The Need for Enhanced Research on Cloud Parameterization Methods and Abrupt Climate Change

Prepared by the Subcommittee on Global Change
Research Programs of the
DOE Biological and Environmental Research Advisory
Committee (BERAC)

April 2005

CHARGE TO THE SUBCOMMITTEE

The Biological and Environmental Research Advisory Committee (BERAC) Subcommittee on Global Change met on November 17and 18, 2004, to consider several questions as requested by Department of Energy (DOE) Office of Science Director, Dr. Raymond Orbach in his letter dated September 23, 2004, to Dr. Keith Hodgson, Chairman of BERAC. Dr. Orbach's concerns were "the current rate of progress using statistical cloud parameterizations schemes is inadequate and that a new and different strategy is needed to accelerate progress in [climate] model development." Specifically he asks for advice on:

"Accordingly, I request that BERAC advise me on whether the Biological and Environmental Research Program (BER) should invest more in research to evaluate the viability and effectiveness of other approaches to modeling cloud processes and properties and their effects on climate. I am especially interested in whether it should invest more in research to explore the capabilities of the so-called superparameterization approach, including its data and computational needs. Should BER support a major research effort to develop improved superparameterization methods and to evaluate the application of such methods to the simulation of regional and global-scale climate responses to human-induced forcing? If so, and if no new funding for such an investment is forthcoming, what areas of climate change research in BER's current portfolio does BERAC suggest be reduced, delayed, or terminated to free funds for new investments on this or other approaches?

The second area on which I would like advice from BERAC is the issue of abrupt climate change. A recent National Research Council report on this topic highlighted the need to improve both the fundamental knowledge base related to abrupt climate change modeling focused on abrupt change. It also identified a need to investigate no-regrets strategies to reduce vulnerabilities to abrupt climate change. If so, what specific areas of research on this topic does it recommend BER undertake that would effectively complement what other agencies are currently supporting and leverage DOE capabilities and strengths? Finally, if no additional funds are forthcoming to invest in such research, which areas of climate change research currently supported by BER would BERAC recommend delaying or terminating to make funds available for the new investment?"

The members of the Subcommittee as well as the presenters to the meeting are listed at the end of the report and a copy of the charge letter is also included.

THE STATUS OF CLOUD PROCESSES IN CLIMATE MODELS

Clouds are known to be important in many climate problems through their impacts on the radiation budget of planet, their role in precipitation processes (e.g., droughts and floods) and the hydrologic cycle, and linkages to aerosols and atmospheric chemistry. Thus, their correct representation in climate models is vitally important. Representing clouds in these models – the "parameterization problem" – is difficult because the scales of cloud motions and the cloud particles themselves are much smaller than the horizontal resolution of today's climate models which is of order 100 kilometers. The method of representing smaller scale process such as clouds is termed parameterization in which the smaller scale detailed processes are determined as a function of larger scale parameters or variables that are defined at the grid scale. It has been argued that progress with current methods is too slow. Furthermore it has been suggested that progress may be more rapid with other approaches such as that offered by "super-parameterization". These subjects are discussed below.

Contrary to suggestions of some, there is no cloud parameterization deadlock. We find that there has been steady progress in improving the representation of clouds and their associated processes in the current climate models. For example, most climate models today include a prognostic cloud parameterization. In this parameterization, the mass of water condensed in clouds is treated as a prognostic variable of the model (much like water vapor) with physically based sources and sinks of cloud water such as precipitation, condensation, and evaporation. This has led to demonstrable progress in the simulation quality of weather and climate models. For example, the forecast skill of the weather prediction models of both the National Center for Environmental Prediction and the European Centre for Medium Range Weather Forecasts improved following the inclusion of a prognostic cloud scheme. [Moorthi et al. 2001] In addition, there are abundant new ideas for the treatment of clouds and their associated processes. Some of these ideas include statistical cloud schemes [Tompkins, 2002], unified eddy-diffusion and mass-flux approaches, [Soares et al, 2005, Teixera and Seibesma, 2000, and Lappen and Randall, 2001], the use of stochastic techniques for cumulus parameterization [Lin and Neelin, 2002], and the coupling of boundary layer turbulence to cloud top radiative cooling [Lock, et al, 2000]. The last mentioned approach has led to a marked improvement in the simulation of stratocumulus cloud decks in climate models, a long-standing problem [Lock et al, 2000; Lock, 2004]. The abundance of new ideas does not suggest that there is a "deadlock" to cloud parameterization.

