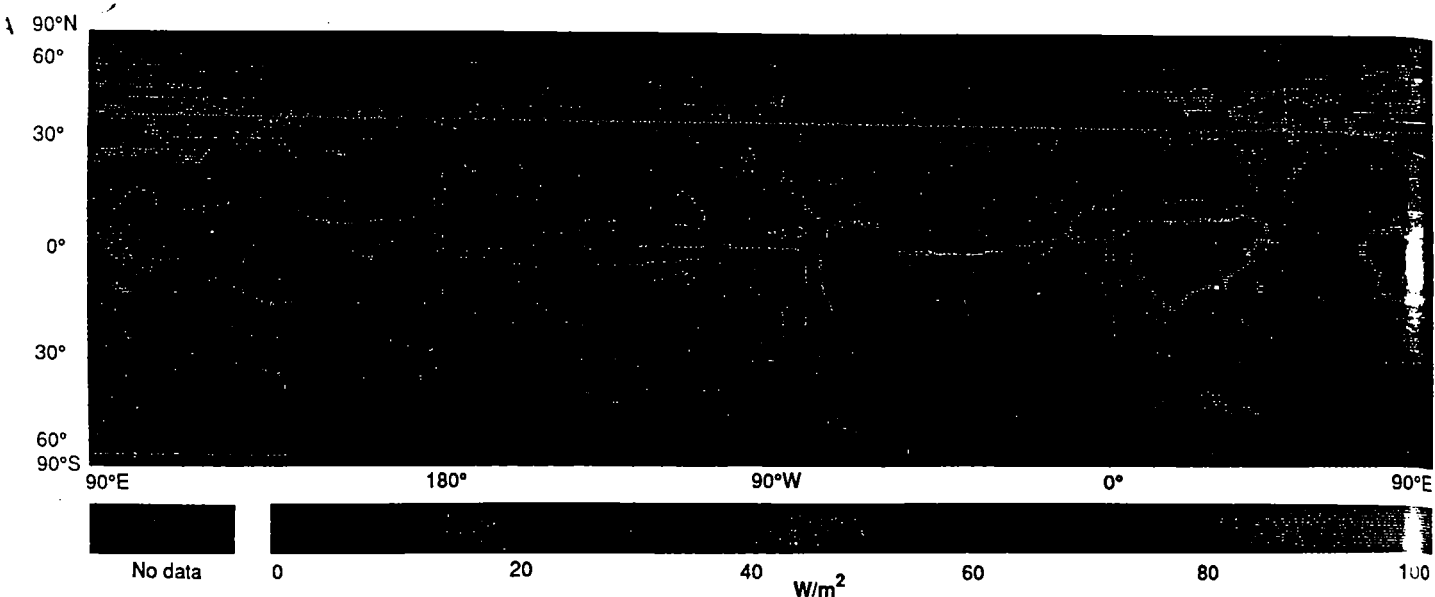


Fig. 3. The LW (A) and SW (B) cloud forcing for April 1985. The uncertainties in the estimated values are about $\pm 10 \text{ W/m}^2$. Estimates over snow-covered regions may potentially have larger uncertainties because of difficulty in distinguishing clear from cloudy regions over the bright snow-covered regions.

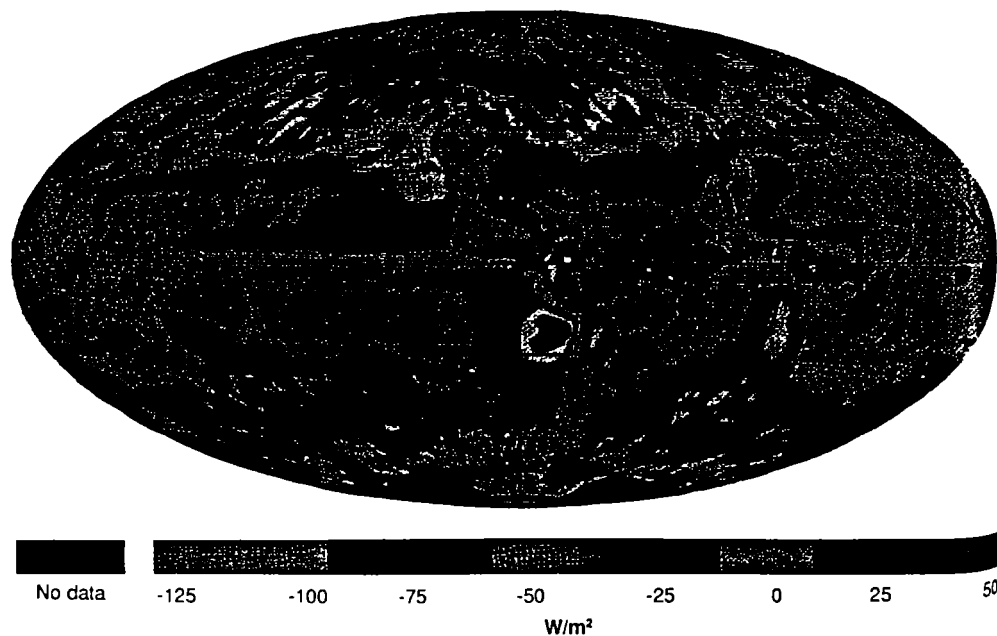


Fig. 4. Net ($C_{LW} + C_{SW}$) cloud forcing for April 1985. The positive values of cloud forcing, including those seen in North America and in the polar regions, do not exceed 25 W/m^2 .

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Table 2. Global summary of radiation budget. Average incident solar radiation for April was 342 W/m².

Item	Albedo (%)	SW absorbed (W/m ²)	LW emitted (W/m ²)	NET heating (W/m ²)
Clear sky	16.5	285.6	265.8	19.8
Average	29.5	241.1	234.5	6.6

Table 3. Comparison of global cloud forcing estimates in watts per meter squared.

	ERBE data (W/m ²)				GCM's†
	April 1985	July 1985*	October 1985*	January 1986*	
C _{LW}	31.3	30	32	30.6	23 to 55
C _{SW}	-44.5	-46.4	-49.4	-51.9	-45 to -74
C	-13.2	-16.4	-17.4	-21.3	+1 to -34

*Analysis not completed for these months. †On the basis of a summary of six model studies (16) for model simulations with January and July boundary conditions.

and temporal scales (Table 1). The clear-sky σ 's were always less than 10 W/m² (Table 1). In addition, sampling error for the monthly averaged regional estimates would be even smaller than the σ 's shown in Table 1 (11). Thus, the statistics in Table 1 suggest that sampling errors for regional clear-sky fluxes are significantly smaller than the regional cloud forcing discussed below (11).

Errors in clear-sky fluxes can also arise from cloud contamination of the so-called clear scenes. Only data from instruments with much better resolution than the ERBE scanner can provide an accurate estimate of this bias error. Lacking such data, we attempted various consistency checks on a sample of the clear-sky fluxes to examine the size of the error. (i) We applied stringent homogeneity criteria in the identification of clear scenes. (ii) We chose scenes for which the eight surrounding scanner pixels were also clear. (iii) We adopted only those scenes for which the σ of the LW radiance was less than 1 percent of the mean LW flux for the nine pixels. The use of these criteria, chosen because of the results presented in (12), yielded lower albedos (Fig. 2) and larger LW fluxes than the general results for these scenes (Fig. 1). This response to editing of the data suggests that clouds did contaminate the operational data. However, the bias is only +0.8 percent for albedo and -4 W/m² for LW flux. The positive bias in the clear-sky albedo reduces the size of the negative SW cloud forcing. In contrast, the negative bias in the clear-sky LW flux reduces the size of the LW cloud forcing. Because the two forcing terms have opposite signs, the two bias errors partially cancel in the net cloud forcing (Fig. 2). The observed albedos are also consistent with those computed from a detailed theoretical model (Fig. 2) (10). The consistency between theory and observations builds confidence in the retrieved clear-sky fluxes. More detailed studies of scene identification errors with several alternative techniques (7) also gave results that were similar to those shown in Fig. 2.

LW and SW cloud forcing. The LW cloud forcing (Fig. 3A) reaches peak values over tropical regions and decreases toward the poles. In general, clouds reduce the LW emission to space. This reduction in emission is effectively an increase in the radiation energy absorbed in cloudy regions (compared with the energy in clear-sky regions). Because the reduction in the LW emission is largely a result of the emission from cold cloud tops, optically thick, high clouds reduce the emission more than low clouds. Hence, cloud forcing of 50 to 100 W/m² is at a maximum in regions with extensive cirrus cloud decks. Maxima occurred in three regions: (i)

the tropical Pacific and Indian oceans surrounding Indonesia and the Pacific intertropical convergence zone north of the equator; (ii) the monsoon region in Central Africa and the deep convective regions of the northern third of South America; and (iii) the mid-latitude storm tracks in the Pacific and Atlantic oceans.

The SW cloud forcing (Fig. 3B) shows peaks in the mid-latitudes, unlike the LW forcing. In the tropics, large negative values were observed in the tropical monsoon and deep convective regions (Fig. 3A). These are areas where the LW forcing was equally large; the SW forcing was also large north of 30°N in the Atlantic and Pacific oceans. In these regions, the reduction of absorbed solar radiation as a result of clouds exceeded 100 W/m². Cloud systems associated with the mid-latitude storm tracks and extensive stratus decks over the colder oceans were responsible for this large reduction (13). Large (negative) values were also observed over the oceans in the mid-latitude Southern Hemisphere. These regions are known as the "roaring 40's" because of the persistence of cyclones. Both SW and LW cloud forcing were negligible over the narrow band of oceanic upwelling regions of the eastern and central Pacific oceans. In summary, cloud forcing patterns, even for observations during 1 month, reflect the major climatic regimes and the organized cloud systems of the planet. Distinguishing between clear and cloud scenes over the bright ice and snow-covered regions is difficult, and therefore the positive SW forcing results over and near the Arctic are less accurate than elsewhere; even the sign of the effect may be uncertain.

In tropical regions, where the clouds significantly affected the LW and SW fluxes, the LW and SW terms nearly cancel each other. The net forcing there (Fig. 4) was within ± 10 W/m², roughly the estimated uncertainty in our regional estimates of the net cloud-radiative forcing. Between 15°N and 15°S, the zonally averaged forcing was slightly negative and was about 10 to 20 percent of the SW forcing. Earlier workers (14) anticipated the competing nature of the two forcing terms. However, their near cancellation is surprising. We do not understand the physical and dynamical constraints that require these cloud systems to organize in such a manner. The only exceptions to the near cancellation of the cloud forcing in the tropics are marine stratocumulus cloud systems. These systems commonly occur off the coast of Chile (in South America) and the coasts of Angola and Namibia in Africa.

Near cancellation of the column-integrated radiative forcing does not imply a negligible role of clouds in the regional climate. Modeling results (6) suggest that the negative C_{SW} is due to divergence (cooling) of SW flux at the earth's surface. In contrast, the positive C_{LW} in the tropics is due to convergence (heating) of LW flux in the troposphere. Thus these cloud systems may lead to a significant perturbation of the vertical gradients of radiative heating or cooling patterns (6, 15).

Over the mid- to high-latitude oceans, poleward of 30° in both hemispheres, cloud forcing is negative. The negative forcing is particularly large over the Pacific and Atlantic oceans where C is between -50 and -100 W/m².

Another anomalous feature (Fig. 4) is the positive cloud forcing regions in the Western Sahara Desert and the Sahel regions of Africa. The positive values over the desert regions arise from the LW cloud forcing (Fig. 3), accompanied by negligible SW forcing. Cloud forcing is also positive over the snow-covered regions of Canada and the Arctic, where both the LW and the SW forcing terms are positive. However, as mentioned earlier, the clear-sky estimates over snow-covered regions are subject to large uncertainty. A better clear-sky discriminator and more extensive seasonal sampling are needed to confirm the forcing estimates over these regions.

Climatic implications. Cloud forcing reduces the absorbed solar radiation by 44.5 W/m² and the LW emission to space by 31.3 W/m²

when averaged over the globe (Tables 2 and 3). Thus, globally, clouds reduce the radiative heating of the planet by 13.2 W/m^2 (Table 3). This conclusion is based on data from just 1 month. Data for July 1985, October 1985, and January 1986 are now being processed. Preliminary analyses of these months confirm the basic finding of this study: clouds have a net cooling effect on the global climate. There are significant month-to-month differences in the net cooling effect. It attained a maximum value of -21.3 W/m^2 in January 1986 (Table 3). The differences in the monthly values are a result of both seasonal and interannual variations in the parameters that govern cloud forcing. The data for the 4 months indicate the likely range of planetary radiative cooling due to clouds during a year.

Studies with GCM's provide some assessment of the climatic significance of this radiative cooling. Several studies have suggested that radiative heating of a mere 4 W/m^2 resulting from a doubling of CO_2 concentrations in the atmosphere would lead to a global warming of 3.5 to 5 K (4). The negative cloud-radiative forcing is three to five times as large as the doubled CO_2 forcing. The size of the forcing suggests that the planet would be significantly warmer without the current cloud-radiative forcing.

Cloud forcing has also been inferred from GCM's (15, 16). The GCM results are in qualitative agreement with those shown here. For both observations and models $C_{\text{LW}} > 0$, $C_{\text{SW}} < 0$, and $C < 0$. However, there are significant quantitative differences between the various models (Table 3) (16). The next step in identifying deficiencies in model simulations is to compare the regional and seasonal variations in the cloud forcing fields.

Cloud-climate feedback. A change in climate can perturb the cloud forcing, which in turn can feed back into the initial climate change. Thus, observations of long-term changes in cloud forcing can provide insights into the nature of the cloud-climate feedback. Two of the important feedback mechanisms suggested by our data are described below.

In mid- to high-latitude oceanic regions, strong negative forcing over the oceans coincides with regions of stratus and the storm tracks of mid-latitude cyclones. The frequency, as well as the latitudinal extent of these storms, couples to latitudinal temperature gradients (13). Large changes in the latitudinal temperature gradients accompany a climate change, such as the last ice age which occurred about 15,000 years ago (17). For example, during the glacial maximum, the mid-to-polar Atlantic Ocean was 5 to 10 K cooler than at present, while the subtropical oceans were less than 2 K cooler (17). In response to this enhanced temperature gradient and southward migration of the cold waters, the storm track clouds and the stratus decks might have shifted southward. Then, the regions where C was less than -50 W/m^2 would have also shifted southward and amplified the cooling. This mechanism is similar in principle to the ice-albedo feedback (1, 4). The effect of a shift from 45°N to 35°N of, for example, the -50 to -75 W/m^2 cloud forcing region is large. Such a shift, if it persists through the year, could induce a hemispherical average radiative cooling of roughly 3 W/m^2 . This cooling is larger than the radiative effect of the observed decrease in CO_2 concentration from 300 to 180 ppm that occurred during the glacial maximum 15,000 to 20,000 years ago (18).

Tropical convective cloud systems contain a mixture of cumulus, cumulonimbus, and cirrus anvils (19). Despite the considerable discussion on the effect of tropical clouds, we still do not know whether the reflective cloud forcing of the cumulus clouds or the heating effect of the cirrus is dominant (4, 5). Our data suggest that these effects nearly cancel when integrated over the column. Some GCM's had anticipated this near cancellation of the LW and SW cloud forcing (6). However, these clouds can play a substantial role in climate change for two reasons: (i) The height of cloud tops

largely governs the LW cloud forcing, but the water and ice content determine the SW forcing. (ii) Surface temperature influences the height but low-level convergence governs the water content. As an example, a warming due to the observed increase in CO_2 and other trace gases could increase the height of these clouds (5), which would increase C_{LW} . Because the individual forcing terms are large, a change in either of them would have a similar effect on the net cloud forcing.

In summary, the cloud forcing concept contributes to our understanding of climate and climate change. First, cloud forcing is an important part of the energy flow of the earth-atmosphere system. Second, we can quantitatively estimate cloud forcing from radiation budget measurements by broadband scanners. Third, we must be able to predict changes in cloud forcing if we are to predict the total response of climate to various perturbations. Such perturbations include orbital variations that have been implicated in earlier ice age episodes and changes that are expected from trace gas increases.

Observations of long-term changes in cloud forcing can be used directly to provide confirmation of previously untestable ideas (5) and climate model results (4) regarding climate change. For example, results from some GCMs suggest that severe drying of the mid-continental regions in North America and Europe could result from a doubling of the CO_2 concentrations (4, 20). In the Great Plains region of North America, the summer soil wetness in one model is decreased by 50 percent (20, figure 7), which suggests that a positive feedback between clouds and land surface could be a factor in soil drying (20). An initial tendency for drying causes decreased cloudiness, which leads to increased solar heating of the soil, thus amplifying tendency toward drying. The positive cloud feedback mechanism implies that the size of the (negative) SW cloud forcing would decrease significantly during a drought event. According to Manabe and Wetherald (20) the decrease could be as much as 25 W/m^2 in the Great Plains. The LW forcing should also decrease, but the model results suggest that changes in the SW cloud forcing dominate the feedback. Cloud forcing data could verify this postulated positive cloud feedback. For example, this mechanism would imply that the summertime SW cloud forcing over the Great Plains was anomalously low during the 1988 drought. Comparison of the cloud forcing for this year with the forcing for other years should confirm or refute this suggestion.

REFERENCES AND NOTES

1. R. D. Cess, *J. Atmos. Sci.* **33**, 1831 (1976); J. S. Ellis, thesis, Colorado State University, Fort Collins (1978). These are two of the earlier studies in which an attempt was made to assess the role of clouds from satellite radiation budget measurements. Ellis also estimated cloud-radiative forcing from regional radiation budget data. See S. H. Schneider [*J. Atmos. Sci.* **29**, 1413 (1972)] for a discussion of the cloud-climate feedback.
2. Cess and Ellis (1) estimated that the global greenhouse effect due to clouds was between 20 and 40 W/m^2 . A hundredfold increase in CO_2 concentration would effectively trap about 25 W/m^2 .
3. D. L. Hartmann et al., *Rev. Geophys. Space Phys.* **24**, 439 (1986).
4. J. Hansen et al., *Climate Processes and Climate Sensitivity*, Maurice Ewing Series (American Geophysical Union, Washington, DC, 1984), p. 130; C. A. Wilson and J. F. B. Mitchell, *J. Geophys. Res.* **92**, 13315 (1987); W. M. Washington and G. A. Mehl, *ibid.* **89**, 9475 (1984); R. T. Wetherald and S. Manabe, *J. Atmos. Sci.* **45**, 1397 (1988).
5. R. C. J. Somerville et al., *J. Geophys. Res.* **89**, 9668 (1984); R. J. Charlson, I. E. Lovelock, M. O. Andreae, S. O. Warren, *Nature* **326**, 665 (1987).
6. V. Ramanathan, *J. Geophys. Res.* **92**, 4075 (1987).
7. B. R. Barkstrom, *Bull. Am. Meteorol. Soc.* **65**, 1170 (1984); ERBE science team (B. R. Barkstrom et al.), *ibid.* **67**, 818 (1986); R. B. Lee, B. R. Barkstrom, R. D. Cess, *Appl. Opt.* **26**, 3090 (1987).
8. The ERBS is in a midinclined orbit, which precesses through all local hours at the equator in 36 days. The NOAA-9 is in a sun-synchronous orbit with equator crossing times at 0230 and 1430 local solar time. This multisatellite configuration significantly reduces the temporal sampling errors in earlier satellite measurements. For example, see E. F. Harrison, P. Minnis, G. G. Gibson, *J. Spacecr. Rockets* **21**, 491 (1983).
9. Satellite radiation budget data are the traditional source for domain average values of F , α , and H [see T. H. Vonder Haar and V. E. Suomi, *Science* **163**, 667 (1969)].

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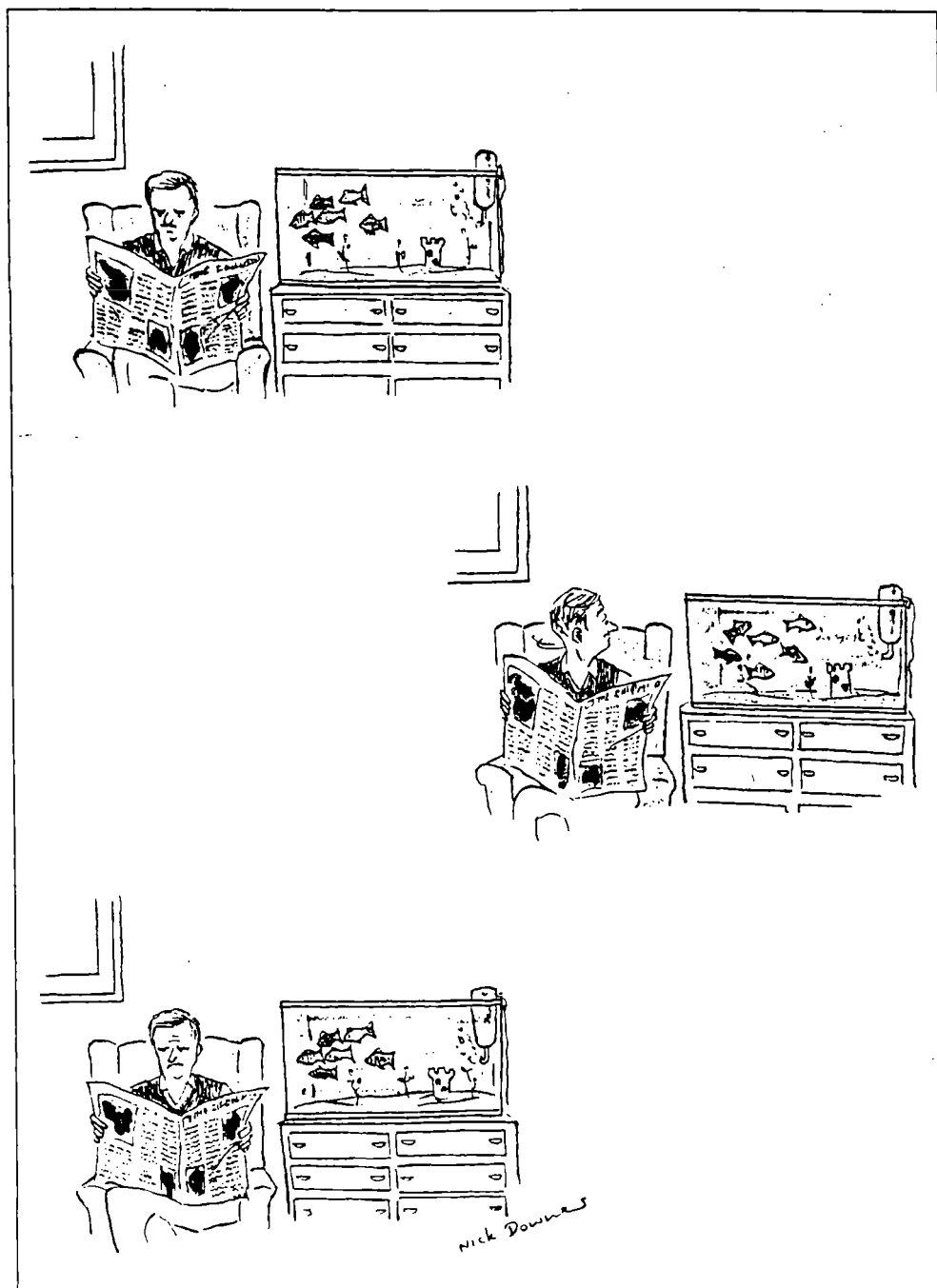
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We refer to these domain average values as cloudy-sky values. They are, in principle, a composite of clear and overcast sky values. To compute cloud forcing, we require both these cloudy-sky values and the clear-sky values. From the scanner pixels, we look for hole in the cloud cover. These holes we identify as the clear-sky scenes. Their fluxes give us the clear-sky values in each domain of 2.5° latitude by 2.5° longitude. (Further details of the clear-sky algorithms are given in B. A. Wielicki and R. N. Green, in preparation.)

