Center for Multiscale Modeling of Atmospheric Processes

Principal Investigator: David A. Randall, Colorado State University

This is a proposal to renew the Center for Multiscale Modeling of Atmospheric Processes (CMMAP) for five more years of support as an NSF Science and Technology Center. The lead institution is Colorado State University.

Research

CMMAP's research vision is to dramatically improve our ability to understand and predict the role of cloud processes in the climate system. Such predictions are made using climate models, which include physically based representations of the atmosphere, the ocean, the land-surface, and the cryosphere. The models run on the most powerful computers available. They are being used to forecast the climatic effects of anthropogenic changes in the composition of the Earth's atmosphere. These forecasts serve as input to policy decisions that have enormous economic implications for the U.S. and the world. Cloud feedbacks are the largest sources of uncertainty in climate-change predictions. A broad international community of reseachers is working to improve the representation of clouds in climate models. CMMAP's unique role, within this larger community, is to take advantage of its academic setting, sustained funding, and talented research team to attack important research problems that are too risky to undertake in a mission-oriented center or laboratory. CMMAP's research goals are to create a flexible new family of global atmospheric models based in part on explicit simulation of individual large clouds, with state-of-the art parameterizations of cloud particle formation, turbulence, and radiation. CMMAP models are used in "academic applications" focused on multiscale interactions of the atmosphere with the ocean (including sea ice) and the land-surface. We perform and analyze extended simulations of present and future climates, and critically evaluate the results using a wide range of observations. CMMAP's research is important because our models, especially the Multiscale Modeling Framework, uniquely avoid the questionable closure approximations used to represent deep cumulus clouds in conventional models, while still running fast enough to be used in simulations of climate change.

Knowledge Transfer

CMMAP's work benefits both climate modeling centers and numerical weather prediction centers. Our main Knowledge-Transfer partnership in the climate modeling arena is with the Community Climate System Model (CCSM) project, which is led by the National Center for Atmospheric Research. CMMAP will collaborate with CCSM in connection with the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), which will be completed in 2013. CMMAP and CCSM scientists will perform simulations of direct relevance to AR5, using CMMAP computing resources, and a unique model created by CMMAP using some components from the CCSM. Analysis of the simulation results will provide a basis for evaluation of the cloud-related feedbacks on climate change, in comparison with results from a conventional version of the CCSM. Our results will be provided as input to the IPCC's Assessment. On the weather prediction side, CMMAP will continue its partnership with the National Centers for Environmental Prediction (NCEP), and will also begin a new partnership with the Earth System Research Laboratory (ESRL). CMMAP will organize an international intercomparison of very high-resolution global dynamical cores.

In addition, CMMAP will organize both graduate university classes and summer schools aimed at training future global modelers. The content will deal with both the conceptual basis and the practical implementation of global models. Our goal is to create a national training resource for global modelers.

CMMAP will create a non-technical online publication, tentatively called *ClimateSense*, whose mission is to provide a venue for a multidisciplinary conversation surrounding the Earth's climate and climate change, and to promote Earth-Science literacy.

Education

According to Ralph Cicerone, the President of the National Academy of Sciences, "scientists are necessary but not sufficient to solve the climate problem.” CMMAP’s educational initiatives will both train necessary scientists and contribute to a sufficiently-educated larger culture. We will continue to support 25 graduate students at seven universities who are up to their eyeballs in the details of inventing the new multiscale mdoels of the climate system.These students will be among the leadership of an emerging generation of climate scientists, and besides their outstanding scientific education they are being trained as professionals in teaching, writing, and research skills. They participate in summer workshops on proposal writing, supercomputing, classroom teaching, and in undergraduate teaching fellowships. They learn about the role of science in hte larger culture through intensive workshops in climate policy and in focus groups with school teachers and other community leaders. At the undergraduate level, we will offer three new courses in global change at CSU and Colorado College. CMMAP will support ChangingClimates @ CSU, a curriculum infusion program designed to enhance undergraduate climate content across all academic disciplines. We sponsor climate lectures attended by thousands of undergraduates each year, and have engaged over 80 faculty members from 37 departments, and are working to disseminate this approach to colleges and universities nationwide. CMMAP supports K-12 science and Earth Science education through the Little Shop of Physics (LSOP), which develops curricular materials and visits engages more than 20,000 students in public schools each year with its unique brand of hands-on inquiry-based investigations. Each year, we conduct classes for middle school science teachers, a summer camp for middle school students from underrepresented groups, and a statewide conference on climate change for high school students. Our educational materials are disseminated world-wide to teachers and students in both Spanish and English through the *Windows to the Universe* website, reaching over 20 million unique useers each year.We will study, document, and disseminate experimental research on all these activities through structured partnerships with sociologists and educational psychologists.

