1. Cover Page

Proposal to the National Science Foundation for a Science and Technology Center:

Center for Multi-Scale Modeling of Atmospheric Processes

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2. Project Summary

We are proposing an NSF Science and Technology Center that will focus on the representation of cloud processes in climate models. The STC's name is the "Center for Multi-Scale Modeling of Atmospheric Processes" (MMAP), and the lead institution is Colorado State University (CSU; acronyms for the names of partner institutions are given in a table later, and the acronyms for the names of collaborating institutions are defined as needed). The goal of MMAP is to break the "deadlock" that has stalled the progress of climate research for several decades.

Climate modeling began in the 1960s. The models are physically based and include representations of the atmosphere, the ocean, the land-surface, and the cryosphere. They run on the most powerful computers available. They are now providing predictions of future climate change due to anthropogenic changes in the composition of the Earth's atmosphere. These predictions are being used as input to policy decisions that have enormous economic implications for the U.S. and the world.

It has been true for decades now that our inability to simulate the interactions of clouds with large-scale atmospheric circulations is one of the most important limitations on the reliability of climate-change simulations. Poor simulations of cloud systems also reduce the skill of weather forecasts, especially for precipitation. MMAP will address this problem through a *revolutionary new approach* called the "multi-scale modeling framework" (MMF), in which fine-grid Cloud-System Resolving Models (CSRMs) are embedded within the much larger grid cells of an atmospheric general circulation model (GCM). In an MMF, the CSRM takes the place of the single-column "conventional parameterizations" that are used in current GCMs. Whereas conventional parameterizations are based on statistical theories involving uncertain closure assumptions and little or no information about the spatial structure of the cloud field, MMFs resolve cloud processes explicitly down to a scale of a few kilometers, and so represent some aspects of the spatial structure explicitly. The first MMF was created by MMAP scientist W. Grabowski of NCAR. In most of the prototype studies carried out to date, the CSRM is two-dimensional (2D), with periodic boundary conditions. It represents a "sample" of the clouds in a GCM grid column. The CSRM's high-resolution depiction of a cloud field can be used to compute statistics (e.g., the precipitation rate and fractional cloudiness) for the sampled portion of the GCM's grid column, and these statistics are applied to the entire grid column. A key point is that MMFs can represent the *cloud-scale* interactions among the many physical and chemical processes that are active in cloud systems, including cloud dynamics, microphysics including aerosols, turbulence, and radiation. MMFs eliminate the need for closure assumptions to determine the strength of deep convective activity. They eliminate the need for cloud-overlap assumptions in the radiative transfer and microphysics parameterizations. They have the potential to represent the interactions of both clouds and gravity waves with orography. They are also particularly attractive for the simulation of chemical species transports and transformations within cloud systems, as well as small-scale interactions between the atmosphere and the biological and hydrological processes of the land-surface. MMFs must still include parameterizations of critical sub-cloud-scale processes, including microphysics, turbulence, and radiative transfer. Because these processes are represented on the cloud-scale, however, they can be parameterized in relatively straightforward ways. A further very important strength of an MMF is that the results produced can be evaluated by comparison of simulated and observed cloud-scale processes.

Recent work at CSU has shown that, relative to a control simulation with a conventional GCM, a prototype MMF produces greatly improved simulations of atmospheric variability on a variety of time scales, from diurnal to intra-seasonal. It also gives more realistic simulations of cloudiness and precipitation. Experiments with the MMF have already shown that cloud-scale variability of the radiative heating rate is important, as is convective momentum transport, which is included in a new version of the MMF that uses a 3D CSRM.

A key part of the proposed research consists of further development of the MMF concept, beginning with a new version of the MMF in which the periodic boundary conditions of the CSRM are eliminated, and multiple 2D CSRMs are combined to create a "quasi-3D" MMF. Removal of the 2D constraint permits convective systems to have arbitrary orientation and to vertically transport horizontal momentum. Removal of the periodic boundary conditions allows convective systems to propagate from one GCM grid column to the next, and prevents the convection from being artificially "squeezed" as the periodic domain decreases in size. Because there is no reason to alter the formulation of the embedded CSRM when the GCM's resolution is increased, the formulation of the quasi-3D MMF is independent of the spacing of the outer grid. In addition, realistic topographic forcing can be prescribed from data, and used to simulate orographic gravity waves and orographic clouds. Finally, a quasi-3D MMF converges in a smooth and natural way to a global CSRM, as the size of the outer grid is refined. We emphasize that no existing GCM has this convergence property. *We plan to develop, evaluate, and apply a quasi-3D MMF as the central, organizing activity of the proposed research*. This work will involve MMAP scientists at CSU, UCLA, NCAR, UU, and UW. We will also work to improve the parameterizations of microphysics, turbulence, and radiation in the MMF. This work will involve partners at NCAR, UU, MSC, and HU.

Model performance will be evaluated through exhaustive and elaborate comparisons with observations. This work will be led by partners at CSU, LLNL, PNNL, Columbia University, NCAR, and UCLA. We will also benefit from collaborations with NASA through the Goddard Space Flight Center (GSFC), the Langley Research Center (LaRC), and the Goddard Institute for Space Studies (GISS).

The MMF will make it possible to produce more robust simulations of future climate change. MMAP will address this issue through partnerships with institutions that are involved with such simulations, including NCAR, the U.S. Department of Energy through research at LLNL and PNNL, academic partners at CCSR in Tokyo, and Japan's FRSGC. We will also use our partner institutions to explore the utility of the MMF for numerical weather prediction (NWP) and data assimilation. This work will be done with partners U MD, UU, LLNL, and the BMRC in Melbourne, Australia. In addition, we will benefit from the participation of collaborators at the European Centre for Medium Range Weather Forecasts (ECMWF) and the U.S. National Centers for Environmental Prediction (NCEP).

Further development of statistical cloud parameterizations will be accelerated through the analysis of MMF results. MMAP's work in this area will be carried out by MMAP partners CSU, NCAR, UW, UCLA, and CU.

The MMF is much more expensive to run than a conventional GCM, and so MMAP includes a strong computational focus, and has an Associate Director for Computation. Research issues include performance optimization, visualization of the MMF results, and management and distribution of the large data volume that must be accessed by many investigators at very different locations around the U.S. and the world. MMAP's computational research is organized around partnerships with SDSC, NCAR, LLNL, PNNL, and Apple Computer. We also have a collaborative relationship with IBM, which built all of the supercomputers on which the MMF has been running up to now.

Many of MMAP's investigators are professional educators, and all of our research occurs in the context of education, which is arguably the most important work for any culture. MMAP's education and human-resource goals are to provide first-rate graduate education in Atmospheric Science; to interest undergraduates in graduate education and careers in climate science; and to develop and disseminate teaching materials designed to inform K-12 students (and their teachers) about the nature of the climate system and the career opportunities in climate science. In each of these areas, MMAP will make a special effort to include students from groups that are under-represented among climate-science professionals. Naturally, MMAP will support the educations of numerous graduate students in Atmospheric Science, taking advantage of the existing graduate programs at CSU, UCLA, UU, UCSD, HU, and UW. Our undergraduate educational activities include the development of new trans-disciplinary courses in cooperation with the Department of Physics at CSU and the Environmental Sciences Program at CC, support for undergraduate research experiences, and outreach to under-represented groups through the SOARS (Significant Opportunities in Atmospheric Research and Science) program. Our K-12 educational activities are organized through partnerships with the Poudre and Thompson School Districts in Colorado, with the Outreach offices of UCAR, with the Little Shop of Physics, which is based in CSU's Department of Physics, and with the Catamount Institute. We propose to do K-12 curriculum development, delivery of instructional materials to K-12 schools in part through a television program, K-12 teacher training through workshops, and K-12 classroom visits by MMAP scientists.

MMAP's Knowledge-Transfer goals are of two types. First, we will work with our research partners to transfer MMAP research results and technologies into our national atmosphere-modeling "infrastructure," for both climate simulation and weather prediction. This will include the exchange of concepts, codes, and results with the Community Climate System Model, with MMAP's NWP partners at LLNL, NCAR, and BMRC, and with MMAP's climate-modeling partners at NCAR, CCSR, PNNL, LLNL, and FRSGC. Second, we will undertake two publishing projects that will significantly enhance scientific communication in our field: the creation of a new and unique online technical journal devoted to global modeling, and the production of an edited book on the history of global climate modeling, including transcripts of interviews with the key participants.

The intellectual merit of MMAP's research lies in its revolutionary approach to the cloud-climate problem. *We can learn a lot about the global climate system by approaching the problem of climate modeling from a new and different perspective*, and this new knowledge is the most valuable thing that will flow from MMAP's research. The research will have broad impacts on both science and society, because it will increase both our understanding of climate dynamics, and our ability to make reliable predictions of cloud feedbacks on climate change.

The legacy of MMAP will include important new modeling tools that will provide substantially more reliable predictions of anthropogenic climate change. In addition, MMAP will demonstrate new ways to compare high resolution observations with global model results, enable improved weather forecasts by the operational centers, strengthen the scientific interactions between global modelers on the one hand and cloud-scale observers and cloud modelers on the other, create a heightened awareness of the excitement and opportunities of climate research among both female and male students from all ethnic backgrounds and at all levels, inaugurate a unique new scholarly journal, and produce a book that captures the history of global climate modeling with an emphasis on the cloud parameterization problem.

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4. Project Description

4.a Rationale for Center Concept

As described in Section 4.c below, ***we are proposing to develop and apply a radically new kind of global atmospheric model designed for use in climate change simulations.*** Global atmospheric modeling has been an active area of research for about 40 years. The models are very successful when they are applied to numerical weather prediction, but their application to the simulation of climate change has been more problematic. The most severe difficulties are associated with our inability to realistically simulate the interactions between cloud systems and the global-scale circulation of the atmosphere.

Better climate models can be made by reducing the horizontal grid spacing to a few kilometers or less, but for the next several decades limitations of computer power will prevent this. Better models can also be made by improving the parametric representations or "parameterizations" of important unresolved processes, but at present our limited understanding prevents this. We are proposing a third approach that is just barely feasible with current supercomputers, and which appears to be within reach of our current understanding. We call our new approach t he "Multi-scale Modeling Framework" (MMF). It is explained in Section 4.c.

We are proposing an NSF Science and Technology Center called the "Center for Multi-Scale Modeling of Atmospheric Processes" (MMAP) that will focus on the representation of cloud processes in climate models. *MMAP's research program will create and nurture a major and radically new activity in the field of global atmospheric modeling, that will enable rapid progress towards more realistic climate-change simulations*. In order to accomplish this, our plan is to engage the scientific expertise of a significant fraction of the climate-modeling research community, and to tap computing resources at multiple supercomputer centers. A multi-institutional Center is an ideal vehicle for such an initiative. A second consideration motivating a Center approach is that, quite obviously, substantial funding will be required to support MMAP research. It is essential that we obtain this funding without cannibalizing the resources that are already being allocated for research on climate modeling. Because STCs are not funded from the disciplinary divisions within NSF, funding for our proposed STC will represent a net increase of the resources supporting climate-modeling research. This additional allocation is highly appropriate given the national and international importance of the climate change problem (Global Change Research Information Office, 2003).

During the 1990s, Prof. V. Ramanathan of the Scripps Institution for Oceanography led an STC called the Center for Clouds, Chemistry, and Climate (C4). Ultimately C4 organized two major field campaigns, both of which provided new data relevant to climate modeling, especially on the radiative effects of clouds and aerosols, and the links between atmospheric chemistry and climate. MMAP will build on what C4 achieved, in a highly complementary and non-duplicative manner. MMAP will not organize field programs, but will instead focus on developing a modeling framework compatible with understanding gleaned from previous and ongoing field work. As discussed later, MMAP will include a task on modeling the effects microphysical processes on the global energy and water cycles, including the effects of prescribed aerosol concentrations. MMAP will not organize field programs, but will focus strongly on the modeling side of the cloud-climate problem.

MMAP includes a strong Education and Outreach (E/O) initiative, designed to foster a stronger and more diverse new generation of climate scientists. This work addresses all educational levels from K-12 to postdoctoral, and includes a formal and quantitative assessment of the impact of MMAP's E/O program. In addition, MMAP has an Knowledge Transfer (KT) component that includes research collaborations with the climate-change and numerical weather predictions communities, as well as a pair of publishing initiatives designed to enhance academic communication and the historical record of climate change research. The E/O and KT components of MMAP fit very naturally with its research component. Many of MMAP's researchers are also professional educators, all of MMAP's researchers are motivated to improve our society's efforts in the areas of climate and weather prediction, and all of MMAP's researchers are engaged in scholarly writing activities. Research, education and outreach, and knowledge-transfer are already the primary activities of MMAP's academic professionals.

The *long-term goals* of MMAP are: to achieve a much better understanding of the role of clouds in climate variability, to develop and demonstrate new ways to compare high-resolution observations with global model results by creating stronger and more fruitful interactions between global modelers on the one hand and cloud-scale observers and cloud modelers on the other, to enable major and rapid progress towards reliable simulations of anthropogenic climate change, to contribute to the development of improved weather forecasts from the operational centers, to foster a heightened awareness of the excitement and opportunities of climate research among students from diverse backgrounds and at all educational levels, to create a unique new scholarly journal on global environmental modeling, and to produce a book that records for posterity the history of global modeling with an emphasis on the cloud-parameterization problem.

4.b Narrative Description of the Management Plan for the Research, Education, and Knowledge Transfer activities of the Integrated Center

Partner Organizations and Lead Personnel

The lead institution for MMAP is Colorado State University (CSU), which will carry out a wide range of research activities, plus graduate and undergraduate (Physics) education, and K-12 education through the Little Shop of Physics. CSU will also carry out a tracking study of female students and science education. The lead individuals at CSU are MMAP's Director Prof. David Randall, the Associate Director for Education and Outreach, Prof. A. Scott Denning, the Associate Director for Knowledge Transfer, Prof. Wayne Schubert, and the Center Coordinator, Cindy Carrick. The other lead partner institutions are the National Center for Atmospheric Research (NCAR), which employs MMAP's Deputy Director, Dr. Chin-Hoh Moeng; and the University of California at San Diego (UCSD), which is home to the San Diego Supercomputer Center (SDSC) and Dr. John Helly, MMAP's Associate Director for Computation.

Fig. 1 summarizes the management structure of MMAP, which is designed to be minimally hierarchical, to enhance the flow of information throughout MMAP, and to minimize bureaucratic bottlenecks. The organizational structure is "flat." Such an organic structure eases the task of communicating vision throughout the organization, is less bureaucratic and more flexible than a more hierarchical structure, and makes full use of the staff's talents. The MMAP Center Director has overall management responsibility for the Center, but delegates to and relies heavily on the other members of the management team. This structure makes it possible for the Center Director to continue to function as a scientist, which is a requirement if he is to provide scientific leadership of MMAP. The lines in the figure are intended to show the *primary* channels of communication, but not the only channels. All of the doors of the Center will be open, including most of all the Director's door.

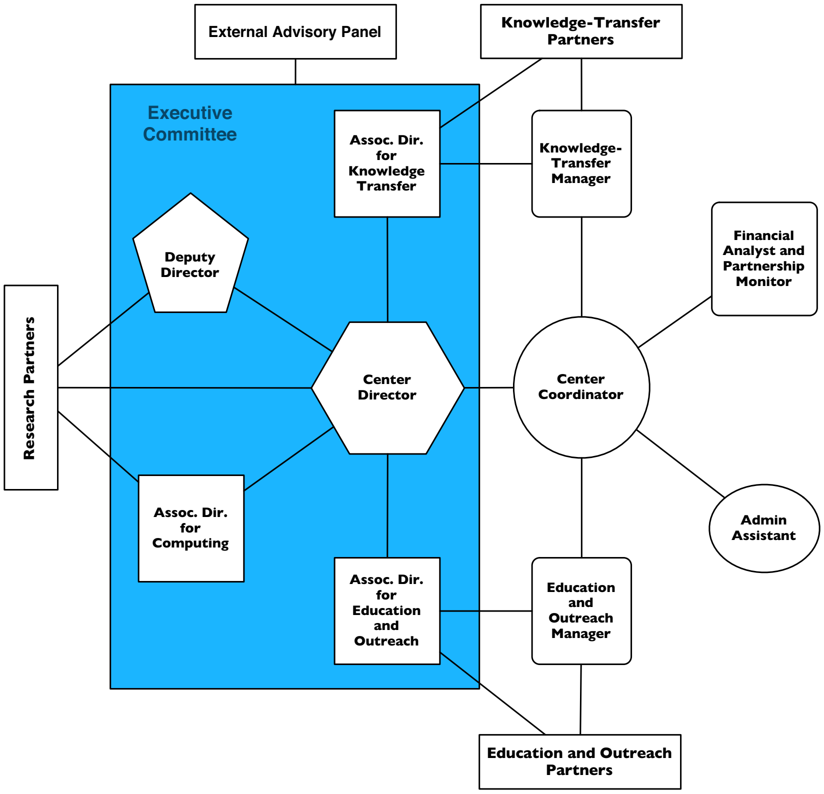

Figure 1: The minimally hierarchical management structure of MMAP. This is a "flat" organizational structure.

MMAP's Principal Investigator and Center Director will be Prof. David Randall of CSU, who will devote 50% of his time to this activity, and direct the research activities of MMAP. He is currently supervising and financially supporting a research group consisting of seven graduate students and fifteen full-time staff. Over the past ten years he has been Principal Investigator on numerous grants and contracts with NSF, NASA, DOE, and NOAA, totaling more than $15 million, and during the same decade he has authored or co-authored more than 100 refereed journal articles. He has also chaired major science teams, panels and committees. Since July 1995 he has been the Chief Editor of the *Journal of Climate*. Prof. Randall will step down from his Chief Editorship and many of his other outside commitments, in order to focus on MMAP. He will participate in the National Network of STC Directors.