10. B. P. Briegleb et al., *J. Climatol. Appl. Meteorol.* 25, 214 (1986).
11. A simple picture of the sampling error suggests that it should vary as $\sigma/\sqrt{N}$, where N is the number of independent samples. Typically, for a region 2.5° by 2.5°, over a period of 1 month, N should be about 10. The main point is that the sampling error should be smaller than the σ (Table 1) by a factor of 2 or more.
12. J. A. Coakley and F. P. Bretherton, *J. Geophys. Res.* 87, 4917 (1982). This paper shows that the clear-sky LW radiance over the oceans is characterized by very low σ 's.
13. E. Palmén and C. W. Newton, *Atmospheric Circulation Systems* (Academic Press, New York, 1969).

14. D. L. Hartmann and D. A. Short, *J. Atmos. Sci.* 37, 1233 (1980); G. Ohring and P. F. Clapp, *ibid.*, p. 447.
15. T. D. Charlock and V. Ramanathan, *ibid.* 42, 1408 (1985); A. Slingo and J. M. Slingo, *Q. J. R. Meteorol. Soc.* 114, 1027 (1988).
16. R. D. Cess and G. L. Potter, *Tellus* 394, 460 (1987).
17. H. H. Lamb, *Climatic History and the Future* (Princeton Univ. Press, Princeton, NJ, 1985).
18. J. Jouzel et al., *Nature* 329, 403 (1987).
19. A. F. Bunker and M. Chaffee, *Tropical Indian Ocean Clouds* (East-West Center Press, Honolulu, HI, 1969).
20. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* 44, 1211 (1987).
21. Supported in part by the NASA ERBE Project; NSF grant ATM8700286 (V.R. and E.A.). We thank the ERBE Science Team and the project scientists at NASA Langley Research Center for making this work possible, G. Gibson for the graphics, and two anonymous referees for their comments.

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An Oceanic Indication That Earth's Climate Might Regulate Itself

Thicker clouds block more sunlight, Pacific study shows.

By WILLIAM K. STEVENS

DOES the earth's climate regulate itself, enabling global temperatures to stay within certain broad limits?

The question fascinates scientists, especially at a time of concern and contention about global warming, and now climatologists have produced evidence that clouds act as a natural thermostat that keeps the temperature of the oceans' surface from rising above a certain point.

While the evidence comes primarily from the tropical Pacific Ocean, climate experts say it suggests that the earth's closely coupled ocean-atmosphere system could act as a more general thermostat to prevent any warming of the global climate from spiraling out of control.

The evidence raises the tantalizing possibility that a natural regulatory mechanism could set a ceiling on the global warming that scientists say will result from emissions of heat-trapping gases like carbon dioxide. At present rates of emission, they calculate, atmospheric concentrations of these greenhouse gases will double by the middle of the 21st century, eventually raising the average surface temperature of the earth by 2 to 9 degrees Fahrenheit. They say that a warming in the upper end of that range would have catastrophic results for the world's climate.

It is not yet known whether the effects of the predicted warming would be mitigated by the thermostatic effect that scientists say they have now demonstrated. But the new findings may rule out the direst scenarios about the greenhouse effect, in which global warming would escalate until it ultimately makes the earth inhospitable to life. Scientists and environmentalists who fear this possibility point out that this is precisely what happened on Venus.

Ships and Satellites

"I cannot see how the planet can have a runaway greenhouse effect" given the new findings, said Dr. Veerabhadran Ramanathan, a climatologist at the Scripps Institution of Oceanography at La Jolla, Calif. With a colleague, Dr. William Collins, he

presents the evidence for the thermostatic mechanism in the current issue of the British journal *Nature*.

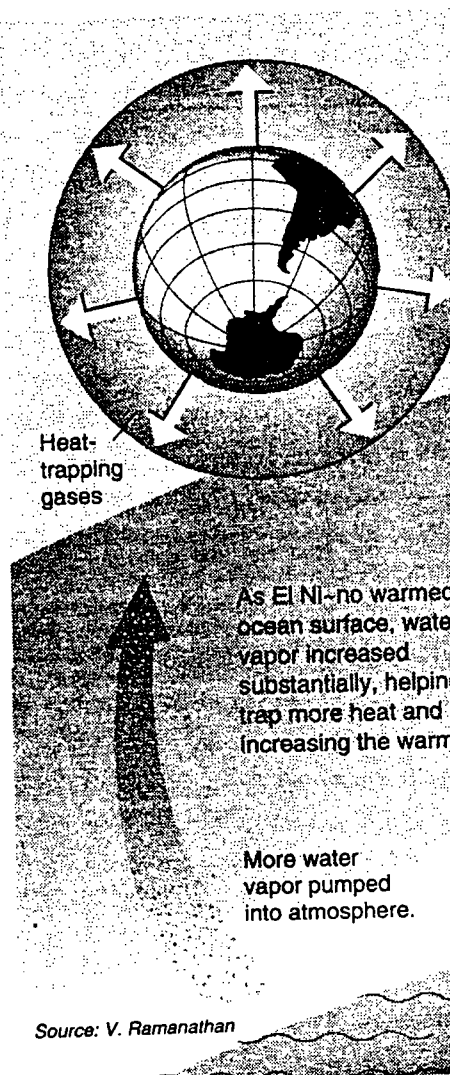
Even so, said Dr. Ramanathan, global warming could still cause vast climatic disruptions. This, he said, is because the thermostatic mechanism, if it operated globally, would probably lead to a radical change in the large-scale circulation of huge rivers of air, like the jet streams, that create and define regional climates. These climates could be transformed in ways yet unfathomed. Moreover, he said, the temperatures of most of the world's oceans, unlike those in the tropics, are so far below the limit imposed by the thermostat that most of the earth's surface could warm significantly before the thermostat kicked in globally.

The new evidence for a climatic thermostat comes from an analysis of data on changes in temperature and sunlight gathered by satellites and ships. Dr. Ramanathan and Dr. Collins studied the behavior of the ocean-atmosphere system over the eastern and central Pacific at the equator in 1987 when El Niño occurred. In this periodic event, naturally occurring changes in ocean currents caused the equatorial sea surface to warm by five to seven degrees. For Dr. Ramanathan and Dr. Collins, it provided a natural experiment in which to look at the relationship between temperature and clouds as the climate actually changes.

They found that as the sea surface grew warmer, water vapor increased substantially in the air. Water vapor is the most powerful greenhouse gas — it amplifies the effects of other causes of heating, including both carbon dioxide and sunlight — and in this case it produced what Dr. Ramanathan calls a "super-greenhouse effect."

At the same time, huge, tall thunderclouds formed. As they reached freezing altitudes, the tops of the clouds turned into monstrous, flat "anvils" of cirrus clouds made of ice crystals. Together, at their maximum extent, the cirrus clouds covered nearly four million square miles of the earth's surface. Normally, cirrus clouds help trap heat in the atmosphere. But the thicker they become, the more sunlight they reflect. Eventually, said Dr. Ramanathan, "the cirrus becomes so thick and so highly reflective that it shuts off the sunlight reaching the ocean."

This was more than enough to counterbalance the warming below, the scientists say, and the net effect was to prevent the sea surface from



warming further. Once the cooling begins, they found, the tall thunderclouds and the cirrus dissipate, and the process starts again.

'A Very Simple Effect'

The ceiling beyond which the ocean warms no further, Dr. Ramanathan and Dr. Collins say, appears to be about 90 degrees Fahrenheit on a monthly average. The ceiling might be pushed upward by two or three degrees, Dr. Ramanathan said, by an unexpectedly large buildup of atmospheric carbon dioxide concentrations. But for that to happen, he said, the concentrations would have to increase tenfold rather than merely double.

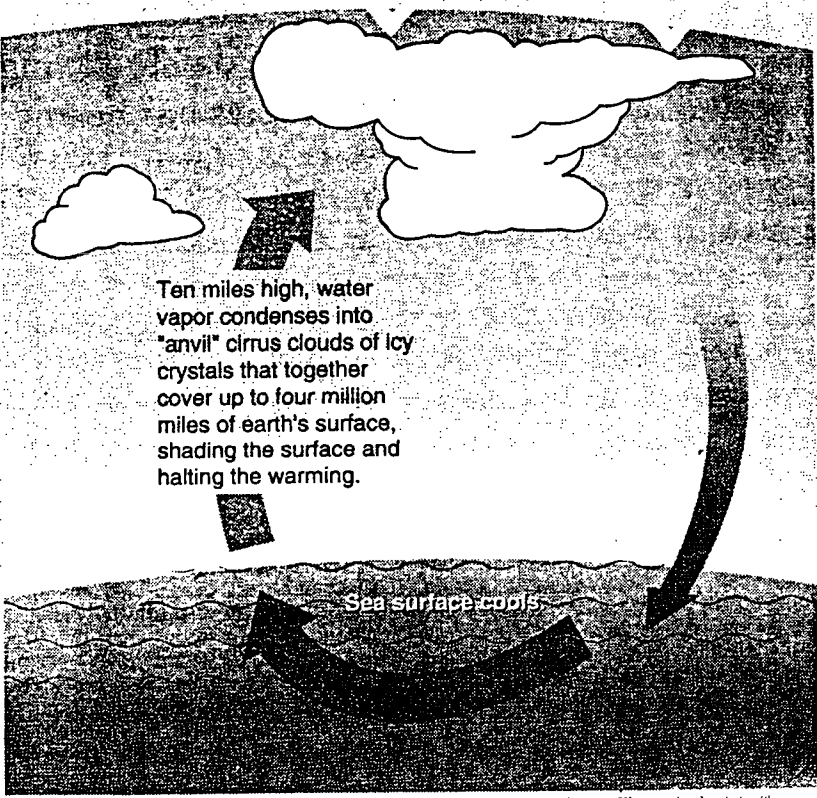
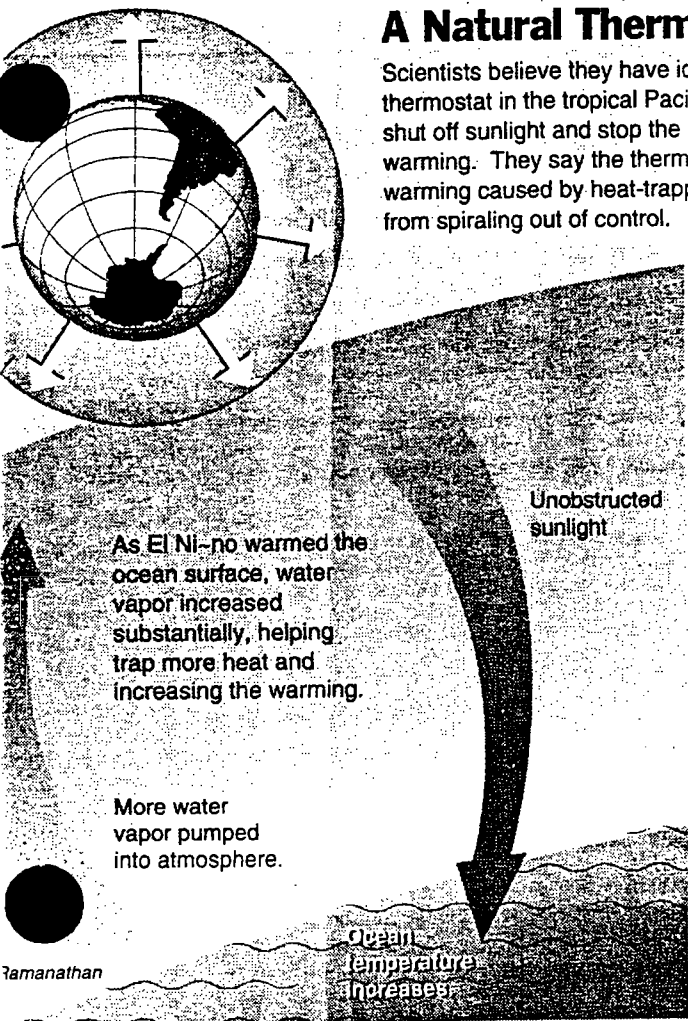
The thermostatic process also appears to take place in the tropical Atlantic and Indian Oceans, the scientists say, although the El Niño experiment is in some ways considered the best test of the thermostat hypothesis.

"It's a very simple effect, but no one had demonstrated it effectively until now," said Dr. Andrew J. Heymsfield, an atmospheric physicist at the National Center for Atmospheric Research in Boulder, Colo., who wrote a commentary for *Nature* on the new research. In an interview, he called the study "first rate" and

A Natural Thermostat?

Scientists believe they have identified a climatic thermostat in the tropical Pacific, where clouds act to shut off sunlight and stop the sea surface from warming. They say the thermostat could prevent warming caused by heat-trapping atmospheric gases from spiraling out of control.

Sunlight is reflected.



The New York Times; Illustration by Julie Shaver

further. Once the cooling they found, the tall thunder- clouds dissipate, and the cycle starts again.

Simple Effect?
Going beyond which the ocean warms further, Dr. Ramanathan and Collins say, appears to be degrees Fahrenheit on average. The ceiling might rise upward by two or three degrees. Dr. Ramanathan said, by an equally large buildup of atmospheric carbon dioxide concentrations for that to happen, he said, the concentrations would have to increase tenfold rather than merely

A thermostat process also might take place in the tropical Indian and Indian Oceans, the scientists said. Although the El Niño experiments have considered the possibility of the thermostat hypothesis,

very simple effect, but no one had demonstrated it effectively. Dr. Andrew J. Collins, an atmospheric physicist at the National Center for Atmospheric Research in Boulder, Colo., said in a commentary for Nature magazine. In an interview, he said the study "first rate" and

Experts examine the tantalizing possibility of a natural ceiling on global warming.

Dr. Ramanathan said he thought its conclusions were correct for the tropical Pacific. He also called the results "provocative" in suggesting the possibility of a climatic thermostat that might affect human-induced global warming. But, he said, "it's not at all straightforward." It is not clear, for instance, whether heat produced by global warming at the surface of the continents could be transported to the tropical oceans, where the thermostat effect might offset it. The tropical oceans, with their enormous amounts of heat energy, drive the planet's climate, and in doing so they create huge, circulating wind currents that transport heat from one part of the earth to another. Another uncertainty, Dr. Heymsfield said, has to do with the source of the warming in the Ramanathan-Collins study and the

source of the human-induced global warming that scientists predict. In the former, the source is sunlight and surface sea currents. In the latter, it is heat-trapping atmospheric gases. Dr. Ramanathan and Dr. Collins add their own caveats. They say their findings constitute experimental evidence of an important feedback arrangement in the climate system. But there are many others about which little is known, and Dr. Ramanathan says that any number of climatic factors could upset the workings of the mechanism on a global scale. The findings do suggest, he said, that greenhouse warming, if it is large enough, could cause the much cooler oceans outside the tropics to warm to the maximum, establishing a more or less uniform oceanic temperature throughout the world. This in itself would have profound effects on the world's climate, he said, since it is the differences in temperature among the oceans that largely sets in motion the planetary winds that create and shape regional climate. With these differences eliminated, regional climates could be expected to change profoundly and disruptively. This may be the most significant aspect of the Ramanathan-Collins paper, said Dr. William A. Nierenberg, a geophysicist who is director emeritus

of the Scripps Institution and who has expressed doubt that global warming will be as severe as some scientists have predicted. A number of feedbacks might act to limit global warming, he said. "In fact," he said, "the average global temperature change could be almost zero" because of the many feedback mechanisms. But the operation of the mechanisms could nevertheless impose a "severe" price in terms of the regional climate changes they would cause. Some scientists say the Ramanathan-Collins findings could lead to better predictions about the extent of the expected global warming. The predictions rest largely on computerized mathematical models of the climate system that all scientists agree are crude and flawed. One of the major flaws has to do with the effect of clouds. Already, the findings cast doubt on some features of the models. For instance, Dr. Ramanathan said, some models predict that if atmospheric carbon dioxide concentrations are doubled, the surface temperature of the western Pacific will rise to about 93 degrees, well above the ceiling that he and Dr. Collins believe they have discerned. "If our hypothesis is valid," Dr. Ramanathan said, "that's not possible."

GREENHOUSE EFFECT

Gauging water-vapour feedback

Robert D. Cess

In 1861, Tyndall¹ described the 'greenhouse' effect caused by atmospheric water vapour, pointing out that water vapour transmits a large fraction of the incident solar radiation but strongly absorbs infrared radiation emitted by the Earth's surface. More than a century later Möller² suggested that this greenhouse effect might also act as an amplifying (positive) climate feedback mechanism, a point later emphasized by Manabe and Wetherald³. These and subsequent investigations used theoretical climate models. On page 758 of this issue⁴, however, Raval and Ramanathan cleverly employ satellite measurements to quantify the greenhouse effect and to demonstrate its positive correlation with surface temperature — that is, positive water-vapour feedback.

The explanation for this feedback mechanism is as follows. If the Earth were to warm, for example owing to an enhanced greenhouse effect caused by increasing atmospheric CO₂, the warmer atmosphere should contain more water vapour, which as a greenhouse gas would amplify the initial warming. To put it another way, an anthropogenic increase in one greenhouse gas (CO₂) causes an increase in yet another greenhouse gas (water vapour). It is important to differentiate, in this example, between what is meant by the greenhouse effect, climate forcing and climate feedback.

Raval and Ramanathan's observational elucidation of the greenhouse effect provides a convenient means of making these distinctions within the conventional interpretation of climate change as a two-stage process: forcing and response. The global-mean direct radiative forcing, H , of the surface-atmosphere system is evaluated by holding all other climate parameters fixed. For an increase in atmospheric CO₂, H is the reduction in the top-of-the-atmosphere infrared flux caused solely by the CO₂ increase. The response, within which climate feedback mechanisms are contained, is the ensuing change in climate that is required to restore the top-of-the-atmosphere radiation balance.

Because Raval and Ramanathan's demonstration of water-vapour feedback refers to clear-sky conditions, I will use a hypothetical planet to illustrate the process. This planet has the same global-mean surface temperature (288 K) as Earth, and its atmosphere is cloud free and corresponds to the clear-sky observations employed by Raval and Ramanathan. A further assumption is that absorption of solar radiation by the surface-atmosphere system is invariant to climate change, making

this planet quite different from Earth. Finally, the direct radiative forcing will arbitrarily be chosen to be 4 W m^{-2} . Although this corresponds to a doubling of CO₂ in the Earth's atmosphere, bear in mind that our hypothetical planet lacks many of the Earth's climate feedback mechanisms; the goal here is to focus solely on clear-sky water-vapour feedback.

By Raval and Ramanathan's definition, the greenhouse effect is $G = E - F$, where E is the infrared surface emission and F is

Responses of the hypothetical planet's climate system to a 4 W m^{-2} direct forcing through, say, increased CO₂

Process	$\Delta T_s (\text{K})$	$\Delta G (\text{W m}^{-2})$	$\Delta F (\text{W m}^{-2})$
1 Direct forcing	0	4.0	-4.0
2 Response with fixed $g=0.327$	1.09	1.9	4.0
3 Further response to variable g	0.64	3.6	0
Total Response	1.73	9.5	0

emission at the top of the atmosphere. The base value they determine as 146 W m^{-2} . Their normalized greenhouse effect is $g = G/\sigma T_s^4$, where T_s is surface temperature and σ is the Stefan-Boltzmann constant. Raval and Ramanathan impressively demonstrate (their Fig. 3a and b on page 760) that g is a function of the surface temperature, this being a consequence of the related dependence of atmospheric

water-vapour abundance upon T_s , so that $g(T_s)$ represents the water-vapour feedback mechanism. If g were independent of T_s , there would be no feedback. Furthermore, it is easily shown that

$$F = (1 - g(T_s))\sigma T_s^4$$

where $g(T_s)$ is given in Raval and Ramanathan's Fig. 2.

The hypothetical planet's climate responses are summarized in three stages (see table). The direct infrared forcing (process 1) simultaneously reduces F and increases G , so that the planet emits 4 W m^{-2} less energy than it absorbs from the Sun. This imbalance causes global warming that, without water-vapour feedback, increases T_s by 1.09 K (process 2). G is increased by 1.9 W m^{-2} because of the enhanced surface emission, and the flux F at the top of the atmosphere is increased by 4 W m^{-2} , restoring the net balance of incident and outward flux. Further warming then occurs when water-vapour feedback is allowed (process 3).

This simple illustration demonstrates how the direct greenhouse forcing of 4 W m^{-2} is first amplified to 5.9 W m^{-2}

through temperature feedback (process 2) and then to 9.5 W m^{-2} by water-vapour feedback (process 3). The combined forcing and feedbacks thus increase the clear-sky greenhouse effect from its initial value of 146 W m^{-2} to nearly 156 W m^{-2} . Note that water-vapour feedback amplifies surface warming by roughly 60 per cent.