If there is a reason that progress has been viewed as slow, it is that successful implementation of new ideas into climate models is a difficult process. This difficulty arises in part because of the nature of the interactions that arise between complicated parameterizations of the processes involved. It also arises because new parameterizations are often constructed based upon a limited set of "cases" which are both observed and simulated with cloud-scale models. These limited set of "cases" do not have all of the conditions that a new parameterization would experience in a global simulation. Another reason for difficulty is that the first test of a new parameterization in a global model may expose problems because the prior version of the parameterization was incorrectly compensating for errors in other parameterizations. As a result, the time and effort between the first test of a new parameterization in a model and its successful adoption into the core model can be lengthy. In addition this process is not very rewarding in terms of scientific publications and thus is viewed unattractively by many scientists whose skills are nonetheless needed since this process requires scientific intuition and not an engineering approach. Despite all of this, we encourage the agencies and departments to continue to fund activities which accelerate this process.

It should be noted that observational programs such as the Atmospheric Radiation Measurement (ARM) program are very supportive of the improvements in climate models discussed above. The ARM program has been taking very detailed observations of clouds and the environment in which they form at a few fixed sites around the world for about 10 years. The application of high-end remote sensing instruments to observe clouds and radiation has led to the production of data with great value such as its unique observations of the vertical structure of clouds. The dedication to continuous monitoring of the environment – as opposed to field campaigns of only a few weeks duration – has led to data that sample a wide variety of conditions and can be used to reliably test new cloud parameterizations. In recent years, the knowledge of how to convert raw instrumental signals into geophysical quantities of interest to the modeling community has matured. The recent generation of this value-added data is expected to play a major role in the improvement of cloud-scale models as well as climate models, due to the very detailed statistics sampled by the instruments.

The behavior of clouds in a changed climate is often cited as the leading reason that climate models have widely varying sensitivity when they are given identical forcing such as that provided by a doubling of carbon-dioxide. [Cess et al.1989 and Weilicki et al. 1996] One important way to reduce this uncertainty is to build models with the greatest possible simulation fidelity when compared to the observations of current climate. While the climate modeling community is making important and demonstrable progress towards this goal, the predictions of all types of models – including models such as “super-parameterization” – will remain uncertain at some level. In this context, there also needs to be an emphasis on understanding that is often lacking in the “brute-force” approaches. In particular, a basis for prediction can arise from detailed analysis of observations oriented towards understanding the behavior of clouds and their relationships to the environment. An example of this approach is the “fixed anvil temperature” hypothesis [Hartmann and Larson, 2002] which posits that the tops of tropical anvil clouds are fixed to the level in the atmosphere with a fixed temperature which is related to the temperature at which the water vapor abundance is low enough that significant long wave radiative cooling of the atmosphere ceases. The development of this hypothesis has been aided by physical reasoning, and supported by careful analysis of both observations and results from cloud-scale models. In sum, the goal of this type of research is the construction of hypotheses that are supported by sound physical arguments and are independent of a numerical model. Without such physically based understanding of the behavior of climate models, their predictions remain mysterious and uncertain. [Held, 2005] "Super-parameterization" will provide an interesting additional tool for the climate change problem – but its value can only be achieved through the understanding of its predictions. Such "understanding" based approaches are worthy of support.

Multi-scale Modeling Frameworks and Superparameterization

Over the last decade, the climate modeling community has employed several new tools to develop and test column physics parameterizations for coarse resolution GCMs used for decadal and centennial scale climate simulations. Non-hydrostatic dynamical mesoscale models developed for high-resolution simulations of boundary-layer, cloud and storm structures have been configured and applied to produce observational data surrogates to evaluate GCM parameterizations, because they can explicitly simulate aspects of clouds and convection. More recently, groups at NCAR and Colorado State University (CSU) have taken this approach to the next level by incorporating these cloud system resolving models (CSRMs) directly into GCMs to explicitly simulate sub-grid scale clouds and convection [Randall, et al., 2003 hereinafter RKAG]. The developers originally named this approach superparameterization, but have more recently added the term multi-scale modeling framework (MMF) to differentiate the methodologies used for embedding high resolution CSRMs inside of GCMs. Randall made the following distinction between the two in his presentation to the committee.