Diversity

Understanding the climate system and addressing the concerns of our society requires engagement with the full suite of cultural perspectives and the human capital of the larger US population. During Years 6 - 10, we will enhance connections between LSOP, SOARS and other diversity and education efforts. Our annual summer course on Teaching Climate will focus on schools with populations of students that are underrepresented in science fields. We will continue to work with Native American populations, building on the relationships we have already established with schools on Pine Ridge, Navajo, and Mountain Ute lands. We will continue to offer a one-week summer workshop on weather and climate as part of CSU’s participation in the NSF-supported Math-Science Partnership. CMMAP is participating in an NSF-sponsored initiative to develop a unique course on climate and global change to be taught at Tribal Colleges across the USA. Scott Denning and Raj Pandya attended the planning workshop for this activity in 2009, and will continue to participate in years one and two of the renewal.

We will conduct a transdisciplinary and multicultural conversation about climate change with leaders from diverse schools across our region, on native lands and in tribal colleges, in inner-city and rural farm communities, and with stakeholders and policymakers at various levels of government. We have designed and implemented a mostly qualitative study to track the experiences of women and men across ethnicities and nationalities from the undergraduate to the early postdoctoral years in Climate Science and related STEM fields. We will study how the atmospheric/climate science “leaky pipeline” can be made less porous using existing institutional data sets. .

Legacy

The legacy of CMMAP will include important new modeling tools that are used to provide substantially more reliable predictions of climate change, as well as more accurate weather forecasts. Our most important legacy will be the cadre of diverse young scientists we have trained, who will share a sense of the context of their work in the larger culture, and the many thousands of K-12 students who we have influenced through the Little Shop of Physics and our Teacher Training course.

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*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

III. Project Description

(3a) Rationale for Center Concept

CMMAP's research and knowledge-transfer (RKT) goals are to drastically improve the representation of cloud processes in global atmospheric models through the explicit representation of cloud processes on fine grids, accomplished through various computational strategies including the multi-scale modeling framework (MMF) and global cloud-resolving models. Today, many of the world's major modeling centers are moving quickly to develop such capabilities. CMMAP is a Center, not a project, in part because it brings together scientists from a broad range of disciplines at dozens of institutions to work towards this common goal. The team includes climate modelers, cloud modelers, and experts on turbulence, radiation, cloud physics, and observations. The end results include improved understanding of important climate phenomea, such as the Madden-Julian Oscillation and cloud feedbacks on climate change.

In addition, however, CMMAP is a Center because, like all STCs, its mission goes far beyond research. CMMAP devotes enormous amounts of time and energy to its Education and Diversity (ED) components. Although, at the beginning, CMMAP's ED plans were, quite frankly, developed in response to NSF guidelines, once the Center was up and running we quickly found that the ED activies provide as much satisfaction as the RKT work. With this proposal, for example, we are designing more complex and more evidence-based evaluations of CMMAP's educational activities, with an eye towards strengthening the claims we make for causal links between our activities and important participant outcomes. Now, with the perspective that comes from 3+ years of nurturing the Center, we can see that CMMAP's ED mission is highly complementary to its RKT mission. We have vertical integration within our RKT and ED stovepipes, but we also have horizontal integration between RKT and ED. Our ED activities make our RKT activities work better, and vice versa. The interdisciplinary collaborations within the Center allow us to accomplish more than ED or RKT could do separately.

CMMAP's students, teachers, and researchers fit together comfortably and productively as a team. The broad spectrum of CMMAP's activites has made the Center into a true collaborative community, populated by a variety of people with a range of interests, skills, goals, and ages, working together to help each other succeed. CMMAP integrates atmospheric scientists, writers, sociologists, computer scientists, policy analysts, educational psychologists, and others, who work together towards common goals whose value and importance we collectively acknowledge and appreciate. CMMAP has a culture. It is much more than a conventional "three years and a cloud of dust" research project.

CMMAP's graduate students are immersed in the Center's culture. They see, and some of them participate in, the training of high-school science teachers and the teaching and mentoring of diverse undergraduates. The students work collaboratively with faculty, solving problems together. Through "the Center experience," these future leaders are gaining a broad and deep perspective on what it means to be a scientist. In years to come, the larger U.S. society will benefit from this.