On a further point, Raval and Ramanathan show that their observational interpretation of water-vapour feedback is compatible with results from climate models, and it is worth expanding on this point. Our recent intercomparison⁵ of 14 atmospheric general circulation models (GCMs) shows significant disagreements amongst the models' global-mean dF/dT_s values. This, however, is primarily caused by differences in the depiction of cloud feedback. When output from the GCMs is processed in the same way as the data used by Raval and Ramanathan, to average clear-sky regions separately, there is quite good agreement in their clear-sky dF/dT_s values: the average for the 14 GCMs is $2.38 \pm 0.16 \text{ W m}^{-2} \text{ K}^{-1}$, which compares favourably with Raval and Ramanathan's observational value, $2.31 \text{ W m}^{-2} \text{ K}^{-1}$,

derived using the equation above. But if the water-vapour feedback is suppressed by making $g(T_s)$ fixed in the equation, the observational value would be $3.67 \text{ W m}^{-2} \text{ K}^{-1}$, significantly exceeding the GCM values.

As Raval and Ramanathan emphasize, their observed water-vapour feedback has a very simple explanation: it is dominated by the saturation vapour pressure of water through the Clausius-Clapeyron equation. The same explanation would seem to apply to the GCMs. With all the uncertainties in our knowledge of climate processes, especially cloud feedback⁵, it is gratifying that at least one such process has a simple explanation. $\square$

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1. Tyndall, J. *Philos. Mag.* **22**, 273-285 (1861).
2. Möller, F. J. *Geophys. Res.* **68**, 3877-3886 (1963).
3. Manabe, S. & Wetherald, R. T. *J. Atmos. Sci.* **24**, 241 (1967).
4. Raval, A. & Ramanathan, V. *Nature* **342**, 758-761 (1989).
5. Cess, R. D. et al. *Science* **245**, 513-516 (1989).

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hold
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THE ROLE OF CLOUDS IN CLIMATE CHANGE

Testimony of

Dr. Kevin E. Trenberth*
National Center for Atmospheric Research**

before

The U. S. Senate Committee on Commerce, Science, and Transportation
The United States Senate
SR-253 Russell Senate Office Building
9:30 a.m., October 7, 1991

* Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the National Science Foundation.

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Introduction

My name is Kevin Trenberth. I am the Head of the Climate Analysis Section and Deputy Director of the Climate and Global Dynamics Division at NCAR, the National Center for Atmospheric Research. In my work, I am especially interested in global-scale climate dynamics; the observations, processes and modeling of climate changes from monthly to interannual to decadal time scales. I am from New Zealand and I believe that I have unique experience and expertise on the Southern Hemisphere and global atmospheric circulation. I was one of the instigators of the International Tropical Oceans Global Atmosphere (TOGA) programme (under the World Climate Research Programme) and I have served in the U.S. and still serve internationally on TOGA advisory panels. I have served on many National Academy of Science committees, panels and/or boards, and I serve on the NOAA Climate and Global Change Advisory Panel. I have been involved in the global warming debate and the Intergovernmental Panel on Climate Change (IPCC) scientific assessment activity.

With regard to the subject of clouds, I will first summarize the state of knowledge concerning basic water vapor observations in the atmosphere and briefly comment on the relevance of these observations to simulating climate with general circulation models. Water vapor is the most important greenhouse gas in the atmosphere. It is fairly transparent to solar radiation but modulates the outgoing longwave radiation (OLR). Good measurements of water vapor exist throughout the troposphere, but not with global coverage. The climate models indicate that convective clouds play a vital role in moistening the upper troposphere.

A debate has developed over the Ramanathan-Collins (1991) hypothesis concerning the role of clouds as a thermostat on the climate system. They suggested that in the region of high sea surface temperatures, deep convection develops that produce clouds which block out the sun and thus limits further sea surface warming. However, there are examples where this does not work, and the mechanism should not be applied locally because there are nearby regions of compensating effects. The hypothesis does not have general applicability and there are other known limiting mechanisms.

A focus of the impacts of clouds on climate has been their radiative effects, but I am concerned that the role of atmospheric flow in determining patterns of clouds should not be overlooked. Recently, a very useful construct called "cloud forcing" has been introduced. It deals with the radiative effects of clouds, and so can be divided into shortwave (solar) cloud forcing and longwave (infrared) cloud forcing. However, it often tends to ignore other aspects of clouds, such as where the moisture comes from to form the clouds, why clouds occur where they do, why they have the form that they take, and the fact that in forming precipitation latent heat is realized in the clouds, thereby heating the atmosphere. All these factors mean that the atmospheric dynamics are critical in forming patterns of clouds. At the same time the atmospheric flow is strongly affected by the radiative cloud forcing and the latent heating. As a result, there is a strong coupling between clouds, the atmospheric dynamics, and the underlying surface of the ocean or land that can only be properly approached by studies that address these interactions. For example, TOGA is concerned with tropical ocean-atmosphere coupling. Interannual variations in the climate system, which are also a subject of central interest to TOGA, have been used as an indication of what may happen in longer-term climate change. However, clouds have not been a principle concern in the El Niño studies because they are of secondary importance in that phenomenon. This may not be the case in global change.

Atmospheric water vapor: What do we know?

The main measurements of atmospheric water vapor are from *radiosondes*, which consist of a package of instruments flown through the atmosphere on a balloon twice daily at many hundreds of stations all around the world. The package is expendable, so the instrumentation is as cheap as possible. Over the years, the radiosonde itself has evolved, different countries use different instruments with differing accuracy and precision. For water vapor, the sensor measures relative humidity (RH) and has changed with time. Special problems occur at low humidity measurements and these continue unnecessarily. In the U.S. a lithium chloride element was introduced in 1943 but was incapable of making any measurements for relative humidities less than 20%. About 1965, a new carbon element was gradually introduced to measure humidity. In 1973 the housing of the radiosonde was changed and this affects the radiative and ventilation characteristics of the instrument, thereby changing the readings. Recently, in 1989, a second manufacturer was added in the U.S. that currently supplies about 20 western U.S. stations. However, problems with the new instrument continue. For example, the black paint used in the air intake to the instrument turned out to be hygroscopic (water attracting) and comparisons between radiosondes from the two manufacturers reveal differences.

There are some problems with the instrument. There is a time lag response in both temperature and relative humidity measurements. There is some hysteresis in the moisture sensor (it remembers moisture), creating differences in readings of up to about 3%. There have long been errors in the treatment of RH for values $<20\%$, a heritage of the early sensor. In the U.S. this is coded as "30" dew point depression, which the National Meteorological Center (NMC) interprets as 15% RH, while the National Climate Data Center uses 19%. Neither is correct. The actual sensor works fine but simply has not had a calibration curve supplied. Overseas, fairly widespread use is now made of a Vaisälä radiosonde instrument that measures low humidities.

Aside from the low humidity problems, the accuracy of the humidity sensor on the U.S. radiosonde is 4 to 7% RH (high end because of hysteresis effects). With uncertainties in other instruments and balloon location drift, the net uncertainty (assigned by the European Centre for Medium Range Weather Forecasts (ECMWF)) is : 10% from 1000 to 500 mb (lower troposphere) and 20% from 500 to 300 mb (upper troposphere).

What area of the globe is one measurement representative of? One fundamental problem in using the measurements is that water vapor is not well mixed in the atmosphere, so that there are large spatial gradients (e.g. clouds, fronts), and there are rapid changes in time. The representativeness of one measurement is difficult to assess. ECMWF uses an influence radius of 250 km at 1000 mb and 300 km in upper troposphere (Illari, 1989). Thus there are too few radiosonde measurements to determine global fields.

Another form of measurement of water vapor is from satellite sensing in the infrared and microwave. These measurements have the advantage of global coverage, but at present give poor vertical resolution. Also, the retrieval algorithms make assumptions, and there are several different algorithms. The microwave results are sensitive to surface emissivity, so that the method can only be applied over the ocean and the algorithms must remove the influence of

surface wind. Comparisons between radiosonde and infrared (TOVS, the TIROS Operational Vertical Sounder) retrieval measurements indicate errors of 15% in tropics, and 35% in mid latitudes (biggest errors where RH is small) (Illari, 1989). Recently, new measurements have been reported from the SAGE II instrument of RH from 6 to 12 km altitude at 1 km vertical resolution are accurate to 10% (Rind et al., 1991).

Given the basic data, how do we get global fields of relative humidity analyses? The method used is through a process called four-dimensional data assimilation at major centers like NMC and ECMWF. The analyses are univariate for RH, which means RH is analyzed by itself as a combination of measurements and information from the numerical weather prediction model used to provide a "first guess" as to what the field looks like. This first guess is actually a forecast from the previous analysis and is subject to errors of perhaps 20%. Global RH analyses have not compared well with observations (Illari, 1989) and have changed erratically with time as the numerical weather prediction model used in the data assimilation has changed, see Fig. 1 (Trenberth and Olson, 1988). Use has been made of satellite data in recent years. However, because of low humidities in the upper troposphere there is no RH analysis above 300 mb at ECMWF.

In summary, reasonably good RH information is available from radiosondes, although information in the upper troposphere is mostly confined to local or special measurements. Mean values are better known than daily and monthly time series, and the evolution of global fields is not well enough known for climate purposes.

Climate models have not been able to simulate observed moisture levels in the mid to upper troposphere without including effects of vertical transport of moisture by convective clouds. Specifically, in developing the Community Climate Model at NCAR, my colleagues have found it necessary to include a convective parameterization that detrains moisture into the upper troposphere. Any model convection scheme that "rains out" all the moisture in these clouds and which does not detrain a fraction fails to come close to reproducing observed moisture concentrations (Fig. 2). The vertical moisture transport by convection is vital in forming the observed tropical moisture concentrations in the atmosphere which, in turn, has a strong greenhouse effect.

The Dynamics of Cloud Forcing

The cloud radiative forcing method for analyzing the effects of clouds on the earth's radiation budget was developed by Charlock and Ramanathan (1985). It contrasts the radiation composites for clear sky conditions with the total observed, and the difference is a direct measure of the effects of clouds on the radiation balance of the earth. In this section, it is emphasized that these are not the only effects of clouds and that there are several issues linked to cloud forcing.

Firstly, the tropical convective regions where optically thick upper level clouds occur require a supply of moisture, since precipitation exceeds evaporation in these regions.

Secondly, the latent heating from precipitation in the convective regions requires upward motion and an export of heat in the atmosphere. This heating helps drives large-scale over-

turning in the atmosphere.

Because atmospheric mass is conserved, the rising motion in the convective regions must be balanced by **sinking motion** elsewhere. This can be seen by the divergent flow in the upper troposphere which changes with season (Fig. 3). The dominant patterns in Fig. 3 constitute what is known as the Hadley (north-south) and Walker (east-west) cells of large-scale overturning. In practice, the compensating sinking motion occurs over fairly warm water in the tropics and subtropics.

The large-scale subsidence creates a strongly stable atmosphere which **suppresses cloud** development and the vertical transport of free-atmosphere water vapor, and produces the dry zones in the tropics, some of which have high sea surface temperature. This is where the top-of-the-atmosphere outgoing longwave radiation is largest and the absorbed solar radiation at the surface is increased.

In view of the above, it is clear that an increase in shortwave cloud forcing and greenhouse effect, due to increased water vapor, in one location in the tropics necessarily means a **compensating** decrease in these factors someplace else in the tropics. While it appears that cloud forcing has one effect in convective areas, it has the opposite effect nearby and the two regions are closely coupled through the atmospheric dynamics. Therefore the net cloud forcing should not be considered locally, but should be averaged over the regions coupled through the dynamics (Hartmann and Michelsen, 1991).

Sea Surface Temperature (SST) controls in the tropics

Ramanathan and Collins (1991) proposed that optically thick clouds in the tropics act as a thermostat in controlling high SST (above about 31°C). They hypothesize that in high SST regions, deep convection develops and creates such clouds that block out the sun ("shortwave cloud forcing") and thus limit further sea surface warming.

Discussion:

Several points relevant to this mechanism and its possible general applicability need to be made:

- 1) Locations of convective cloud do not depend solely on SST but also on SST gradients, and on land heating (land-sea contrasts and monsoons) from more remote regions, as well as on atmospheric dynamics (Trenberth, 1991). Consequently, spatial patterns of cloud do not closely follow those of SST, see for example see Fig. 4, for March, April, May (MAM) 1987, from Hartmann and Michelsen, 1991).

Over the Indian Ocean, where the influence of the Asian landmass cannot be ignored, regions of high SST (in MAM 1987 the highest, of over 31°C, Fig. 4) occur but often with subsiding air aloft, so that the atmosphere becomes stable and suppresses convection.

Because regions of upward motion must be balanced by regions of downward motion in the atmosphere, cloud and convection cannot occur everywhere (even if SST is high everywhere). Convection is organized by atmospheric dynamics into "convergence zones" (see Fig. 5) and monsoons; (cf. the Hadley and Walker Circulations, Fig. 3). The upward motions are concen-

trated into small regions where there are collections of convective clouds, whereas the subsiding motions are more gradual and widespread.

Because of the atmospheric dynamics involved in generating cloud from deep convection (moisture supply, export of heat, conservation of mass) an increase in shortwave cloud forcing in one area must be compensated by a decrease somewhere else, and radiative cloud forcing is inherently not a local problem, as noted above.

2) Ramanathan and Collins (1991) did not fully discuss the role of evaporation, and thus surface latent heat loss, as a further controlling mechanism. In general this appears to be the dominant controlling mechanism for SST in the tropics, with increases in latent heat loss from the surface of $\sim 10 \text{ W m}^{-2}$ per $^{\circ}\text{C}$ change in SST. In the tropics, this partly arises simply from the fact that warmer air can hold much more water vapor (the Clausius-Clapeyron equation). But, in addition, in regions of convection, gusty winds and cooler drier downdrafts can greatly enhance surface evaporation to twice this value (Moncrieff, 1990). Typical surface heat losses from evaporation in warm pool regions are 100 to 150 W m^{-2} .

3) Surface thermal radiation toward space also contributes significantly to controlling SST (higher SST, higher radiation) with a heat loss of $\sim 6 \text{ W m}^{-2}$ per $^{\circ}\text{C}$ increase in SST in the tropical warm pools. Typical surface thermal radiative heat losses in warm pool regions are 60 W m^{-2} .

4) In general, when there are changes in SST, as in an El Niño event, there are strong compensations between changes in shortwave cloud (Fig. 6) and longwave cloud plus water vapor (greenhouse) effects. The increased cloudiness blocks the sun, but is more than compensated for by the increased greenhouse effect of increased water vapor plus the trapping of heat by the clouds. In regions of higher SST convective cloud typically increases, but in nearby regions there are decreases in convective cloud, so that opposite effects take place. The sum of the changes in the two radiation components (short- and longwave) with changes in SST indicates heat increases of $\sim 6 \text{ W m}^{-2}$ per $^{\circ}\text{C}$ change in SST which virtually offsets the surface thermal radiation effects (in 3)), so that the change in net radiation terms in the tropics sums close to zero. This is very robust over many areas in which there are increases and/or decreases in cloud (Hartmann and Michelsen, 1991).

5) It is likely, however, that the distribution in the vertical atmospheric column of the long- and shortwave radiative heating is different. Changes in solar radiation are more apt to be felt at the surface, whereas the longwave heating is distributed throughout the atmosphere. Therefore changes in cloudiness should have a direct effect on heating at the surface. Over the ocean, this can impact SSTs, as suggested by Ramanathan and Collins, but the effect is complicated by changes in the ocean currents and upwelling induced by changes in the atmospheric winds.

6) There is no good reason for a "magic" number such as 31°C for SST maxima, and higher SSTs could occur under global warming. There are good reasons why SSTs and air temperatures are fairly uniform over large areas of the tropics and the upper limit should be fairly well defined (Wallace, 1991). Wallace argues that the distribution of SSTs in the tropics should be skewed to an absence of hot spots (i.e. large warm pools should form) because of

the uniformity of atmospheric temperatures in the troposphere and rapid equilibration between atmosphere and ocean. The atmospheric temperatures are relatively uniform in the tropics because even small pressure (or temperature) gradients set up strong winds that usually quickly remove inhomogeneities.

Summary

Cloud forcing in the atmosphere is inherently a nonlocal process. There is a strong interplay between the atmospheric dynamics, cloud and with the surface of the earth or underlying ocean. Questions such as why atmospheric convergence zones and associated cloud occur where they do are inherently questions of the coupled atmosphere-ocean system that must be addressed in programs such as TOGA and Global Change.

Ramanathan and Collins (1991) proposed an effective mechanism for regulating increases in SSTs in the tropics, but other limiting factors appear to be more important. Many of the factors contributing to the balance of SST are somewhat uncertain, especially in the very warm pool regions of the globe. The TOGA COARE* Program is designed to address them as best they can with the resources available through a major international field program to take place from November 1992 to February 1993 in the tropical west Pacific. It is very important that adequate funding should be allocated to the U.S. research component of this international Programme.

A summary of cloud knowledge?

I've looked at clouds from both sides now

From up and down, and still somehow

It's cloud illusions I recall

I really don't know clouds at all.

"Both sides, now"

Joni Mitchell

References

- Charlock T. P., and V. Ramanathan, 1985: The albedo field and cloud radiative forcing produced by a general circulation model with internally generated cloud optics. *J. Atmos. Sci.*, 42, 1408-1429.
- Hartmann, D. L., and M. L. Michelsen, 1991: Tropical sea surface temperature regulation. *Nature*, submitted.
- Illari, L., 1989: The quality of satellite precipitable water content data and their impact on analyzed moisture fields. *Tellus*, 41A, 319-337.

* COARE is the Coupled Ocean-Atmosphere Response Experiment.

- Moncrieff, M. W., 1990: Influence of atmospheric deep convection on boundary layer and surface processes. *Intl. TOGA Scientific Conf. Proc.*, Honolulu, HI, 16-20 July 1990. WCRP-43, WMO/TD-No. 379. 145-152.
- Ramanathan, V., and W. Collins, 1991: Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Niño. *Nature*, 351, 27-32.
- Rind, D., E.-W. Chiou, W. Chu, J. Larsen, S. Oltmans, J. Lerner, M. P. McCormick and L. McMaster, 1991: Positive water vapour feedback in climate models confirmed by satellite data. *Nature*, 349, 500-503.
- Trenberth, K. E., and J. G. Olson, 1988: An evaluation and intercomparison of global analyses from NMC and ECMWF. *Bull. Amer. Meteor. Soc.*, 69, 1047-1057.
- Trenberth, K. E., 1991: General characteristics of El Niño-Southern Oscillation. Chapter 2 of a book *ENSO Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*. M. H. Glantz, R. W. Katz, and N. Nicholls, Editors, Cambridge University Press, 13-42.
- Wallace, J. M., 1991: Is the upper limit of tropical sea surface temperature fixed or relative? *Nature*, submitted.

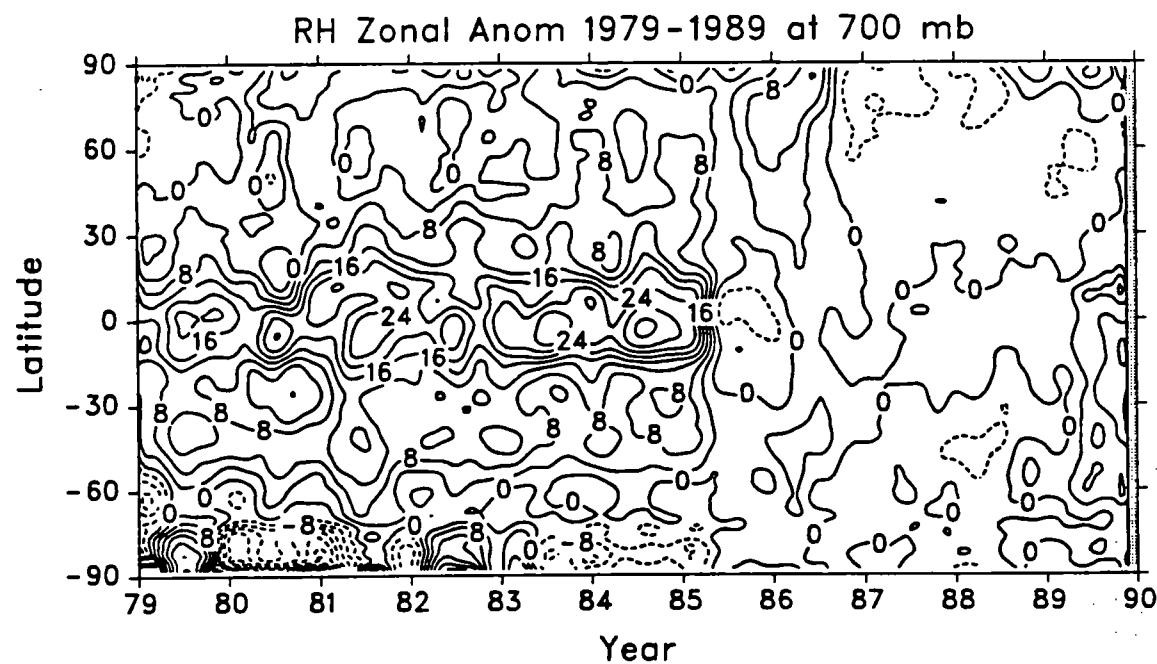
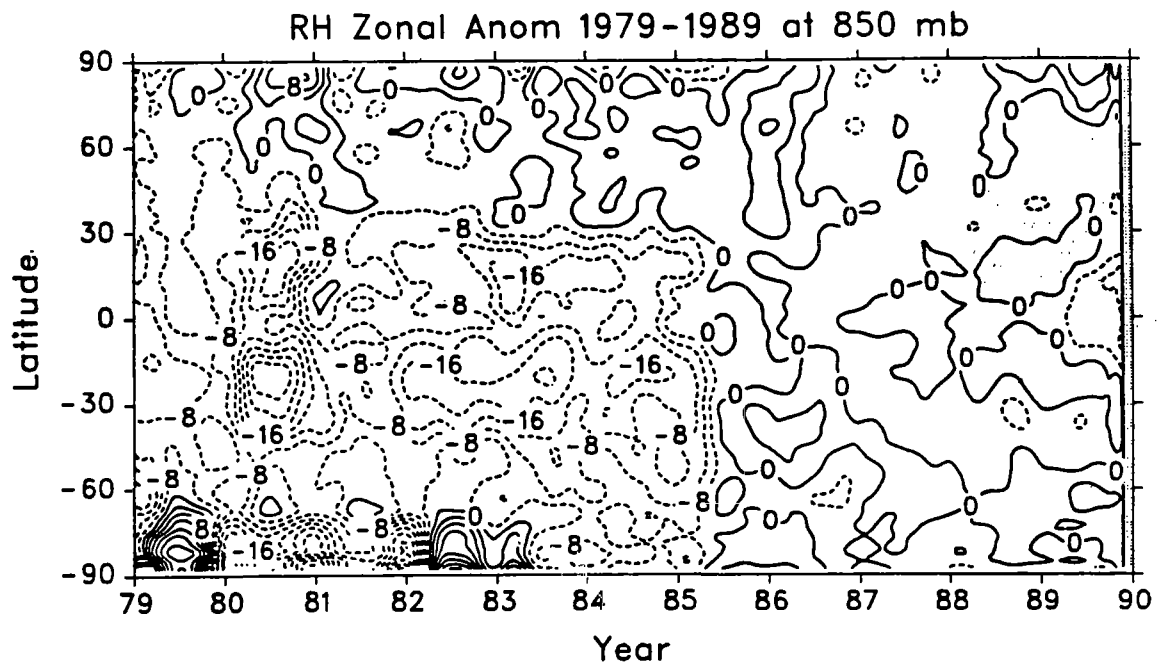


Fig. 1 Latitude-time series for several quantities from the ECMWF WMO archive. Shown are departures from the mean annual cycle from May 1985 to May 1989 of the relative humidity at 850 and 700 mb, in %. Most changes seen here are spurious and associated with changes in the data assimilation system.