Superparameterization refers to the use of a CSRM solely to replace elements of existing GCM column physics. Typically, each GCM grid element has its own CSRM with periodic boundary conditions and communication between grid columns is accomplished on the GCM grid alone. This is displayed graphically in Figures 16 and 17 from RKAG.

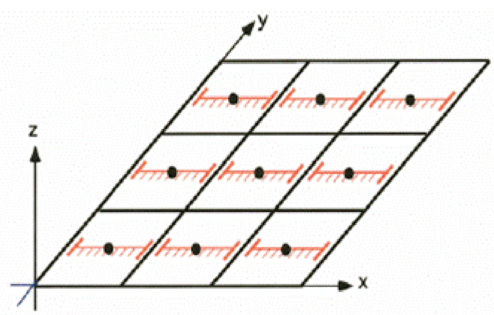

FIG. 16. The black squares represent an array of GCM grid boxes, and the red lines represent embedded two-dimensional CSRMs. The CSRM domains do not extend to the edges of the GCM grid boxes. The lateral boundary conditions on the CSRMs are periodic. At the black dots, the GCM and the domain average of the CSRM interact.

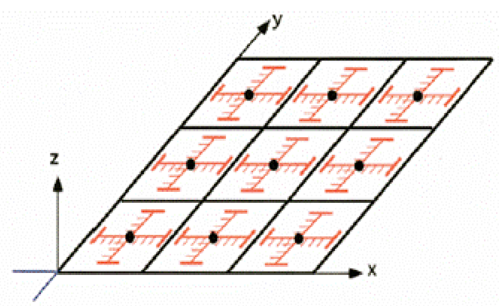

FIG. 17. An evolved version of the original superparameterization concept depicted in Fig. 16. Two CSRMs are embedded in each GCM grid box. They are oriented at right angles to each other. They have periodic boundary conditions, as before. At the point where the two high-resolution grids overlap, the CSRM is three-dimensional. Elsewhere, it is two-dimensional.

In the MMF, the CSRMs communicate across GCM grid boundaries, essentially resulting in two overlapping model grids, as is shown in RKAG Figure 18. In the MMF configuration, the CSRMs not only predict GCM sub-grid scale properties, but also participate in the simulation of the large-scale atmospheric dynamics with the primary GCM. Continuing this line of reasoning, superparameterization may be considered a subset of MMF.

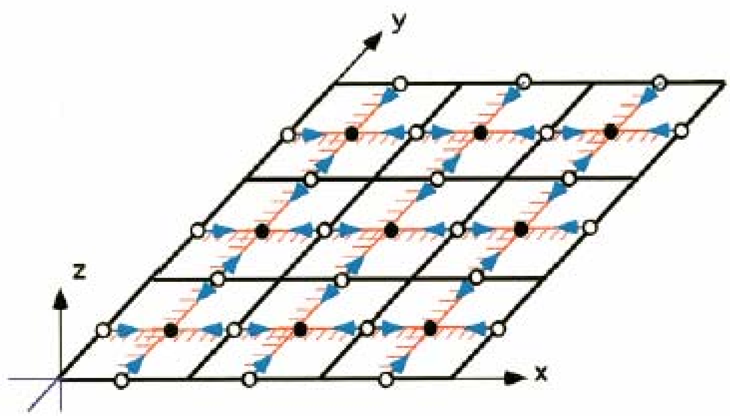

Fig. 18. Here the two orthogonal high-resolution grids are extended to the walls of the GCM grid cells. The periodic boundary conditions are replaced by a direct coupling of the CSRMs in neighboring GCM cells, as depicted by the blue arrows. The open circles represent points at which the large-scale winds are predicted. At a CSRM grid point that is not at the intersection of the two high-resolution grids, we can do a quasi-three-dimensional calculation by interpolation between the neighboring orthogonal high-resolution grids.