The Center's research, education, and diversity missions have the potential to feedback positively on each other. Through its outreach and education work, CMMAP has built credibility with diverse communities. This credibility invites those communities to consider how CMMAP's science mission can serve their priorities. CMMAP's experience in knowledge transfer provides strategies for moving from the basic research to practical knowledge that the communities can use. Finally, the broad experiences of CMMAP graduate students prepare them to link research, education, and diversity. This a positive feedback loop that enriches the research, attracts diverse communities and students, and transfers knowledge to users, all based on the connections that are forged within the Center.

Writing this renewal proposal has focused our thoughts on the post-STC legacy of CMMAP. We want the important work that we have started to continue. On the Research and Knowledge Transfer side, sustainability can be achieved through future grant proposals, combined with continuing cost-share from our institutions. We are planning to spin-off a self-supporting non-profit corporation that can contine our

ED work. Through personal contacts created during the life of the STC, we will maintain the connections between the RKT and ED components of our work.

(3b) Narrative Description of the Management Plan

Partner Organizations and Lead Personnel

The lead institution for CMMAP is Colorado State University (CSU), which carries out a wide range of research activities, plus graduate education, and K-12 education through the Little Shop of Physics (LSOP). CSU also conducts a study of diversity in climate science, and an evaluation of the impact of the LSOP program. In addition, CMMAP is infusing CSU's undergraduate curriculum with climate -related content.