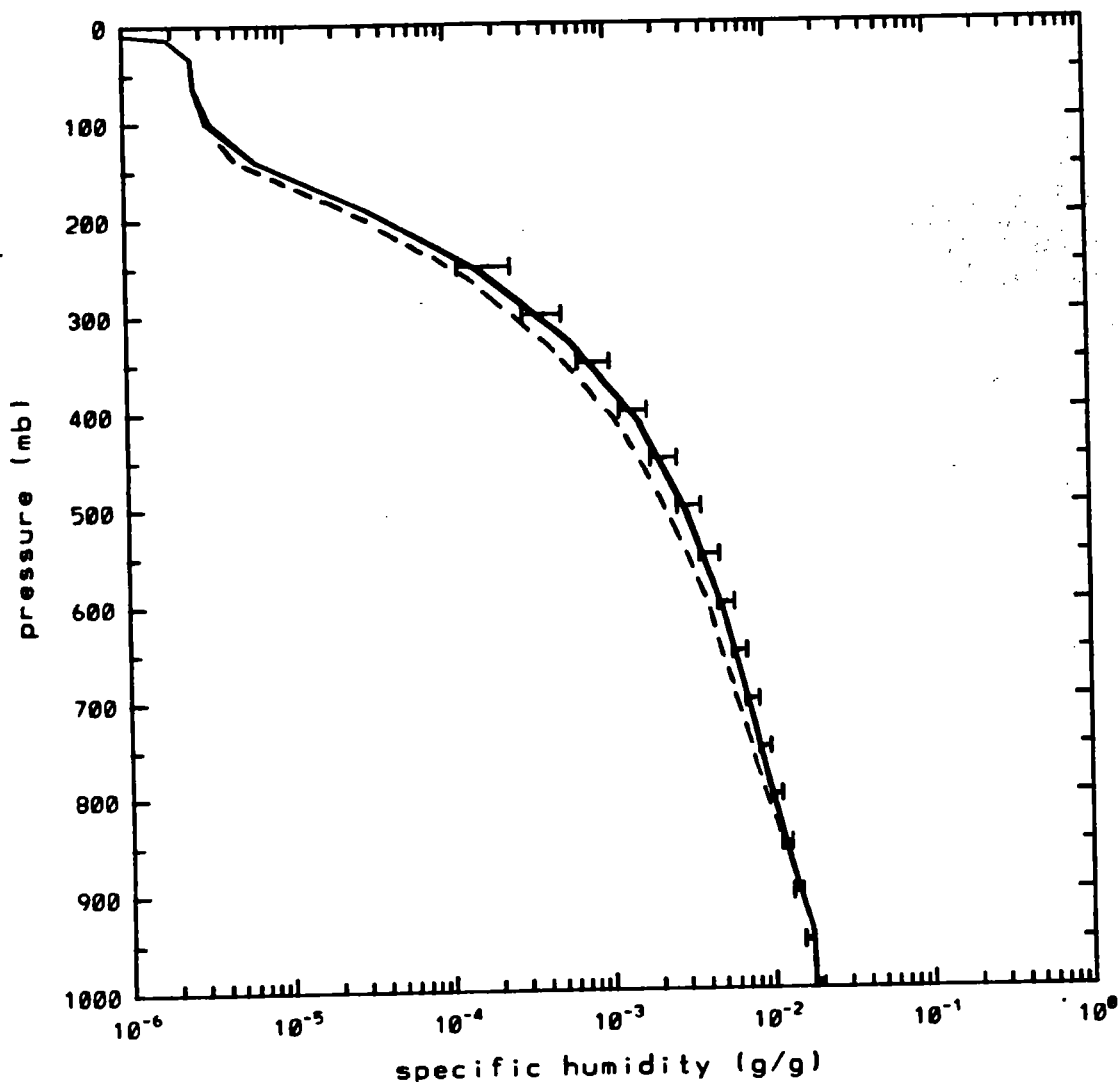


Fig. 2 The vertical profile of specific humidity at the location of Truk island (7.5°N 151°E) in the tropical west Pacific. The horizontal bars show the range (as given by plus and minus one standard deviation) of monthly mean observations from radiosondes at the island for the month of July. Note the horizontal scale is logarithmic and water vapor amounts (in grams of water vapor per gram of air) decrease rapidly with height. The solid profile is the result for the monthly mean from a simulation with the NCAR CCM2 climate model in which a mass flux convection scheme is included which features an overshoot of clouds and detrainment of moisture into the troposphere at cloud top. The dashed profile is the model simulated result when all the condensation in clouds is forced to precipitate out. The result in the latter case is a deficit of moisture in the troposphere compared with observations, which leads to temperatures that are too cold because of the reduced greenhouse effect. (Courtesy J. Hack, NCAR).

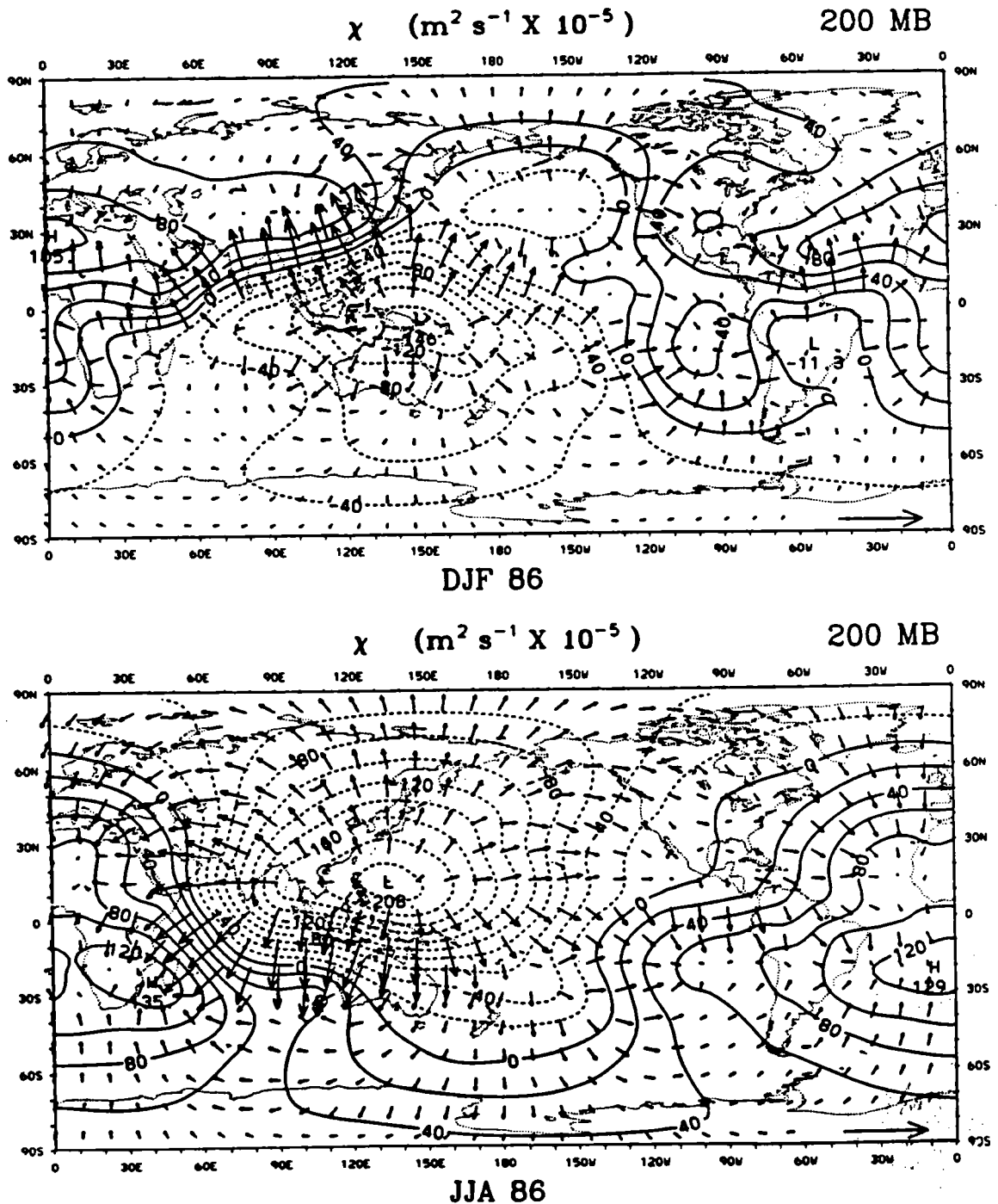
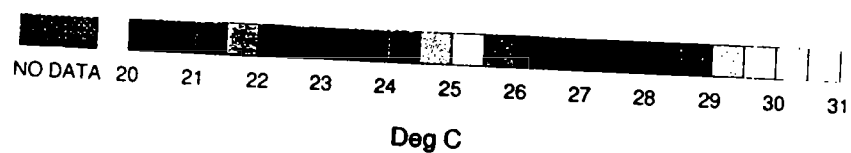
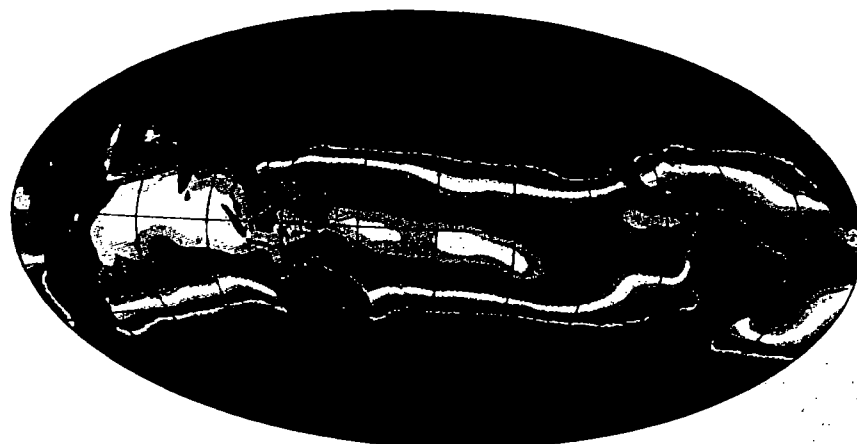


Fig. 3 Seasonal mean velocity potential and the divergent component of the wind vectors at 200 mb for (a) December–February 1985–86, and (b) June–August 1986. The vector plotted at lower right depicts 10 m s^{-1} . From Trenberth (1991). The arrows depict the upper tropospheric flow from regions of intense upward motion in convective areas to regions of more gradual downward motion.

Sea Surface Temperature
MAM 1987



Shortwave Cloud Forcing
MAM 1987

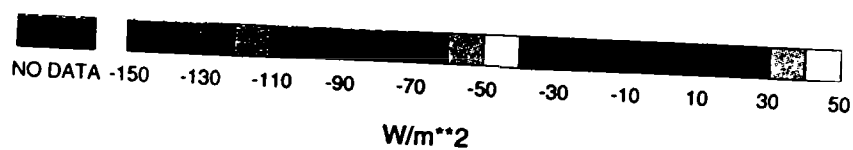
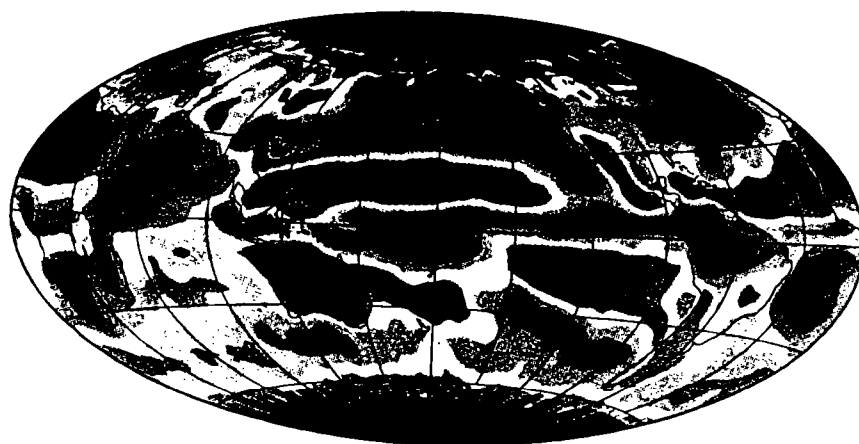
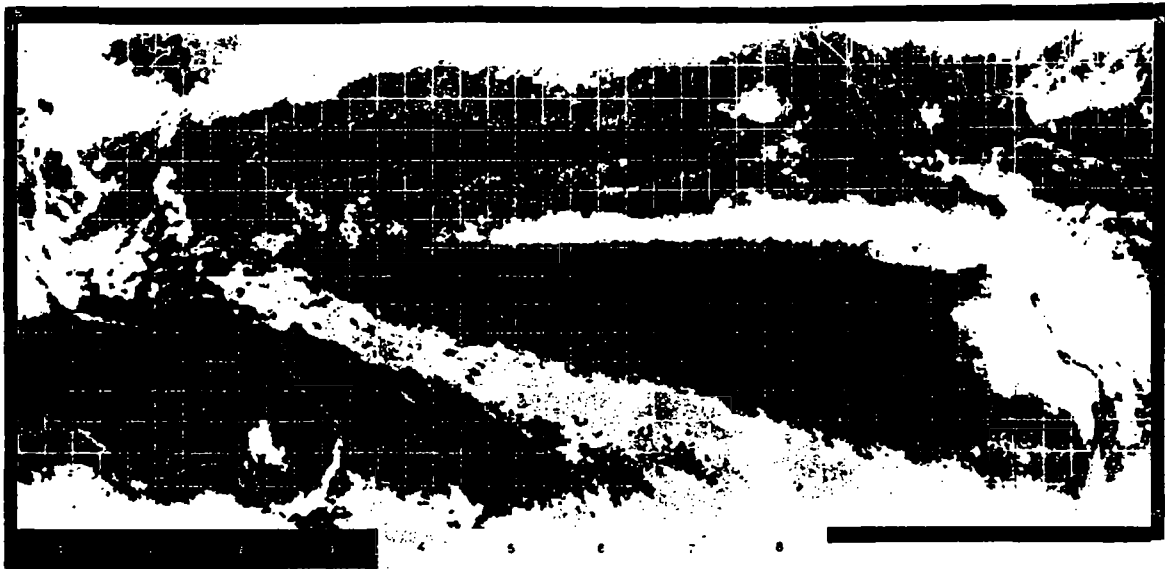


Fig. 4 a) Sea surface temperature (°C) and b) shortwave cloud forcing (W m^{-2}) for March-May 1987 mapped on a Hammer equal area projection. The originals are in color and the SST map colors were chosen to emphasize the tropics. From Hartmann and Michelsen (1991).



Mercator Satellite Relative Cloud Cover, 1400 Local, 40°N to 40°S, Mean Octas, October 1967-1970.

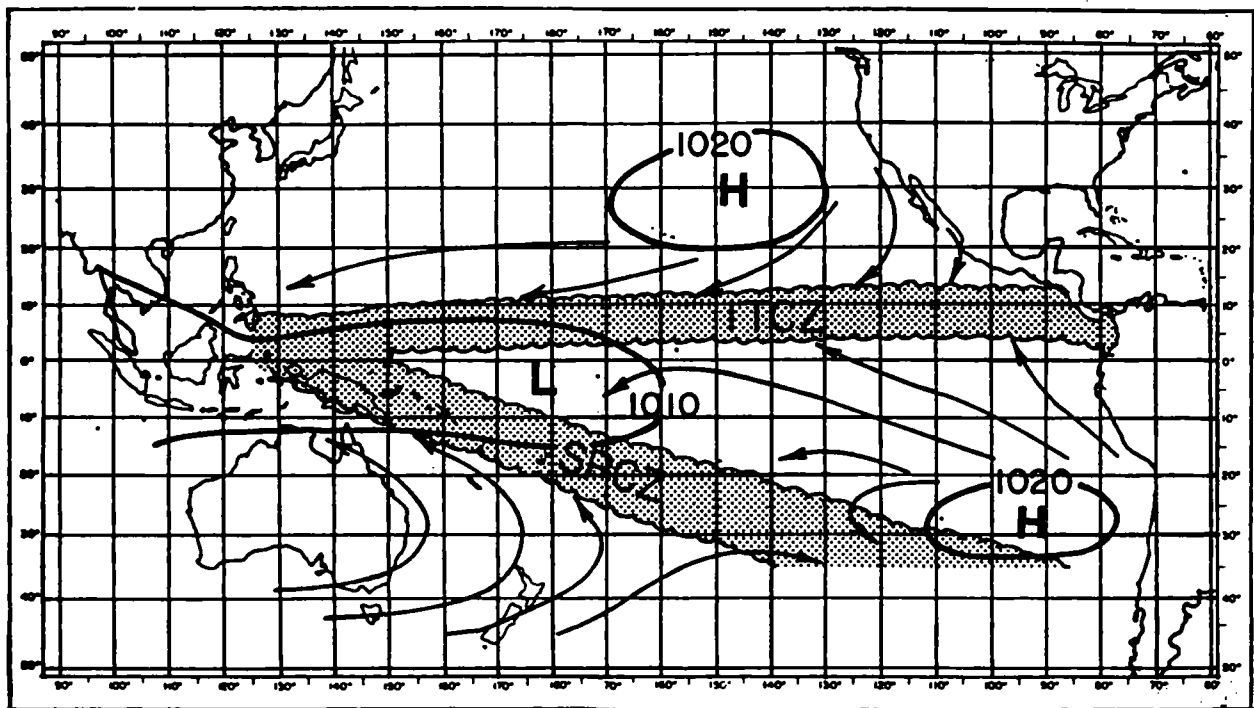
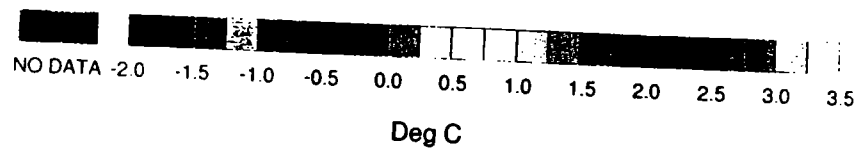


Fig. 5 a) Mercator satellite picture of cloud cover 40°N to 40°S for October 1967 to 1970; and b) pictorial representation of the key features in a) showing the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ), with the annual mean sea level pressure field superposed along with schematic surface wind streamlines.

Sea Surface Temperature
MAM 1987-1985



Shortwave Cloud Forcing
MAM 1987-1985

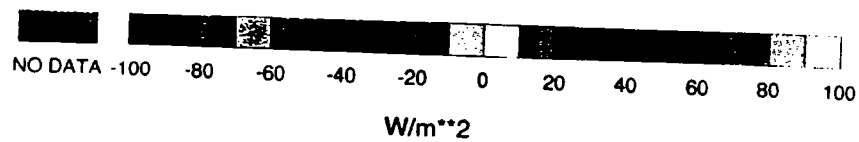


Fig. 6 a) Sea surface temperature ($^{\circ}\text{C}$) and b) shortwave cloud forcing (W m^{-2}) differences between March-May 1987 – 1985 mapped on a Hammer equal area projection. The originals are in color. From Hartmann and Michelsen (1991).

SENATE COMMERCE COMMITTEE MEETING ON ROLE OF CLOUDS IN CLIMATE CHANGE

October 7, 1991

Statement by:

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Subject: GLOBAL WARMING AND THE TROPICAL WATER BUDGET

1. Background

I was born and educated in England, with a BA (and MA) in Natural Sciences (Theoretical Physics) from the University of Cambridge in 1967, and a PhD in Meteorology from Imperial College, of the University of London, in 1970. I came to the Department of Atmospheric Science at Colorado State University in 1970 to work on the analysis of a tropical field experiment in Venezuela (VIMHEX: the Venezuelan International Meteorological and Hydrological Experiment), in which I had participated in 1969. I remained on the academic faculty at CSU until 1978, when I moved to Vermont to continue my research work independently. For the past 13 years, I have lived and worked in Vermont, supported by direct grants and contracts from the National Science Foundation and the National Aeronautics and Space Administration.

My research has dealt with atmospheric convection and clouds; their description by observations and theory, and the representation of their energy and water transports in global models, both numerical weather prediction and climate models. In the 1970s my research concentrated on convection in the tropics, and I helped plan and execute the Global Atmospheric Research Program Atlantic Tropical Experiment in 1974 (GATE) (Betts, 1974, Houze and Betts, 1978), as well as a second VIMHEX Experiment in 1972. For this research, I was awarded the Richardson Prize of the Royal Meteorological Society in 1974, the Meisinger Award in 1977 and a Special Award in 1978 by the American Meteorological Society. I co-ordinated the convection research for GATE for the National Academy of Science panel. In the past decade my research has broadened to cover as well the analysis of clouds and convective boundary layer processes over land and the oceans, both in the tropics and mid-latitudes, and the representation of convective processes in global models. I am currently a member of the National Academy panel for the International Satellite Cloud Climatology Project.