MMAP's Deputy Director will be Dr. Chin-Hoh Moeng, who is a Senior Scientist at NCAR. She is a leading expert on large-eddy simulation of boundary-layer processes, and also the physical processes of PBL clouds. She has made important contributions to the planning and organizational process that went into this proposal.

The Associate Director for Education and Outreach will be Prof. A. Scott Denning of CSU. Prof. Denning has worked with local schools for several years to teach weather and climate to K-12 students. His research on the global carbon cycle has demonstrated the importance of cloud transport for interpretation of atmospheric observations. To assist Prof. Denning, MMAP will employ a full-time Education/Outreach Manager who will be responsible for managing the interactions of MMAP with the Education Partners, with the guidance of the Associate Director for Education. The Education/Outreach Manager will be in residence at CSU, but will make frequent visits to MMAP's Education/Outreach Partners. Each partner school will have a designated education representative whose activities are coordinated by the Associate Director for Education and Outreach and the Education and Outreach Manger.

The Associate Director for Knowledge Transfer will be Prof. Wayne Schubert of CSU. Prof. Schubert has been very active in atmospheric research, including both cloud parameterization and numerical modeling, for more than 30 years. He also has experience as past Co-Chief Editor of the *Journal of the Atmospheric Sciences*, and as past Publications Commissioner for the American Meteorological Society. To assist Prof. Schubert, MMAP will employ a full-time Knowledge-Transfer Manager, in residence at CSU, who will be responsible for coordinating interactions with MMAP's Knowledge Transfer Partners. The Knowledge-Transfer Manager will track the progress of MMAP's newly created academic journal towards the goal of financial independence from MMAP. He or she will also collect and organize materials for reports to NSF on MMAP's progress and accomplishments, and will make much of this same information available on the MMAP Web site.

The Associate Director for Computation will be Dr. John Helly of the San Diego Supercomputer Center. Dr. Helly is an expert on the management of scientific data, and has experience in supercomputing with climate models.

MMAP will employ Cindy Carrick, currently Prof. Randall's Research Coordinator, as a full-time "Center Coordinator," the senior administrative position in the Center. The Center Coordinator will serve as a "Chief of Staff." She will coordinate the MMAP's daily administrative, research and educational activities, and facilitate interactions among center personnel and with external entities. She will make sure that MMAP meets the NSF reporting requirements in a timely fashion, and ensure the Center's compliance with university and Federal policies. She will supervise a full-time administrative assistant.

MMAP will employ a full-time Financial Analyst and Partnership Monitor, in residence at CSU. He or she will be responsible for tracking the financial operations of MMAP, including those associated with the various subcontracts, and for collecting and maintaining records on the progress of partner institutions towards fulfilling the terms of their subcontracts.

Building and maintaining an effective and integrated team

Our planning for MMAP began in late 2001, long before the NSF Solicitation was issued.We held two planning workshops prior to submission of the Pre-Proposal in June 2003, and three more in December 2003 to prepare for the full Proposal. These planning activities began the process of team building for MMAP.

MMAP involves dozens of scientists at widely separated institutions. Communication within the team will be a key to MMAP's success. We plan two MMAP meetings per year, each lasting two or three days. The meetings will be conducted as "Workshops," with presentations focusing on recent results and near-term plans, and a lot of discussion time. Each Workshop will also include several longer, invited talks, including some by scientists who are not part of MMAP. Half of the Workshops will be held in Fort Collins, and half elsewhere. In addition, we have budgeted in the first year for an "Access Grid" teleconferencing system, which will permit more frequent and effective communications than can be achieved through Workshops alone.

The MMAP Executive Committee (EC) will consist of the Center Director, the Deputy Director, and the three Associate Directors. The EC members orchestrate MMAP's overall scientific direction; recruit new partners and collaborators as appropriate; enforce the highest standards in ethics and research quality; develop diversity; monitor progress relative to established milestones; and promote broad dissemination of results. The EC will teleconference at least twice per month, to maintain tight communications across the project. The Center Coordinator and other MMAP personnel will participate in the teleconferences as appropriate. The EC will also meet face-to-face in conjunction with each of the twice-yearly MMAP Workshops. Each of the partner institutions will be required to provide twice-yearly written summaries of progress to the EC.

MMAP will create an External Advisory Panel (EAP) that meets at least once per year. The EAP will consist of six members, including a Chair. The members will include representatives of academia, atmospheric science research centers, a computing center or company, and the education sector. The EAP will monitor MMAP's progress, and make recommendations to the EC. The members of the EAP will serve three-year terms, and the Chair will change every two years. Prof. Kerry Emanuel of the Massachusetts Institute of Technology has agreed to be the first Chair of the EAP. The other initial members of the EAP will be chosen later, through discussions between the EC and Prof. Emanuel.

Succession plan

NSF requires that this proposal include a plan for succession of the Center leadership. In the unlikely event that Prof. Randall is unable to continue as the MMAP P.I./Center Director, he will be replaced by Prof. Graeme Stephens of CSU. Prof. Stephens has the required expertise in the area of cloud-climate research, and has experience in leading large multi-institutional research activities. His time is currently very heavily committed in his role as the P.I. on CloudSat, but this burden will be dramatically reduced by 2006, shortly after the planned beginning of MMAP funding. He has agreed to be designated as "next in line" for the MMAP directorship.

If the Deputy Director or one of the Associate Directors steps down, a successor will be chosen by the EC, in consultation with the EAP.

4.c Narrative Description of the research objectives of the integrated center

Once and future schemes

Climate is the (in principle infinite) collection of statistics based on the evolving state of the atmosphere, including not only simple averages (e.g., average surface temperature) but also variability on a range of time scales from hours to decades. Among the many atmospheric processes that play a role in climate, cloud processes are among the most important and also among the most difficult to understand and predict.

Comprehensive climate models include atmospheric "general circulation models" (GCMs) that are used to simulate climate change compute hour-by-hour variations of the weather over the entire atmosphere, using grids composed of cells on the order of 100 km wide and hundreds of meters deep. The models are based on such principles as conservation of mass, momentum, and energy. The simulated climate is determined by computing the statistics of the weather simulated by the model. Direct calculation of the climate statistics would arguably be more elegant, but no one knows how to do that.

The representation of cloud processes in climate models, which is a key aspect of what we will call the "*cloud-climate problem*," has been recognized for decades (e.g., Arakawa, 1975; Charney, 1979; Houghton et al., 2001) as the festering source of much of the uncertainty surrounding predictions of climate change. Clouds usually form in rising air, which expands and cools until cloud formation occurs. Cloud processes include: cloud-dynamical processes associated with the motion of the air on the scale of large clouds (e.g., thunderstorms) and "mesoscale" cloud-groups; microphysical processes, involving cloud drops, ice crystals, and aerosols; the flow of both solar and terrestrial radiation through the cloud field, including emission, absorption, and scattering, depending strongly on wavelength; and turbulent processes, which include boundary-layer (near-surface) turbulence, the entrainment of environmental air into the clouds, and the formation of small clouds. These various processes interact with each other on space scales of a few kilometers and time scales of a few minutes, and jointly interact with larger-scale circulation systems. Cloud processes affect the climate system by regulating the flow of radiation at the top of the atmosphere, by controlling precipitation, and through additional mechanisms too numerous to list here (Arakawa, 1975, 2004).

In many weather regimes, clouds and precipitation are produced almost exclusively in concentrated updrafts that are too small to resolve in a conventional GCM. In addition, holes in clouds can be produced by small-scale downdrafts. GCMs must therefore incorporate "parameterizations" of cloud formation and dissipation, as well as the microphysical, radiative, and turbulent processes associated with clouds. Cloud parameterizations are theories that are designed to describe the statistics of the cloud field, e.g, the fractional cloudiness or the area-averaged precipitation rate, without describing the individual cloud elements. Existing parameterizations address only a subset of the processes mentioned above, and even those that are included are, for the most part, assumed to interact with each other primarily through the large-scale environment, rather than on the cloud scale itself. Parameterization research has been a major focus of atmospheric science since the 1960s. A lot of progress has been made, but our current parameterizations are inadequate to support the societal need for robust simulations of future climate (Global Change Research Information Office, 2003). Differences in cloud-radiation parameterizations are responsible for most of the inter-model differences in sensitivity to greenhouse gas increases. One striking set of numerical experiments (Senior and Mitchell, 1993) produced global average surface temperature changes due to doubled carbon dioxide ranging from 1.9 to 5.4°C, simply by altering the way in which these cloud-climate feedback mechanisms were treated in the model. This range roughly matches the factor-of-three difference in global sensitivity between GCMs that has been revealed by extensive model intercomparisons (e.g., Cess et al., 1989). Until our models incorporate more realistic representations of cloud processes, predictions of future climate change will be devalued by such uncertainties. The improved parameterizations of the future will also have a positive impact on weather forecasting, especially for precipitation. In addition, they will permit more realistic simulations of global chemical cycles, including those linked to atmospheric aerosols. As discussed by Houghton et al. (2001), uncertainties in the representation of cloud processes are the dominant reason for uncertainties in calculations of the lifetime of key species such as sulfur.

A sober assessment suggests that with current approaches the cloud-parameterization problem will not be "solved" in any of our lifetimes (Randall, 2003 b). As explained below, we propose to follow a *revolutionary new approach* that offers the potential for major progress on the cloud-climate problem within the lifetime of MMAP, and which will be pursued in parallel with the conventional approach to cloud parameterization. Our research team includes many of the top scientists in the field. We have been energized by the new ideas, and we are resolved to bring much-needed focus and organization to the modeling side of the cloud-climate research problem, coupled with a commitment to deliver to the community major and timely new results and capabilities in terms of both scientific understanding and practical applications. We are going to pull the sword from the stone.

The Multi-Scale Modeling Framework: Concept and results to date

Our new approach is based on the use of "Cloud-System Resolving Models" (CSRMs), which have resolutions fine enough to represent cloud processes on the scale of individual cloud elements, combined with space/time domains that are large enough to encompass many cloud elements over many cloud lifetimes. As discussed by Randall et al. (2003 a), CSRMs have been shown, through a number of case studies, to give better results than the parameterizations used in GCMs. A global 3D CSRM, i.e., a (non-hydrostatic) GCM with the spatial resolution of a CSRM and an appropriately reduced time step, would consume about 10^6 times as much computer resource per simulated year as a current, conventional climate model. It is possible now to make short runs of a few simulated days with a global CSRM, and this will happen soon. Century-long climate simulations with global CSRMs will become possible in a few decades, but they are out of the question at present.

We propose a new approach that is designed to harness the power of CSRMs at an affordable cost. The basic idea, which follows the pioneering work of Grabowski and Smolarkiewicz (1999), and subsequent elaborations (e.g., Grabowski, 2001; Khairoutdinov and Randall, 2001; Randall et al., 2003 b; and Khairoutdinov et al., 2004), is to replace conventional GCM parameterizations with embedded high-resolution cloud-system-resolving models. Because this approach allows one to explicitly represent a range of atmospheric processes on their native scale we refer to this approach generically as the multi-scale modeling framework (MMF). One way to think of the MMF is in terms of subsampling, whereby CSRMs represent a "sample" of a GCM grid column, analogous to a population sample used in an opinion poll. The CSRM's high-resolution depiction of a cloud field can be used to compute statistics (e.g., the average precipitation rate and fractional cloudiness) for the sampled portion of the GCM's grid column, and these statistics are applied to the entire grid column, much as an opinion pollster computes statistics from a sample of a population and applies them to the whole population. In the context of the MMF, the embedded CSRM has been referred to as a "super-parameterization" (Randall et al., 2003 b), to distinguish it from the conventional parameterizations discussed earlier. Although revolutionary in its scope, the idea of the MMF was anticipated in earlier work. For example, Krueger (1993) embedded a precursor of ODT (the one-dimensional turbulence model, Kerstein, 1999) to simulated turbulent mixing in a cloud-topped boundary layer by fully resolving the range of eddy sizes in a 1D domain. Related approaches have been developed to simulate 2D turbulent flows (Schneider and Farge, 2000), and subgrid-scale motions in LES (large-eddy simulation; Dubrulle et al., 2002). MMF-like approaches are also increasingly popular with the material science community (Starrost and Carter, 2002; see also the equation-free multiscale computation approach of Kevrekidis, as described for example by Theodoropoulos et al., 2000). They are a topic of great interest within the applied mathematics community (e.g., the heterogeneous modeling methodology of E and Engquist, 2003).

What is the optimal embedding strategy? What is the best way to learn from the new approach? Our work to date has been based on the prototype MMF developed by Khairoutdinov and Randall (2001), who embedded a two-dimensional (2D) CSRM within each grid column of the CAM (Community Atmosphere Model), which is the atmosphere sub-model of the Community Climate System Model (CCSM; Blackmon et al., 2001). The 2D CSRMs were oriented in the east-west direction, and replaced the CAM's stratiform and convective cloud parameterizations. Each CSRM included 64 grid columns, with a rather coarse grid spacing of 4 km. The CSRM is forced by advective tendencies simulated by the GCM, and the GCM feels the heating and drying simulated by the CSRM. The use of a 2D model in this initial framework precluded the inclusion of the effects of convective momentum transport on the large-scale circulation. Khairoutdinov et al. (2004) extended this work by performing an annual cycle simulation with the prototype MMF. The results of these studies show a vigorous Madden-Julian Oscillation (MJO) with a realistic structure, in contrast to the control run with conventional parameterizations, in which the MJO is virtually non-existent. Higher-frequency variability, e.g., Kelvin wave activity, is also realistically simulated by the prototype MMF. Further tests show that the MMF produces realistic simulations of large-scale cloudiness including both cirrus and stratus clouds, a realistic diurnal cycle of precipitation over both continents and oceans, and a realistic frequency of precipitation. These are all major improvements over the standard version of the CAM. In addition to the generally encouraging results mentioned above, there are many a priori reasons to expect that MMFs can provide more realistic, more complete, more reliable, and generally more useful simulations of weather and climate. In particular, the MMF can produce explicit simulation of the full life cycles of large convective clouds and organized mesoscale convective systems, realistic evolution of convectively generated upper tropospheric stratiform clouds, and realistic cloud overlap and horizontal inhomogeneity for radiation and microphysics. Further discussion is given by Randall et al. (2003 b).

Beyond providing better simulations, prototype MMF experiments are already teaching us new things. For example, notwithstanding the many improvements, in our initial experiments the tropical western Pacific was unrealistically humid and rainy during the Northern-Hemisphere summer (Khairoutdinov et al., 2004). Recent work with a doubly-periodic, three-dimensional (3D) CSRM with the same number of grid columns (this time arranged in an 8x8 square rather than in a line) shows that this failing was related to the omission of convective momentum transports in the 2D framework. Experiments with and without cumulus-momentum transports using the MMF with a 3D-CSRM show that convective momentum transports eliminate the west-Pacific problem as well as improving other aspects of the general circulation (e.g., alleviating the "double ITCZ" problem). These early experiments are providing powerful evidence for the importance of cumulus momentum transport in the general circulation, itself a longstanding and vexing issue. These results strongly indicate that future versions of the MMF must represent the three-dimensionality of the cloud field in some way, because the momentum transport depends on the organization of the cloud field including its spatial orientation. A next-generation "quasi-3D" MMF is discussed under Milestone 2 below.

Another example of how the MMF can teach us things relevant to conventional parameterization is from a recent analysis of early MMF simulations. Cole et al. (2004) found that fluctuations in the radiative cooling rate (i.e., locally enhanced or reduced radiative cooling with a horizontal scale of a few kilometers) produce changes in the cloud-scale air motion, which in turn produce changes in cloud formation or desiccation processes. Such cloud-scale interactions are not included in conventional parameterizations but are easily simulated with the MMF. In both the case of cumulus momentum transport and cloud-scale interactions the MMF has helped identify important priorities and directions for future research on conventional parameterizations.

Good things come at a price. The MMF consumes two orders of magnitude more computer time than a conventional GCM. Supercomputer speed increases by about a factor of 100 over ten years, however, so that today's expensive experiments can quickly become tomorrow's routine calculations. We recognize that the computational performance of the MMF is a key issue for MMAP, and for this and other reasons computational science forms an important element of our proposal, as discussed further below.

A very compressed summary of our planned research program is given below, organized by Milestones, and within Milestones by Tasks. For each Milestone, the lead MMAP partner institutions and key individuals are identified. All acronyms for institution names are defined in Tables given later in this proposal; the tables also list all of MMAP's senior scientific personnel and their affiliations.

Milestone 1: Extensions, evaluations and applications of the prototype MMF

In the near term, we must make some straightforward extensions of the prototype MMF already implemented in the CAM, and explore more fully its capabilities and limitations. Tasks include: running the MMF with several alternative spatial resolutions for both the GCM and the CSRM, to gain an understanding of how the model's performance depends on these choices; coupling the GCM's land-surface model to the CSRM, so that land-surface processes including surface fluxes and biological/hydrological processes can be computed at the scales of surface heterogeneity; conducting a multi-year simulation with prescribed observed sea-surface temperatures from real individual years; and performing a short coupled ocean-atmosphere simulation. This first Milestone can be completed by the end of the first year of MMAP; in fact, some of the work is already under way as this Proposal is being written. The primary partners for this Milestone will be CSU (Randall, Khairoutdinov), NCAR (Grabowski, Collins, Hack, Moncrieff), HU (McCormick), LLNL (Cederwall, Potter, Duffy), Columbia University (Hansen), and PNNL (Ackerman). We will also benefit from collaborations with NASA's Langley Research Center (LaRC; Wielicki, Xu) and the Goddard Institute for Space Studies (GISS; Rossow).