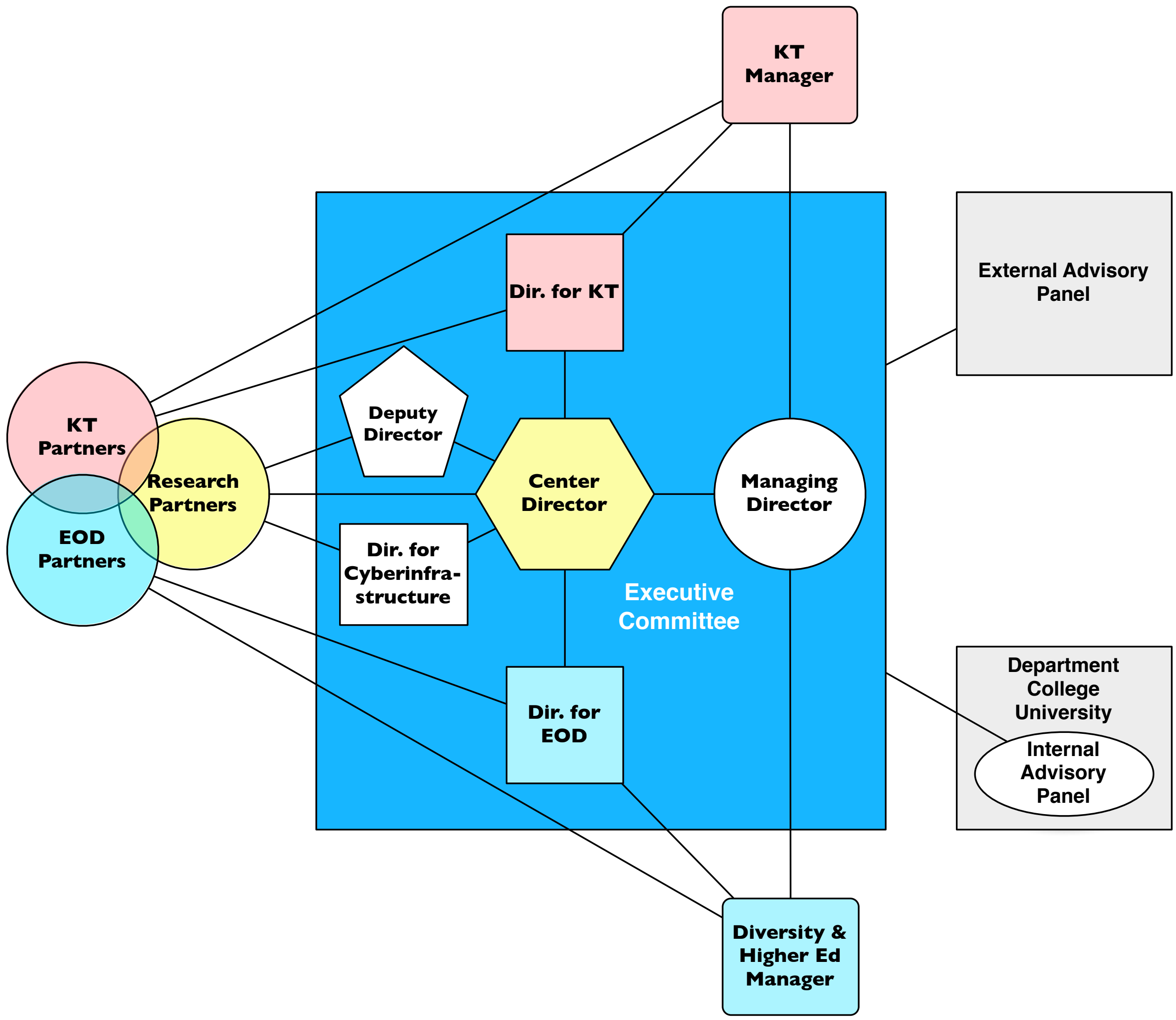

Figure M1: CMMAP's management structure. Here "KT" stands for Knowledge Transfer, "EOD" stands for Education, Outreach, and Diversity, and MD stands for Managing Director. The blue box represents the Executive Committee.

Within CSU, CMMAP is a project within the Department of Atmospheric Science, which, in turn, is part of the College of Engineering. The Head of the Department of Atmospheric Science has lead responsibility for personnel actions, account management, and space allocations. CMMAP management relies on Department of Atmospheric Science staff to approve purchases. CMMAP is comfortably housed in a building that was created for it. The building was completed in April 2009. It is managed by the Department of Atmospheric Science.

The lead individuals at CSU are CMMAP's Director, Prof. David Randall; the Director for Education and Outreach, Prof. A. Scott Denning; the Director for Knowledge Transfer, Prof. Wayne Schubert; and the Managing Director, Cindy Carrick. The other lead partner institutions are the National Center for Atmospheric Research (NCAR), which employs CMMAP'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 employs Dr. John Helly, CMMAP's Director for Cyberinfrastructure.

Fig. M1 summarizes CMMAP's management structure. 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 are open, including especially the Center Director's door.

The CMMAP Center Director has overall management responsibility for the Center, but delegates to and relies heavily on the other members of the management team. CMMAP's Principal Investigator and Center Director is Prof. David Randall of CSU, who devotes 50% of his time to this activity, and directs the research activities of CMMAP. Prof. Randall has conducted extensive research on global atmospheric models and cloud processes over the past 35 years. The Center Director has the lead responsibility for the overall direction of the Center. In addition, he has the lead responsibility for managing interactions with CMMAP's Research partners.

CMMAP's Deputy Director is 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 Deputy Director

The Director for Education, Outreach, and Diversity (EOD) is Prof. A. Scott Denning of CSU. Prof. Denning's research on the global carbon cycle has demonstrated the importance of multiscale interactions between the atmosphere and the land surface. To assist Prof. Denning, CMMAP employs a full-time Diversity and Higher Education Manager, Melissa Burt, who has a Master's Degree in Atmospheric Science. The Director for EOD has the lead responsibility for managing interactions with CMMAP's EOD partners.

The Director for Knowledge Transfer (KT) is Prof. Wayne Schubert of CSU. Prof. Schubert has been very active in research on cloud parameterization and numerical modeling, for more than 35 years. To assist Prof. Schubert, CMMAP employs a full-time Knowledge-Transfer Manager, Rodger Ames, who has a Master's Degree in Atmospheric Science, and has played a particularly strong role in CMMAP's publishing activities. The Director for KT has the lead responsibility for managing interactions with CMMAP's KT partners.

The Director for Cyberinfrastructure is 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. He has responsibility for managing CMMAP's cyberinfrastructure needs, including computing resources, data archival and distribution, and a variety of other issues related to high-performance computing.

CMMAP's Managing Director is Cindy Carrick. She functions as a "Chief of Staff." She manages the Center's finances, coordinates activities, and facilitates interactions among center personnel and with external entities. She participates in program development. She ensures that CMMAP meets the NSF reporting requirements in a timely fashion, and monitors the Center's compliance with university and Federal policies. She supervises a full-time assistant and the Center's part-time Ethicist, and co-supervises the Managers of KT and EOD.