2. Water vapour and the climate system

The earth's climate system, which involves not only the atmosphere, but the ocean circulations and the biosphere, is exceedingly complex. As a result of theoretical studies, a global observing system, and the development of computers fast enough to model the global atmosphere at sufficiently high resolution, we have made remarkable progress in our understanding in the past 20 years. Yet our present models are still extremely simple, when compared with the complexity of the real climate system of the earth. As a result our global climate models are only as good as the conceptual components of which they are made.

I wish to discuss the links in the chain between the known global increase of the gases such as CO₂, CH₄ and the CFC's, which are due to anthropogenic activity, and the changes of temperature, water vapour and clouds in the tropics; which in turn primarily control the surface equilibrium temperature of the earth. I will focus my discussion on water vapour: others here will discuss the radiative effects of the clouds themselves. Water vapour is the major absorber in the infrared contributing to the greenhouse effect. Unlike the other greenhouse gases, whose global concentrations are slowly increasing because of anthropogenic

activity, the concentration of water vapour is controlled by the transport and precipitation processes in clouds. Generally the water vapour content increases with temperature, because the saturation vapour pressure increases with temperature. In the tropics, water evaporates primarily from the oceans, which are heated directly by incoming solar energy, rises in cumulonimbus clouds (thunderstorms), where it condenses, releasing the latent heat of condensation and freezing. This latent heat release both drives the vertical circulation and balances the net infrared cooling of the atmosphere. The air which flows out of these storms in the upper troposphere is full of ice, which forms the extensive picturesque anvils so characteristic of thunderstorms. In the tropics, clusters of thunderstorms produce extensive anvil clouds, which are readily visible on satellite pictures. These anvils, which are often 400 mb thick, last for many hours, sometimes even a day, since they are maintained by dynamical, convective and radiative processes. As they decay and their ice crystals evaporate, they are responsible for most of the water vapour input to the upper troposphere. Estimates from GATE (Gamache and Houze, 1983) have suggested that up to 10% of the water which is evaporated at the ocean surface is injected into these thick anvils. Away from convective disturbances where air sinks as it slowly cools radiatively, the relative humidity in the tropical upper troposphere is around 30 - 40% up to about 350 mb, where routine rawinsonde measurements become unreliable. At higher levels, the data from the Stratospheric Aerosol and Gas Experiment (SAGE-II) suggest that the relative humidity (away from deep convection) is about 20-25% at 200 mb. The annual variation is small, with higher values on the summer side of the equator.

3. Lindzen's argument

Lindzen (1990) has argued that there is a possibility that deep convection might dry the upper troposphere. This is important because absolute decreases of water vapour at high levels can offset the effect of increases at low levels in their greenhouse effect.

His argument is as follows. *Boundary layer temperature and moisture increase with increasing sea surface temperature, so that the tops of the deep convective clouds in the tropics will go higher.* This is correct. If the temperature at the tropopause falls, then the highest outflows from these clouds will be at colder temperatures. Since the saturation mixing ratio over ice decreases with temperature, Lindzen argues *that the cumulonimbus outflow will therefore inject drier air at the highest outflow level; and then the subsidence of this dry air between clouds will produce a drier upper troposphere.*

This idea is wrong (Betts, 1990), because deep convective clouds inject water (as ice and vapour) into the upper troposphere at all levels above their freezing level (this is near the middle troposphere in the tropics; about 550 mb), not just at their tops. Near their highest outflow levels, most of this water is in the form of ice (the anvil clouds), so that the comparatively small value of the saturation mixing ratio plays a relatively insignificant role in the water budget at the highest levels. If Lindzen's model were right, the present upper troposphere would be very dry. In fact, the relative humidity near the freezing level in the deep tropics is about 40%. This is consistent with a subsidence of order 20 mb/day (which is roughly in thermal balance with the radiative cooling rate), and the injection of 10% of the surface evaporation as ice into the upper troposphere (mentioned above).

Lindzen's model is implausible on more general grounds. If the sea surface temperature rises in the tropics, the troposphere as a whole is warmed to a higher temperature, so that, at any given pressure, the saturation mixing ratio increases significantly. For the absolute mixing ratio to decrease at any level, the relative humidity must therefore decrease significantly (by 12 - 15% for a 2°C rise in sea surface temperature). The theoretical evidence is to the contrary. If the temperature warms (towards a warmer "moist adiabat") the stability of the atmosphere increases proportionally more than the increase in the radiative cooling rate, so that the mean sinking motion between the convective systems decreases (Betts and Ridgway, 1989). This reduced subsidence would tend to increase (not decrease) the relative humidity at any level (Betts and Albrecht, 1987). In this simple coupled model of Betts and Ridgway (1989), doubling CO₂ increased the tropical surface temperature by 2 to 3°C, consistent with

the increase shown by global circulation models.

Clearly, we need better observations of water vapour in the tropical upper troposphere, but the evidence we have is consistent with a relatively tight coupling of water vapour to temperature in which the relative humidity changes rather little.

4. Conclusion

I have concentrated on the role of water vapour in the tropics on the greenhouse effect. It is probable that water vapour, because it is coupled thermodynamically to the temperature, will increase as the temperature of the troposphere increases. This coupling leads to an important amplification of the greenhouse effect, as is shown by both global climate models (e.g. Cess et al., 1990) energy balance models (e.g. Betts and Ridgway, 1989) and observational studies (e.g. Raval and Ramanathan, 1989). The radiative role of clouds is more complex, and others here will discuss this in more detail.

As a society we have many choices, but one basic dilemma concerning climate change. The waste products of our civilization are significantly modifying the atmosphere, making it more opaque to infrared radiation. The coupling of temperature and water vapour amplify this effect, while the effects of changes in cloudiness are more complex. Modelling studies suggest that a warming of the atmosphere of several degrees will result if present trends continue. Because of the natural fluctuations of the climate system, it may be a decade or more before we can have confidence that the recent climate warming reflects a long-term trend. Because of the complexity of the earth system, our relatively simple models might mislead us, but again the improvement of our models is a steady incremental process which also takes decades.

If we wait a decade or two for increased certainty, the climate impact will be much larger, harder to reverse, and the impact on the earth's natural ecosystem may be severe. A wise society would take action now to reduce emissions to the atmosphere, in order to limit and delay the long-term impact on our climate. Much can be done at little incremental cost. The scientific community can present the evidence, but political resolve and global co-operation are clearly needed. Changing the direction of our industrial society towards one which is more respectful of its impact on our global environment will take time, probably decades, even if we begin now.

References:

- Betts, A.K., 1974: The scientific basis and objectives of the US Convection Subprogram for the GATE. *Bull. Amer. Meteor. Soc.*, 55, 304-313.
- Betts, A.K., 1990: Greenhouse warming and the tropical water budget. *Bull. Amer. Meteor. Soc.*, 71, 1464-1465.
- Betts, A.K., and B.A. Albrecht, 1987: Conserved variable analysis of boundary layer thermodynamic structure over the tropical oceans. *J. Atmos. Sci.* 44, 83-99.
- Betts, A.K., and Ridgway, 1989: Climatic equilibrium of the atmospheric convective boundary layer over a tropical ocean. *J. Atmos. Sci.* 46, 2621-2641.
- Cess et al., 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, 95, 16601-16615. (32 authors).
- Gamache, J.F., and R.A. Houze, 1983: Water budget of a mesoscale convective system in the tropics. *J. Atmos. Sci.* 40, 1835-1850.
- Houze, R. A., and A.K. Betts, 1981: Convection in GATE. *Rev. Geophys. and Space Phys.* 19, 541-576.
- Lindzen, R.S., 1990: Some coolness concerning global warming. *Bull. Amer. Meteor. Soc.* 71, 288-299.
- Raval, A., and V. Ramanathan, 1989: Observational determination of the greenhouse effect. *Nature*, 342, 758-761.

STATEMENT OF SENATOR ALBERT GORE, JR.
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
HEARING ON THE ROLE OF CLOUDS IN CLIMATE CHANGE

MONDAY, OCTOBER 7, 1991

Good morning. Today, the Commerce Committee will examine some of the latest research on one of the key scientific questions regarding global change -- the role of clouds. Clouds play a key role in global warming, the worst environmental threat we face. It has the potential to fundamentally alter our lives, the lives of our children and grandchildren, and every generation to follow. According to the best available scientific analysis, over the next hundred years there could be radical shifts in weather patterns and disruption of ecosystems, with some of the world's most productive farmland turned to desert and low-lying coastal areas around the world flooded.

Confronting this threat will require major changes in energy use, agriculture, transportation, and other activities worldwide. It will require an international commitment to slow the emission of greenhouse gases into the atmosphere, and if that commitment is not made now, the consequences later will demand even more. Making intelligent choices on how to deal with global warming will require the best scientific information available on the causes and effects of global warming.

To provide estimates of the extent and timing of global warming, researchers are using some of the world's most powerful supercomputers to build general circulation models. These models predict that the earth's temperature will increase between 1.5 and 4.5 degrees Celsius by the end of the next century. But the different models do not all agree, particularly when it comes to predicting local and regional climate changes.

One of the main reasons for these discrepancies is that different models treat clouds differently. Clouds play a fundamental role in the Earth's heat budget. Researchers have found that high-altitude clouds can act like an insulating blanket, amplifying the warming due to greenhouse gas accumulation. On the other hand, clouds can also reflect incoming solar radiation and thereby decrease warming.

Today, we will examine the different approaches that modelers are using and how they might be improved so that uncertainties in the models can be reduced. Doing that will require research on many different scales, from microscopic to global. The scientists here today are at the forefront of that research.

In addition to examining the latest research on clouds, we have representatives from NASA, NOAA, and the Air Force to discuss how their agencies have and will contribute to our understanding of global warming.

It is unusual for the Congress to focus in such detail on a complicated scientific question like the one we are considering today. But I believe it is essential that we understand thoroughly what the science can tell us and what it can't so that we can effectively meet the threat of global warming.

Today, we will not be using the standard hearing format. Rather than having panels of witnesses, I have asked everyone to join in a roundtable discussion. This will ensure a free and open exchange on the various scientific questions that researchers are trying to answer and help us all see clearly where there is general agreement and where there is disagreement in the scientific community.

In the coming months, I hope to conduct similar hearings on some of the other key scientific issues regarding global change. Last year, the Federal government spent almost one billion dollars on global change research, and I feel it is critically important that this Committee and the entire Congress keep abreast of the work being done.

I want to welcome our witnesses and thank them for being here today. Many of them have come a long way and rearranged very busy schedules to join us and I want to thank you all.

To begin the discussion, I think it would be most useful if we just went around the table and had everyone briefly introduce themselves and quickly summarize their research. Since we have so many people here today, I would ask you to try to hold your remarks to about three minutes. I guarantee you that we will have a lot of time to get into the details later.

SENATE COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION

Witness List

Hearing on

Global Change Research:

The Role of Clouds in Climate Change

Monday, October 7, 1991, 9:30 a.m.

in Room SR-253 of the Russell Senate Office Building

Roundtable Discussion Participants:

Dr. Albert Arking, Senior Scientist, NASA Goddard Space
Flight Center, Greenbelt, MD 20771

Dr. Alan K. Betts, Meteorologist, RD2, Box 3300, Middlebury,
VT 05753

Dr. Robert Cess, Professor of Atmospheric and Physical
Sciences, Institute for Atmospheric Sciences, State
University of New York at Stony Brook, Stony Brook, NY
11794

Dr. Robert Charlson, Professor of Atmospheric Sciences and
Adjunct Professor of Chemistry, Department of
Atmospheric Sciences, University of Washington, Seattle,
WA 98195

Dr. Michael Hall, Director, Office of Global Programs,
National Oceanic and Atmospheric Administration,
1335 East-West Highway, Silver Spring, MD 20910

Dr. Richard S. Lindzen, Alfred P. Sloan Professor of
Meteorology, Department of Earth, Atmospheric and
Planetary Sciences, Massachusetts Institute of
Technology, Cambridge, MA 02139

"Lindzen Mechanism"

Dr. V. Ramanathan, Alderson Professor of Ocean Sciences,
Scripps Institution of Oceanography, University of
California at San Diego, Mail Code 0221, La Jolla, CA
92093

Dr. William B. Rossow, Physical Scientist, NASA Goddard
Institute of Space Studies, 2880 Broadway, New York, NY
10025

Dr. Shelby Tilford, Director of Earth Science and Application
Division of the Office of Space Science and
Applications, Code SE, National Aeronautics and Space
Administration, Washington, DC 20546

Colonel Ronald Townsend, Chief, Weather Plans, XOWX,
Directorate of Weather, Headquarters, United States Air
Force, Department of Defense, The Pentagon, DC 20330

Dr. Kevin Trenberth, Head of Climate Analysis, National
Center for Atmospheric Research, PO Box 3000, Boulder,
CO 80307

**STATEMENT OF SENATOR ALBERT GORE, JR.
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
HEARING ON THE ROLE OF CLOUDS IN CLIMATE CHANGE**

MONDAY, OCTOBER 7, 1991

Good morning. Today, the Commerce Committee will examine some of the latest research on one of the key scientific questions regarding global change -- the role of clouds. Clouds play a key role in global warming, the worst environmental threat we face. It has the potential to fundamentally alter our lives, the lives of our children and grandchildren, and every generation to follow. According to the best available scientific analysis, over the next hundred years there could be radical shifts in weather patterns and disruption of ecosystems, with some of the world's most productive farmland turned to desert and low-lying coastal areas around the world flooded.

Confronting this threat will require major changes in energy use, agriculture, transportation, and other activities worldwide. It will require an international commitment to slow the emission of greenhouse gases into the atmosphere, and if that commitment is not made now, the consequences later will demand even more. Making intelligent choices on how to deal with global warming will require the best scientific information available on the causes and effects of global warming.

To provide estimates of the extent and timing of global warming, researchers are using some of the world's most powerful supercomputers to build general circulation models. These models predict that the earth's temperature will increase between 1.5 and 4.5 degrees Celsius by the end of the next century. But the different models do not all agree, particularly when it comes to predicting local and regional climate changes.

One of the main reasons for these discrepancies is that different models treat clouds differently. Clouds play a fundamental role in the Earth's heat budget. Researchers have found that high-altitude clouds can act like an insulating blanket, amplifying the warming due to greenhouse gas accumulation. On the other hand, clouds can also reflect incoming solar radiation and thereby decrease warming.

Today, we will examine the different approaches that modelers are using and how they might be improved so that uncertainties in the models can be reduced. Doing that will require research on many different scales, from microscopic to global. The scientists here today are at the forefront of that research.

In addition to examining the latest research on clouds, we have representatives from NASA, NOAA, and the Air Force to discuss how their agencies have and will contribute to our understanding of global warming.

It is unusual for the Congress to focus in such detail on a complicated scientific question like the one we are considering today. But I believe it is essential that we understand thoroughly what the science can tell us and what it can't so that we can effectively meet the threat of global warming.

Today, we will not be using the standard hearing format. Rather than having panels of witnesses, I have asked everyone to join in a roundtable discussion. This will ensure a free and open exchange on the various scientific questions that researchers are trying to answer and help us all see clearly where there is general agreement and where there is disagreement in the scientific community.

In the coming months, I hope to conduct similar hearings on some of the other key scientific issues regarding global change. Last year, the Federal government spent almost one billion dollars on global change research, and I feel it is critically important that this Committee and the entire Congress keep abreast of the work being done.

I want to welcome our witnesses and thank them for being here today. Many of them have come a long way and rearranged very busy schedules to join us and I want to thank you all.

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Dr. Kevin Trenberth, Head of Climate Analysis, National
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Statement of
Dr. Albert Arking
Senior Scientist
Laboratory for Atmospheres
NASA Goddard Space Flight Center

before the

United States Senate
Committee on Commerce, Science, and Transportation

October 7, 1991

Mr. Chairman and Members of the Committee:

It is a pleasure for me to appear before you today and comment on what I believe are some of the difficulties in trying to assess the causes of recent temperature trends and to predict the climatic consequences of increasing greenhouse gases.

The ultimate test of understanding of any object or system is the ability to describe its behavior under various conditions. So it is with climate. What will happen to the world's climate under any of a large number of possible scenarios--whether man-induced, by burning fossil fuels, or natural events, such as the eruption of Mt. Pinatubo? Are there other deterministic factors, such as variations in the output of the sun, that may be causing changes in climate, and is it possible that internally-induced changes take place that are inherently unpredictable? Unfortunately, the answers to these questions are at this time far less precise than we would like them to be.

We have a good understanding of many of the physical processes that govern atmospheric behavior. But some processes are quite complicated and they continue to elude us. While the elusive processes often appear like details in a large system where one would otherwise expect systematic behavior, it is not the

case. Sometimes the "details" turn out to be critically important. The more reliable parts of our models tell us, for example, that changes in the minute amounts of water vapor in the upper troposphere can have a greater impact than comparable changes (on a percentage basis) in the lower troposphere, where the bulk of atmospheric water vapor resides. Or, just shifting 10% of the clouds from daytime to nighttime, without changing the daily mean cloud cover, will have a substantially greater effect than doubling of the greenhouse gases. So, before we can assess the impact of the doubling of the greenhouse gases, we will have to find out what happens to the water vapor in the upper troposphere as the earth begins to heat up, and how the clouds will respond. That is where the models are least reliable.

Water in all of its forms is the weak point in our attempts to understand climate. If somehow the water did not change--i.e., its distribution as a gas within the atmosphere, or as small droplets in the form of clouds, or as ice or snow on the surface, did not change as the earth warmed up in response to the greenhouse gases, the problem would be much simpler. In that case the mean temperature of the earth would increase by about 1° Celsius in response to a doubling of the greenhouse gases, and there is little dispute on this result. Models that indicate responses as high as 5° Celsius include the secondary effects associated with changes in water--what are called feedbacks. Here is where there are wide differences amongst models.

The water vapor feedback exhibited by most models goes something like this: As the atmosphere and surface warm in response to the direct effect of the increase in greenhouse gases, there is greater evaporation and greater precipitation, and the atmosphere retains more water in its gaseous form (confusingly called water vapor). Since water vapor is itself a greenhouse gas, it further warms the atmosphere and surface, so that the net effect on the climate system is much greater than if water vapor remained fixed.

Professor Richard Lindzen of MIT has questioned this process, exposing a potential weak point in climate models. He agrees that water vapor increases in the lowest levels of the atmosphere, the boundary layer, where there is a lot of mixing and interaction with the surface, but in the upper troposphere Lindzen maintains that water vapor actually decreases. In terms of water vapor amount, the increase in the boundary layer greatly exceeds the decrease in the upper troposphere, so that total water vapor indeed increases. But, according to Lindzen, the decrease in the upper troposphere, albeit the amounts are minute, is far more important as far as the greenhouse effect is concerned. A water molecule in the upper troposphere can have a greenhouse effect that is hundreds

of times greater than in the lower troposphere. So the issue of water vapor feedback depends critically on whether water vapor increases or decreases in the upper troposphere as the climate system responds to the effects of CO₂ and other greenhouse gases.

Water, in the form of clouds, participates in another feedback process. Only in this case it is not Lindzen against the models, it is models against models. Or even with the same model, just make some changes in the way one treats clouds--as was done recently at the British Meteorological Office--and you can change cloud feedback from being large and positive (i.e., strongly reinforcing the effect of the greenhouse gases) to a negative feedback, which counteracts the greenhouse gas effect.

Clearly, we need more data, we need time to analyze the data, and we need to improve and validate our models. I see the focus of research over the next few years on the problem of how water vapor gets distributed to the upper troposphere, and how clouds change as the earth and surface warm up and circulation patterns change in response to the direct effects of the increase in greenhouse gases.

Clouds pose a particularly difficult problem because of their extreme inhomogeneity. Simple descriptions like "50% cloud cover at an altitude of 5 kilometers" are not enough. Even the amount of liquid water in the cloud does not necessarily convey how much sunlight the cloud will reflect, absorb, or transmit; it depends on microphysical features, such as the size of the particles, as well as macrophysical features, such as the spatial distribution of the cloud.

Satellites provide a unique vantage point from which to measure cloud properties, because a few satellites can cover the entire globe. Although radiometric sensors can be designed to provide excellent horizontal resolution, the poor vertical resolution is a limitation. Without an active system, such as a lidar, it is difficult to get information about the vertical structure of clouds, which often are multi-layered. Often one has to use indirect means--e.g., combining radiance measurements in the visible, near infrared, and thermal infrared spectrum, and applying theoretical models--in order to determine the parameters we need to measure. Up to now, satellite-based cloud data sets have been based on *sensors of opportunity*--i.e., sensors that were designed primarily for other purposes. Much of my own research is now focused on developing techniques for improving the retrieval of cloud parameters from space, including the design of sensors dedicated to measurement of cloud parameters.

As we develop improved techniques for measuring cloud parameters and obtain more and better information about clouds--and let me add the same holds true for atmospheric water vapor, especially the critical measurements needed in the upper troposphere--we will develop a better understanding of the physical processes involving water, as a gas and as clouds in the atmosphere, and as liquid, ice, or snow on the surface, and we will be able to improve our climate models.

I thank you for this opportunity to present a brief comment on what I believe are the main obstacles to our ability to predict the future course of the world's climate, and indicate the role that satellites might play in helping overcome those obstacles. I will be happy to answer questions.

Robert D. Cess
Distinguished Service Professor
State University of New York at Stony Brook

For the past several years I have been in charge of a DOE-sponsored project, the goal of which is to intercompare and understand radiative climate feedback mechanisms as produced by a number of general circulation models (GCMs). There are currently 18 institutions, spanning nine different countries, participating in this project. A primary conclusion to date is that cloud-climate interactions comprise a major uncertainty with respect to the use of GCMs as vehicles for projecting future climate change as caused by increasing concentrations of atmospheric greenhouse gases.

**Introductory Statement
by Professor Robert Charlson
for Hearings by the
U.S. Senate Commerce, Science and Transportation Committee
7 October 1991**

My name is Robert Charlson. I am a Professor of Atmospheric Sciences and of Chemistry at the University of Washington in Seattle. My area of study is atmospheric chemistry, with emphasis on the role of chemical processes as determinants of the physical properties of atmospheric aerosol particles. I and my research group have done substantial field observations, both in pristine areas and in polluted, industrial regions. We also have performed theoretical and modelling studies of the particles in the air with emphasis on rainwater composition, visual air quality and, more recently, on the role of the atmospheric aerosol in regional and global climate. The latter is the topic that I will address today.