Milestone 2: Developing a second-generation MMF

Task: A Quasi-3D MMF

We propose the following *requirements* to guide the development of a next-generation global model, and especially its representations of physical processes: *1) When sufficient computing power is available, the model should be capable of running as a global 3D CSRM, simply by assigning an appropriately small GCM grid spacing. 2) The model should be sufficiently flexible that it can also run in much less expensive modes. 3) The formulation of the model physics should be exactly the same for both options above; in particular, the formulation should be independent of the GCM's grid size, even though the results obtained will depend strongly on the GCM's grid size*. If these requirements are met, the model will converge to a global 3D CSRM. Work towards satisfying these requirements will tend to favor a unification and improved coordination of the community-wide atmospheric modeling enterprise, with enhanced interactions between, e.g., global modelers and cloud modelers. In order to satisfy the requirements, it will be necessary to re-invent the science of global atmospheric modeling. Fig. 2 illustrates our approach. The sketch on the left represents a global CSRM. The sketch on the upper right represents a model with a much coarser grid; such a model will give poor simulations of cloud processes unless it is endowed with a satisfactory cloud parameterization. The sketch on the lower right illustrates an intermediate approach, which is essentially an improved MMF. The improved MMF has an outer, coarse grid, corresponding to the GCM's grid. Along each wall of each coarse grid cell we define a much finer, cloud-resolving mesh. (In most cases, the difference between the coarse and fine grid sizes would be much greater than is shown in the figure.) The fine meshes intersect at the corners of the coarse cells; there are no artificial periodic boundary conditions. Taken together, the fine meshes can represent structures in all three spatial dimensions, but with "gaps" on the scale of the coarse grid. The gaps can be filled by a regression/interpolation technique applied to the fine mesh (Arakawa, 2004). Such methods can be used, for example, to approximate derivatives in the direction normal to

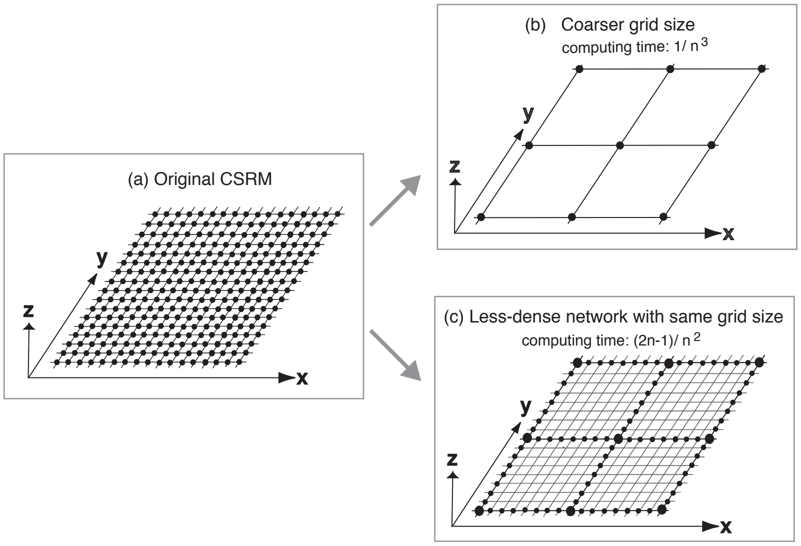

Figure 2: One way to generate a less expensive model from a CSRM (left) is to use coarser grid spacing (top right). Another way is to provide a less-dense network with the same grid spacing and regression/interpolation (bottom right).

each segment of the fine mesh. In this way, the improved MMF can act as a "quasi-3D" model. The embedded CSRM essentially replaces the GCM as far as the thermodynamic fields (including mass) are concerned. The GCM's dynamical core lives on, however, through the *large-scale* wind fields, which continue to be predicted on the coarse outer grid. The CSRM predicts the small-scale structure of the wind field on its high-resolution grid. The horizontal winds predicted by the CSRM are "nudged" towards the large-scale winds predicted on the outer grid. Further discussion is given by Randall et al. (2003 b) and Arakawa (2004). The quasi-3D approach represents a major advance over the 2D approach that has been followed up to now, First of all, 2D is replaced by quasi-3D. Our hypothesis is that the quasi-3D approach will permit a satisfactory simulation of such inherently 3D processes as momentum transport; one of our research goals is to test this hypothesis. Removal of the periodic boundary conditions in the quasi-3D MMF means that convective systems can propagate from one GCM grid column to the next and that the convection simulated by the CSRM is not artificially "squeezed" as the GCM grid cells decrease in size. Because there is no reason to alter the formulation of the embedded CSRM when the GCM's resolution is increased, the formulation of the quasi-3D MMF is independent of the spacing of the outer grid. In addition, with the quasi-3D MMF realistic topographic forcing can be prescribed from data, and used to simulate orographic gravity waves and orographic clouds. Finally, a quasi-3D MMF *converges* in a smooth and natural way to a global CSRM, as the size of the outer grid is refined (Jung and Arakawa, 2004; Arakawa, 2004). We emphasize that no existing GCM has this convergence property. In short, the quasi-3D MMF has the potential to satisfy the three requirements listed above. *We plan to develop, evaluate, and apply a quasi-3D MMF as the central, organizing activity of the proposed research.* The proposed work with the quasi-3D MMF presents an opportunity to interact synergistically with the U.S. Department of Energy's Climate Change Prediction Program (CCPP), which is aimed at the development of improved climate models. The MMAP P.I. is funded by CCPP to develop and demonstrate a new coupled ocean-atmosphere-land surface model based on geodesic grids (derived from the icosahedron; Heikes and Randall, 1995; Ringler and Randall, 2002), and making use of quasi-Lagrangian vertical coordinates for both the atmosphere and ocean. The first version of the new coupled model is nearing completion as this proposal is being written. Plans call for a follow-on version that will make use of the non-hydrostatic equations suitable for use with a CSRM. MMAP will create an MMF based on the new coupled model. In particular, we plan to develop an MMF that makes use of a geodesic grid; obviously such a geodesic quasi-3D MMF will look different from what is shown in Fig. 2, but the basic concept is the same. The geodesic quasi-3D MMF will be a contribution to both MMAP and CCPP.

We expect to complete the geodesic quasi-3D MMF by the end of MMAP's third year. The primary partner institutions for this Milestone are CSU (Jung, Khairoutdinov, Schubert, Randall), UCLA (Arakawa), NCAR (Grabowski, Moeng), and the University of Utah (Krueger).

Task: A global CSRM

It is possible to use a global CSRM today in short simulations, and we can learn a lot by doing so. By 2010, it should be possible to extend such runs to a simulated annual cycle. *We plan to develop a global CSRM early in the work of MMAP*, for two reasons. First, a global CSRM is simpler than an MMF. Many of the technical issues that arise in connection with the MMF are avoided with a global CSRM, most importantly those related to the coupling of the CSRM with the GCM. Second, results obtained with a global CSRM can be compared with those obtained from the second-generation quasi-3D MMF, as discussed above. We expect to complete the global CSRM by the end of MMAP's second year. The primary partner institutions for this Milestone are CSU (Jung, Khairoutdinov, Schubert, Randall), UCLA (Arakawa), NCAR (Grabowski), the University of Utah (Krueger), and the University of Washington (Bretherton).

Milestone 3: Developing improved parameterizations for use in the MMF

Like conventional GCMs, an MMF must include parameterizations of small-scale turbulence and convection, land-surface processes, radiative transfer, and microphysical processes. With conventional parameterizations, errors in the simulated cloud-scale dynamics are the primary factor limiting the realism of the parameterized cloud processes. With the MMF, *errors in the simulated microphysical and turbulent processes emerge as the primary limiting factors*. This is an interesting shift in the conceptual landscape.

Task: Turbulence

With its coarse horizontal grid spacing (4 km), the current prototype MMF cannot resolve most boundary layer cloud processes, and as a result it does not adequately simulate the global radiative effects of boundary layer clouds. It also cannot resolve stable or most dry convective boundary layers over land and ice. For these reasons, the parameterization of turbulence and small-scale convection is an important component of the MMF, just as it is in a conventional GCM. Our initial focus will be on the marine stratocumulus regime and its transition to the trade-wind cumulus regime; both are crucial for climate. Because of its relatively high resolution, the MMF should permit parameterizations of shallow convection and turbulence that are more robust than those used in conventional GCMs. Radiation, cloud, and turbulence are all parameterized within the same framework, so their interactions and feedback are more direct than those in the traditional GCMs. These interactions are particularly important for the stratocumulus-topped PBL where the major driving force for turbulence is cloud-top radiation. The amount of cloud-top radiation depends strongly on the cloud amount and the cloud amount in turn depends strongly on turbulence (i.e., through transport and entrainment processes). We will explore how these PBL cloud processes can be represented within the MMF. Initial work will explore multiple alternative approaches including higher-order closure (Krueger, 1988; Cheng and Xu, 2004), a bulk approach with an explicit boundary-layer top and multiple layers within the boundary layer (Lappen and Randall, 2001), a "mini-LES," and ODT. The mini-LES would explicitly represent boundary-layer turbulence using a grid with ~100 m horizontal spacing and a vertical grid spacing of ~25 m. Thus the vertical grid would be considerably finer in the lower troposphere than that of the host GCM. Probably only 2D is practical, with 32 to 64 points in the horizontal. At least in the initial version, the mini-LES and the CSRM would communicate only through the GCM's grid-mean quantities. ODT, mentioned earlier in the proposal, is essentially a 1D LES, and would be configured similarly. We also recognize the need to parameterize turbulence and small-scale convection above the boundary layer, e.g., in upper-tropospheric cloud systems.

The relevant partners for this task are NCAR (Moeng), CSU (Randall, Lappen, Schubert), UW (Bretherton), UU (Krueger), and UCLA (Arakawa, Stevens). We will also benefit from a collaboration with LaRC (Xu).

Task: Land surface and the carbon cycle

One potential benefit of the MMF is that heterogeneous vegetation, terrain, soil moisture, clouds, radiation, and precipitation will interact on small scales, as they do in the real world. For example, heavy precipitation may fall on only a small fraction of a large GCM grid cell, but in many conventional GCMs its effect on soil moisture is "diluted" across the whole cell. We will explore the impacts of small-scale topographic and surface type variation on the simulation through their effects on driving small-scale circulations that interact with the PBL. This can be true even over the ocean; an example is convective plumes generated by openings in sea ice (Zulauf and Krueger, 2003). Among the most important interactions between the atmosphere and the land surface are those involving the flow of carbon through the carbon system. Roughly half of current anthropogenic CO_2 emissions are removed from the atmosphere by "sinks" in the oceans and on land. The locations, mechanisms, and futures of these sinks are inadequately understood. The U.S. Climate Change Research Initiative has identified carbon cycle research as one of the highest priority areas for near-term acceleration. Sources and sinks of CO_2 are being explored through inverse modeling of tracer transport. Uncertainties in the parameterized small-scale vertical mass fluxes used in tracer transport models are a leading cause of uncertainty in these calculations (Gurney et al., 2002, 2003). A huge new effort to measure atmospheric CO_2 is being planned for deployment by the middle of this decade. The utility of these observations for inverse modeling will be limited by the realism of the atmospheric transport models used. Finally, improved representations of surface-atmosphere interactions can help improve models of key aerosol sources such as wind-blown dust, sea salt, and biogenic emissions. The MMF provides a unique opportunity to link models of surface climate, biogeochemistry, clouds, precipitation, atmospheric transport, and CO_2 mixing ratios at their native scales of heterogeneity. The relevant partners for this task are CSU (Denning, Randall, Lappen, Kreidenweis), NCAR (Moeng, Collins), and UCLA (Arakawa, Stevens).

Task: Radiation

The MMF provides an opportunity to explore cloud-radiation interactions that cannot be examined with conventional GCMs. One important area that research using the MMF will advance concerns the current problem in GCMs of representing subgrid-scale variability that is above and beyond layer cloud fraction. For example, conventional GCMs treat the vertical variation of cloud overlap entirely empirically yet these empirical methods are known to produce biases in modeled radiation budgets. Similarly, horizontal variability of cloud within a GCM grid box is either neglected entirely or treated with simple, highly idealized methods (Oreopoulos and Barker 1999; Cairns et al. 2000). Either way, significant biases are introduced into modeled energy budgets. The MMF overcomes these problems by resolving vertical and horizontal variability directly. In current MMF simulations, cloud-scale variability and its effects on radiation provide important feedbacks on the global distribution of clouds that fundamentally altering these distributions. Thus the MMF provides frameworks not only for evaluating the global effects of these gross empirical parameterizations, but also for better representing these effects in global models.

Initial work on radiative transfer will focus on the quality of radiation codes used in the MMF and upgrading the MMF's treatment of radiative transfer from one-dimensional to three-dimensional. The MMF's current radiation codes will undergo offline assessment using benchmark results from recent and planned model intercomparison studies (e.g., Barker et al., 2003). If need be, the gaseous transmittance and particulate optical property parameterizations will be improved. Currently, the MMF employs the Independent Column Approximation (ICA) to handle atmospheric radiative transfer. With the ICA, a 1D radiative transfer solver is applied to each CSRM column. Heating rates are computed for each CSRM cell, and domain average fluxes are obtained by horizontal averaging the independent column results. Although differences between domain averages computed by ICA and a 3D solver are often small, studies with offline models show that differences in local heating rates can be quite large (e.g., O'Hirok and Gautier 1998). Since our work to date has shown that cloud-scale fluctuations in radiative heating can be quite important for the global distribution of cloudiness (Cole et al., 2004), we plan to conduct experiments with 3D radiative transfer in the MMF.

The MMF also provides the opportunity to explore other cloud-scale radiation interactions, including those associated with cloud-scale variations in cloud droplet size, hydrometeor type, aerosol, and surface albedo. None of these interactions are addressed by existing conventional GCM radiation schemes. Moreover, explicit inclusion of these interactions contributes directly to other MMAP tasks such as those involving land surface and aerosol processes.

Major progress towards this Milestone will occur by the end of the second year of funding. The primary partner institutions for this task are CSU (Stephens), NCAR (Collins), and the Meteorological Service of Canada (Barker).

Task: Microphysics and aerosols

Microphysical processes in clouds include drop and crystal formation, growth, and evolution into precipitation. GCMs and many CSRMs currently represent cloud microphysical processes with overly simple parameterizations. For example, although warm cloud radiative properties and the initiation of precipitation are affected by the droplet size spectrum, many microphysics parameterizations do not predict the shape of the spectrum but rather make an assumption about it based on another variable such as liquid water content. Drizzle production and autoconversion to rain are critical processes that are currently poorly described in large-scale models. In the era of the MMF, there is a need for improved, physically based parameterizations of aerosol-cloud-radiation interactions that can capture the actual response of the climate system to changes in warm and cold clouds. Fortunately, the MMF is well suited to the parameterization of microphysical processes -- much more so than conventional parameterizations. For example, cloud-scale vertical velocities can be a key input parameter for a microphysics parameterization; the MMF can simulate these, while conventional parameterizations can provide (at best) only crude estimates. Further, the MMF is a unique tool for uncovering, understanding, and fixing problems with microphysical parameterizations because its output is more compatible with the in situ cloud-scale observations, as discussed further under Milestone 4.

Clouds are nucleated on atmospheric particles, and thus it is reasonable to expect that changes in the atmospheric aerosol will propagate to changes in clouds. Indeed, due in part to the field studies carried out by an earlier NSF Science and Technology Center, the Center for Clouds, Chemistry, and Climate (C4), it is now accepted that aerosols play a significant role in climate dynamics (e.g., Ackerman et al., 2000). Aerosol impacts are generally discussed in terms of the so-called direct and indirect radiative effects. Here “direct” refers to the interactions of particulate matter with solar radiation, and “indirect” refers to the influence of aerosols on the microphysical and radiative properties of the clouds. In the past decade, the magnitude of global forcing due to aerosols has been estimated, as discussed by Houghton et al. (2001), who rate our understanding of aerosol-related climate effects, and especially the indirect effects, as low. Comprehensive simulations of global aerosol indirect effects lie outside the scope of MMAP’s work. Nevertheless, the MMF will represent the most advanced tool for making such assessments, and it is reasonable to expect that at a future time it will applied to this important problem. Because of this anticipated application, it is appropriate that MMAP’s microphysical models be designed so that they can be linked to global aerosol models, i.e., they should be able to respond realistically to variations in the aerosols available for warm and cold cloud formation. MMAP's focus will be on developing methods to use the most recent findings on the relationships among aerosol and cloud particles and cloud radiative properties, including the findings from C4, ACE-I, ACE-II, Ace-Asia, and other experiments. MMAP's emphasis on developing improved microphysics parameterizations for the MMF represents a natural historical link to C4. The first priority under this task will be with the parameterization of cold-cloud microphysics. This is where current parameterizations are weakest, and where the greatest potential payoff lies. Upper-tropospheric clouds, and particularly cirrus, play a major role in regulating the planetary radiation budget (Ackerman et al., 1988; Hartmann, 1993). Existing parameterizations of ice nucleation are based on sparse data obtained up to the early 1990s and must be updated on the basis of a dramatically enhanced data base from laboratory studies and several recent field campaigns (e.g., SUCCESS, CRYSTAL-FACE, SPIN). Further, current models for predicting heterogeneous ice nuclei (IN) concentrations assume an infinite supply of particles, whereas field experiments have clearly shown regions of significant depletion of IN. The new parameterization must be able to respond to such aerosol data if it were provided by a fully coupled aerosol model (although during MMAP, we will use a simplified treatment of aerosols). The next priority task will be to include and test multi-moment schemes (e.g., prognostic mass and number concentrations) for all or most hydrometeors; some (but not all) of these are already in place in the current CSRM. We expect to complete changes to the water and ice cloud microphysical schemes by the end of MMAP's second year, although modifications will continue through MMAP's lifetime as new information emerges from the many ongoing and upcoming field campaigns that address aerosol and cloud microphysics (e.g., ABC; AMMA, RICO, and a major ARM-sponsored experiment to be conducted in northern Australia in early 2006). To fully exercise the new microphysics parameterization, we will need realistic assumptions about the global distributions of key natural and anthropogenic aerosols. MMAP partner NCAR can provide estimates based on their detailed models of sulfur-derived, sea salt, and dust particles. Most importantly, for the first time, it will be possible to evaluate our model results against collocated vertical profiles of aerosols and cloud ice, which will be provided by the Calipso and CloudSat (Stephens et al. 2002) satellite missions that are planned for launch in early 2005.