The Executive Committee

CMMAP's Executive Committee (EC) consists of the Center Director, the Deputy Director, the Managing Director, and the Directors of Education and Diversity, Knowledge Transfer, and

Cyberinfrastructure. The EC members orchestrate CMMAP's overall scientific direction, manage the budget, initiate or discontinue partnerships and collaborations, monitor progress relative to established milestones, develop diversity, enforce the highest standards of ethics and research quality, and promote broad dissemination of results.

The EC teleconferences frequently in order to conduct business without excessive travel. Other CMMAP personnel participate in the teleconferences as appropriate. The EC meets face-to-face in conjunction with each of the CMMAP Team Meetings, NSF Site Visits and External Advisory Panel (EAP) meetings, for a minimum of four times per year.

Financial management

In order to efficiently satisfy NSF reporting requirements, we have created separate CSU accounts for each of the Objectives under Research, EOD, and KT,. We also have a separate account for Management-related expenses. In addition, we have three cost-share accounts, and a gift fund account.

Financial transactions initiated by any CSU CMMAP Team Member are approved by staff in the office of the Department of Atmospheric Science. Required backup documentation and transaction paperwork are relayed to CMMAP staff, who use that information to reconcile CMMAP accounts. During reconciliation, CMMAP staff can identify inappropriate transactions, and make any necessary journal-entry corrections. CMMAP staff follow up with Department staff to resolve issues, as needed.

Maintaining an effective and integrated team

CMMAP involves dozens of scientists at widely separated institutions. Communication within the team is a key to CMMAP's success. We hold two CMMAP Team Meetings per year, each lasting three days. The meetings are conducted as "Workshops," with presentations focusing on recent results and near-term plans, and a lot of discussion time. Each Team Meeting also includes several longer, invited talks, including some by scientists who are not part of CMMAP. Half of the Team Meetings are held in Fort Collins, and half elsewhere. We also use teleconferences and video conferences as appropriate.

CMMAP has created Research Working Groups that undertake projects aimed at making progress towards CMMAP's Research Objectives. The Working Groups have breakout sessions at CMMAP Team Meetings. The number and make-up of the Working Groups evolve as appropriate over the life of the Center.

Advisory Panels

CMMAP's EAP meets at least once per year. It consists of six members, including a Chair. The members include representatives of academia, atmospheric science research centers, a computing center or company, and the education sector. The EAP monitors CMMAP's progress, and makes recommendations to the EC. The members of the EAP serve three-year terms, and the Chair rotates every two years. The current members are George Kiladis (Chair, NOAA), Larissa Back (MIT), Michael Wehner (Lawrence Berkeley National Laboratory), Brian Mapes (U. Miami), Marco Molinaro (UC Davis), and Anthony DelGenio (NASA Goddard Institute for Space Studies).

For Years 6 - 10, CMMAP will have an "Internal Advisory Panel" composed of CSU Administrators and faculty, and Chaired by CSU's Vice President for Research and Engagement, currently William Farland. The Internal Advisory Panel provides advice to CMMAP's Executive Committee.

Succession plan

NSF requires that this proposal include a plan for succession of the Center leadership. If Prof. Randall is unable to continue as the CMMAP P.I./Center Director, he will be replaced by Prof. Wayne Schubert of CSU, who has agreed to be designated as "next in line" for the CMMAP directorship.

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

(3c) Narrative description of the Research Objectives of the Integrated Center

Vision Statement for Research

Cloud and aerosol feedbacks are the largest sources of uncertainty in 50-year forecasts of climate change (Solomon et al., 2007; Bony et al., 2006). Both deep thunderstorms and shallow stratiform clouds have powerful effects on the climate system. A broad international community of reseachers is working to improve the representation of these clouds in global atmospheric models. CMMAP's unique role, within

Objectives	Focus areas	Key Scientists	Timeline
1. Further development of global models with diverse representations of cloud processes	Continue work with the prototype MMF	Khairoutdinov**, Randall**	Ongoing
	Complete development of the Q3D MMF, and perform climate simulations with it	Arakawa, Jung, Konor, Heikes	Global version by Year 6
	Complete development of the GCRM, and perform short climate simulations with it	Heikes, Konor, Randall	First version by Year 6
	Development of a unified parameterization	Arakawa, Randall, **Krueger**, Jung	Ongoing
2. Further development and testing of improved parameterizations of microphysics, turbulence, and radiation	Develop and test improved microphysics parameterizations	**Morrison**, Grabowski, Ghan, P. DeMott, