MODELING GREENHOUSE CLIMATE EFFECTS

Statement of:

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PREFACE

This statement is based on studies carried out with my colleagues David Rind, Andy Lacis, Tony DelGenio, Reto Ruedy, Sergej Lebedeff, Michael Prather and Peter Stone, at the NASA Goddard Institute for Space Studies. The opinions expressed represent our scientific conclusions, but they do not necessarily represent NASA policy or a consensus of the scientific community.

My testimony is addressed to the following questions:

(1) Can global climate models provide information about *regional* climate impacts of increasing greenhouse gases?

(2) Can we identify potential climate "*surprises*" which may occur as a result of climate feedback processes which are poorly simulated in current climate models?

(3) Is future climate sensitive to plausible alterations of anthropogenic trace gas release rates?

(4) What are the main requirements for obtaining improved climate models, and thus more reliable climate predictions?

1. Regional Greenhouse Climate Effects

Global climate models (GCMs), along with empirical evidence from past climate changes, provide our primary tool for anticipation of future climate change due to increases of greenhouse (infrared-absorbing) gases. GCMs are mathematical representations of the atmosphere and ocean used to simulate weather and climate change on large-scale computers.

GCMs, at present, only crudely reproduce current climate patterns. As such, their principal use has been to identify and analyze key climate processes - processes which must be understood before we can accurately predict the consequences of increasing greenhouse gases. It is generally recognized that these models cannot yet provide reliable assessments of regional climate change, principally for two reasons. First, the representations of atmospheric and surface processes in current climate models are highly simplified, and the models show a wide range of predictions for climate change in any particular region. Second, none of the existing climate models simulates the ocean realistically, and changes in ocean currents could alter regional climate.

Thus, it is difficult to predict climate change at a specific place. However, an increasing greenhouse effect undoubtedly implies some broad changes in the nature of regional climate, which it may be possible to investigate with existing modeling capabilities. We have initiated studies of several aspects of regional climate, as summarized here and in the attached preprint (Appendix A). Although these results require confirmation from other models and appropriate observations, certain fundamental conclusions emerge which we believe are very unlikely to change as knowledge of the climate system becomes more precise.

Drought. In our climate simulations, the frequency of droughts increases substantially during the next few decades at middle and low latitude land areas, if greenhouse gases continue to increase rapidly. Figure 1 shows a drought index in four specific years for a scenario with rapid growth of trace gas emissions, e.g., 1.5%/year for CO_2 and 3%/year for CFCs (chlorofluorocarbons); this is our[1] scenario A, described as "business as usual." This drought index is defined[2] as a simple function of the difference between atmospheric supply of moisture (precipitation) and atmospheric demand for moisture (potential evaporation, i.e., the evaporation that occurs if water is available); but we find qualitatively similar results for the more complex Palmer Drought Index commonly used by the National Weather Service.

Although the exact patterns of drought index are not significant, the model suggests a tendency for increased drought in the 1990's and a great intensification of drought by the 2020's if trace gases increase rapidly. But there is an intensification of *both* dry and wet extreme conditions as global temperature increases; indeed, annual mean precipitation shows little change or increases over most land areas in the model as greenhouse gases increase. The fundamental mechanism is the increased greenhouse heating of the surface. In regions which happen to be relatively dry, the increased heating raises the temperature and exacerbates the dry conditions. But over oceans and over land regions which happen to be wet, the added greenhouse heating increases evaporation rates, leading to more intense storms, as discussed below, and to increased rainfall. Dynamical processes tend to reinforce these effects, i.e., increased condensation heats the atmosphere, enhancing rising motion and condensation, while decreased condensation cools the upper air, causing subsidence and suppression of convection.

The magnitude of the drought intensification is undoubtedly model-dependent. Alternative formulations of key physical processes, such as the ground hydrology, moist convection, clouds, and ocean transports, as well as the model's resolution, can alter the degree of drought intensification. But the main factor increasing the drought index is the higher surface air temperature, which occurs in all studies of an increasing greenhouse effect. Other GCM studies, e.g., with the GFDL (Geophysical Fluid Dynamics Laboratory) and NCAR (National Center for Atmospheric Research) models,[3,4] also imply strong drought intensification for a doubled CO_2 climate. Although the representation of physical processes needs to be made more realistic in all these models, we believe it is very unlikely that this overall conclusion - drought intensification at most middle and low latitude land areas, if greenhouse gases increase rapidly - will be modified by improved models.

Storms. Storms are generally not resolved by the coarse resolution of present global climate models. However, the models provide climate diagnostic parameters which indicate how certain storm intensities are likely to change with increased greenhouse warming. As shown in Appendix A, our climate simulations indicate that a greenhouse warmed climate is likely to have deeper, more intense thunderstorms with greater rainfall. In addition, Emanuel[5] used a simple hurricane model to estimate the effect of greenhouse warming on the maximum intensity of tropical cyclones, based on the sea surface temperature changes in a doubled CO_2 experiment of the GISS model. He found that the maximum wind speed increased from about 175 mph to about 220 mph, and that the destructive potential of the hurricanes increased 40-50%. Besides increasing hurricane strength, it seems likely that higher ocean temperatures will lead to an expansion of the region which hurricanes frequent.

The picture that emerges from the model diagnostics for a greenhouse-warmed world is an increased intensity of storms driven by latent heat of condensation, both ordinary thunderstorms and mesoscale tropical storms. The basis for this is the global increase of evaporation and the higher temperatures at low levels in the atmosphere. Certainly, the magnitudes and spatial and temporal patterns of changes in storms are sensitive to uncertainties in the parameterization of

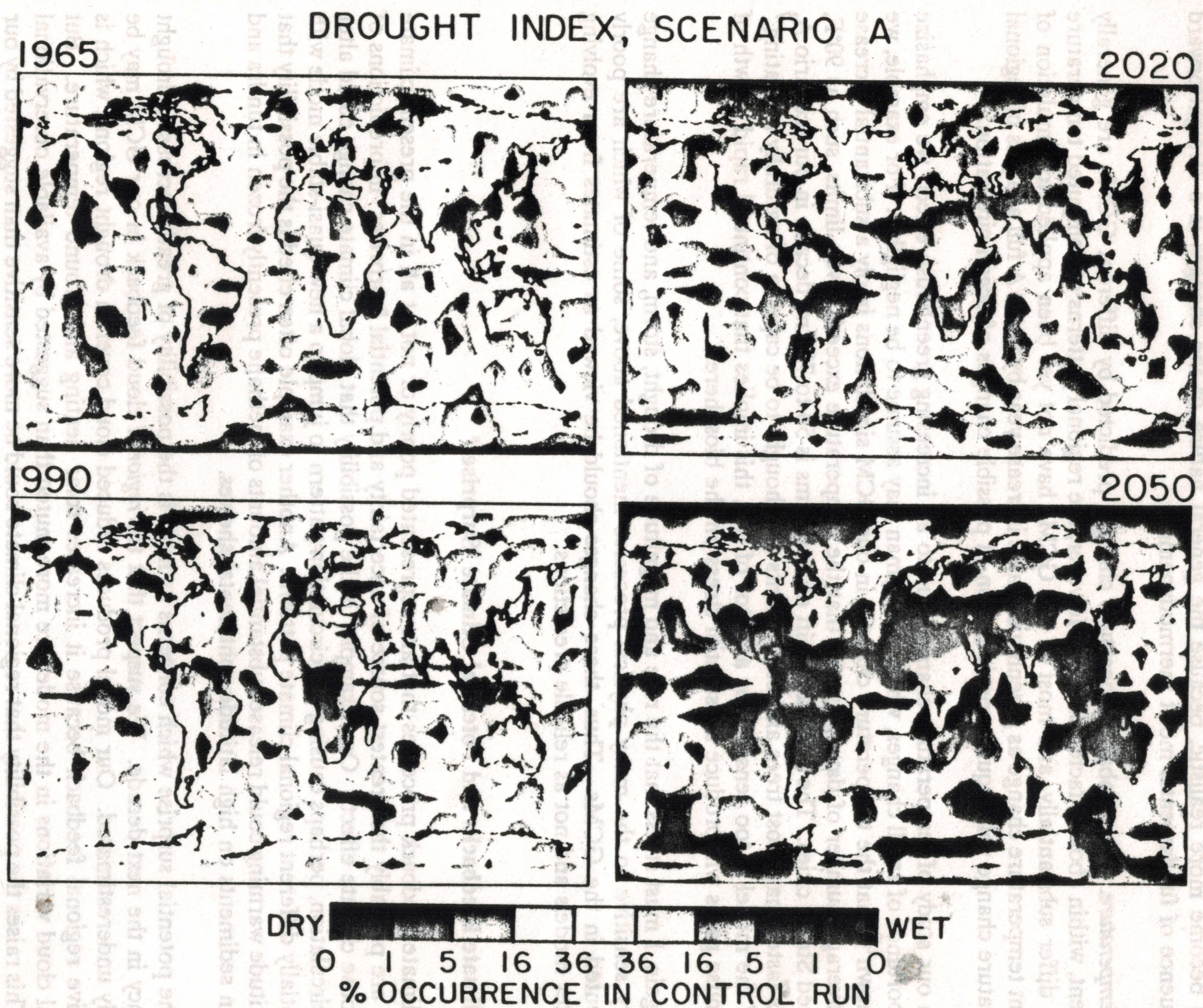

Figure 1. Drought index for June-July-August in the GISS global climate model simulation for trace gas scenario A. The color scale is set by the frequency of occurrence of a given drought index in the 100 year control run which had 1958 atmospheric composition. (The color version of this figure is published as Figure 1 in reference 2, which is included as an appendix to this testimony.)

moist convection and feedback processes in the model. The implied storm intensification would presumably be less for those GCMs which have smaller increases of ocean temperature. However, we believe that the qualitative nature of the changes we have described will be maintained as the models become more realistic, because the general nature of the changes is a straightforward consequence of fundamental moist thermodynamics.

Temperature. The global temperature changes predicted by different GCMs are generally consistent, within about a factor of two. However, the regional patterns of computed temperature change differ substantially, and most of the GCMs have not yet been applied to simulation of transient temperature change as greenhouse gases increase year by year. A full analysis of regional temperature change will require consideration of possible changes of ocean circulation.

In our study of temperature changes due to an increasing greenhouse effect[1] we emphasize the importance of small changes, which the layman may assume to be negligible. For example, we have shown[1,6] that the temperature changes in our GCM simulations imply a substantial increase in the average number of days per year that the temperature exceeds given limits, such as 90°F, in United States cities. The poleward shift of isotherms is 50 to 75 km/decade in our scenario A, which is faster than most trees and other plants are thought to be capable of naturally migrating.[7] Even if the model is too sensitive by a factor of two, this implies that continued rapid growth of greenhouse gases will produce substantial stress on the biosphere.