The relevant partners for this task are CSU (Kreidenweis, P. DeMott, Fowler), NCAR (Heymsfield, Grabowski, Collins), UU (Krueger), and U MD (Tao).

Milestone 4: The evaluation and interpretation of MMF results using emerging datasets

Comparison of model results with observations is a key element of MMAP's research. Because the MMF incorporates a CSRM, it is possible to compare MMF results with cloud-scale observations, at least in a statistical sense. For this reason, MMAP has an unprecedented opportunity to make use of field data and high-resolution satellite data, and also to entrain the expertise of field observers and cloud modelers, who in the past have not always participated in global model evaluations. Our multi-faceted model-evaluation strategy is based in part on synergistic relationships facilitated by MMAP's well-connected investigators.

The MMF will be evaluated in part by the use of emerging satellite data. NASA is funding CloudSat, which will carry a cloud radar into orbit in 2005, the same year that MMAP will begin its work. The CloudSat P.I. is Prof. Graeme Stephens of CSU, a MMAP scientist. CloudSat will produce data on mesoscale and microscale cloud variability, which can be simulated by the MMF but not with conventional GCMs. MMAP will use CloudSat data as a key resource for the evaluation of MMF results. In addition, several MMAP investigators including Prof. Christian Kummerow of CSU are actively involved in the Tropical Precipitation Mapping Mission (TRMM), and its successor the Global Precipitation Measurement Mission (GPM). MMAP investigators are very actively participating in the GPM Science Team and the GPM Science Steering Committee, and are driving the GPM Ground Validation Project, which will provide observations, including radar data, that are ideally suited for the evaluation of CSRMs. Finally, MMAP has established a collaboration with the Goddard Institute for Space Studies, in order to facilitate the use of global cloud and radiation data from the International Satellite Cloud Climatology Project (ISCCP) for the evaluation of the MMF and conventional parameterizations.

The use of global satellite-based data sets for such an evaluation is complicated by a number of factors, including the fundamentally different resolutions of the two different types of data. Most GCMs and even mesoscale models represent scales that are far coarser than the scale of the observations. This is particularly troublesome when it comes to evaluating clouds since the difference in scales is so great that all that can be done is gross statistical comparisons that prevent any evaluation of the key cloud-scale processes. A second complication derives from the very nature of retrieval methods applied to satellite data. In some cases, such as with estimates of precipitation or upper-tropospheric water vapor, the retrievals are heavily constrained to a priori sources of data (L'Ecuyer and Stephens, 2002). As a result, the retrieved data have poorly understood error characteristics that limit their usability. Because it represents cloud–scale processes explicitly, the MMF overcomes these problems and opens up entirely new possibilities for using existing data in model evaluation. The MMF can simulate the statistics of the satellite observations directly, overcoming many of the existing interpretation problems associated with retrieved products. To address key processes that link convection, layered cloudiness and upper tropospheric humidity, we propose to develop a series of observing-system simulators, including: infrared radiance simulators that will provide a means of comparing the upper tropospheric water vapor radiances observed by operational satellites with simulated radiances; microwave radiance simulators for comparison of MMF results with TRMM measurements; and radar reflectivity simulators that will permit comparisons of MMF results with both TRMM and CloudSat data. An ISCCP simulator currently exists, and has already been incorporated into the prototype MMF.

For the past several years, the Atmospheric Radiation Measurements (ARM) Program sponsored by the U.S. Department of Energy has funded research on the MMF. This will continue under MMAP. As a result of the pioneering work of ARM, there now exists a world-wide network of three ARM sites and half a dozen more ARM-like ground-based sites that acquire cloud, aerosol and radiation data on a continuous basis. These sites employ simultaneous observations by lidar, radar, and a suite of radiometers. The principal goal of the ARM program has always been to improve the treatment of clouds and radiation in global climate models. To date, steps toward this goal have occurred largely indirectly. The MMF promises to improve this situation substantially. First of all, MMF output from a single CSRM cell can be collected and analyzed statistically to compare with observed statistics including diurnal, seasonal, and interannual variability. The goal is to evaluate how well the CSRM predicts the observed statistics, in order to identify specific modeling problems and their causes. In a second approach, clustering algorithms can be applied to large scale fields from both the real world and the MMF to identify similar dynamical systems. We can then analyze the cluster properties in both domains in terms of both probability distribution functions and the temporal evolution of system properties. This approach has been applied to month-long CSRM simulations (Luo et al. 2003). The goal again is to provide a quantitative assessment of the ability of the embedded CSRMs to simulate the observed PDFs and the temporal and spatial evolution of real cloud systems.

The coupling of high-resolution satellite data with the ground based data will be critically important for such analyses. Polar-orbiting satellites provide high spatial resolution but poor temporal resolution, while the ARM-like stations provide the inverse. Coupling the two sets of observations will permit a critical evaluation of MMF cloud properties and assessment of their fidelity to actual cloud properties. More importantly, these data sets can be used to understand the physical causes of poor simulations, as opposed to the current situation where we know there are problems with parameterizations but often cannot diagnose the causes (e.g., Luo and Krueger, 2004). The Climate Physics Group at PNNL will apply its considerable expertise in the analysis of data from both ARM and the NASA MISR and MODIS sensors. The group is currently using ARM data to evaluate simulations of cloud properties by the MMF and the standard CAM. A focus of the PNNL work will be the dependence of the MMF results on the grid size of the embedded CSRM. Ground-based remote sensing data also provides precipitation measurements at cloud-scale resolution. For example, over the U.S,. hourly gridded (4 km x 4 km) precipitation is estimated operationally from a combination of WSR-88D Nexrad radar precipitation algorithms and raingauge reports. On the research side, the NASA Global Precipitation Mission (GPM) Ground Validation Project will provide an unprecedented opportunity to evaluate results produced by the MMF at two "supersites:" Kwajalein, and ARM's Southern Great Plains (SGP) site. The SGP supersite will be directed by MMAP scientist Steven Rutledge of CSU. It will generate detailed observations of clouds and precipitation from a suite of passive and active remote sensing instruments including both cloud and precipitation radars with full polarimetric capabilities, yielding time-continuous measurements of the vertical profiles of hydrometeor type, particle size distributions, and mixing ratios, among other quantities, for a spectrum of warm and cool season precipitation events. The data will be made available to MMAP for use in model evaluation. We also expect to have access to similar data the Kwajalein supersite.

The MMF will also be evaluated by using it as a weather forecasting model. The initial conditions will be based on operational numerical weather prediction (NWP) analyses and run forward to produce forecasts over a few days. When the MMF is run in forecast mode, the results can be evaluated based in part on the use of point measurements such as those made at the ARM sites, and using the probabilistic methods developed for ensemble forecasting systems. Probabilistic evaluation, including the assessment of height-dependent errors in the amount and timing of cloud condensate, makes nearly optimal use of the high-frequency observations made at fixed ground sites, such as the ARM sites. Our specific plan is to test the MMF using the CCPP-ARM Parameterization Testbed (CAPT), which has been developed by LLNL and NCAR and supported by ARM and CCPP. This work has already begun.

The deficiencies of a global atmospheric model become particularly apparent when it is coupled to an ocean model. We therefore plan to place special emphasis on the analysis of coupled simulations with the MMF. The results will of course be evaluated by comparisons with a variety of observations. As the integration time of the coupled ocean-atmosphere simulations will be limited to a few simulated years at most, we must focus on upper-ocean phenomena. Three types of coupled problems seem interesting for investigating the performance of the MMF. In each case, the procedure is to start from an equilibrated solution of the coupled ocean-atmosphere model (without the MMF) and then perform a short integration to study the adjustment of surface properties (e.g. sea-surface temperature (SST), sea-surface salinity (SSS), and heat and freshwater fluxes) when the ocean model is coupled to the MMF. Issues that can be addressed include: the errors still found in non-flux adjusted coupled climate models (such as HadCM3, OPA-ARPEGE and the CCSM) in the time mean SST field; the annual cycle in the Pacific and in particular on the problems current coupled GCMs still have with the migration and spatial pattern of the ITCZ; the western warm pool; heat fluxes in summer over western boundary currents, regions of upwelling, and deepwater formation.

Model-evaluation will be ongoing throughout the lifetime of MMAP. The primary partner institutions will be CSU (Stephens, Kummerow, Rutledge, Dijkstra), HU (McCormick), LLNL (Duffy, Cederwall, Potter), PNNL (Ackerman, Ghan), Columbia University (Rossow), the University of Maryland (Tao), UCLA (Stevens), UW (Bretherton), and UU (Krueger). We will also benefit from collaborations with LaRC (Xu, Wielicki).

Milestone 5: Continuing development of conventional parameterizations

The MMF will supplement but not replace conventional parameterizations. *Conventional parameterizations will always be needed as "encapsulations" of our (gradually improving) understanding of how clouds interact with the large-scale circulation*. Research on conventional parameterizations will progress more rapidly because of what is learned from research with the MMF. We envision a new era in which conventional parameterizations and MMFs will be developed and applied in parallel. MMAP will devote considerable effort to the improvement of conventional parameterizations, using MMF-based research as a guide. MMAP scientists will devise numerical experiments that will provide a basis for new traditional parameterizations. As discussed earlier, we have already seen this happening with the prototype MMF in connection with cloud-radiation interactions and convective momentum transport. CSRMs are already being used profitably in the development and evaluation of traditional parameterizations for large-scale models (e.g., Randall et al, 2003 a), but the MMF activity can go much further because the simulations will be longer, cover a wider range of large-scale conditions, and include on the large-scale weather systems. Finally, the MMF will provide information about the relative frequencies of large-scale regimes and small-scale behaviors.

The representation of convection is one of the most complex and problematic parameterizations in conventional GCMs. Most convection parameterizations represent the vertical transport of material by narrow, intense up- and down-drafts. The relationships between the large-scale state and the convection are based on a mixture of theoretical insight and empirical evidence. Almost all GCMs have difficulty simulating the short-term, small-scale convectively driven variability observed in the atmosphere. The MMF provide detailed information on the range of ways convection responds to identical large-scale weather systems. Traditional parameterizations can then be modified to include a stochastic component, which is naturally a part of the MMF. This might entail making the parameterized convection prognostic, as it is in the MMF. Introducing stochasticity into the parameterized interactions of convection with the large-scale environment may well improve simulations of small-scale variability (e.g., Lin and Neelin, 2002).

The development of conventional parameterizations will continue throughout the lifetime of MMAP. The primary partners involved will be CSU (Randall, Fowler, Lappen, Stephens), UCLA (Arakawa, Stevens), UW (Bretherton), CU (Pincus), and NCAR (Hack, Collins). We will also have the participation of collaborator Leo Donner of GFDL.

The computational side of MMAP

Task: Cycles and their efficient use

In early (2001) tests, the prototype MMF consumed 20 wall-clock days per simulated year on 64 processors of NCAR's IBM-SP "Blackforest." Later we obtained 1.5 wall-clock days per simulated year using 512 processors of NCAR's newer, faster IBM-SP "Bluesky." Most recently, through collaborative work using our NPACI Strategic Application Collaboration (SAC) effort, we have found even slightly better performance on SDSC's IBM-SP "Blue Horizon," due to the lower contention on the 8-way nodes of this machine. We have also achieved nearly linear scaling out to 1024 processors on the "Seaborg" machine at NERSC. These real-world benchmarks show that the MMF scales very well out to approximately 1000 processors, and that even on today's machines it would be (just barely) feasible to use it for a century-long climate-change simulation. From a societal point of view, the high cost of such a simulation would not be out of line with the importance of the climate change problem.

For planning purposes, we assume that in the first year our computing requirements will be the equivalent of 100 simulated years with the current MMF (2005-2006), increasing in the fifth year (2009-2010) to the equivalent of 1000 simulated years with the current MMF. This ten-fold increase in five years is roughly consistent with Moore's Law. To put the numbers in perspective, running 100 simulated years on NCAR's Bluesky would require about 17% of the total machine resource that is available in the course of a year. It is therefore clear that MMAP will have to spread its work over multiple platforms. By taking advantage of MMAP's proposed NSF sponsorship and its partnerships and collaborations with other institutions, we plan to make use of super-computer resources accessible through seven sites, including two NSF sites, three DOE sites, and two NASA sites. We also plan to run the MMF on a modest compute-server budgeted for installation at CSU.

Because MMAP will use large computing resources, it is obliged to ensure that its codes make particularly efficient use of those resources. Various issues arise: To what extent is interprocessor communication a bottleneck with an MMF that uses the quasi-3D approach? How can MMAP take optimal advantage of emerging hardware and software technologies? How can we couple an MMF with an ocean model, a land-surface model, and a sea ice model? Will the coupling represent a computational bottleneck? These issues will be explored by MMAP partners SDSC, NCAR, LLNL, and PNNL, with assistance from MMAP collaborator IBM (Abeles). Although IBM is not formally cost-sharing, it plans to contribute the expertise and resources of IBM Research's Deep Computing Weather Modeling Group, IBM's Advanced Computing Technology Center for application optimization tools and expertise, and IBM Systems' Deep Computing technical support team. MMAP will also be able to utilize IBM's benchmarking center for testing.

Task: Exploring modeling trade-offs

A major increase in computer resources can be used to move from a conventional low-resolution GCM to an MMF, or it can be used to increase the resolution of the conventional GCM. What are the trade-offs? What is the optimal GCM resolution for use with an MMF? What is the optimal resolution of the CSRM used in an MMF? The answers to these and related questions almost certainly differ depending on whether the application is climate simulation or numerical weather prediction. In order to obtain objective and quantitative answers, MMAP will define new and/or adapt existing metrics of climate simulation quality. MMAP will also carry out a systematic program of numerical experimentation, to obtain the needed empirical data. The lead partners on this work will be LLNL (Duffy) and CSU (Randall, Khairoutdinov).

Task: Data management over high-speed networks

What is the best way to record the simulation produced using an MMF? For example, to what extent is it practical to write out the high-resolution cloud fields simulated by the CSRM in each GCM grid cell? Simple estimates show that a detailed record of a simulation can add up to hundreds of terabytes per simulated year, which is not currently feasible. Various sub-sampling strategies can reduce this number to on the order of one terabyte per year, which is still quite large. The results of a simulation performed with the MMF must be accessed by MMAP scientists at many different sites. How can the data be efficiently distributed to the team members? There are trade-offs between moving the data and processing it locally where it is produced (Helly and Elvins et al., 1999, 2002), and these will be analyzed as we develop a data distribution and analysis system designed to support MMAP research. This work, which will be led by SDSC, will take advantage of emerging high-speed network technologies (e.g., Earth Systems Grid, GEON, Teragrid) to facilitate sharing of model results and observations among the various MMAP investigators. The NSF-sponsored Distributed Terascale Facility, also called the TeraGrid, which is a component of the U.S. National Information Technology Infrastructure, will link together many teraflops of computing power, approximately a petabyte of data, multiple high-resolution visualization environments, and toolkits for grid computing at 40 gigabits per second. We will adapt the data publishing approaches that we have developed under other funding, withe the goal of creating a consistent framework that ensures interoperability across the NSF Geosciences programs (GEON, CUAHSI, CHRONOS). We are also collaborating with the Earth Systems Grid project, through our partnership with NCAR (Middleton), to ensure that our data management approach is interoperable across the NSF, DOE, and NASA cyberinfrastructure efforts.

Task: Visualization

MMAP will require new visualization packages designed to facilitate analysis of both the global circulation and the embedded cloud systems. Visualization will be the focus of development work led by SDSC (Helly) and NCAR (Middleton). In addition, Apple Computer (Ackman) has agreed to enter into a partnership with MMAP, and is providing cost-sharing in the form of complimentary access to programming tools and training for MMAP staff. These resources will be useful particularly for the creation of visualization tools.

MMAP's national and international impacts

MMAP's research will transform the science of global atmospheric modeling by creating a major new research pathway based on the MMF. The most important consequence of this will be more rapid progress towards more reliable simulations of future anthropogenic climate change, in support of national and international scientific goals and policy decision-making. MMAP will create new modeling tools that will be at the forefront of climate change research. It will also lead to better weather forecasts. Finally, MMAP will bring about an increased degree of interaction among scientists working in the several sub-disciplines that revolve around the central problem of the role of atmospheric processes in climate. Because MMAP draws its scientific talent from many U.S. and international modeling centers, MMAP research will immediately and naturally influence the ongoing work at those centers.

4.d Narrative description of the Education and Human Resource Development Objectives

A vigorous effort in education and human resources development will play a crucial role in the proposed Center. We envision an integrated effort including educational media development, teacher training, service learning, and instructional activities for grades K-12; enhancements to undergraduate and graduate-level academic programs; and public outreach and education. Each component of our education and outreach activities will include assessment of outcomes. The proposed effort is comprehensive and vertically integrated, and complements activities described below under "Diversity." We plan to develop, implement, and evaluate innovative educational resources and activities in partnership with local and regional schools and institutions, and disseminate them through the peer-reviewed literature, national educational media, and professional organizations. To achieve the goals of the Center, MMAP will partner with a number of very mature and well-established education and outreach programs and institutions that are nationally recognized. Vertical integration of the proposed activities will be enhanced by "cross-training" of scientists across academic levels of the program.

The objectives of the education component of the Center are (1) to enhance the capability of local public school districts to teach science, especially in the areas of weather and climate; (2) to improve academic course offerings related to weather and climate at the undergraduate level at Colorado State University and Colorado College; (3) to enhance graduate education in climate studies at Colorado State University; (4) to enhance public awareness and understanding of climate issues. Recruiting excellent new scientists to work in climate science requires developing an interested, diverse, and well-informed "pipeline" of excellent students at all levels. Weather and climate issues affect every person, and citizens are increasingly called upon to vote on political issues that involve some understanding of the functioning of the Earth system, so we address the needs of K-12 education and public outreach.

MMAP will sponsor scholarly research to formally assess the performance of the K-12 curriculum development, education, and outreach component under the direction of Prof. Michael Lacy, of the CSU sociology department, assisted by a social or behavioral science graduate research assistant. Other education and outreach activities will be evaluated through traditional student evaluation surveys. These data, along with annual participation information for each component, will be provided to NSF in annual reports. The aim of our outcomes assessment work will be to conduct studies that are more rigorous and publication-oriented than what typifies routine evaluations of educational outreach activities. We wish 1) to obtain defensible and measurable assessments of educational outcomes as they affect student learning, rather than to simply obtain "consumer" judgments of whether a particular educational experience was "liked" by teachers and students; and 2) to maintain the randomized controlled trial of an educational intervention as the research design standard to be used whenever feasible, and to be retained as a regulative ideal regardless of perfect feasibility.

An important concept for integrating the education and outreach efforts of MMAP is vertical integration. Each component of the proposed Center will help to sustain the rest through participation of senior personnel in the training and education of junior levels. Atmospheric Science graduate students, for example, will participate in teaching the weather and climate course to K-12 teachers, and will assist in the development of curricular materials and videos. Undergraduate students at CSU will perform "service learning" outreach to support teachers in K-12 classrooms and assist in development and delivery of LSOP materials and demonstrations. High school students will assist in the development and evaluation of enhanced FOSS (Full Option Science System) kits for elementary and junior high school levels. This vertically integrated program will encourage fresh and stimulating presentation of the science, provide mentoring to younger science students, and build confidence and skills for older students.

Curriculum Development and Teacher Training for K-12 Education

The presentation of science as a dynamic, creative, and fascinating endeavor is key to recruitment and retention of potential young scientists. High-quality science education at the K-12 levels is also an important ingredient in redressing the current chronic under-representation of women in science. Weather and climate are experienced by everyone, so excellent science education in these fields can spark young students' interest in science, potentially improving recruitment of such students to broader science fields. Locally-developed programs will be disseminated nationally via the Little Shop of Physics (LSOP) and its companion television program, "Everyday Science," through the UCAR Web Weather for Kids and SEE-ME resources, and through publications in the scholarly literature and presentations at national conferences for educators and scientists.

The Colorado Department of Education Standards for Science mandate that "Students know and understand the general characteristics of the atmosphere and fundamental processes of weather." (CDE Standards, 4.2). Among other outcomes, by the 12th grade, students are required to "analyz[e] the structure of, and changes in, the atmosphere, and its significance for life on Earth; describ[e] how energy transfer within the atmosphere influences weather; and [explain] interrelationships between the circulation of oceans and weather and climate." Successful implementation of these standards requires science teachers to be well educated about weather and climate, and knowledgeable about how to utilize well-developed curricula and materials at the grade levels they teach. Current FOSS kits for teaching weather and climate in local K-12 classrooms are rudimentary, and few teachers have a strong background in atmospheric science. MMAP will assist local and regional school districts in meeting state standards in atmospheric science by developing enhanced weather and climate "kits" for use in schools, by offering a course in weather and climate for K-12 teachers, and by delivering innovative science content in person, by television, and on the World Wide Web.

LSOP is a very well-established, nationally-recognized outreach program of the Physics Department at CSU. It creatively and effectively introduces science to K-12 students and teachers through interactive, hands-on school visits, teacher workshops, a course for future science teachers, a television program called "Everyday Science," and associated hands-on instructional activities. LSOP currently reaches over 15,000 students at 50 schools around the region each year, and has conducted science teacher workshops across the U.S. and in Belize, Chile, Azerbaijan, and Ethiopia. LSOP will work with MMAP researchers to develop MMAP-related episodes of Everyday Science, with accompanying instructional materials and new in-class demonstrations and hands-on activities closely tied to science content standards. These resources will be provided to teachers in the local area and around the state (as well as nationally and internationally) through LSOP workshops, and will be available on DVD as part of independent supplements to the FOSS kits for science education. Materials from the workshops (and episodes of Everyday Science) will also form the core of training for pre-service teachers, who will use these materials in classroom presentations in area schools. Using MMAP funding, LSOP will hire a Teacher in Residence from the local Poudre School District to assist with the development of appropriate instructional materials and the training of future teachers. Having an active local science teacher on staff will help to target efforts where they will be most effective. LSOP will also use MMAP funding to hire student interns who will present school programs and assist in the development of episodes of Everyday Science. In all programs, LSOP will continue to place special emphasis on schools with large populations of students underrepresented in science fields. CSU students will be recruited as volunteers to assist with all LSOP activities.

As a basis for the LSOP and other K-12 educational efforts, an initial survey of Colorado K-12 teachers is proposed to better understand the amount and kinds of materials, content, and delivery that would be most useful to them. A series of studies will then be conducted of each of LSOP's major products, namely 1) educational television programs, 2) instructional materials to accompany those programs, and 3) hands-on LSOP experiments for K-12 school students. The goal with these studies is to adhere to randomized factorial designs, recognizing that with limited resources it may not always be possible to meet this standard. Nevertheless, the goal is to provide defensible quantitative assessment that maintains the randomized controlled trial as a regulative ideal. For example, with the television programs, a study of initial interest would entail estimating the size and characteristics of the population of children that actually watches these programs on an informal, at-home, free choice basis. We will investigate whether students who watch such programs actually experience demonstrable educational gains in both knowledge level and degree of interest in scientific topics. We also would examine their effectiveness when used by teachers as formal classroom teaching supplements. Our studies would encompass, as possible, an examination of whether these materials are comparably effective for different kinds of students (girls vs. boys, children of color vs. white/Anglos). Educational trials will be conducted for the instructional materials developed to accompany the videos. A topic of central interest would be whether and how educational outcomes among children vary according to whether their teachers used these instructional supplements. For example, are there synergistic (non-additive) effects of the instructional materials when used in combination with the television programs (videos)? We will also conduct a study of the functioning and effectiveness of the new hands-on experiments used in the LSOP traveling program. As an example of our evaluation efforts here, we will investigate whether children who are exposed to such experiments actually learn more than children who are taught without them. From such an initial base, our studies will expand toward determining what design features of such experiments, and what ways of using them, are most educationally effective. LSOP has over a decade of positive experience interacting with local and regional school districts. Rigorous evaluation of the program will be facilitated by LSOP's long-standing contacts around the state, and by the presence of a local science teacher on the MMAP staff.

MMAP will also partner with the UCAR Office of Education and Outreach to develop a freely available Web-based educational tool called "SEE-ME," as well as supporting instructional materials. SEE-ME will enable students and the public to visualize the role of clouds as they interact with and influence Earth's climate. UCAR's instructional designer/web designer and K-12 instructional specialist will establish an educational design for SEE-ME, in collaboration with MMAP scientists and K-12 educators. At this time, there is no known interactive electronic medium enabling educational communities to learn how data about the variability and chemistry of cloud cover can influence a range of scenarios in climate study and climate change prediction. SEE-ME will develop such a tool, including background information, instructional and assessment materials, and a CD and web site for its dissemination. SEE-ME will be prototyped and field-tested in classrooms, and evaluated by educators. In particular, Dave Swartz and Derek Widmier of Rocky Mountain High School (of the Poudre School District in Fort Collins, CO) will take an active role in the design, classroom-testing and evaluation of SEE-ME. The instructional materials will establish standards, themes, and benchmarks to be attained.

SEE-ME will be refined as feedback is received from the classrooms. Broad dissemination will occur through the UCAR and NCAR Web sites, including Windows to the Universe and Web Weather for Kids. These web sites already serve an average of about 435,000 users per month, with an average of 55 minutes per visit, and are currently being translated into Spanish. SEE-ME will be entered into the Digital Library for Earth System Education and the National Science Digital Library. SEE-ME and its related educational materials will also be presented in education sessions at meetings of professional organizations such as the National Science Teachers Association, American Meteorological Society, and the American Geophysical Union. Assessment activities through UCAR will include reporting on the numbers and types of users and methodologies of use of these resources.

Working with the CSU College of Education, CSU will offer a one-week summer course for college credit in weather and climate for K-12 science teachers. The course will be developed under the supervision of Prof. Scott Denning in the CSU Department of Atmospheric Science, and will be taught in conjunction with current graduate students in the Department. Professional-level content development will complement deep on-staff expertise in teacher training. Brian Jones of LSOP has worked with regional science teachers for over a decade, and the UCAR-EO office offers workshops in Boulder and at national conferences which currently train over 800 teachers per year. The LSOP Teacher in Residence and the UCAR Teacher on Special Assignment will offer expertise in real application of K-12 science curricula in local schools. The course will include a comprehensive introduction to the physics of the climate system, emphasizing global energy and water cycling, and an overview of the mechanisms responsible for local and regional weather phenomena. In addition, it will include "hands-on" demonstrations of important concepts (e.g., convection, latent heating, vorticity) appropriate for K-12 classroom use. Tuition for the one-credit course will be paid for participating teachers from MMAP funds. The course will be offered twice per summer, with space for up to 20 teachers per 30-hour session. Evaluation of this course will focus on metrics of student performance in weather and climate modules offered by teachers that have and have not taken the course, as well as tracking participation and penetration across local school districts.

Human Resources Development at the Undergraduate Level

Under MMAP sponsorship, CSU's Department of Physics will develop two new courses aimed at introducing their undergraduate majors to the scientific issues under study by MMAP. These courses will be developed in consultation with faculty in CSU's Atmospheric Science Department. It is our hope that the courses and summer internships will stimulate some of the undergraduate Physics majors to pursue graduate education in Atmospheric Science. MMAP will also fund a post-doc who will conduct research supervised cooperatively by faculty from CSU Physics and CSU Atmospheric Science. Our intention is that this will lead to increased research collaborations among the departments involved.

MMAP will also partner with Colorado College (CC), a traditional undergraduate institution located in Colorado Springs. One of our goals is to attract a number of CC's high-quality undergraduates into graduate education in Atmospheric Science. CC is an institution emphasizing cross-disciplinary education of really excellent students, and is expected to serve as a potential source of high-quality graduate students in climate sciences. Professor Howard Drossman of CC also serves as Director of the Catamount Institute (CI), a nonprofit institute targeting outreach in environmental science to underprivileged youth. CC recently initiated a required junior-senior level class called Air that deals with atmospheric physics and chemistry, and there is a proposal for a new two-block class entitled Global Climate Change. These classes will benefit from visiting lecturers by MMAP scientists, as well as class visits and research experiences tied to MMAP. MMAP will support two partial fellowships each year for junior and senior CC students who are considering graduate study in the atmospheric sciences. MMAP will also support two (per year) summer research internships for CC students who are considering graduate study in the atmospheric sciences. Finally, MMAP will support two internships that will include room and board at CSU for 3.5 weeks during the academic year, in order to allow CC students to participate in MMAP research. We will track students that take these courses to document how many go on to graduate study in weather and climate.

The UCLA partners of MMAP will also sponsor two research projects (during MMAP's second and fourth years) as part of the Institute for Pure and Applied Mathematics (IPAM) Research in Industrial Projects for Students (RIPS) program. RIPS is a highly successful program based on the Math Clinic which originated at Harvey Mudd College in the early 1970s. and the Research Experience for Undergraduates (REU) program sponsored by NSF. Teams of three to four advanced undergraduate students, typically from the mathematical sciences, will spend two summer months solving problems posed by MMAP under the mentorship of a MMAP scientist. As with the partnership with Colorado College, the goal of this program is to attract analytically gifted and creative undergraduates into the Earth

Sciences. RIPS graduates will also be tracked to see how their research experience shapes their future study.

Enhancements to Graduate Education

CSU has one of the world's largest and most successful graduate programs in Atmospheric Science, with approximately 90 graduate students in residence at any given time. The graduate programs in Atmospheric Sciences at UCLA, UU, HU, U MD, and UW are also participating in MMAP, and will support and train additional students. The Department has been recognized by the State of Colorado for a number of years as a "Program of Research and Scholarly Excellence." Approximately 80% of the Department's students are U.S.-born, and more than 1/3 are female. A particularly important element of the academic program, of special relevance to MMAP, is the opportunity for CSU's graduate students to obtain hands-on training in climate model development, which feeds crucial human resource needs for future advancements in the understanding of the climate system. Many of our graduates go on to become leaders in the field of climate science, and to teach in top-quality academic departments around the nation and the world. MMAP will thus allow us to "teach the teachers" of future undergraduate and graduate students. Participation of CSU graduate students in the teacher training courses for K-12 science teachers will also enhance interest and skills in teaching beyond what many young scientists have experienced.

SOARS (Significant Opportunities in Atmospheric Research and Science) is dedicated to increasing the enrollment of students from under-represented populations in graduate degree programs, with the goal of increasing ethnic diversity within the scientific workforce. The mission of SOARS is to provide up to four years funding for undergraduate and graduate students, with four summers of research internships. Applicants must have completed their sophomore year, so support covers two years of undergraduate education, and two years of graduate education.

SOARS provides internships and limited graduate school support to applicants who have completed two years of college with a cumulative GPA of 3.0 or higher. MMAP will support two SOARS undergraduate summer internships at CSU or NCAR, and travel to a scientific conference. In addition, MMAP will provide two fellowships each for one year and renewable for a maximum of two years to SOARS graduate students at CSU. The MMAP fellowships will make it unnecessary for SOARS to directly support the graduate educations of the students in question, thus making it possible for SOARS to support other students instead. SOARS will identify prospective students who have interests in line with the research focus of MMAP.

At the undergraduate level, the program goal for SOARS is to enhance the educational opportunities that are available at Minority Serving Institutions (MSIs). SOARS will also identify Minority-Serving Institutions (MSIs) interested in teacher training opportunities that will be supported by MMAP through Workshops held at CSU. SOARS will advertise the training opportunities and encourage MSI faculty to participate. MMAP will support curriculum development, and the MSI faculty will take MMAP-supplied curricular material back to their home institutions. SOARS builds administrative costs into their student costs, so no direct support of SOARS by the STC will be needed, with the possible exception of travel costs for a SOARS representative and possibly a CSU STC person to visit the MSIs.

MMAP will also provide summer internships, either at CSU, or at NCAR, for freshmen and sophomores. The costs to UCAR for these are $25K/year, which 10 weeks in Boulder via hourly pay to the students. Travel to a scientific conference will also be supported.

Finally, MMAP scientists will make presentations at the SOARS Summer Colloquia in Boulder.

International student exchanges

MMAP will support graduate student visits to CSU from the University of Tokyo. A student visit will typically last several months, and will be primarily a research experience although some students may choose to take a course during their visit. This program will enrich the graduate educations of the students involved, and foster enhanced international cooperation in climate science.

4.e Enhancing diversity in climate science

An important issue in atmospheric and ocean science is the significant under-representation of women, ethnic minorities, and people with disabilities in senior research and faculty positions. MMAP will support the education of graduate students from under-represented groups, and train them in cutting-edge climate research. The proposed Center will also support activities to (1) improve understanding of the mechanisms by which this problem persists; (2) assess an existing program of intervention that seeks to increase participation of underrepresented groups; and (3) perform targeted intervention to recruit additional women, ethnic minorities, and disabled students into graduate study in climate science. Research has identified the retention of girls in middle school and junior high school science classes as a critical element in increasing the number of women in science fields. MMAP proposes three areas of scholarly research, intervention, and outcomes assessment to address this issue. In addition, MMAP will support two minority undergraduate summer interns and two graduate research fellowships to minority students through the SOARS (Significant Opportunities in Atmospheric Research and Science) program. Finally, we propose a mentoring program that will pair female junior high school students with successful female graduate students in Atmospheric Science. Progress toward the goals of this program will be measured by conducting interviews and assessment research of the mentoring programs, by publications in the peer-reviewed literature, and by tracking changes in the diversity of MMAP students and early career scientists.

The next subsection describes the involvement of under-represented groups in current research and education by MMAP partners. This is followed by descriptions of research activities targeted at improving diversity in climate science and of the proposed mentoring interventions.

Diversity of MMAP Faculty and Graduate Students

There are 42 scientists from CSU and institutional partners in the proposed Center, of whom five are women. Thirty-eight of the 42 MMAP scientists are Caucasian, and four are Asian. Graduate students to be supported by the Center have not yet been selected. The gender and ethnic diversity statistics of current graduate students and those advised in the past five years by MMAP scientists at partner institutions for which data are available are presented in Table 1.

Table 1: Diversity of Current and Recent Graduate Students (percent) by Partner Institution

Institution	Number	Male	Female	Caucasian	Asian	Hispanic	Black	Other
CSU ATS	91	68.1	31.9	86.8	7.7	3.3	1.1	1.1
CSU other*	26	15.4	84.6	84.6	7.7	0	3.8	3.8
GISS	7	71.4	28.6	57.1	42.9	0	0	0
HU	22	68.2	31.8	0	13.6	0	86.4	0
LLNL	1	100	0	100	0	0	0	0
UCLA	10	50	50	40	30	30	0	0
U MD	2	50	50	0	50	50	0	0
U of Tokyo	7	71.4	28.6	0	100	0	0	0
U of Utah	3	66.7	33.3	33.3	66.7	0	0	0
UW	8	75.0	25.0	100	0	0	0	0
Total	**171**	**59.9**	**40.1**	**67.2**	**15.8**	**4.0**	**11.9**	**1.1**

* *CSU Other refers to graduate students in the Departments of Psychology, Sociology, and Human Development and Family Studies advised by MMAP Professors Canetto, Lacy, and MacPhee.*

Students being advised by MMAP faculty are clearly more diverse than the MMAP faculty themselves. This may reflect a trend toward greater diversity in the climate sciences in the future, or a tendency for diversity to decrease as students move through their early careers, or some combination of factors. As discussed below, MMAP research will investigate this and other questions.

Tracking Women and Under-represented Minorities in the Science Career Pipeline

The representation of women and of certain ethnic minorities drops at successively higher levels of science and engineering training and career advancement. Recruitment and retention of young scientists is especially challenging in climate science because of the strongly interdisciplinary nature of the science. This study will track the trajectory and experience of women and under-represented ethnic minorities from the undergraduate to the early postdoctoral years, as compared to the experience of a matched sample of men from well-represented ethnicities, and in light of the demographic/scholastic descriptive data for students in science/technology at CSU. The information obtained from this study will contribute to the development of more effective recruitment and retention strategies for female and under-represented ethnic minority scientists.

Career trajectories will be tracked via student records and for a subset of participants, via interviews. The experience of female and male science undergraduates, graduate students, postdocs, and early-career scientists will be documented via interviews, for a subset of participants. The questions for this project are as follows:

What are the experiences of women, under-represented ethnic minorities, and disabled persons who are in science and engineering fields, from the undergraduate years to the graduate years to the early careers years, as compared to the experiences of a matched group of men from well represented ethnic groups? How do the aspirations and expectations of female, under-represented ethnic minority, and disabled scientists change as they progress from undergraduate to graduate studies? What are the unique resources (e.g., study habits, economic assets; interpersonal resources) that these students may bring to careers in climate science, as compared to males from well represented ethnic groups? What are the unique challenges (personal, familial, financial, cultural) faced by female and under-represented ethnic minority science and engineering students, as compared to science and engineering males from well represented ethnic groups? What are the factors that lead to the dramatic and persistent decrease in the number of female scientists at each higher level of training and career? What are the factors that lead to the persistent absence of certain ethnic minorities in interdisciplinary science and engineering training and careers? What do female and under-represented ethnic minority science undergraduates do when they graduate from college, as compared to male undergraduates from well-represented ethnic groups? What do female and under-represented ethnic minority atmospheric science graduate students do after they complete their degrees, as compared to male graduates from well-represented ethnic groups? What are the typical personal, academic, financial and cultural characteristics and the family situations of females and under-represented ethnic minorities who complete their graduate atmospheric science degree, as compared to those who drop out? What are the typical personal, academic, financial and cultural characteristics and the family situations/resources/demands (e.g., being single versus being married; childless or with children) of females and males (by ethnicity) who pursue a post-graduate professional career in atmospheric science, as compared to those who do not?

The demographic/scholastic profile for undergraduate and graduate students in science and engineering programs will be obtained via CSU science department records. These records will be supplemented, for a sub-sample of participants, by interviews with female and male students/post-docs at different stages of training/career. The study's design is a mixture cross-sectional/longitudinal. Interviews will be scheduled at the following stages: 1. First semester, first year undergraduate; 2. First semester, third year undergraduate; 3. Last semester, fourth year undergraduate; 4. First semester, first year graduate; 5. First semester, third year graduate; 6. Last semester, last year graduate. 7. First semester, first year post doc; 8. First semester, third year post doc. Each participant will be interviewed one to three times. Five interviews will be obtained for each scientist-in-training/scientist level for women as well as for men across ethnicities for a total of 80 (40 female and 40 male respondents) interviews in each of three years of data collection. The first year will be taken up by work developing and piloting the interview protocol, the interview recruitment plan and the demographic overall quantitative data collection protocol. The fifth year will be used to finish analyzing the qualitative data and integrating them with the quantitative, student demographic/scholastic profile data, as well as developing recommendations for intervention.

Media Images Regarding Gender and Ethnicity in Science

Girls' interest and participation in science and technology drop around high-school age, when they take fewer science/math/computer classes despite their strong science performance up to that point. Several studies have suggested that at that time, both girls and boys think of science/technology as a masculine domain. Some ethnic minorities (e.g., individuals of Hispanic descent) are also under-represented in science/technology activities (e.g., classes, clubs) in the middle and high school years. Assessing the gender/ethnicity messages about science that students are commonly exposed to, from elementary to high school, will be important for developing strategies to change the public image of science/technology and prevent girls' and underrepresented ethnic minorities' progressive disengagement from science/technology.

A study of gender/ethnicity messages about science in late elementary, middle school, junior high and high school texts and/or videos will be performed by Prof. Silvia Canetto (CSU Department of Psychology) and a graduate student. The target population will be late elementary, middle school, junior high and high school students. The study will document the gender/ethnicity and science/technology messages that late-elementary, middle-school, junior-high and high-school kids are exposed to (e.g., Who is a scientist? Are scientists mostly bespectacled, lab-coat, geeky, eccentric, isolated males of European-American background? What do scientists do?). This will be accomplished through an analysis of science media (e.g., school science kits or texts; or popular science videos (e.g., "Beakman's world;" "Bill Nye science guy"), popular science books available in school libraries, and top magazines (about science or not) read by each age group. The hypothesis, based on past evidence, is that in these media, science and technology are presented as domains suited for males, especially males of European or Asian American background. According to past psychological research, increasing a sense of one's visibility in a field may help counteract negative media stereotypes. The findings of this study will be communicated to teachers so that researchers and teachers can collaboratively come up with ways to counteract potentially negative messages about girls and under-represented ethnic minorities in science/technology school texts/materials.

Assessment of the McNair Mentoring Program

A second proposed research project will involve assessing a decade (1995-2004) of the Ronald E. McNair Postbaccalaureate Achievement Program. This is a federally-funded mentoring program for female and under-represented ethnic minorities majoring in science and technology. Data on the characteristics and experience of participants in the McNair program, including the Marcia Identity Development Interview, have been collected since 1995. These data provide information on the participants' science career goals, including commitment, obstacles and alternatives. Analyzing the McNair program data will provide important insights on the experience and consequences of science/technology mentoring of undergraduate female and underrepresented ethnic minority students. The information gained from the McNair program data could be used to improve the McNair mentoring program itself. It will also be used to help develop a science mentoring program (discussed below) for middle and/or high school girls and ethnic minorities under-represented in science. Professor David MacPhee, who has been a faculty mentor and a program evaluator for the McNair program, is uniquely qualified to analyze the McNair mentoring program data.

Mentoring Female Science Students in Junior High and High Schools:

According to past research (Amer. Assoc. University Women, 1998, 2000; Sadker and Sadker, 1994; Steele, 1997), increasing one's presence and having direct positive experience in a field increases the likelihood of participation in that field. Having direct positive experience in a science field may also contribute to reducing stereotyping about who is a scientist and what scientists do. A mentoring program will be developed for girls and under-represented ethnic minorities at a time when we see a drop in their science participation. The program will provide a critical bridge of experience promoting stronger and more enduring engagement of young women and under-represented ethnic minorities in science fields in college. Participants will be solicited through the local Poudre School District. Middle and high school girls and under-represented ethnic minorities will be paired for one semester with female/underrepresented ethnic minority graduate students in Atmospheric Science under the supervision of a faculty member. This program will be organized by the MMAP Education and Outreach Coordinator, and will be advised by Prof. Silvia Canetto and Prof. David MacPhee.

Supporting and Mentoring Under-Represented Undergraduate and Graduate Students in Atmospheric Science

MMAP is partnering with Hampton University (HU), which is an Historically Black College or University. HU graduate students will have an opportunity to participate in MMAP-sponsored research and to interact with MMAP scientists in a variety of venues including MMAP meetings.

SOARS (Significant Opportunities in Atmospheric Research and Science) is dedicated to increasing the enrollment of students from under-represented populations in graduate degree programs, with the goal of increasing ethnic diversity within the scientific workforce. SOARS provides internships and limited graduate school support to applicants who have completed two years of college with a cumulative GPA of 3.0 or higher. MMAP will support two SOARS undergraduate summer internships at CSU or NCAR, and travel to a scientific conference. In addition, MMAP will provide two fellowships each for one year and renewable for a maximum of two years to SOARS graduate students at CSU. SOARS will identify prospective students who have interests in line with the research focus of MMAP, and will also identify Minority-Serving Institutions (MSIs) interested in teacher training opportunities that will be supported by MMAP through Workshops held at CSU. SOARS will advertise the training opportunities and encourage MSI faculty to participate. The MSI faculty will take MMAP-supplied curricular material back to their MSIs. Finally, MMAP scientists will make presentations at the SOARS summer workshops in Boulder.

Institutional Roles in Diversity Plans

CSU will take the lead in scholarly research to investigate the mechanisms by which women, ethnic minorities, and disabled persons become less represented in science, and particularly in the interdisciplinary study of climate, as they progress through their education and early careers. HU will provide the opportunity to increase participation of ethnic minorities in climate research.

4.f Narrative description of the Knowledge-Transfer Objectives of the Integrated Center

MMAP's Knowledge-Transfer goals are of two types. First, we will work with our research partners to transfer MMAP research results and technologies into our national atmosphere-modeling "infrastructure," for both climate simulation and weather prediction. Second, MMAP will undertake two publishing projects designed to significantly enhance the scientific communication that is so essential to the progress of our field.

Scientific applications of the MMF

Task: Climate change

Although we do not claim that a future quasi-3D MMF will immediately solve the cloud-climate problem, we do claim that it will represent a new and faster avenue towards that goal. MMAP is therefore obliged to contribute in an appropriate way to our society's ongoing search for reliable climate-change predictions. Accordingly, MMAP will participate in *exploratory* simulations of climate change, in order to explore the physical processes that lead to cloud feedbacks on climate change. In addition, although MMAP will not undertake "formal" climate-change simulations designed for use by policy makers, IPCC and others, we will work to influence such simulations and their interpretation through interactions with our partner institutions. We therefore list these activities under "knowledge transfer."

The CCSM is arguably the closest thing we have to a U.S. national climate model. Through the research activities of many of its participants, the MMAP team has a close and long-standing relationship with the CCSM, and especially its atmosphere submodel, the CAM. MMAP will make use of the CCSM Working Groups to transfer to the CCSM the fruits of MMAP's research, including scientific understanding, model results, source codes, and diagnostic methods. Many MMAP scientists are already strongly participating in those Working Groups.

Scientists from the DOE national laboratory system have proposed an MMF-based project within DOE. This project is designed to run in parallel with MMAP and will be critically dependent on MMAP's model development efforts. The purpose of the proposed DOE project is to use a tested version of the MMF to investigate the climate sensitivity to a broad range of cloud feedbacks, and then run climate change simulations through the current century. Obviously there is the potential for terrific synergy between MMAP and the proposed DOE project.

MMAP will interact with CCSM, Columbia, and CCSR on an ongoing basis, and will begin influencing climate change studies immediately. Significant impacts will begin to appear by the end of MMAP's third year. The relevant partners are NCAR (Collins, Hack), UW (Bretherton), Columbia (Hansen), CCSR (Kimoto), and PNNL (Ackerman, Ghan). We will also have the participation of collaborator Leo Donner of GFDL.

Task: Numerical weather prediction

For many reasons, MMAP cannot do operational weather prediction. Nevertheless, the MMF has the potential to produce more skillful weather forecasts, especially for precipitation, and makes it possible to assimilate observed statistics characterizing the mesoscale and microscale spatial structures of cloud fields. Assimilation of such data has the potential to produce more realistic analyses of large-scale weather systems, which can then lead to improved forecasts. Finally, NWP is an excellent way to evaluate the performance of a model. For these reasons, MMAP will perform *exploratory* NWP, in cooperation with our partner institutions, in a knowledge-transfer mode. In addition, the U.S. National Centers for Environmental Prediction (NCEP) will test new cloud parameterizations developed by MMF research.

Significant progress on this task can be achieved by the end of MMAP's second year, although the work will continue throughout the life of the Center. The relevant partners are LLNL (Potter, Cederwall), NCAR (Klemp), UU (Krueger), and BMRC (Jakob). In addition, we will have the participation of collaborators at the European Centre for Medium Range Weather Forecasts (ECMWF; Miller), NASA's Goddard Space Flight Center (GSFC), and NCEP (Lord).

Task: Creation of a new scholarly journal

MMAP will create a new all-electronic peer-reviewed non-profit journal, published by CSU's Department of Atmospheric Science, that will serve the global modeling community. The (provisional) name of the new journal is the "Journal of Global Environmental Modeling" (GEM). Nothing comparable to GEM currently exists. Research results on global modeling are scattered in a large number of meteorology, oceanography, mathematics, and physics journals. GEM will be a focus for modeling research involving the global system, including the atmosphere, the oceans, the cryosphere, and the land surfaces. GEM will also encourage submissions dealing with numerical techniques for modeling these systems and with the analysis of observational data for critical evaluation of modeling results. Although MMAP scientists will publish their research results in many different journals, GEM will be designed so that it will be a highly suitable venue for virtually any MMAP research publication.

The journal will be founded on the principles of open access, i.e., online access to GEM will be free to all. This approach has recently been championed by SPARC, the Scholarly Publishing and Academic Resources Coalition, and demonstrated by PLoS, the Public Library of Science. One of the advantages of open access is that it eliminates problems that scientists are presently experiencing with printed, subscription-based journals, which are usually obtained through institutional libraries with limited budgets for journal subscriptions. The costs of publishing GEM will be covered through a combination of page charges and direct funding from multiple agencies. The latter will be obtained via proposals. The business plan for GEM will be developed based on the ideas developed by SPARC, PLoS, and other open access advocates (see, e.g., Crow and Goldstein, 2003).

The costs will be kept to a minimum by the all-electronic nature of the journal and by shifting many of the technical editing aspects of production to the authors, through the use of modern (standardized) electronic publishing methods. Another advantage of GEM will be its short publication time. By eliminating much of the technical editing and the typesetting phases of the production process, publication time will be determined primarily by the peer-review time. For immediate communication of their results, authors will have the option of posting, on the journal website, the submitted version of their paper. MMAP will oversee and partially fund the start-up of GEM, over a period of five years. During this period, GEM will also solicit and publish "high-profile," value-added review articles designed to attract readers to the GEM web site and to aid scientists who are branching into new areas of research. Our intention is that after five years GEM will have assumed a life of its own, and become financially self-supporting. It can then become independent of MMAP.

During its start-up phase, GEM will be directed by a small group: the chief editor, two editors, and an editorial assistant, all of whom will be MMAP project members and will have previous experience in the journal publication process. We will take maximum advantage of the knowledge base that exists in the present *Journal of Climate* editorial office, headed by Prof. Randall. As GEM grows we will appoint additional Editors in new research areas and also establish a group of Associate Editors. It is at this stage that we will entrain more scientists from MMAP's partner institutions and international collaborators. The Editors will also make a concerted effort to use young scientists in the peer review process and to promote to Associate Editor those who provide insightful reviews and are committed to the success of GEM. From this base of young Associate Editors will come the new Editors, as the original group of "founding Editors" steps down. In this way GEM will benefit from a visionary group of Editors who can guide the journal through times of rapid technological change in the scientific communication process.

To encourage communication between MMAP's partners in the operational community and those in the research community, GEM will establish a section of the journal devoted to problems faced in operational numerical weather prediction. Particularly encouraged will be articles concerning operational model performance and comparisons of reanalysis products with newly-acquired research data sets.

Many MMAP scientists have the skill and interest to communicate advances in global environmental science to the general public. To take advantage of this, GEM will establish a section of the journal devoted to "popular science" articles. These articles will be written especially for thoughtful readers who do not have the mathematical and technical background required to understand most scientific journal articles. Well written articles in this section of GEM should be comprehensible to a wide range of readers, including high school students in advanced placement science classes, college undergraduate students, and K-12 teachers. The development of this section of GEM will draw heavily on the expertise of Prof. Denning, Associate Director for Education and Outreach, and on our partner organizations involved in educational outreach.

MMAP's budget provides for personnel and a digital server that will be needed for the start-up phase of GEM. To fill the position involved with knowledge transfer, MMAP will seek an individual with skills in both of the two areas, i.e., to work with our research partners to transfer MMAP research results and to help initiate and complete the publication projects.

Task: Production of a book on the history of global modeling

There is more to our field than current research, of course. The pioneers of atmospheric general circulation modeling, including those involved with early work on cloud parameterization, are at or near the ends of their careers. To capture their stories for posterity, we will create an edited book that will include chapters written by scientists with important past or present involvement with cloud parameterization. The book will also include transcripts of interviews with key modeling pioneers, including those who initiated global atmospheric modeling at GFDL, NCAR, UCLA, and LLNL. Our goal in producing this review of "where we have been" is to better predict "where we are going" in our ability to simulate and predict the atmospheric and oceanic environment.

5. Facilities and Equipment

6. Budget and budget justification

7. References cited

Ackerman, A. S., O. B. Toon, D. E. Stevens, A. J. Heymsfield, V. Ramanathan, E. J. Welton, 2000: Reduction of Tropical Cloudiness by Soot. *Science*, **288**, 1042-1047.

Ackerman, T. P., K.-N. Liou, F. P. J. Valero, and L. Pfister, 1988: Heating rates in tropical anvils. *J. Atmos. Sci.*, **45**, 1606-1623.

Amer. Assoc. University Women, Ed., 1998: *Gender gaps: Where schools fail our children*. Marlowe and Company, 144 pp.

Amer. Assoc. University Women, 2000: *Tech-savvy: Educating girls in the new computer age*. Washington, DC, 82 pp.

National Science Foundation, 2002. Higher education in science and engineering. In *Science and engineering indicators 2002*. Retrieved September 15, 2003 from http://www.nsf.gov/sbe/srs/seind02/start.htm

Arakawa, A., 1975: Modeling clouds and cloud processes for use in climate models. In *The Physical Basis of Climate and Climate Modelling*. GARP Publications Series No. 16, 181-197, ICSU/WMO, Geneva.

Arakawa, A., 2004: The Cumulus Parameterization Problem: Past, Present, and Future. *J. Climate* (in press).

Barker, H. W., and 32 others, 2004: Assessing 1D Atmospheric Solar Radiative Transfer Models: Interpretation and Handling of Unresolved Clouds. *J. Climate* (in press).

Cairns, B., A. A. Lacis, and B. E. Carlson, 2000: Absorption within inhomogeneous clouds and its parameterization in general circulation models. *J. Atmos. Sci.*, **57**, 700-714.

Cess, R. D., and 19 others, 1989: Interpretation of cloud climate feedback as produced by 14 atmospheric general circulation models. *Science*, **245**, 513-516.

Charney, J. G., 1979: *Carbon dioxide and climate: A scientific assessment*. National Academy Press, Washington, D. C., 33 pp.

Cheng, A., and K.-M. Xu, 2004: A Partially Prognostic Third-order Closure Model for Modeling the Boundary Layer Submitted to *J. Atmos. Sci.*

Cole, J. N., H. W. Barker, D. A. Randall, M. F. Khairoutdinov, and E. Clothiaux, 2004: Interactions between Clouds and Radiation at Scales Unresolved by Global Climate Models. Submitted for publication.

Crow, R. and H. Goldstein, 2003: *Guide to Business Planning for Launching a New Open Access Journal*. Open Society Institute, 400 West 59th Street, New York, NY 10019, 66 pp.

Dubrulle, B., and J-P. Laval, P. Sullivan and J. Werne, 2002: A new subgrid model for the atmospheric surface layer, I: The model. *J. Atmos. Sci*, **59**, 857--872.

E, W., and B. Engquist, 2003: The heterogeneous multiscale methods. *Comm. Math. Sci.*, **88D**, 134.

Feingold, G., and S. M. Kreidenweis, 2000: Does Cloud Processing of Aerosol Enhance Droplet Concentrations?, *J. Geophys. Res*, **105**, 24,351–24,361.

Global Change Research Information Office, 2003: *FY 2003 U.S. Global Change Research Program and Climate Change Research Initiative. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research. A Supplement to the President's Fiscal Year 2003 Budget*. Published by the Global Change Research Information Office (GCRIO), P.O. Box 1000, 61 Route 9W, Palisades, New York 10964 USA.

Grabowski, W. W., and P. K. Smolarkiewicz, 1999: CRCP: A cloud resolving convection parameterization for modeling the tropical convective atmosphere. *Physica D*, **133**, 171-178.

Grabowski, W. W., 2001: Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci.*, **58**, 978-997.

Gurney, K. R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, S. Fan, I.Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, E. Kowalczyk, T. Maki, S. Maksyutov, P. Peylin,

M. Prather, B.C. Pak, J. Sarmiento, S. Taguchi, 2003. TransCom3 CO_2 inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information. *Tellus*, **55B**, 555-579.

Hartmann, D.L., 1993: Radiative effects of clouds on Earth's climate, in *Aerosol-Clouds-Climate Interactions*, Int. Geophys. Ser., **54**, edited by P.V. Hobbs, pp. 151-173, Academic, San Diego, Calif.

Heikes, R. P., and D. A. Randall, 1995: Numerical integration of the shallow water equations on a twisted icosahedral grid. Part I: Basic design and results of tests. *Mon. Wea. Rev.*, **123**, 1862-1880.

Helly, J., T. T. Elvins, et al. (1999). A Method for Interoperable Digital Libraries and Data Repositories. *Future Generation Computer Systems*, Elsevier 16(1): 21-28.

Helly, J., T. T. Elvins, et al. (2002). Controlled Publication of Digital Scientific Data. *CACM* May(5): 97-101.

Heymsfield, A.J., and R.M. Sabin, 1989: Cirrus crystal nucleation by homogeneous freezing of solution droplets. *J. Atmos. Sci.*, **46**, 2252-2264.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.

Jung, J.-H., and A. Arakawa, 2004: Resolution dependence of model physics inferred from non-hydrostatic model experiments. *J. Atmos. Sci.*, **61**, 88-102.

Kerstein, A. R., 1999: One-dimensional turbulence: Formulation and application to homogeneous turbulence, shear flows, and buoyant stratified flows. *J. Fluid Mech.* **392**, 277.

Khairoutdinov, M. F., and D. A. Randall, 2001: A cloud-resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary results. *Geophys. Res. Lett.*, **28**, 3617-3620.

Khairoutdinov, M., D. A. Randall, and C. DeMott, 2004: Simulation of the atmospheric general circulation using a cloud-resolving model as a super-parameterization of physical processes. Submitted to *J. Atmos. Sci.*

Krueger, S. K., 1988: Numerical simulation of tropical cumulus clouds and their interaction with the subcloud layer. *J. Atmos. Sci.*, **45**, 2221-2250.

Krueger, S. K., 1993: Linear eddy modeling of entrainment and mixing in stratus clouds. *J. Atmos. Sci.*, **50**, 3078--3090.

Krueger, S. K., Su, C.-W., and McMurtry, P. A., 1997: Modeling entrainment and finescale mixing in cumulus clouds. *J. Atmos. Sci.*, **54**, 2697.

Lappen, C.-L, and D. A. Randall, 2001: Towards a unified parameterization of the boundary layer and moist convection. Part I. A new type of mass-flux model. *J. Atmos. Sci.,* **58***,* 2021-2036.

L'Ecuyer, T. S. and G. L. Stephens, 2002; An uncertainty model for Bayesian Monte Carlo retrieval algorithms: Application to the TRMM Observing System. *Quart. J. R. Meteorol. Soc.*, **128**,1713-1737.

Lin, J. W.-B., and D. J. Neelin, 2002: Considerations for Stochastic Convective Parameterization. *J. Atmos. Sci.,* **59**, pp. 959–975.

Luo, Y., S. K. Krueger, G. G. Mace, and K.-M. Xu, 2003: Cirrus cloud properties from a cloud-resolving model simulation compared to cloud radar observations. *J. Atmos. Sci.*, **60**, 510–525.

Luo, Y., and S. K. Krueger, 2004: Cloud Properties Simulated by a Single-Column Model. Part 1: Comparison to Cloud Radar Observations of Cirrus Clouds. Submitted to *J. Atmos. Sci.*, Sept. 2003.

O'Hirok, W. and C. Gautier, 1998: A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci.*, **55**, 2162-2179.

Oreopoulos, L., and H. W. Barker, 1999: Accounting for subgrid-scale cloud variability in a multi-layer, 1D solar radiative transfer algorithm. *Q. J. R. Meteorol. Soc.*, **125**, 301-330.

Randall, D. A., J. Curry, P. G. Duynkerke, S. Krueger, B. Ryan, D. Starr, M. Miller, W. B. Rossow, and B. A. Wielicki, 2003 a: Confronting models with data: The GEWEX Cloud Systems Study. *Bull. Amer. Meteor. Soc.*, **84**, 455-469.

Randall, D. A., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003 b: Breaking the cloud-parameterization deadlock. *Bull. Amer. Meteor. Soc.*, **84**, 1547-1564.

Rasch P. J., M. C. Barth, J. T. Kiehl, S. E. Schwartz, and C. M. Benkovitz, 2000: A description of the global sulfur cycle and its controlling processes in the National Center for Atmospheric Research Community Climate Model, Version 3. *J. Geophys. Res.*, **105**, 1367-1385.

Ringler, T. D., and D. A. Randall, 2002: A potential enstrophy and energy conserving numerical scheme for solution of the shallow-water equations on a geodesic grid. *Mon. Wea. Rev.*, **130**, 1397-1410.

Sadker, M., and D. Sadker, 1994: *Failing at fairness: How our schools cheat girls*. New York: Touchstone.

Scheider, K. and M. Farge, 2000: Numerical simulation of a mixing layer in an adaptive wavelet basis. *C. R. Acad. Sci. Paris Serie II*, 263-269.

Senior, C. A., and J. F. B. Mitchell, 1993: Carbon dioxide and climate: The impact of cloud parameterization. *J. Climate*, **6**, 393-418.

Starrost, F., and E. A. Carter, 2002: Modeling the Full Monty: Baring the Nature of Surfaces Across Time and Space. *Surface Science Millennium Issue*, **500**, 323.

Steele, C. M., 1997: A threat in the air: How stereotypes shape intellectual identity and performance. *American Psychologist*, **52**, 613-129.

Theodoropoulos, K., Y.-H. Qianandl and I. G. Kevrekidis, 2000: “Coarse” stability and bifurcation analysis using time steppers: A reaction diffusion example. *Proc. Natl. Acad. Sci.*, **97**, 9840-9843.

Zhang, Y., S. M. Kreidenweis, and G. Feingold, 1999: Stratocumulus Processing of Gases and Cloud Condensation Nuclei, Part II: Chemistry Sensitivity Analysis. *J. Geophys. Res.*, **104**, 16,061–16,080.

Zulauf, M. A., and S. K. Krueger, 2003: Two-dimensional cloud-resolving modeling of the atmospheric effects of Arctic leads based upon midwinter conditions at the Surface Heat Budget of the Arctic Ocean ice camp. *J. Geophys. Res.*, **108** (D10), 4312, doi:10.1029/2002JD002643.

8. Biographical sketches

9. Current and pending support --- not required

10. Partner institutions and project personnel

Prof. Kerry Emanuel of the Massachusetts Institute of Technology has agreed to serve as the first Chair of the External Advisory Panel. The remaining members of the panel have not yet been chosen.

10.a Partner Institutions

Table 2: Academic partner institutions, with acronyms in parentheses.

Academic Partner	Role in MMAP
Colorado College (CC)	Undergraduate education/outreach
Colorado State University (CSU)	Lead institution for MMAP; wide range of research activities, plus graduate and undergraduate (Physics) education, and K-12 education through the Little Shop of Physics CSU will also carry out a tracking study of female students and science education.
University of California, Los Angeles (UCLA)	Research on CSRMs, the MMF, and conventional parameterizations, as well as graduate education.
University of Colorado (CU)	Development of conventional parameterizations
Columbia University	Model evaluation using ISCCP data, and knowledge-transfer partner in the area of climate change, as well as graduate education.
Hampton University (HU)	Development of improved CSRMs, and use of MMF to interpret satellite data, as well as graduate education.
University of Maryland (U MD)	Development of improved MMFs, and exploratory assimilation of satellite data using MMFs, as well as graduate education.
University of California, (UCSD) including the San Diego Supercomputer Center (SDSC)	Home institution of the Associate Director for Computation; data management across the Internet; provision of computing resources. Also research on the MMF, and graduate education.
University of Utah (UU)	Development of CSRMs and MMFs, as well as graduate education.
University of Washington (UW)	Investigation of cloud physical processes using CSRMs, as well as graduate education.

Table 3: National Laboratories that are partner institutions, with acronyms in parentheses.

National Laboratory Partners	Role in MMAP
Lawrence Livermore National Laboratory (LLNL)	MMF evaluation using CAPT; tests of high-resolution MMFs, and provision of computing resources
Pacific Northwest National Laboratories (PNNL)	Model evaluation using ARM data, and provision of computing resources

Table 4: Industrial partners, with acronyms in parentheses.

Industry Partner	Role in MMAP
Apple Computer (AC)	Code optimization and access to emerging computer architectures

Table 5: Non-Governmental Partners, with acronyms in parentheses.

Non-Governmental Partner	Role in MMAP
National Center for Atmospheric Research (NCAR)	Development of improved CSRMs and MMFs; development of improved conventional parameterizations; knowledge-transfer partner for NWP using the Weather Research and Forecasting Model (WRF)
The Catamount Institute (CI)	K-12 education for under-represented groups

Table 6: International Partners, with acronyms in parentheses.

International Partners	Role in MMAP
Bureau of Meteorology Research, Australia (BMRC)	Knowledge-transfer partner for NWP
Center for Climate Systems Research, University of Tokyo, Japan (CCSR)	Knowledge transfer partner for MMF development and climate-change research
Frontier Research System for Global Change, Japan (FRSGC)	Knowledge transfer partner for MMF development and climate-change research
Meteorological Service of Canada (MSC)	Development and testing of improved radiative transfer parameterizations for CSRMs and MMFs

10.b Project personnel

Table 7: Project personnel at academic institutions. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Akio Arakawa	University of California, Los Angeles	Development of improved GCMs and cloud parameterizations	P
Christopher Bretherton	University of Washington	Development of improved cloud parameterizations	P
Antonio Busalacchi	University of Maryland	Use of satellite data to evaluate MMF results	P
Silvia Canetto	Colorado State University, Psychology	Study of diversity in connection with MMAP's Education and Outreach activities	P
Alan Scott Denning	Colorado State University	Associate Director for Education & Outreach; use of MMFs to study the carbon cycle	P
Howard Drossman	Colorado College	Liaison to the Colorado College Environmental Studies Program; also listed under the Catamount Institute	P
Laura Fowler	Colorado State University	Development of improved cloud parameterizations	P
James Hansen	Columbia University	Use of satellite data to evaluate MMF results	P
John Helly	University of California, San Diego, and San Diego Supercomputer Center	Associate Director for Computation, and liaison to SDSC	P
Brian Jones	Colorado State University, Physics	Director of Little Shop of Physics; K-12 education	P
Joon-Hee Jung	Colorado State University, Atmospheric Science	Development of the next-generation MMF	P
Michael Lacy	Colorado State University, Sociology	Assessment of Little Shop of Physics	P
Marat Khairoutdinov	Colorado State University	Development of CSRMs and MMFs	P
Sonia Kreidenweis	Colorado State University	Use of MMFs with aerosol and cloud microphysics parameterizations	P
David Krueger	Colorado State University, Physics	Development of transdisciplinary course for CSU undergraduates	P
Steven Krueger	University of Utah	Development of improved MMFs	P
Christian Kummerow	Colorado State University	Liaison to TRMM and GPM; use of these datasets for model evaluation	P
David MacPhee	Colorado State University, Human Development & Family Studies	Study of diversity in connection with MMAP's Education and Outreach activities	P

Table 7: Project personnel at academic institutions. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Patrick McCormick	Hampton University	Use of satellite data to evaluate MMF results	P
Robert Pincus	University of Colorado	Development of conventional cloud parameterizations	P
David Randall	Colorado State University	Principal investigator; further development of the MMF	P
Steven A. Rutledge	Colorado State University	Model evaluation using radar data	P
Wayne Schubert	Colorado State University	Associate Director for Knowledge Transfer; further development of the MMF with an emphasis on the choice of governing equations	P
Richard Somerville	University of California, San Diego	Further development of the MMF	P
Graeme Stephens	Colorado State University	Model evaluation based on CloudSat data	P
Bjorn Stevens	University of California, Los Angeles	Development of conventional parameterizations	P

Table 8: Project Personnel at National Laboratories. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Thomas Ackerman	Pacific Northwest National Laboratories	ARM Chief Scientist; model evaluation using ARM data	P
Ric Cederwall	Lawrence Livermore National Laboratory	Model evaluation using CAPT	P
Philip Duffy	Lawrence Livermore National Laboratory	Role of MMF in high-resolution climate modeling	P
Steven Ghan	Pacific Northwest National Laboratories	Research on aerosols and cloud microphysics in climate change	P
Gerald Potter	Lawrence Livermore National Laboratory	Model evaluation, in part using CAPT	P

Table 9: Project Personnel in the Federal Government. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Robert Atlas	Goddard Space Flight Center, NASA	Use of MMFs for assimilation of cloud and precipitation data	C
Leo Donner	Geophysical Fluid Dynamics Laboratory, NOAA	Development of improved MMFs and improved conventional parameterizations	C
Stephen Lord	National Centers for Environmental Prediction, NOAA	Potential of MMFs to improve weather forecasts	C
William Rossow	Goddard Institute for Space Studies, NASA	Model evaluation, especially using ISCCP data	C
Wei-Kuo Tao	Goddard Space Flight Center, NASA	Development of improved MMFs, and application to data assimilation	C
Bruce Wielicki	Langley Research Center, NASA	Model evaluation using space data	C
Kuan-Man Xu	Langley Research Center, NASA	Development of boundary-layer parameterizations for use in the MMF	C