The underlying principles of dynamical simulation require that a model must have the correct mathematical formulation and sufficient resolution to explicitly simulate the dominant energy-containing scales of motion and the non-linear transfer of energy among different scales of motion in the modeled phenomena. Further, parameterizations of unresolved and under-resolved features should accurately reproduce the effects of the smaller scale processes on the resolved scales. Such a scale analysis is used to ensure that the model formulations and grid resolutions used in GCMs correctly simulate the dynamics that drive the atmospheric general circulation to a very good approximation. In the superparametrization, the GCM cloud parameterization is replaced with a CSRM to explicitly simulate the clouds. Subgrid-scale parameterizations for inherently microscale processes, such as cloud microphysics and turbulence, are still required. Of the five major cloud types studied by the GEWEX Cloud System Study (GCSS) (boundary layer, cirrus, extra tropical layer, precipitating convective and polar), the convective systems are the most tractable to simulate because they have the largest scales of motion. Consistent with the sensitivity analysis done by Redelsperger and Sommeria (1986), case study simulations of individual convective storm events, e.g. Trier, et al (1996), typically employ three-dimensional non-hydrostatic mesoscale models with a horizontal grid spacing of 1000 m or less in order to properly reproduce the observed storm structures. Therefore, one should not infer that superparameterization correctly simulates real cloud systems. The MMF versions of CSRMs are two-dimensional and have grid-spacings of several kilometers. Accordingly, it is more accurate to state that CSRMs, as used in proposed MMF approaches, appear to properly reproduce the cloud system properties that are relevant to GCM modeling. The distinction is not relevant if the decision is simply one of whether to replace existing cloud parameterizations in current GCMs with tested superparameterization methods. The difference is more important, however, when applied to the consideration of future research alternatives.

As noted by RKAG, the routine use of superparameterization in present climate models is still impractical, even with the current generation of high-end computing technology. Nevertheless, several tests of the approach have proven very successful, which has resulted in an effort to expand research in this area so that the methodologies are mature when computing capability catches up with the demand. For the reasons outlined above, the superparameterization appears best suited to modeling precipitating convective systems. This cloud type has particular significance because of its importance to the climate in tropical regions. Current cumulus parameterizations poorly diagnose the source terms for heat and water vapor because of incomplete representations of subgrid-scale vertical advection and mixing. Superparameterization largely overcomes most of these deficiencies because of its explicit simulation of vertical transport by convective plumes. The importance of eliminating persistent, systematic errors in the simulation of tropical climate alone justifies the continued development of the MMF for convective systems and should be encouraged.

On the other hand, MMF approaches may be less successful in simulating cloud systems with weaker dynamics and smaller scale motions. For example, Del Genio showed results from large-eddy model simulations of the GCSS European Project on Cloud System (EUROCS) First ISCCP[1] Regional Experiment (FIRE) stratocumulus diurnal cycle study that exhibit large model-model variations in average cloud layer structure. These clouds are dominated by radiatively driven convective motions with spatial scales of several meters, which are still unresolved on the fine LES grids that have much higher resolution than is feasible for MMF, even with significant computing power increases. This implies that employing MMF may not significantly improve the model representation of marine stratocumulus, polar and cirrus clouds, because their simulation will still rely heavily on parameterized physics based on assumptions that are difficult to verify.

The conceptual leap between the superparameterization shown in RKAG Figure 17 to the MMF in Figure 18 raises major theoretical and practical issues that may be difficult to resolve. Once the CSRM grids are connected across GCM grid elements, the clean scale separation between the motions simulated by the GCM and the

[1] ISCCP is the International Satellite Cloud Climatology Project)

motions simulated by the CSRM becomes less distinct. It is likely that innovative filtering methods will be needed to prevent or limit problems such as aliasing and wave refraction. Given these potential problems, it is not clear that MMF is necessarily competitive with alternative approaches that exploit a high resolution GCM development strategy.

RECOMMENDATION

We recommend that the DOE Climate Change Prediction Program (CCPP) and Atmospheric Radiation Measurement Program (ARM) continue to support and enhance research in the area of cloud parameterization methods that are aimed at being included in present and future climate models. Those methods should include some limited tests of the superparameterization method, while maintaining a balance of other promising alternatives such as high resolution GCM development and further development of “conventional” cloud parameterizations

The cloud parameterization methods should rigorously be compared to ARM, in-situ, and satellite observational data sets. Additionally, the DOE BER Atmospheric Science program that emphasizes the radiative and climatic effects of aerosols could benefit from an enhanced program in cloud parameterizations. Aerosols can strongly affect cloud microphysical processes which in turn can affect cloud amount, extent, and water/ice content.