The atmospheric aerosol consists of small particles of a variety of solid and liquid substances that are suspended in the air. As one particular class of aerosol particle, sulfate compounds are often a component which dominates the mass of the particles as well as their physical properties and effects. These sulfate aerosol particles are produced in the atmosphere from chemically reactive, sulfur-containing gases. Both natural gaseous emissions (like dimethylsulfide from oceanic phytoplankton) and pollution emissions (like sulfur dioxide from burning fossil fuels and from smelting) produce sulfate particles which range in composition from sulfuric acid to ammonium sulfate.

There are two main physical effects of these submicrometer-sized particles. First, they reflect some sunlight back to space, thereby reducing the amount of solar energy absorbed at the earth's surface. Second, these same particles can act as the nuclei for formation of cloud droplets, and in this role they are a major factor controlling the amount of sunlight that is reflected upward by the clouds. The former is referred to as the direct effect of the particles because they interact directly with sunlight. The latter is called the indirect effect of particles on the reflectivity of clouds. The magnitude of the direct effect can be estimated with an uncertainty of roughly a factor of two. The magnitude of the

indirect (cloud nucleating) effect is much less certain although the sense of both effects is to reflect sunlight away from the earth and to cool parts of the planet.

Our studies of the direct effect of anthropogenic sulfate aerosol indicate that it produces a loss of about one watt per square meter when averaged over the Northern Hemisphere. Its effect in the Southern Hemisphere is essentially zero. This aerosol loss of one watt per square meter is comparable in magnitude but opposite in sign to the current forcing by anthropogenic CO₂, which is about 1.5 watts per square meter. While anthropogenic sulfate aerosol may thus appear to compensate for some greenhouse warming over the Northern Hemisphere, it is important to note that it does so only in the hemispheric average. The highly non-uniform geographical distribution of the sulfate, which is caused by its short (few day) lifetime in the atmosphere results in patches of higher reflectivity over and down-wind of the industrial regions of the Northern Hemisphere. This haze is easily recognized by travelers in commercial aircraft over the eastern U.S. One of the well-known results of this is a substantial loss of solar energy reaching the ground. The annual average loss is estimated to be around 7% for much of the eastern United States, or several watts per square meter. Again, I reiterate, greenhouse gas effects and aerosol effects cannot simply cancel each other because they do not coincide at the same place and time.

While the magnitudes of the greenhouse and direct aerosol forcings can be estimated and while their mechanisms are well understood, it is much more difficult to understand and predict the meteorological consequences of the geographically dependent forcing. In this context, it seems important to point out that the concern over global climate change has more to do with the geographical distribution of the weather (i.e., amounts of rainfall and sunshine, wind, storms, etc.) than it has to do with the global average temperature.

I will conclude with two questions: Why did we fail to discover earlier this large climate-related forcing and are there any other aerosol terms missing from the heat balance

equation? Both of these questions can best be answered by a clear statement that research in the United States on atmospheric aerosol has been inadequate. There are several reasons for this. First, funding for such studies has emphasized applied research -- cloud seeding, engineering and military objectives. This practical focus did not provide adequate support for either the fundamental science or global-scale studies. Second, funding has fluctuated with the urgency or popularity of the application. Third, and perhaps most important, most studies of the atmospheric aerosol have been carried out within the confines of narrow academic disciplines. This resulted in a lack of coupling of the studies of the chemical processes that produce and control the amount of aerosol to the studies of the physical consequences of the aerosol. So, at the moment, it is not possible to provide quantitative estimates of the magnitude of the so-called indirect (cloud mediated) effect, nor can we know with certainty whether we have even identified all the major aerosol-related terms in the heat balance equation. We cannot even indicate whether or not feedback exists in the natural sulfur cycle, involving biogenic dimethylsulfide.

What is needed to remedy this situation is a program of research which integrates all the necessary scientific disciplines, ranging from chemistry and physics to meteorology. In order to achieve this, it appears necessary to involve four key governmental units in an integrated aerosol research program: NASA, NOAA, DOE and NSF. CEES may be an appropriate entity to assist in achieving the needed integration.

Thank you for the opportunity to make this statement.

TESTIMONY
OF
DR. J. MICHAEL HALL
DIRECTOR, OFFICE OF GLOBAL PROGRAMS
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

BEFORE THE
COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION
UNITED STATES SENATE

OCTOBER 7, 1991

RE: THE ROLE OF CLOUDS IN GLOBAL CLIMATE CHANGE

INTRODUCTION

I would like to express my appreciation to the Committee for the opportunity to discuss a topic that is undeniably recognized within the scientific community as the most critical area forestalling progress in our understanding of the global climate system. Climate changes may arise from natural forces within the earth system, or as a consequence pressures on our natural resources by an increasing world population, and by an increasing capacity to exploit those same resources to achieve technological progress.

The current urgency felt by the scientific community to produce accurate predictions of change under a regime of significantly enhanced atmospheric carbon dioxide and other "greenhouse" gases, has pushed computerized models of the climate system beyond a satisfactory level of credibility. Different general circulation models of the climate system, forced in identical ways, produce new "climates" that are similar in their gross characteristics,

but differ significantly in detail. At a regional level, for example over parts of the continental U.S.A., the differences can be so large that conflicting guidance would be given to those planning strategies to adapt to changing climatic regimes.

Detailed studies of the root causes of these differences reveal that they are typically caused by subtle variations in the way different models attempt to mimic physical processes operating in the total global system, and by the number of such processes different models attempt to incorporate. Processes which operate at scales smaller than the spatial and temporal resolutions of the simulation models are represented by physically based but approximate mathematical schemes (parameterizations). These schemes include attempts to distribute incoming and outgoing radiant heat energy, develop the many cloud forms, allow for the presence of atmospheric aerosols, cause clouds to precipitate, and partition the precipitation into the surface components of the hydrological cycle, eg. surface runoff, infiltration etc.

THE SCIENTIFIC ISSUES

Clouds and water vapor together are the dominant control on the amount of solar energy reaching the earth's surface and the infrared emission to space. The "greenhouse" effect as we all know is critical for life on earth. Direct anthropogenic enhancement of other radiatively active trace gases in the atmosphere (CO₂, methane, chlorofluorocarbons etc) that has the

potential for causing major climatic change may be amplified or diminished by feedbacks within the global energy and water cycle, especially those that affect the development and distribution of clouds. NOAA is engaged in major monitoring and research programs to improve our understanding of atmospheric trace gases that influence the Earth's chemical and radiative balance. NOAA is also committed to a climate model development program to increase skill in representing the many complex feedbacks in the global climate system.

Atmospheric aerosols are increasingly seen as an important factor in the atmospheric component of the global energy and water cycle. As a direct modulator of the greenhouse effect, atmospheric aerosols can interact with radiant energy through scattering and absorption processes. In a more indirect way, atmospheric aerosols also modulate the greenhouse effect since they are critical as nuclei for the formation of clouds and cloud properties, such as brightness enhance the ability of clouds to reflect incoming solar radiation back to space. Atmospheric aerosols are therefore a pervasive and necessary component of the climate system yet their roles are poorly represented, if at all, in the current generation of climate models. Furthermore, just as human activity is changing the background levels of some radiatively active gases, so too it is changing the levels of atmospheric aerosols. Unlike the principal radiatively active anthropogenic gases which generally become well-mixed throughout

the atmosphere, anthropogenic aerosol loadings tend to have maximum concentrations downwind of major centers of population and industry. The impacts of anthropogenic aerosols on the climate system, therefore, are likely to be manifested in ways quite unlike the impacts of the enhanced greenhouse gases. NOAA scientists are engaged in research projects to monitor the sources and sinks of both natural and anthropogenic aerosols in order to assess the relative changes in concentrations. We are also working closely with other agencies on the need for a comprehensive research plan to address this complex issue.

THE INTERNATIONAL RESPONSE

Small-scale processes in climate models such as evaporation and the formation of clouds have been collectively described as the "fast component" of the climate system. The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) have developed the Global Energy and Water Cycle Experiment (GEWEX) as a focus for this component of their jointly sponsored World Climate Research Programme (WCRP). The Tropical Oceans and Global Atmosphere (TOGA) Project and the World Ocean Circulation Experiment (WOCE) of the WCRP are concerned with longer time-scale processes of the climate system.

The nature of GEWEX is such that its objectives underpin progress on all time scales. Similarly, TOGA is primarily concerned with prediction on seasonal and inter-annual time scales, but

understanding and modeling latent and sensible heat fluxes as well as radiative fluxes at the air-sea interface, are critical for getting the right distribution of clouds and cloud types in the coupled global climate models that will be used in various configurations to predict on seasonal, inter-annual and decadal time scales. The Coupled Ocean Atmosphere Response Experiment (COARE), a major field program in TOGA is planned for the Western Pacific region from November 1992 through February 1993. It will address many of the key problems in understanding why this region of the globe is such a critical area for large-scale, seasonal and inter-annual fluctuations in the climate system. However, COARE will also provide opportunities to gather data on unique features of tropical cloud systems. TOGA COARE, therefore is one of the most important initiatives in this decade directed at improving our understanding of the climate system. NOAA, NSF, NASA, ONR, and the U.S. academic community along with the scientific communities of many other nations are devoting considerable resources towards ensuring its success.

The earth's biosphere also plays a substantial, interactive role in partitioning energy and water in the climate system, and the potential exists for major impacts on the current make-up and distribution of ecosystems as a consequence of climate change. To study and understand better the sensitive balance between the physical and living components of the earth and its climate system, International Council of Scientific Unions (ICSU) has

instituted the International Geosphere Biosphere Programme (IGBP). In view of the strong interaction between climate and the biosphere, the WCRP and IGBP are developing common planning processes in several key areas including the hydrological cycle. However, just as with TOGA COARE, the international agencies sponsoring these programs look to individual, national funding agencies to respond in a coordinated way to the variety of scientific initiatives being proposed to tackle the many global change research issues. NOAA plans to continue its support for many of these initiatives which include the very successful International Satellite Cloud Climatology Project, the developing Global Precipitation Climatology Project and the emerging GEWEX Continental-scale International Project (GCIP).

GCIP warrants special mention since it will enable the U.S. to offer a significant portion of its land mass - the Mississippi Basin - for an intensive large-scale climate data gathering and modeling study. In turn, the U.S. will reap the benefits of an international scientific effort to understand and model the complex hydrological cycle of this region. Skills learned in this data rich region, will help us to improve our models in those regions of the globe with poorer climatic records. Much of the data for GCIP will come from existing NOAA data bases and observing systems, and from planned upgrades to those systems. A successful GCIP will also speed the benefits of the next era of space-based remote sensing satellites.

Statement on Global Change

Richard S. Lindzen, Alfred P. Sloan Professor of Meteorology
Massachusetts Institute of Technology

October 7, 1991

Global warming is almost certainly inevitable — regardless of man's presence on earth. So is global cooling. The Earth's climate has been both warmer and colder than it is at present (mostly warmer); climate is always changing and there is virtually no chance that we will alter this state of affairs. However, the quantitative expectation of *substantial* global warming (more than 1°C or so) arising in the next century because of man's production of minor greenhouse gases (CO₂, CFC's, methane, etc.) is without substantive scientific foundation. It is worth noting that the major greenhouse substance is water in the form of water vapor and layer clouds — which accounts for over 98% of the current greenhouse effect. It is sometimes noted that many minor greenhouse gases are directly related to man's activities, whereas water vapor and layer clouds are internally established by the atmosphere. However, it is obvious that models that do not properly deal with the major greenhouse substances will be inadequate for evaluating the response to minor greenhouse gases. As concerns catastrophic predictions (5°C warming), it should be emphasized that we are not dealing with plausible consequences of a well established understanding, but rather with the consequences of identifiable model errors. Such consequences are, moreover, inconsistent with the history of the Earth's climate to date.

As concerns past climate, it is noted in the IPCC Scientific Assessment (Houghton, et al, 1990) that the observed warming over the past century (during which time we have increased minor greenhouse gases by about 50%) is most consistent with an increase in temperature, for a doubling of such gases, of about 1.2°C (page 246). This estimate includes the delaying effect of the oceans and *assumes* that all observed warming over the past century ($0.45^{\circ}\text{C} \pm 0.15^{\circ}\text{C}$) is due to increasing greenhouse gases. However as the IPCC Assessment notes (p. 254), "it is not possible to attribute all, or even a large part, of the observed global-mean warming to the enhanced greenhouse effect on the basis of the observational data currently available." The reason for this inability is simply that the global mean temperature naturally fluctuates by this amount over periods as short as 5 years.

It has been noted that the upper limit of the IPCC range of warming predictions for the end of the next century (5°C) would leave the Earth warmer than it has been at any time in human history. This assertion is, in fact, modest. According to the distinguished paleoclimatologist, Rhodes Fairbridge of Columbia University and GISS, the average temperature of the Earth has been in the range $18^{\circ}\text{C} \pm 5^{\circ}\text{C}$ for about 4 billion years — during much of which time the atmosphere contained many times the CO₂ projected for the next several centuries (Fairbridge, 1991). The model predictions exceed this range. Fairbridge also notes that equatorial sea surface temperatures have been in the range $30^{\circ}\text{C} \pm 1^{\circ}\text{C}$ during this period. Virtually all models predicting large global warming predict 2-4°C warming at the equator. Under any normal circumstances, one would conclude that the models are misbehaving — even allowing for some uncertainty in the data.

Beyond the *prima facie* evidence that model predictions are inconsistent with observations (and the inconsistency far transcends the above examples), are there other reasons for questioning model behavior? Indeed, there are many reasons; everyone has their favorite, and each is enough to

swamp the effect of increasing CO₂ (recall that CO₂ contributes only about 1% to the greenhouse effect and model errors are far larger than this). Indeed, no current model can predict the mean temperature of today's Earth without what is euphemistically called 'tuning'.

One issue I have been focussing on in the past few years has been the role of water vapor. This issue is summarized in the accompanying statement prepared at the invitation of the IPCC in connection with the preparation of an update to their 1990 document. (It is worth noting that the preparation of an update so soon after the original publication is indicative that the original document was hardly canonical.) The main points in the accompanying document are:

1. Water vapor and layer clouds account for over 98% of the greenhouse effect.
2. The ability of models to predict layer clouds depends on the ability of models to predict water vapor.
3. In the absence of positive feedbacks, the equilibrium response to a doubling of CO₂ is in the range 0.6°C to 1.2°C. Larger responses *require* positive feedbacks. Negative feedbacks will, of course, reduce the response.
4. The largest positive feedback by far in current models is due to water vapor.
5. Without the positive water vapor feedback, no model would obtain an equilibrium warming due to doubling CO₂ as large as even 2°C (assuming other feedbacks are positive — a matter of great doubt).
6. Water vapor is not equally important at all levels in the atmosphere. A molecule of water vapor at 12 km altitude is about 1000 times more important than a molecule at 2 km in its contribution to the greenhouse effect. The effect of molecules near the surface is almost nil. Thus, although most of the atmosphere's water vapor resides in the bottom 2 km of the atmosphere, it is the water that resides elsewhere that is crucial to the Earth's climate response¹.
7. Water vapor is not monitored above 6-9 km.
8. We do not understand the physical processes which determine water vapor above 2-3 km.
9. Due to numerical problems, models cannot currently deal with a substance like water vapor which varies so rapidly with altitude (it varies by 3-4 orders of magnitude between the ground and the

¹ The reason for this is that, counter to the popular picture of the greenhouse, the Earth's surface does not cool primarily by infrared emission. Rather, heat (in various forms) is bodily carried from the surface by air currents to regions of much reduced greenhouse potential (at higher altitudes and latitudes), and from these regions, the heat is radiated to space. Thus, it is greenhouse gas concentrations in those regions of the atmosphere where motions deposit heat that are most important in determining the surface temperature. (The situation is schematically illustrated in the accompanying figure.) It follows that models that do not accurately depict transports by air currents, cannot accurately predict the temperature of the Earth. Current models do, in fact, have severe problems with transport.

tropopause). Current models commonly produce regions of negative water vapor, and the arbitrary 'fixes' introduced to eliminate such impossibilities frequently play a major role in determining model water vapor.

10. It has been asserted that the observational analysis of Raval and Ramanathan (1989) proved that the water vapor feedback is positive². That result is significantly due to a faulty assumption in their analysis — namely, that the shape of temperature profiles are independent of surface temperature. The interpretation of their results is also confused by the absence of consideration of lateral heat transport.

In view of the above alone, it is clear that models are presently incapable of calculating the response to enhanced CO₂. The situation hardly improves when we consider the uncertainties in clouds (barely touched in the above discussion), the uncertainties in ocean transport, and even the uncertainties in the behavior of CO₂ itself. There is simply no basis for saying that the range 1.5°C-5.0°C is 'likely' — especially since all these values are excessive according to the behavior of the climate over the past century.

Where then does this leave us. At the least, it leaves us with a self-evident need to understand our climate, and, more generally, our environment. It seems entirely reasonable for wealthy, scientifically and technologically advanced societies to set themselves the goal of understanding the physical environment they reside in. Such an understanding would be among the greatest gifts we could leave to our successors on this planet. Such an understanding would not only enable us to anticipate currently unexpected dangers, but would also help us avoid being exploited by dangerous hysteria based on ignorance. In emphasizing understanding, I must point out that although understanding benefits from large observational programs and supercomputers, it is primarily an activity of the intellect. The development of a sound conceptual framework is essential to the planning and evaluation of large programs. Such development is monetarily cheap but difficult, and large programs can tend to deemphasize such theoretical efforts — not only because they are cheap but also because it would be embarrassing to admit that the conceptual foundations for large efforts might sometimes be absent. As a theoretician, it is clear that my concern about conceptual foundations is self-serving; I believe the concern is also well founded.

Turning more specifically to the problem of global climate change, we must certainly develop an adequate understanding of the behavior of water vapor in the atmosphere. Monitoring must be extended to the upper troposphere. Much work needs to be done to improve our understanding of the microphysics of deep convective clouds in order to know how these clouds determine the balance between the water and ice they pump into the environment and the precipitation that falls to the surface.

Of course, understanding water vapor is not the whole story. Nor are all aspects of water vapor equally important to the prediction of climate sensitivity. We need to determine what role the oceans may play in transporting heat and material. We also need to understand what determines the transport of heat, momentum, and material by the large scale circulation of the atmosphere. We are

² A recent study by Sun and myself suggests, on the basis of paleoclimatic data from the last major glaciation, that the water vapor feedback may, in fact, be strongly negative.

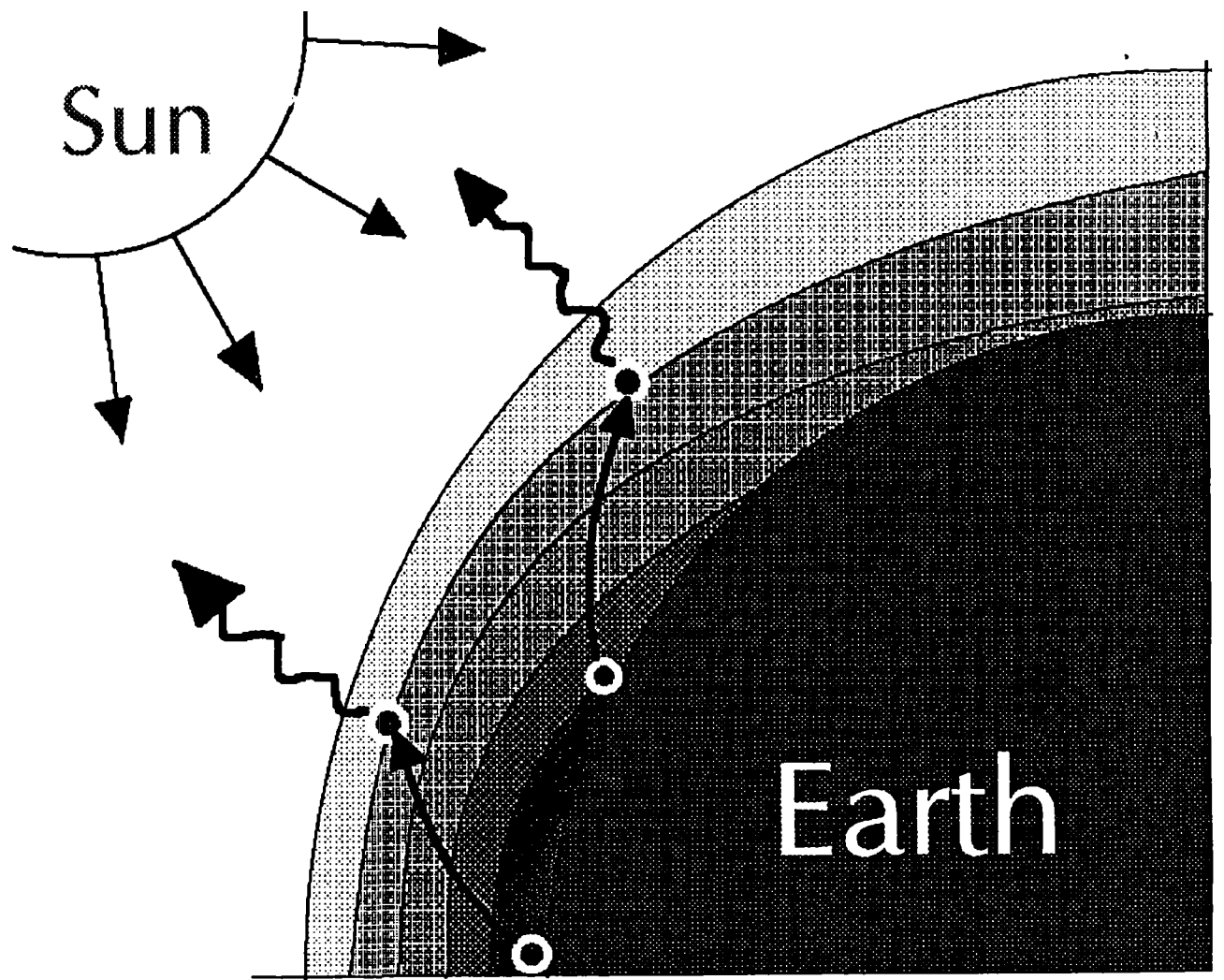
still in a position where we do not quantitatively know what determines the equator to pole temperature difference. Yet, over the history of the Earth, climate variations have been far more associated with changes in the equator to pole temperature difference than with changes in the global average temperature. Improved data for both the atmosphere and the ocean is certainly essential. However, observations must be based on well determined needs rather than available instruments and platforms. The mundane issue of the numerical and computational methodology for evaluating the equations for climate is basic. The behavior of CO₂ remains rich in puzzles. It is essential that we understand the sources and sinks of CO₂ over land and sea, and that we understand why CO₂ has varied in the past without human intervention. Indeed, although we cannot obtain data for the future, the past, in varying degrees, is accessible. Every effort should be made to collect, assemble, analyze and organize data for the past so as to be able to reconstruct as accurately as possible the climate of the last decade, the last century, the last millennium, the last million years, and even the last several billion years. Such reconstructions will provide the best opportunity for us to test our understanding of climate. The fact that no current model can simulate the cycles of glaciation over the past 2 million years (which we currently believe, on the basis of observations, to be forced by the Earth's orbital variations) hardly lends confidence to our predictions for the future.