Table 10: Project Personnel in the private sector. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Kurt Ackman	Apple Computer	Liaison to Apple Computer	P

Table 10: Project Personnel in the private sector. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
James Abeles	International Business Machines	Liaison to International Business Machines	C

Table 11: Project Personnel in Non-Governmental Organizations. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
William Collins	National Center for Atmospheric Research	Developer of radiative transfer parameterizations; Liaison to CCSM	P
Howard Drossman	The Catamount Institute	Liaison to the Catamount Institute; also listed under “Colorado College”	P
Susan Foster	University Corporation for Atmospheric Research	Lead developer of SEE-ME	C
Wojciech Grabowski	National Center for Atmospheric Research	Development of improved CSRMs and MMFs	P
James Hack	National Center for Atmospheric Research	Development of cloud parameterizations, development of simple models that capture the essence of the cloud-climate problem; Liaison to CCSM	P
Andrew Heymsfield	National Center for Atmospheric Research	Parameterization of ice microphysics	P
Joseph Klemp	National Center for Atmospheric Research	Liaison to WRF	P
Donald Middleton	National Center for Atmospheric Research	Data management and high-speed networking strategy	P
Chin-Hoh Moeng	National Center for Atmospheric Research	Deputy Director; development of boundary-layer parameterizations for use in the MMF	P
Mitchell Moncrieff	National Center for Atmospheric Research	Development of the MMF	P
Rajul Pandya	University Corporation for Atmospheric Research	Director of SOARS	C

Table 12: Project Personnel in State and Local Government. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Kenneth Bennett	Thompson School District, Loveland, Colorado	Liaison to Thompson public schools; development and evaluation of SEE-ME	C
David Swartz	Poudre School District, Fort Collins, Colorado	Liaison to Poudre public schools; development and evaluation of SEE-ME	C

Table 13: International Project Personnel. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Howard Barker	Meteorological Service of Canada	Radiation parameterization for the MMF, including multi-dimensional radiative transfer; scientific participant in MMAP workshops	P
Christian Jakob	Bureau of Meteorology Research, Australia	Model evaluation, especially based on ARM data; scientific participant in MMAP workshops	P
Masahide Kimoto	Center for Climate Systems Research, University of Tokyo, Japan	Scientific participant in MMAP Workshops; development of improved MMFs	P
Martin Miller	European Centre for Medium Range Weather Forecasts, England	Scientific participant in MMAP Workshops; model evaluation through NWP	C
Tomoe Nasuno	Frontier Research Project for Global Change, Japan	Scientific participant in MMAP Workshops; development of improved CSRMs	P

11. Ethics and intellectual property rights

MMAP's research is highly academic in character and is not expected to produce any patentable items. MMAP's scientific results will be promptly published in the peer-reviewed literature. MMAP's modeling techniques, including source codes, will be made freely available to the academic community immediately after publication by the scientists involved in their development. For these reasons, issues associated with intellectual property rights are expected to be very minimal.

MMAP personnel must recognize that their personal conduct reflects on the integrity of the Center, and should take care that their actions have no detrimental effect on the institution. Therefore, each MMAP staff member is expected to:

a. Perform their duties in a courteous and professional manner.

b. Use MMAP funds, facilities, equipment, supplies, and staff only in the conduct of MMAP duties, exceptions to be made only under specific MMAP policies.

c. Maintain a high level of discretion and respect in personal and professional relations with research colleagues, students, educators, and the public.

d. Compensate MMAP personnel (including students) fairly for work performed that is related to professional activities beyond one's MMAP assignment.

e. Recognize fairly and accurately the extent of the contribution of others to one's professional work.

f. Avoid non-MMAP activities that could significantly interfere with carrying out assigned MMAP responsibilities.

g. Refrain from disclosing confidential information that was acquired by nature of one's activities within MMAP.

h. Abide by MMAP policies pertaining to patents, publication, copyrights, consulting, off-campus employment, and conflict of interest.

j. Eschew misconduct such as fabrication, falsification, and plagiarism, in proposing, conducting, and reporting research or in scholarly or creative endeavors, or in identifying one's professional qualifications.

MMAP will set up an online ethics training course, and will require all Center and subawardee staff and students to complete the course. The training will cover the nature of MMAP's research as it relates to intellectual property issues, MMAP's policies and expectations with respect to intellectual property rights, and the code of ethical behavior outlined above.

As part of its regular business, the MMAP Executive Committee will monitor ongoing and proposed MMAP activities to detect any emerging issues in connection with intellectual property rights or unethical behavior, and will take action to deal with such issues as they arise.

12. Shared experimental facilities

CSU will set up a Compute Server to serve MMAP; funds for this are included in MMAP's budget. The facilities provided will be suitable for model development and short test runs, but not for full production runs, which will have to be carried out on at external supercomputer centers. Computing resources will be made available, via the Internet, to MMAP investigators at other institutions. The Compute Server will be protected against extended downtime by a maintenance contract with the commercial vendor. Local system administration and routine maintenance such as software installation will be performed by a System Administrator who will be on the MMAP payroll. We plan to allocate time on the Compute Server through an informal process that uses the System Administrator as a gatekeeper. Control is exercised through the creation and removal of password-protected user IDs. Priorities for use of the Compute Server will be set by the MMAP Executive Committee.

13. Projected Committed Funding by Source

Table 14: Summary of committed funding for cost-sharing. No Federal dollars will be used.

	Year 1		Year 2		Year 3		Year 4		Year 5		Total	
	Cash $	In-Kind $	Cash $	In-Kind $	Cash $	In-Kind $	Cash $	In-Kind $	Cash $	In-Kind $	Cash $	In-Kind $
Academic Institutions												
CSU	626942	0	635734	0	628678	0	635980	0	644126	0	3171460	0
UCLA	60000	0	60000	0	60000	0	60000	0	60000	0	300000	0
UW	21000	0	21000	0	21000	0	21000	0	21000	0	105000	0
UU	36000	0	36000	0	36000	0	36000	0	36000	0	180000	0
CU	16154	0	16154	0	16154	0	16154	0	16154	0	80770	0
UCSD	0	60000	0	60000	0	60000	0	60000	0	60000	0	300000
CC	9275	0	9275	0	9275	0	9275	0	9275	0	46375	0
UMD	0	27000	0	27000	0	27000	0	27000	0	27000	135000	0
HU	15626	0	16094	0	16576	0	17074	0	17586	0	82956	0
National Laboratories												
PNNL	110330	0	110330	0	110330	0	110330	0	110330	0	551650	0
LLNL	25000	0	25000	0	25000	0	25000	0	25000	0	125000	0
Industry												
Apple Comp.	0	13000	0	3000	0	3000	0	3000	0	1000	0	25000
Non-governmental organizations												
NCAR	75000	0	75000	0	75000	0	75000	0	75000	0	375000	0
Catamount Inst.	5600	0	5700	0	5600	0	5700	0	5700	0	28400	0
International												
MSC	21000	5000	21000	5000	21000	5000	21000	5000	21000	5000	105000	25000
BMRC	19720	0	19720	0	19720	0	19720	0	19720	0	98600	0
U. Tokyo	32134	0	32134	0	32134	0	32134	0	32134	0	160670	0
FRSGC	9900	0	9900	0	9900	0	9900	0	9900	0	49500	0
Totals	1083681	105000	1093041	95000	1086467	95000	1094267	95000	1102925	95000	5460381	485000

14. Institutional Support

CSU will construct a new 15,000-square-foot building to house the MMAP staff and facilities. The building will include space for two faculty, twelve research staff, fourteen students, and three administrative staff. It will also feature a conference room, a classroom, and a computer lab. If MMAP is funded in June 2005, building occupancy will commence in May of 2007. Additional CSU space will be made available to MMAP prior to the completion of the new building, and also after completion as necessary.

As a further component of its cost-sharing, CSU will create a new faculty position in the Department of Atmospheric Science. The new faculty member will have a specialization that fits with the research activities of MMAP. Applicants from under-represented groups will be very welcome.

The MMAP building and the new faculty position represent major, high-quality institutional commitments to MMAP on the part of CSU. In total, CSU is providing over 3.1 M$ in cost-sharing over a period of five years. This is particularly remarkable in light of the recent severe budget cuts to public higher education in Colorado.

MMAP's other academic partners, UCLA, UC San Diego, U. Washington, U. Utah, Hampton U., U. Colorado, U. Maryland, and Colorado College, are providing cost-sharing totaling 1.4 M$.

Eight NCAR scientists from three different NCAR divisions are participating in MMAP. NCAR is providing 375 K$ of cash cost-sharing, all from non-Federal funds. Organizing this substantial cost-sharing required a significant effort on the part of NCAR management, and MMAP is very fortunate to have such strong participation by NCAR. NCAR is also providing "Co-Sponsorship" of MMAP in the amount of 550 K$. This amount cannot be counted as cost-sharing because the funds come from Federal sources. The Co-Sponsorship funds will be used to support additional NCAR staff time for MMAP research.

Although the U.S. DOE laboratories PNNL and LLNL are not receiving any MMAP funding, they will each provide over 100 K$ of cost-sharing from non-Federal sources. This is an indication of the interest with which the U.S. Department of Energy views MMAP's plans.

The non-profit Catamount Institute is providing cost-sharing in the form of staff time, for a total of 28.4 K$.

Our international partners, the Meteorological Service of Canada, BMRC in Australia, CCSR at the University of Tokyo, and the Frontier Research System for Global Change, also in Japan, are generously providing cost-sharing in excess of 400 K$.

Apple Computer is providing cost-sharing of $25 K, in the form of free technical training that will be useful in setting up MMAP's visualization systems.

In addition to these cost-sharing arrangements, MMAP will also benefit from collaborative interactions, at no cost to the Center, from the following entities: ECMWF, which has already paid travel expenses for participation in MMAP planning meetings; IBM, which is very interested in MMAP because the achievements with the MMF to date have been based entirely on the use of IBM supercomputers; UCAR, which is involved with the Education/Outreach component of MMAP through SOARS and SEE-ME; GSFC, which is constructing its own MMF in collaboration with MMAP scientists, under NASA funding; GISS, and LaRC, which will collaborate with MMAP in the use of satellite data to evaluate MMF results; the Poudre and Thompson school districts in Colorado, which have joined enthusiastically in MMAP planning and stand to benefit from MMAP's Education and Outreach activities; and NCEP, which is collaborating with MMAP on the development of improved conventional parameterizations for use in numerical weather prediction.

15. List of Personnel, Collaborators, and Affiliates

15.a Project personnel

Table 15: Project personnel at academic institutions. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Akio Arakawa	University of California, Los Angeles	Development of improved GCMs and cloud parameterizations	P
Christopher Bretherton	University of Washington	Development of improved cloud parameterizations	P
Antonio Busalacchi	University of Maryland	Use of satellite data to evaluate MMF results	P
Silvia Canetto	Colorado State University, Psychology	Study of diversity in connection with MMAP's Education and Outreach activities	P
Alan Scott Denning	Colorado State University	Associate Director for Education & Outreach; use of MMFs to study the carbon cycle	P
Howard Drossman	Colorado College	Liaison to the Colorado College Environmental Studies Program; also listed under the Catamount Institute	P
Laura Fowler	Colorado State University	Development of improved cloud parameterizations	P
James Hansen	Columbia University	Use of satellite data to evaluate MMF results	P
John Helly	University of California, San Diego, and San Diego Supercomputer Center	Associate Director for Computation, and liaison to SDSC	P
Brian Jones	Colorado State University, Physics	Director of Little Shop of Physics; K-12 education	P
Joon-Hee Jung	Colorado State University, Atmospheric Science	Development of the next-generation MMF	P
Michael Lacy	Colorado State University, Sociology	Assessment of Little Shop of Physics	P
Marat Khairoutdinov	Colorado State University	Development of CSRMs and MMFs	P
Sonia Kreidenweis	Colorado State University	Use of MMFs with aerosol and cloud microphysics parameterizations	P
David Krueger	Colorado State University, Physics	Development of transdisciplinary course for CSU undergraduates	P
Steven Krueger	University of Utah	Development of improved MMFs	P
Christian Kummerow	Colorado State University	Liaison to TRMM and GPM; use of these datasets for model evaluation	P
David MacPhee	Colorado State University, Human Development & Family Studies	Study of diversity in connection with MMAP's Education and Outreach activities	P

Table 15: Project personnel at academic institutions. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Patrick McCormick	Hampton University	Use of satellite data to evaluate MMF results	P
Robert Pincus	University of Colorado	Development of conventional cloud parameterizations	P
David Randall	Colorado State University	Principal investigator; further development of the MMF	P
Steven A. Rutledge	Colorado State University	Model evaluation using radar data	P
Wayne Schubert	Colorado State University	Associate Director for Knowledge Transfer; further development of the MMF with an emphasis on the choice of governing equations	P
Richard Somerville	University of California, San Diego	Further development of the MMF	P
Graeme Stephens	Colorado State University	Model evaluation based on CloudSat data	P
Bjorn Stevens	University of California, Los Angeles	Development of conventional parameterizations	P

Table 16: Project Personnel at National Laboratories. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Thomas Ackerman	Pacific Northwest National Laboratories	ARM Chief Scientist; model evaluation using ARM data	P
Ric Cederwall	Lawrence Livermore National Laboratory	Model evacuation using CAPT	P
Philip Duffy	Lawrence Livermore National Laboratory	Role of MMF in high-resolution climate modeling	P
Steven Ghan	Pacific Northwest National Laboratories	Research on aerosols and cloud microphysics in climate change	P
Gerald Potter	Lawrence Livermore National Laboratory	Model evaluation, in part using CAPT	P

Table 17: Project Personnel in the Federal Government. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Robert Atlas	Goddard Space Flight Center, NASA	Use of MMFs for assimilation of cloud and precipitation data	C

Table 17: Project Personnel in the Federal Government. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Leo Donner	Geophysical Fluid Dynamics Laboratory, NOAA	Development of improved MMFs and improved conventional parameterizations	C
Stephen Lord	National Centers for Environmental Prediction, NOAA	Potential of MMFs to improve weather forecasts	C
William Rossow	Goddard Institute for Space Studies, NASA	Model evaluation, especially using ISCCP data	C
Wei-Kuo Tao	Goddard Space Flight Center, NASA	Development of improved MMFs, and application to data assimilation	C
Bruce Wielicki	Langley Research Center, NASA	Model evaluation using space data	C
Kuan-Man Xu	Langley Research Center, NASA	Development of boundary-layer parameterizations for use in the MMF	C

Table 18: Project Personnel in the private sector. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Kurt Ackman	Apple Computer	Liaison to Apple Computer	P
James Abeles	International Business Machines	Liaison to International Business Machines	C

Table 19: Project Personnel in Non-Governmental Organizations. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
William Collins	National Center for Atmospheric Research	Developer of radiative transfer parameterizations; Liaison to CCSM	P
Howard Drossman	The Catamount Institute	Liaison to the Catamount Institute; also listed under “Colorado College”	P
Susan Foster	University Corporation for Atmospheric Research	Lead developer of SEE-ME	C
Wojciech Grabowski	National Center for Atmospheric Research	Development of improved CSRMs and MMFs	P

Table 19: Project Personnel in Non-Governmental Organizations. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
James Hack	National Center for Atmospheric Research	Development of cloud parameterizations, development of simple models that capture the essence of the cloud-climate problem; Liaison to CCSM	P
Andrew Heymsfield	National Center for Atmospheric Research	Parameterization of ice microphysics	P
Joseph Klemp	National Center for Atmospheric Research	Liaison to WRF	P
Donald MIddleton	National Center for Atmospheric Research	Data management and high-speed networking strategy	P
Chin-Hoh Moeng	National Center for Atmospheric Research	Deputy Director; development of boundary-layer parameterizations for use in the MMF	P
Mitchell Moncrieff	National Center for Atmospheric Research	Development of the MMF	P
Rajul Pandya	University Corporation for Atmospheric Research	Director of SOARS	C

Table 20: Project Personnel in State and Local Government. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Kenneth Bennett	Thompson School District, Loveland, Colorado	Liaison to Thompson public schools; development and evaluation of SEE-ME	C
David Swartz	Poudre School District, Fort Collins, Colorado	Liaison to Poudre public schools; development and evaluation of SEE-ME	C

Table 21: International Project Personnel. In the rightmost column, a P indicates that the institution is a MMAP Partner (cost-sharing) while a C indicates that the institution is a collaborator (no cost sharing).

Name	Institution	Role in MMAP	Collaborator or Partner?
Howard Barker	Meteorological Service of Canada	Radiation parameterization for the MMF, including multi-dimensional radiative transfer; scientific participant in MMAP workshops	P
Christian Jakob	Bureau of Meteorology Research, Australia	Model evaluation, especially based on ARM data; scientific participant in MMAP workshops	P
Masahide Kimoto	Center for Climate Systems Research, University of Tokyo, Japan	Scientific participant in MMAP Workshops; development of improved MMFs	P
Martin Miller	European Centre for Medium Range Weather Forecasts, England	Scientific participant in MMAP Workshops; model evaluation through NWP	C
Tomoe Nasuno	Frontier Research Project for Global Change, Japan	Scientific participant in MMAP Workshops; development of improved CSRMs	P

15.b List of Collaborators/Individuals with Conflicts of Interest.