BER should consider using part of the CCPP and ARM Science Team funding to support visits by senior university researchers to the major US climate modeling institutions. These visits would be awarded through a competitive, peer-reviewed process and would be designed specifically to implement and test new ideas within the large model development programs. The success of such a program necessitates that the modeling centers create the infrastructure for these visits, which currently does not exist, similar to the very successful paradigm employed by the European Center for Medium Range Weather Forecasting. An NSF/NOAA “Climate Process Team (CPT)” is already working with their “liaisons” posted at the modeling centers which are supposed to facilitate the incorporation of the new parameterization ideas. The DOE should benefit from the lessons learned from CPT on how to do this rightly or wrongly.

ABRUPT CLIMATE CHANGE

The BERAC Global Change Subcommittee, meeting on 17-18 November, was, also, charged with providing advice on whether BER should initiate a focused investment in research specifically targeted on scientific uncertainties of abrupt climate change. The subcommittee was briefed by W. Broecker, reviewed National Research Council (NRC) and United Kingdom's National Environmental Research Council (NERC) materials, and the subcommittee discussed this topic within the meeting. We have two specific recommendations.

There is increasing observational evidence that the climate has changed abruptly in the past and is changing now. This evidence includes such phenomena as decadal or century-scale droughts in middle latitudes, decadal or century-scale changes in monsoon rainfall, decadal or century-scale changes in the ocean thermohaline circulation and mid-to-high latitude climate regimes, and changes in the frequency of extreme events in many regions. Moreover, analysis of models indicates that abrupt changes occur in simulations of past, present, and future climates. The vulnerability of ecosystems and societies to abrupt climate changes is considerable. These topics are covered in significant detail in a recently published report of the National Research Council --- Abrupt Climate Change: inevitable surprises (National Academy Press, 2002). In the UK, the National Environmental Research Council (NERC) has used this kind of information on abrupt climate change as grounds to develop a "Rapid Climate Change Science Plan."

RECOMMENDATION

While recognizing that this important topic is already being supported to some degree by ongoing research on climate modeling within DOE, we recommend increased emphasis on this topic within DOE, as well as more coordination between DOE and other agencies. Specifically, we recommend:

1) A research initiative to encourage further analysis of climate simulations with specific emphasis on abrupt climate change.

The existing climate simulations are in three categories: multi-century simulations of pre-industrial climates, simulations of the transition from pre-industrial climate to modern climate, and simulations of potential future climates with doubling or quadrupling of greenhouse gases. The point to be emphasized is that such simulations have already been made, and are continuing to be made with newer-generation models. Therefore this initiative makes use of existing simulations and is aimed primarily at encouraging more detailed analysis of these results with emphasis on abrupt change.

These analyses could have the following goals:

a) To identify and characterize abrupt changes or regime shifts in monsoon rainfall, mid-latitude droughts or pluvials, or polar climates, and the associated changes in large-scale circulation of atmosphere and ocean. The tasks of identification and characterization include work on defining space/time structures, extreme events, and other features. We note that even the definition of abrupt change raises interesting issues. While some scientists have used this term to describe rapid one-way transitions, others use the term to describe shifts in regimes of variable duration (decades, centuries, etc). One operational definition of an abrupt change has been that the duration of the change is significantly longer than the periods of transition that precede or follow the change. Both observations and simulations can help to provide useful characterization of these kinds of phenomena.
b) To identify the causes, triggers, thresholds, and underlying processes of abrupt changes and regime shifts in the simulations.
c) To investigate the sensitivity of these simulated events to changes in the level of greenhouse gases and land use changes. These simulated changes may also be triggered by external forcing from solar variability or volcanic activity. Moreover, the sensitivity of abrupt changes or regime shifts to external forcing may depend upon the level of greenhouse gases; this too needs to be studied.
d) To estimate potential impacts of the simulated abrupt changes or regime shifts on water resources, food supplies, biodiversity, and episodic events such as fires, floods, and hurricane frequency.
e) To assess the extent to which current coupled models are able to simulate the full range of observed past abrupt change, and also to improve the realism of models in this regard.
f) To provide input into the design of observing systems (instrumental, satellite and paleo) for the study of abrupt change; as well as the possible design of early warning systems that could inform society of possible impending abrupt climate change.

The committee noted that the current round of IPCC model simulations is also being made available to interested scientists by the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) to explore regional climate changes and changes in variability or extremes. A research initiative within DOE could complement that effort.