References

Fairbridge, Rhodes W., 1991: Planetary beats and geology. in *New Approaches in Geomagnetism and the Earth's Rotation*, Stig Flodmark, Editor. World Scientific, London, pp 222-244.

Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, editors, 1990: *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 365 pp.

Infrared opacity is greatest at the ground over the tropics, and diminishes as one goes poleward and upward. Air currents bodily carry heat to regions of diminished infrared opacity where the heat is radiated to space -- balancing absorbed sunlight.



Lighter shading schematically represents reduced opacity due to diminishing water vapor density.

altering surface temperature. Thus, the role of water vapor both as a greenhouse gas and relatedly as a feedback factor depends primarily on water vapor at upper levels. Unfortunately, in dealing with upper level water vapor we are confronted with three major difficulties: 1) We have no routine measurements of water vapor above about 6-9 km; 2) We do not know the basic physics involved in the water vapor budget at these levels; and 3) Our current numerical models are unable to numerically deal with the advection of rapidly varying (spatially and probably temporally) small quantities of water vapor. With respect to the last item, most models produce regions of negative specific humidity which are filled in by arbitrary borrowing algorithms. These 'borrowing' routines commonly play a major role in model water vapor budgets. Even ignoring numerous other factors, the above 3 items alone make it virtually impossible for models today to meaningfully predict the climatic impact of increasing minor greenhouse gases. As a result, discrepancies between model predictions and historical climate behavior cannot be surprising.

Much of the above has been known for some time; however, much has also been done in the past two years to clarify matters. The state of observations is well described in NASA (1991). Papers by Rasch and Williamson (1991a,b) amply document numerical problems involved in calculating atmospheric water vapor. Lindzen (1990) explained the reasons why upper level water vapor is important to the overall greenhouse effect, and Arking (1990) has documented the fact that the minuscule amounts of water vapor in the upper troposphere are as important as the vastly greater amounts of water vapor in the lower troposphere in determining surface temperature. Arking, in fact, showed that it was entirely possible to increase the column density of water vapor while markedly reducing the net greenhouse effect. The source of upper level water vapor is still not well understood, though it is likely to be transported via cumulonimbus convection. However, the actual amount of water vapor supplied to the upper troposphere depends critically on the water and especially the ice content of the detrained cloud air and the survival of such hydrometeors in the ambient air. Without detrained ice and water, detrained saturated cloud air would only maintain a very dry upper troposphere. This fact, while widely known, was emphasized by Betts (1991). Unfortunately, we do not currently know what determines such matters as the ice content of detrained air. There are also discrepancies between observations and calculations for the lifetime of detrained ice crystals (Braham and Duran, 1967). Some of these matters are discussed by Sun and Lindzen (1991) wherein it is shown that the easiest explanation of the increased lapse rates during the last major glaciation 18,000 years ago (Broecker and Denton, 1989) calls for a great increase in upper level water vapor during this period. This would imply a strong negative water vapor feedback.

The IPCC Assessment (Houghton, et al, 1990) took a more certain view of the role of water vapor than can now be maintained. In part, this was due to the assumption that near surface water vapor (which retains relatively fixed relative humidity) which dominates the water vapor column density also dominates water vapor's contribution to the greenhouse effect. It was also believed that Raval and Ramanathan (1990) had observationally

demonstrated the positive water vapor feedback using satellite observations of outgoing long wave radiation. Raval and Ramanathan had defined a local greenhouse parameter which ignored the existence of lateral heat transport (i.e., transport from tropics to poles, transport from the warm maritime continent to the cooler eastern Pacific, etc.). In assessing the variation of this parameter with surface temperature, moreover, Raval and Ramanathan assumed that lapse rate distributions were independent of surface temperature. Arking (1991b) has shown that at least half the effect that Raval and Ramanathan attribute to water vapor is obtained using fixed specific humidity and using US Standard Atmosphere temperature profiles appropriate to different surface temperatures (viz Figure 1). This is almost certainly an underestimate of the real variation of temperature profiles. Indeed, it is readily shown that deviations of temperature profiles by only a degree or two from assumed constant lapse rates wrecks havoc with the results of Raval and Ramanathan. Thus, a 'certainty' which was essential to any confidence at all in model results is now known to be lacking.

References

- Arking, A., 1990: Feedback processes and climate response. in *Climate Impact of Solar Variability*, NASA Conference Publication 3086, K.H. Schatten and A. Arking, Eds., NASA, 219-226.
- Arking, A., 1991: The radiative effects of clouds and their impact on climate. *Bull. Amer. Met. Soc.*, 72, 795-813.
- Arking, A., 1991b: Temperature variability and water vapor feedback. in preparation.
- Betts, A.K., 1991: Greenhouse warming and the tropical water budget. *Bull. Amer. Met. Soc.*, 71, 1464-1465.
- Braham, R.R. and P.S. Duran, 1967: Survival of cirrus crystals in clear air. *J. Appl. Met.*, 6, 1053-1061.
- Broecker, W.S., and G.H. Denton, 1989: The role of ocean-atmosphere reorganization in glacial cycles. *Geochim. Cosmochim. Acta*, 53, 2465-2501.
- Hansen, J., E. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, 1981: Climate impact of increasing atmospheric carbon dioxide. *Science*, 213, 957-966.
- Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, editors, 1990: *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 365 pp.

Kiehl, J.T. and D.L. Williamson, 1991: Dependence of cloud amount on horizontal resolution in the National Center for Atmospheric Research Community Climate Model. *J. Geophys. Res.*, **96**, 10955-10980.

Lindzen, R.S., 1990: Some coolness concerning global warming. *Bull. Amer. Met. Soc.*, **71**, 288-299.

NASA 1991: *The Role of Water Vapor in Climate - A Strategic Research Plan for the GEWEX Water vapor project (GVaP)* NASA Conference Publication 3120. Available from Dr. S.H.Melfi, Head, Environmental Sensors Branch, NASA Goddard Space Flight Center, Code 917, Greenbelt, MD 20771.

Rasch, P.J., and D.L. Williamson, 1990: Computational aspects of moisture transport in global models of the atmosphere. *Quart. J. Roy. Met. Soc.*, **116**, 1071.

Rasch, P.J., and D.L. Williamson, 1991: The sensitivity of a general circulation model climate to the moisture transport formulation. *J. Geophys. Res.*, **96**, 13123-13137.

Raval, A. and V. Ramanathan, 1989: Observational determination of the greenhouse effect. *Nature*, **342**, 758-761.

Schlesinger, M.E., 1986: Equilibrium and transient climate warming induced by increased atmospheric CO₂. *Clim. Dyn.*, **1**, 35-51.

Sun, D.-Z., and R.S. Lindzen, 1991: Negative feedback of water vapor inferred from the mountain snowline record. submitted to *J. Clim.*

Figure Legend

Figure 1. The normalized greenhouse parameter, g , as defined by Raval and Ramanathan (1989). Observed values as a function of analyzed surface temperature for $2.5^\circ \times 2.5^\circ$ regions are shown by scattered points, as is R&R's least squares linear fit through these points (solid line). Also shown is the calculated distribution of g -- assuming a fixed distribution of water vapor appropriate to subarctic summer (SAS), and various standard atmosphere temperature profiles (midlatitude winter (MLW), midlatitude summer (MLS), tropics (TRO) and subarctic summer (SAS)). This is shown by a dashed line which was calculated by Arking (1991b). The temperature effect accounts for half of R&R's slope. Much of the remaining slope is due to the omitted effect of equator to pole heat flux.

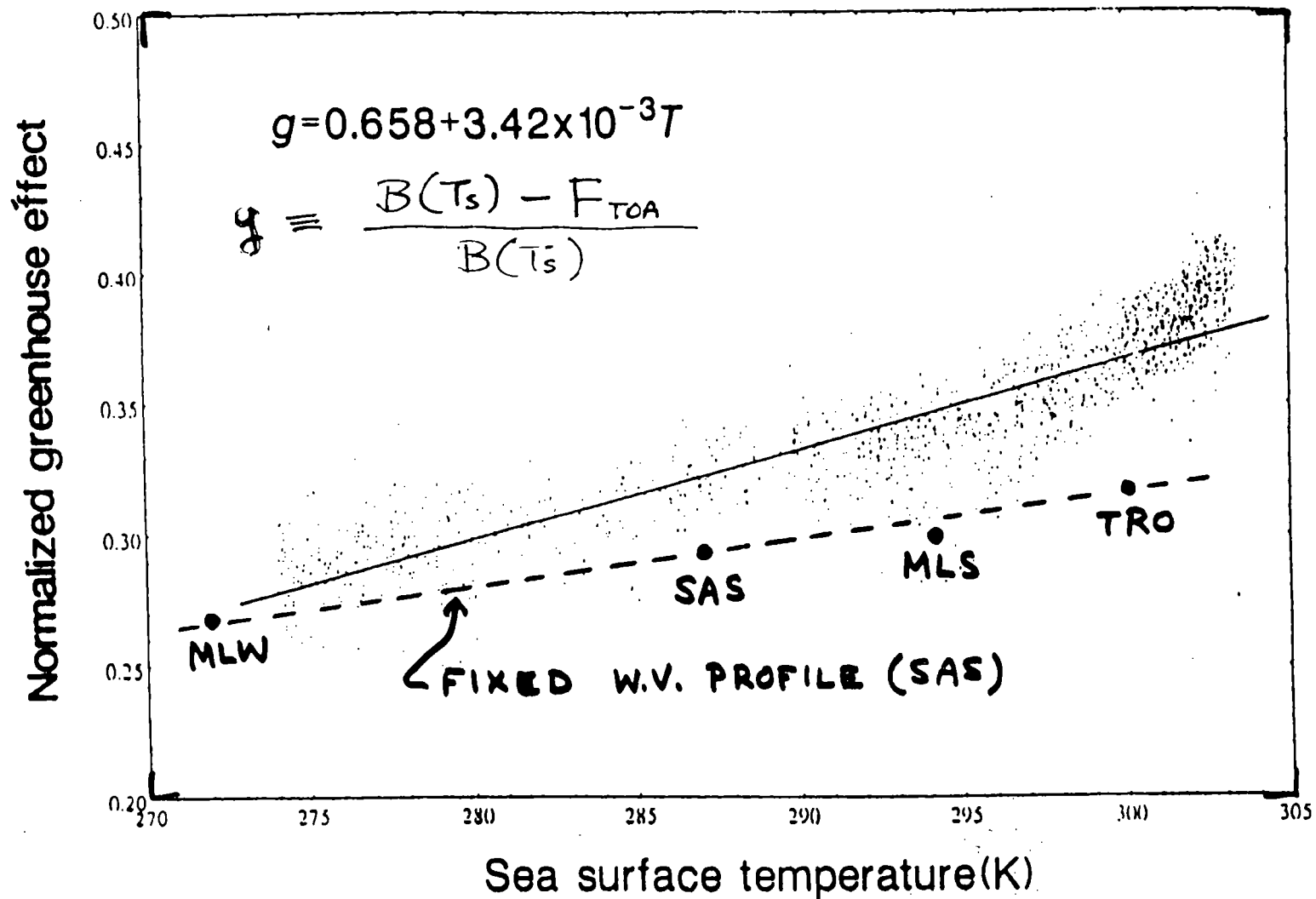


FIG. 1 Clear-sky greenhouse effect normalized by infrared emission (g) as a function of surface temperature, April 1985. Values are monthly averages for each $2.5^\circ \times 2.5^\circ$ region. The solid line indicates a least-squares fit through all the points. Fits done individually through Northern and Southern Hemisphere points do not deviate by more than 3%.

Short Biography

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Richard S. Lindzen (b. February 8, 1940 in Webster, Massachusetts) attended the Bronx High School of Science and Rensselaer Polytechnic Institute. He received his A.B. (1960), S.M. (1961) and Ph.D. (1964) degrees from Harvard University. The first degree was in physics; the last two were in applied mathematics. His thesis on the interactions of ozone chemistry, radiative transfer, and dynamics in the middle atmosphere brought him into the atmospheric sciences where he continues to work and teach. He was a postdoctoral fellow at both the Universities of Washington (1964-65) and Oslo (1965-66). He was a research scientist at the National Center for Atmospheric Research (1966-68). He taught at the University of Chicago (1968-1972) before moving to Harvard University where he held the Burden Chair in dynamic meteorology and served as director of the Center for Earth and Planetary Physics. Since 1983, he has been the Alfred P. Sloan Professor of Meteorology at M.I.T. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences, the American Geophysical Union, and the American Meteorological Society. He is a recipient of the Macelwane medal of the American Geophysical Union, and of the Meisinger and Charney Awards of the American Meteorological Society. He has been a visiting professor at Tel Aviv University, a Lady Davis visiting professor at the Hebrew University, a Vikram Ambalal Sarabhai professor at the Physical Research Laboratory in Ahmedabad, and a visiting professor at Kyushu University under a fellowship from the Japanese Society for the Promotion of Science. He is also a Distinguished Visiting Scientist at the Jet Propulsion Laboratory. He serves on the National Research Council's Space Studies Board and the Board on Atmospheric Sciences and Climate. He is on the editorial boards of **Pure and Applied Geophysics** and **Geophysicae**. He is the coauthor (with the late Sidney Chapman) of a monograph, *Atmospheric Tides*, the author of *Dynamics in Atmospheric Physics*, a coeditor (with Edward Lorenz and George Platzman) of *The Atmosphere - A Challenge: The Scientific Work of Jule Gregory Charney*, and the author or coauthor of over 150 papers in the scientific literature.

Professor Lindzen's scientific interests include the dynamics of the earth's general circulation and climate, the middle atmosphere, and planetary atmospheres. He has contributed to the theory of hydrodynamic instabilities and waves. He is an active photography enthusiast and a radio amateur. Since 1968 he has been married to the former Nadine Lucie Kalouguine. He is the father of two sons, Eric and Nathaniel.

Cloud- Radiative Forcing and the Atmospheric Greenhouse Effect :
Results from NASA's Earth Radiation Budget Experiment (ERBE)

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Testimonial Presented at the hearing of the United States
Senate Committee on Commerce, Science and Transportation
Washington D.C 20510-6125

October 7, 1991

Honorable Mr. Chairman and the Honorable members of the committee :

I thank you for the opportunity to address your committee. My research focuses on the role of the clouds and the atmospheric greenhouse effect on climate and climate change.

Water vapor and carbon dioxide are the most important atmospheric greenhouse gases that trap the thermal radiation emitted by the Earth's surface. Ozone and other trace gases contribute about 10% of the total trapping. This trapping effect by gases in the atmosphere is referred here as the *atmospheric greenhouse effect*. Clouds, like atmospheric gases, also trap thermal radiation and make an important contribution to the greenhouse effect of the planet. Clouds, in addition, reflect significant amount of solar radiation back to space, and determine the amount of solar energy absorbed by the surface-atmosphere system. The cloud reflection of incoming solar energy, which would tend to cool the climate is referred as the *cloud shortwave forcing*; ... the greenhouse effect of clouds, which would tend to warm the climate, is the *cloud longwave forcing*; ... the net effect of the two competing influences of clouds is referred as the *cloud-radiative forcing*.

The ERBE, which is a multi-satellite experiment launched in late 1984 by NASA, has yielded valuable insights into the atmospheric greenhouse effect and the cloud-radiative forcing. In this testimony, I will summarize the results relevant to the topic of this hearing, obtained by my colleagues Drs B. Barkstrom, E. Harrison (both at the NASA Langley Research Center), Professor. R. D. Cess (SUNY, Stony Brook) and my group. A more complete summary of the important ERBE results obtained by several other ERBE science team groups in the U.S, Germany and England can be obtained from Dr. Barkstrom who is the leader of the ERBE science team.

I. Cloud - Radiative Forcing :

Globally, clouds have a net radiative cooling effect on the present day climate. That is, the solar energy reflected by clouds exceeds their greenhouse effect. Thus ERBE estimates that clouds have a net cooling effect on the present day climate. The ERBE data also reveal that the cloud-radiative forcing varies significantly with latitude, longitude, seasons and from year to year. Scientists are using these variations to understand how the surface temperature

distribution and atmospheric circulation patterns are linked with the radiative effects of clouds.

Implications to Global Warming: *The net cooling effect of clouds on the present day climate does not necessarily imply or even suggest that clouds will offset the global warming due to the increases in greenhouse gases.* For example, some of the climate models which predict a global warming of 2 to 4 C due to doubling of CO₂ also simulate the cooling effect of clouds on the model's control climate. The feedback effect of clouds on climate will depend upon how clouds and their radiative forcing will respond to global warming. These feedback effects are largely unknown at present. However, ERBE data reveal that the magnitude of the individual longwave and shortwave cloud forcing terms are so large that, just a small change in these terms can have a substantial feedback effect.

Impact on Global Climate Models: The data are already having a substantial impact on three dimensional global climate models used in global warming studies. For example, the most recent generation of models developed at the National Center for Atmospheric Research (Drs. J. Kiehl & P. Rasch), Colorado State University (Dr. D. Randall) amongst several others, have used the ERBE cloud forcing data to validate and improve the treatment of clouds. In the next few years we should learn the impact of the improved cloud treatments on global warming predictions.

II. Atmospheric Greenhouse Effect: The role of Water Vapor Feedback

Water Vapor concentrations in the atmosphere vary significantly due to thermodynamic and dynamic processes such as convection and large scale circulation. As surface and atmospheric temperatures increase, the saturation vapor pressure of vapor increases significantly; For example, it increases by about 15 % for a 3 C increase in temperature. As the saturation pressure increases, the vapor concentration should increase provided the dynamic processes do not offset this increase by, for example, offsetting the moistening in the lower altitudes with a large drying of the upper altitudes. Increases in the vapor concentrations will lead to increases in the trapping of thermal radiation. This thermodynamic theory for the positive coupling between temperature, water vapor concentration and its atmospheric greenhouse effect(the so-called

water vapor feedback) contributes to a significant positive amplification of the global warming predicted by climate models. If this thermodynamic theory represents a fundamental property of the Earth's climate, it should exist in the present climate system as indeed confirmed by the ERBE data analyses by Raval and Ramanathan and by Professor G. Stephens of Colorado state university.

ERBE data in conjunction with NOAA's sea surface temperature(SST) data have been used to estimate the thermal radiation trapped by the atmosphere over oceanic regions. From the SST, the thermal radiation emitted by the sea surface can be computed by using fundamental laws of physics; From ERBE, we obtain the thermal radiation escaping to space in regions of cloudless skies; the difference between the surface emission and that escaping to space over cloudless skies is the energy trapped by the gases which is an estimate of the *atmospheric greenhouse effect, Ga*. *It is important to note that Ga measures the trapping by the entire atmosphere from the surface to the top of the atmosphere.*

These results quantified the magnitude of Ga as well as its variations. The most relevant part is that Ga increased significantly from the cold mid and high latitude oceans to the warm tropical oceans. The major source for this increase is the increase in atmospheric water vapor concentrations(since CO₂ does not vary with latitude or with SSTs) with sea surface temperature. However, variations in Ga with SSTs are governed not only by total water vapor content of the atmosphere but also by the vertical distributions of water vapor concentrations and of temperatures from the surface to the tropopause. Thus it is very significant that, for hemispherical averaged conditions, the rate of increase of Ga with SST is nearly similar for the various seasons and, for the same season, it is also similar for the northern and southern hemisphere oceans. *Furthermore, the mean rate of rise of increase of Ga with SST is consistent with the thermodynamic theory for the coupling between temperature, water vapor concentration and its greenhouse effect.* The data also reveal the importance of dynamic processes. For example, in regions of deep convection over warm oceans such as the equatorial western Pacific ocean, the greenhouse effect reached maximum values exceeding(by about 20%) the value that can be ascribed to the thermodynamic coupling, while in regions of sub-tropical oceans Ga is less by about 20%.

Implications to Global Warming : The hemispherical or global rate of increase of Ga with SST as estimated from the ERBE data for the present day climate, is

within 20% of that predicted by the climate models that yield between 2 to 4 C warming due to doubled CO₂. *This agreement, by itself, does not necessarily demonstrate proof or a convincing evidence for the positive amplification of the water vapor feedback in global warming.* We are a long way from establishing such a proof. However, the following two results provide a compelling evidence for the positive water vapor feedback effect. First, the mean rate of rise of Ga with SST in the model control climate is similar to that in the observed data. Second, more detailed studies with the ERBE data have shown similar rise of Ga with SST obtained by correlating monthly variations for nearly 60 months of available ERBE data.

III. Thermostat hypothesis for regulating maximum SSTs in the Present Climate:

Dr. W. Collins and I published a paper on this topic in the May 1991 issue of the British journal Nature. This paper used ERBE and SST data along with other available meteorological data. It dealt primarily with the equatorial Pacific which is an important region atmospherically because it contains a large pool of very warm water with SSTs peaking between 30 C(86 F) to 31 C(the maximum temperature for the present day world oceans). This is especially true during the so-called El-Nino events(which occur once every 2 to 6 years) when the warm pool spreads from the western to the central equatorial Pacific across the date line. These warming events are well known to be a result of the natural oscillations of the coupled ocean-atmosphere system. An El-Nino event happened in 1986/87 and we used this as a natural experiment to understand how the water vapor greenhouse effect and cloud forcing responded to the ocean warming. Over just the equatorial Pacific, we found large increases in the atmospheric greenhouse effect, cloud greenhouse effect and comparable increases in the cloud reflection of solar energy. These increases are due to large increases in water vapor and thick ice clouds ^{resulting from} ~~causing~~ the effects of deep convection forming preferentially over the warmer oceans.