Again, I must stress that the rate and magnitude of drought, storm, and temperature change are very sensitive to the many physical processes mentioned above, some of which are poorly represented in the GCMs. Thus, these changes should be viewed as estimates from evolving computer models and not as reliable predictions.

2. Climate Feedbacks and Potential Climate "Surprises"

Climate feedback processes that are represented poorly or not at all in the present climate models are probably the greatest source of uncertainty and potential "surprises" in predictions of greenhouse climate effects. One example[8] is the possibility that global climate change could alter ocean circulation, perhaps causing the circulation pattern to jump to a new quasi-stable mode with substantially different regional climate patterns. Another example often cited is the possibility that high latitude warming could release substantial amounts of methane presently frozen in tundra and in ocean sediments on high latitude continental shelves.

The potential surprise which concerns us most is the possibility of greatly increased drought frequency in the next decade. We suspect that the *regional* cloud feedback in our GCM may be seriously underestimated. Our model produces reduced cloud cover in drought regions, which is a positive regional feedback because it increases solar heating and ground temperature. But regional cloud variations in the model are more muted than suggested by available observational data. This raises the possibility that regional climate could be more sensitive than suggested by our current model. Clearly, cloud data and further research on cloud feedback mechanisms are needed to address this question.

A second reason for our concern about the possibility of greatly increased drought is the fact that the severe droughts of the 1930's came at a time of exceptional warmth. The observed global warmth could have arisen from purely internal fluctuations of the climate system. Our GCM produces similar long term variations in the absence of greenhouse forcing increases.[1] On the other hand, it is also possible that the warmth of the 1930's was related to global forcings, such as the net effect of the near absence of volcanic eruptions in the period 1910–1940, the growth of greenhouse gases in that period, and perhaps other factors such as change of solar irradiance. In any event, the Northern Hemisphere was very warm in the 1930's and the present Northern Hemisphere temperature seems to be approaching a similar degree of warmth. This is another reason to be concerned about a possible relationship between large scale warming and drought.

Is it possible that regional droughts could become substantially more frequent, in effect a near-term severe local manifestation of the greenhouse change, analogous to the Antarctic "hole" of ozone depletion? Recent events, such as the North American drought of 1988, provide little guidance. A single drought cannot be used to either prove or disprove a role of greenhouse warming. Concurrent and antecedent meteorological factors, such as jet stream, soil moisture, and ocean temperature distributions, provide "causes" of every specific drought pattern and timing, but these "explanations" are irrelevant to the issue of whether greenhouse warming is increasing the frequency and coverage of drought.