While this particular initiative should be focused on encouraging more detailed analysis of existing model simulations, studies will of course benefit from making comparisons between the simulated climates and observed events - using both instrumental records and paleoclimatic proxy records. However, this initiative is not intended to support the acquisition of new observations, or projects that have a sole goal of synthesizing existing observations. Rather, we strongly encourage DOE-funded modeling work include, to the extent possible, the explicit comparison of simulated abrupt changes, and their broader climate dynamics contexts, with observed abrupt change of the past. By doing so, DOE can help lead efforts to understand abrupt change dynamics, as well as to ensure that models being used to simulate future change are able to simulate prospects for abrupt change in a realistic manner. While new data acquisition is needed, it is not proposed as part of this initiative and it should not be a DOE responsibility. Other agencies involved in the federal Climate Change Science Program are supporting such work.

2) An Advisory Panel on Abrupt Climate Change

An advisory panel should be formed within DOE to provide advice to the Subcommittee on Global Change Research Programs of BERAC and with appropriate links to other agencies to provide advice on the topic of abrupt climate change. Although most advice by the panel would be given to CCPP, there may be interactions with other Climate Change Research Division programs in BER. This advice could include matters related to the analysis of simulations, the need for acquisition of new observations, the monitoring of current climatic trends and potential abrupt shifts in atmosphere, land surface, and oceans, and the assessment of possible impacts and vulnerabilities. Although abrupt climate change has been a characteristic of earth’s climate throughout the geologic record, we recommend that the primary focus of this panel (and the associated research initiative within DOE) should be limited primarily to climates of the past millennia, or the past few centuries, and potential future climates.

OVERALL RECOMMENDATION WITH RESPECT TO BER RESEARCH PRIORITIES

The subcommittee does not support deep cuts in the existing DOE BER climate change research to support additional research in cloud parameterizations and abrupt climate change. We do support moving the existing research program toward supporting more research in these two high priority research areas.

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SUBCOMMITTEE MEMBERS

Warren M. Washington, Chair
National Center for Atmospheric Research

David Bader
Program for Climate Model Diagnosis and Intercomparison (PCMDI)

James Hack
National Center for Atmospheric Research

Richard Hallgren
Retired, Former Head of National Weather Service

Stephen A. Klein
Atmospheric Science Division
Lawrence Livermore National Laboratory

John Kutzbach
University of Wisconsin

Jonathan Overpeck
University of Arizona

Joyce Penner
University of Michigan

Robert White
Washington Advisory Group

PRESENTERS (in order of presentation):

Anjuli Bamzai
Department of Energy

Wanda Ferrell
Department of Energy

David Randall
Colorado State University

James Hack
National Center for Atmospheric Research

Tony Del Genio
Goddard Institute for Space Studies

Leo Donner
NOAA, Geophysical Fluid Dynamics Laboratory

Joao Teixeira
Naval Research Laboratory

Wally Broecker
Lamont-Doherty Earth Observatory
Columbia University

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Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

April 21, 2004

Dr. Keith O. Hodgson
Director, Stanford Synchrotron Radiation Laboratory
Department of Chemistry
Stanford University
Stanford, CA 94305

Dear Dr. Hodgson:

By this letter, I am charging BERAC to provide advice to the Office of Science on two climate change research issues related to predicting future changes in climate and understanding the potential for and risks of future changes in climate.

BER conducts research to reduce the scientific uncertainties in simulating and modeling the effect of clouds and cloud feedbacks on climate. It has been argued that the current rate of progress using statistical cloud parameterization schemes is inadequate and that a new and different strategy is needed to accelerate progress in model improvement.

Accordingly, I request that BERAC advise me on whether BER should invest more in research to evaluate the viability and effectiveness of other approaches to modeling cloud processes and properties and their effects on climate. I am especially interested in whether it should invest more in research to explore the capabilities of the so-called superparameterization approach, including its data and computational needs. Should BER support a major research effort to develop improved superparameterization methods and to evaluate the application of such methods to the simulation of regional and global-scale climate responses to human-induced forcing? If so, and if no new funding for such an investment is forthcoming, what areas of climate change research in BER's current portfolio does BERAC suggest be reduced, delayed, or terminated to free funds for new investments on this or other approaches?

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I request that BERAC report on its findings and recommendations at the November 3-4, 2004, meeting of the BERAC.

Sincerely,

Raymond L. Orbach

Raymond L. Orbach
Director

cc: Ari Patrinos
Jerry Elwood
David Thomassen