Our paper's central hypothesis - *as yet unproved* -- is that a possible ^{water vapor} ~~causing~~ "super greenhouse effect" which we found to occur in regions where maximum SSTs and deep convection occur together, would be moderated by increased cloudiness resulting from deep convection. We say this because we have observed that increased ice clouds significantly reduce the solar energy incident

on the equatorial ocean during the El-Nino warming. We hypothesize that, this cloud induced reduction of solar energy should limit maximum SSTs to less than 32 C(about 90 F).

This thermostat hypothesis , even if it is proved, is valid only for the present climate and that too only for regions of maximum SSTs accompanied by deep convection.

We are far away from proving this. A hypothesis including ours, by definition is a tentative explanation of empirical data. It is possible that alternate hypotheses can be formulated to explain our data.

Implications to Global Warming: *It is premature to extrapolate the thermostat hypothesis to the global warming since we have not even proved it for the present climate. Let us consider the purely hypothetical situation that the hypothesis applies in the greenhouse rich atmosphere. Even if it is valid globally it will have minimal impact on global warming estimates since the mean temperature of the ocean is less than the maximum SST by about 10 to 15 C. If, on the other hand it is valid regionally such as the equatorial Pacific ocean, it may only exacerbate the global warming problem. Because, if the warmest waters do not respond but the rest of the oceans warm, the horizontal gradients in SST will be altered. There will then be significant perturbation to the circulation and weather patterns since SST gradient is one of the controlling parameters for the meteorology .*

Impact on Climate Models: The changes in the SSTs along with the observed changes in atmospheric circulation, convection, the atmospheric greenhouse effect and cloud forcing make the El-Nino event a critical natural experiment to test and validate our model treatment of equatorial ocean-atmosphere coupling, convection and cloud-radiative interactions.. These are some of the central issues of global warming. This is the fundamental message of our paper.

Statement of

**Dr. Shelby G. Tilford
Director, Earth Sciences and Applications Division
Office of Space Science and Applications
National Aeronautics and Space Administration**

before the

Committee on Commerce, Science and Transportation

United States Senate

October 7, 1991

Mr. Chairmen and Members of the Committee, I am pleased to appear before you today to discuss the role of cloud research in the U. S. Global Change Research Program (USGCRP), the Global Energy and Water Cycle Experiment (GEWEX), and how NASA's Mission to Planet Earth Program plans to address these issues.

The U.S. Global Change Research Program: Goals and Priorities

The interagency Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) has developed the U.S. Global Change Research Program over the past five years in cooperation with the National Academy of Sciences (NAS) and a number of agency Advisory Committees and Panels. The overarching and long-term goal of the USGCRP is to establish the scientific basis for national and international policymaking relating to natural and human-induced changes in the global Earth system. To meet the long-term objectives of the USGCRP requires balance between the scientific objectives in both the short and long-term. These are:

- o Observations of long-term trends, ensuring integrity of calibration
- o Process studies for improved understanding
- o Model development for predictive capability

The thirty year CEES objectives for the USGCRP include development of an international operational Global Climate Observing System (GCOS), and a predictive capability on a global and regional scale.

Within the CEES, a priority framework has been identified which includes strategy priorities, integrating priorities and science priorities. In terms of the science priorities, the role of clouds, ocean circulation and heat flux, land/atmosphere/ocean water and energy fluxes, and coupled climate system links have been rated as some of the highest priority science objectives within the USGCRP.

Key uncertainties in quantifying long term climate change have been identified, quantified and put in priority order by the National Academy of Sciences (NAS) and international Intergovernmental Panel on Climate Change (IPCC) assessments.

The IPCC identified three highest priority uncertainties that need to be addressed:

- o Greenhouse gases, which control the magnitude and timing of climate change, with emphasis on the carbon cycle (carbon dioxide, methane and tropospheric ozone precursors), sulfur and ozone, and the response of these chemicals to environmental change (climate and atmospheric composition)
- o Clouds, which affect the magnitude of climate change (Water and Energy Cycles: clouds and radiative properties, hydrology and moist processes)
- o Oceans, which affect the timing and regional patterns of climate change

Three other priority areas were identified by IPCC:

- o Land-surface hydrological processes, which affect regional climate change and water availability
- o Polar ice sheets, which affect regional climate change and sea level rise
- o Ecological processes, which affect greenhouse gas emissions and ecosystem productivity

The U. S. and the international research communities over the past few years have consistently identified the areas of this hearing as being very important in global climate change. As a result, NASA, NSF, NOAA, DOE and the other U.S. agencies have factored these priorities into their planning for the future. Within NASA, cloud research has been a high priority objective in our planning for the Mission to Planet Earth (MTPE) and Earth Observing Satellite (EOS) Programs.

The Global Energy and Water Cycle Experiment

The Global Energy and Water Cycle Experiment (GEWEX) is a program initiated by the World Climate Research Programme (WCRP) to observe, understand, and model the hydrological cycle and energy fluxes in the atmosphere, at land surface, and in the upper oceans (Attachment 1). The goal of the GEWEX program is to reproduce and predict, by means of suitable models, variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources. This data will help scientists understand the response of these processes to changes in the environment, such as an increase in greenhouse gases. GEWEX is being designed to provide an order of magnitude improvement in the ability to model global precipitation and evaporation, as well as to enable accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change.

The objectives of the GEWEX Program have been defined as follows:

1. Determine the hydrological cycle and energy fluxes by means of global measurements of atmospheric and surface properties
2. Model the global hydrological cycle and its impact on the atmosphere and oceans
3. Develop the ability to predict variations in global and regional hydrological processes and water resources, and their response to environmental change
4. Foster the development of observing techniques and data management and assimilation systems to meet the above objectives

The GEWEX Program Strategy is to:

1. Build on existing programs and data
2. Conduct modeling programs to model all aspects of the hydrologic and energy cycles with evolving, fully coupled atmosphere-land-ocean components
3. Make recommendations to the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA) and the National Space Development Agency (NASDA) (Japan) with respect to instruments planned for future space platforms
4. Conduct studies with international participation encompassing the full range of experimental scales from small scale process studies (1 x 1 km to 100 x 100 km), to continental scale process studies, to global process studies

The GEWEX Science Plan has been published and the Implementation Plan is in preparation. Both an International GEWEX Project Office and a U.S. GEWEX Project Office have been established in Washington, D.C., principally supported by NASA.

The U.S. Role in GEWEX

In defining important projects, the Committee on Earth and Environmental Sciences (CEES) agencies have considered both the highest-priority scientific uncertainties identified by groups like IPCC, the International Council of Scientific Unions (ICSU), WCRP, and WMO as well as their own special mission responsibilities in the area of global change or climate change. The Global Energy and Water Cycle Experiment (GEWEX) of the WCRP, and the Biospheric Aspects of the Hydrological Cycle (BACH), the core project of the International Geosphere-Biosphere Program, are the primary international research efforts dealing with issues of regional climate change. The U.S. has become the major participant in both of these projects.

The GEWEX Continental International Experiment (GCIP), planned to begin operational phase in FY 1994, is designed to carry out a comprehensive study of the Mississippi River Basin. In conjunction with this and other international efforts, especially BACH, the International Satellite Cloud Climatology Project (ISSCP), and the International Satellite Land Surface Climatology Programme (ISLSCP), the USGCRP plans to support field experiments designed to obtain accurate estimates of fluxes of water, energy and other biogeochemical substances. These research projects are essential to improving the representation of the land surface processes in the integrated climate system models - a highly recommended IPCC priority.

Fulfilling the objectives of international programs such as GEWEX, the World Ocean Circulation Experiment (WOCE), the international Joint Global Ocean Flux Studies (JGOFS), and others requires resources. The U.S. continues to be looked to as the key to successful acquisition of those resources. However, longstanding, ongoing efforts like the Tropical Ocean Global Atmosphere Program Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) and the International Global Atmospheric Chemistry program (IGAC), which are producing valuable input to decisionmakers, simply cannot be abandoned to support new large programs. The CEES believes that new multifunded international programs should simply not be started until the prospect for sufficient funding can be ensured.

Current U.S. efforts in these areas are critically dependent upon the availability of sufficient resources in several USGCRP participating agencies. I am deeply concerned that the final USGCRP budget for FY 1992, and the outyear projections, will seriously jeopardize interagency and international commitments to this major research effort aimed at achieving predictive understanding of the regional impacts of climate change on water resources in the United States.

Mission to Planet Earth (MPTE) and Cloud and Radiation Budget Research

A significant number of U.S. agency programs are directed to improving the current understanding of clouds and their radiative balance, including precipitation. Key programs include: (1) the Department of Energy's Atmospheric Radiation Measurement (ARM-DOE) program; (2) the emerging GEWEX program, which will conduct its first continental-scale experiment within the U.S., (NOAA, NASA, NSF, and DOI); (3) the International Satellite Cloud Climatology Program (ISCCP-NASA, NOAA, NSF); and several ongoing Research and Analysis Programs (NASA, NSF, and NOAA). These latter include the development of advanced aircraft and Shuttle lidar aerosol and water vapor measurement systems.

Development of the space component of GEWEX requires substantial investments before and during the Mission to Planet Earth era. Missions to fly in the early- to mid-1990's such as TOPEX/Poseidon, ADEOS, ERS, the Japanese Earth Remote Sensing Satellite (JERS), and TRMM provide global observational data critical to the development of the GEWEX program. One key Earth Probe is the joint U.S.-Japanese Tropical Rainfall Measurement Mission (TRMM). Current plans include measurements of the Earth radiation budget using Clouds and Earth's Radiant Energy System (CERES) instruments on TRMM (1997), on the European Polar-Orbiting Platform (1997) and the first EOS platform (1998). Cloud images and aerosol measurements are highly desirable to complement the Earth Radiation Budget measurements. Measurements of clouds and aerosols and their effect on the Earth radiation budget is critical for understanding global change. To meet this high priority need, the instruments must be well calibrated for continuity with the planned CERES measurements. A number of global data sets have been determined to be important to the GEWEX program (Attachment 2).

The Earth Observing System will establish a comprehensive, integrated program of space-borne observations that will improve understanding of Earth system processes and develop a fifteen year long-term calibrated global data set to observe natural and human-induced changes. EOS instruments under consideration to be launched first on the initial two or three platforms in the 1998 - 2002 time frame include several that will observe clouds and the radiative budget. These instruments have been identified by the GEWEX program as important. They include:

ACRIM	Solar output
AIRS/AMSU/MHS	Improved infrared and microwave temperature and water vapor soundings of the atmosphere
ASTER	Fine-resolution measurements of surface from visible to infrared (HIRIS on second launch)
CERES	Total Earth's radiation balance
EOSP	Tropospheric aerosols
HIRDLS	Stratospheric trace gases (ozone, methane, water vapor), stratospheric temperature, etc.

LIS	Lightning
MIMR	Microwave radiometer for sea ice, snow cover, atmospheric water vapor, and precipitation index
MISR	Multi-angle measurements for tropospheric aerosols, surface bidirectional reflectance
MODIS-N	Visible - infrared global mapping of vegetation, oceans, atmospheric temperature, cloud detection and characterization
MOPITT	Carbon monoxide and methane in the troposphere
SAGE III	Stratospheric aerosols and ozone profiles

In addition, a number of the interdisciplinary investigations which have been selected for EOS have direct application to GEWEX. The following investigations are especially important:

- o Global Water Cycle: Extension Across the Earth Sciences
- o The Development and Use of a Four-Dimensional Atmospheric/Ocean/Land Data Assimilation System for EOS
- o Long-term Monitoring of the Amazon Ecosystems through the EOS: From Patterns to Processes
- o Hydrology, Hydrochemical Modeling and Remote Sensing in Seasonally Snow Covered Alpine Drainage Basins
- o Estimation of the Global Water Budget
- o Internannual Variability of the Global Carbon and Energy Cycles
- o Hydrologic Cycle, Semi-Arid Areas, Climatologic Processes
- o Investigation of the Atmosphere/Ocean/Land System Related to Climatic Processes
- o Biosphere/Atmosphere Interactions
- o Clouds and Earth's Radiation Budget System: Analysis (CERES-A)

International Cooperation

NASA is firmly committed to international cooperation in Earth science research. The questions we are studying and the problems we seek to understand are inherently global, and our international partners possess important scientific expertise and data which can contribute to our common success. EOS has been planned with this philosophy strongly in mind. It includes extensive international coordination of both the science and the technology involved. The Earth Observation International Coordination Working Group (EO-ICWG) is the primary mechanism for international coordination of EOS. Its members are NASA (with the cooperation of NOAA), the Canadian Space Agency, the European

Space Agency (ESA) and Japan, led by their Earth observation offices, with participation by their operational meteorological agencies. Through EO-ICWG, the payload planning for EOS has been conducted in concert with planning for the European and Japanese platforms, to ensure rational and harmonized use of the collective assets of the partners. Work is underway currently in EO-ICWG on a number of other important related coordination issues, such as data policy, data management, calibration and validation, and mission operations. EO-ICWG has provided the framework for each participant to maintain total control over his program while fully coordinating plans and taking into account partners' interests, contributions, and decisions.

On a broader level, the international coordination of the space segment of global change is the responsibility of the Committee on Earth Observations Satellites (CEOS) which was created as a result of the 1984 Economic Summit. CEOS brings together agencies responsible for Earth observations space activities, including Landsat and Systeme Pour l'Observation de la Terre (SPOT), the European Remote Sensing Satellite, ERS-1 and the Japanese Earth Remote Sensing Satellite (JERS-1), TOPEX/Poseidon, the Japanese Advanced Earth Observing System, ADEOS, as well as planned Brazilian and Indian missions. CEOS meets biennially. One of its objectives is to ensure close coordination with the international global change scientific programs such as IGBP and WCRP. The CEOS Working Group on Data has been active in defining common data formats for user products to facilitate the use of similar data from different satellites. The Working Group is also responsible for a common pilot international directory now being installed in the US, Europe, Canada, and Japan. CEOS is expected to become much more active in the next few years, and will play the lead role in international coordination of space observation programs.

Conclusion

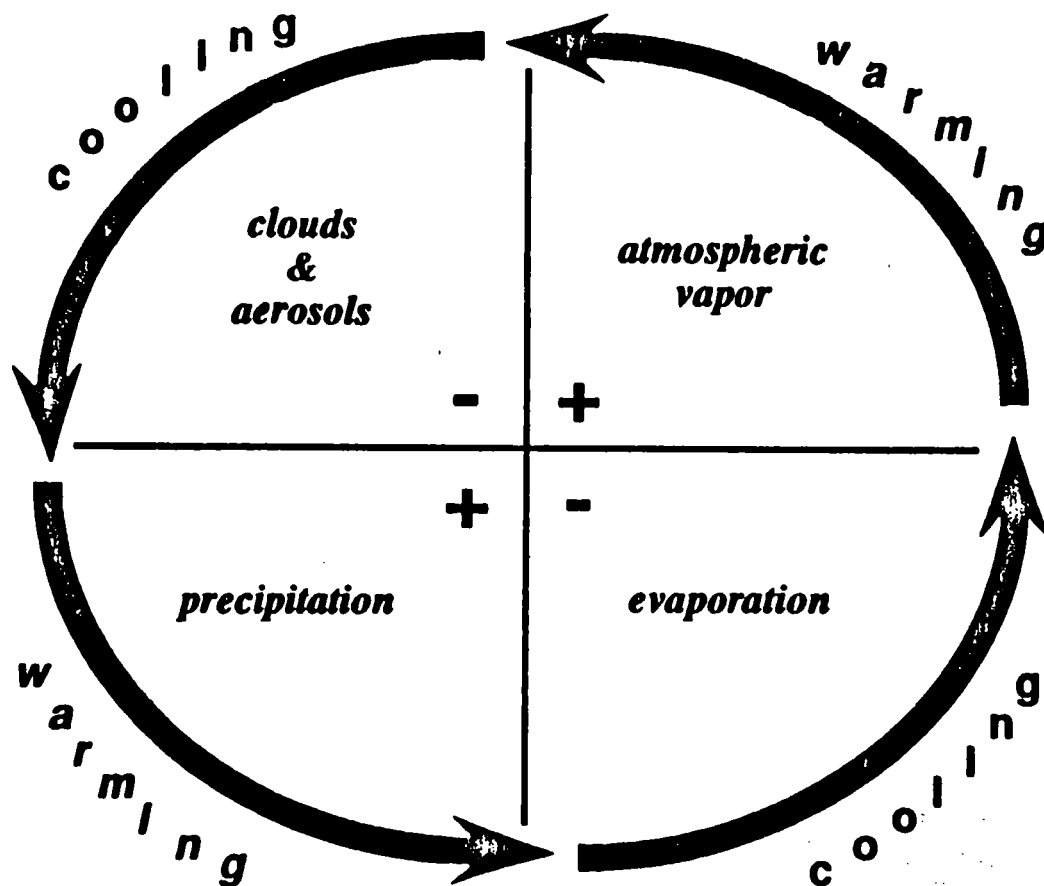
I appreciate this opportunity to discuss the GEWEX program and other efforts to understand the role of clouds in the Earth's environment. This issue is without question critical to understanding global change.

Acronyms/Abbreviations

ACRIM	Active Cavity Radiometer Irradiance Monitor
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
ARM-DOE	Atmospheric Radiation Measurement - Department of Energy Program
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BACH	Biospheric Aspects of the Hydrological Cycle
CEES	Committee of Earth and Environmental Sciences
CEOS	Committee for Earth Observing Satellites
CERES	Clouds and Earth's Radiant Energy System
DOI	Department of Interior
EO-IWCG	Earth Observations International Coordination Working Group
EOS	Earth Observing System
EOSP	Earth Observing Scanning Polarimeter
ESA	European Space Agency
FCCSET	Federal Coordinating Council for Science, Engineering and Technology
GCIP	GEWEX Continental International Experiment
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Cycle Experiment
HIRDLS	High-Resolution Dynamics Limb Sounder
HIRIS	High Resolution Imaging Spectrometer
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry Program
IGBP	International Geosphere Biosphere Program
IGFA	International Group of Funding Agencies
INC	International Negotiating Committee (for a climate change convention)
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ISLCP	International Satellite Land Surface Climatology Programme
JERS	Japanese Earth Remote Sensing Satellite
JGOFS	Joint Global Ocean Flux Studies
Lidar	Light Detection and Imaging
LIS	Lightning Imaging Spectrometer
MHS	Microwave Humidity Sounder
MIMR	Multifrequency Imaging Microwave Radiometer
MISR	Multi-Angle Imaging Spectro-Radiometer
MODIS-N	Moderate Resolution Imaging Spectrometer-Nadir
MOPITT	Measurements of Pollution in the Troposphere
MPTE	Mission to Planet Earth
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation

SAGE-III Stratospheric Aerosol Gas Experiment - III
 TOGA-
 COARE Tropical Ocean Global Atmosphere Program - Coupled
 Ocean-Atmosphere Response Experiment
 TOPEX/
 Poseidon Ocean Topography Experiment (U.S./France)
 TRMM Tropical Rainfall Measurement Mission
 UNEP United Nations Environment Program
 UNESCO United Nations Educational, Scientific and Cultural
 Organization
 USGCRP United States Global Change Research Program
 WCRP World Climate Research Programme
 WMO World Meteorological Organization
 WOCE World Ocean Circulation Experiment

The Complex Role of Water in Climate Processes



Types of Global Data Needed for GEWEX

Basic meteorological parameters

- Atmospheric temperature and humidity
- Ocean surface temperature, stress and topography
- Surface meteorological observations

Tropospheric wind vector

- Global Doppler wind lidar
- Upper air winds

Precipitation

- Global rain radar data
- Rain gauge and land-based rain radar data
- Ocean salinity

Radiation and clouds

- Solar irradiance
- Spectral outgoing long-wave radiation
- Reflected solar radiation at the top of the atmosphere
- Net flux at the surface
- Earth radiation budget
- Greenhouse trace gases
- Aerosols
- Stratospheric water vapor
- Cloud amount, type and heights of base and top

Land surface data

- Surface albedo and roughness
- Skin surface temperature and emissivity
- Vegetation Index
- Snow cover, depth and water content
- Soil moisture and water runoff

OPENING STATEMENT

by

Colonel Ronald D. Townsend, United States Air Force

at Hearing on

Global Change Research:

The Role of Clouds in Climate Change

I am Colonel Ron Townsend, Chief of the Plans Division in the Directorate of Weather under the Deputy Chief of Staff, Plans and Operations, Headquarters United States Air Force. It is a pleasure to participate in this discussion of the role of clouds in climate change. I offer a perspective of what the Air Force has in terms of satellite data and cloud databases that may apply to research in this area.

The Air Force, through the Air Force Global Weather Central at Offutt Air Force Base, Nebraska, collects and processes weather satellite data and weather observations on a continuous basis to update a global cloud database every three hours.

With respect to satellite data, we have the Defense Meteorological Satellite Program. There are normally two satellites in polar orbit providing visual and infrared imagery. With the transition to automated soft copy display at the Global Weather Central, the archive of hard copy imagery is not complete. We are planning to

implement the capability to archive digital DMSP data by February 1992.

The Global Weather Central uses the satellite data and weather observations to build a global cloud database in real time. This cloud database is sent to an Air Force operating location collocated with the National Climatic Data Center at Asheville, North Carolina. The cloud database is unclassified and is available for access by any agency through the National Climatic Data Center.

As a specific example, the Real Time Nephanalysis has evolved as the Air Force's most sophisticated cloud database. This database contains global information on cloud type, altitude of cloud bases and tops, and total cloud coverage valid at three hourly increments for each day. The Global Weather Central generates this data from conventional surface weather observations, upper-air soundings, and satellite data. This database is available for the period from January 1984 to the present.

Recognizing the national interest in cloud data, the Geophysics Directorate of Phillips Laboratory has helped develop a Cloud Information Reference Library and Archive. This on-line computer listing describes the availability and contents of government and non-government cloud databases. The initiative recognizes the need

for close cooperation between the Department of Defense and other agencies to share data.

Thank you for inviting me to participate in these discussions. We are ready to assist in providing any data we have that is applicable to the study of clouds and global change.