A better understanding of the impact of the increasing greenhouse effect on drought frequency will require improved global models and appropriate observations. The models especially need to simulate regional clouds, convection, ground hydrology, and evapotranspiration more realistically, as well as other processes. The feedbacks involving these physical processes, for example, changes in regional clouds, need to be verified by observations in drought and non-drought situations.

3. Trace Gas Release Rates

Is continued rapid growth of trace gas emissions inevitable? Most projections, including our ("business as usual") scenario A, the trace gas study of Ramanathan *et al.*,[9] and many others, are based on the assumption that trace gas emissions will continue to increase. The most common assumption is that emissions will increase annually by some percentage of current emissions; even if that percentage is small, it leads to exponential growth of the greenhouse climate forcing.* Greenhouse climate change predictions depend greatly on the assumed scenario for trace gas growth.

We show here an example in which trace gas emissions were constrained, resulting in a dramatic decrease in the greenhouse climate forcing. Production of chlorofluorocarbons (CFCs) was increasing about 10% per year in the early 1970's, as shown in Figure 2a. But after concern emerged about the possible impact of CFCs on the ozone layer, consumers began to turn away from use of CFCs as aerosol propellants, and the United States, Canada and some European countries banned certain uses of CFCs. This caused a sharp break in the growth curve of CFC production.

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*A climate forcing is a change of climate boundary conditions (such as atmospheric composition or solar irradiance) which would tend to alter the Earth's temperature. It is commonly measured in terms of the temperature change of the Earth's surface which would be required to restore energy balance with space if no climate feedback processes operated (see Section 6 of attached paper).

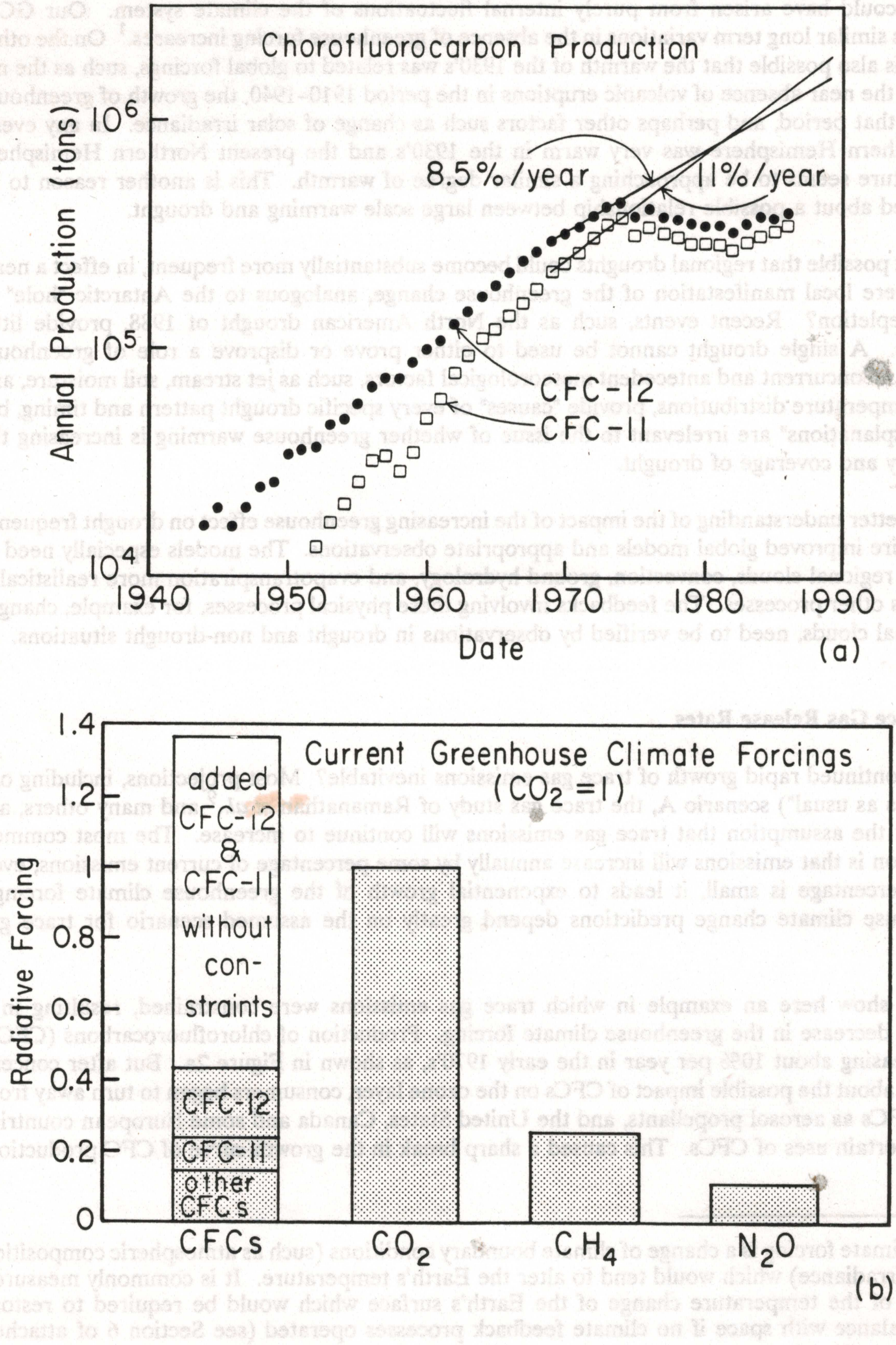

Figure 2. (a) Annual production of CFC-11 and CFC-12 by reporting companies, as tabulated by the Chemical Manufacturers Association, and extrapolations based on growth rates of the early 1970's. (b) Global mean radiative forcing of the climate system due to measured increases of trace gases, including the CFC climate forcing which would have occurred for the extrapolated CFC production in (a). Calculated radiative forcings are the current annual increments.

If the earlier CFC growth rates had been maintained during the past 15 years, the annual increase of the greenhouse effect due to CFCs would now exceed that due to CO_2, as shown in Figure 2b. Although the growth rates of CFC production may have declined naturally, it is obvious that CFC greenhouse forcings would have been at least of a comparable magnitude to that for CO_2 if "business as usual" had prevailed. We conclude that the environmental concerns of consumers and legislators, prompted by the ozone issue, had a major impact in reducing the present and future greenhouse problem.

This example illustrates the impact of breaking from a path of exponential growth; it is not necessary to eliminate emissions to have an eventual large effect on greenhouse climate forcing. One point that remains scientifically unknown is the relative contribution of natural processes and human activities to non-CFC climate forcing. Although it will be more difficult to constrain CO_2 emissions than was the case for CFCs, any policy options which should reduce atmospheric CO_2 growth rates should make good economic and environmental sense, independent of concerns about an increasing greenhouse effect.

4. Improved Climate Predictions

Improvements can be made in current global models by incorporating more realistic representations of certain physical processes and by increasing model resolution. But it will be impossible to obtain reliable climate predictions without fundamental advances in our understanding of the global system. The required advances depend upon appropriate observations of the entire biogeophysical system, but, more fundamentally, on the development of the brainpower required to analyze the observations and convert them into knowledge and predictive capabilities.

A relevant analogy is the brainpower requirement which existed, and was addressed, in the 1960's when the United States developed a space science capability. Federal funding supported hundreds of traineeships at top graduate schools across the United States. There was also a major space science post-doctoral research program supported by the federal government. These programs fueled the United States space research program, at the universities and at federal research centers. The brainpower requirements for earth studies now are at least comparable to the needs of space science in the 1960's. Some universities have noticed an upturn of student interest in earth environmental areas in graduate school applications this year. The earth science community must begin to attract and capture more of the "best and brightest" students, if we wish to achieve understanding and predictive capabilities for global change.

Finally, the need for balanced development of the science and balanced allocation of resources must be stressed. I fear that sudden realization of the shortcomings in our understanding of the global system may tempt Congress to direct resources mainly at the most visible needs - global observations and GCMs. But if hardware and large computers are supported at the expense of basic science and brainpower development, the resources will have been wasted. Global observations will only be useful if the ability has been developed to interpret and utilize the data, and if support is enhanced for maintaining and analyzing existing data sources. Also, it must be recognized that the large GCMs are only one of a broad range of analytic tools that are needed to analyze global change; indeed, most advances in our understanding have come via simple models and studies, not from GCMs. These comments are not meant to denigrate the need for global observations and GCMs, which are critical components of global change research, but only to stress the need for a balanced research program.

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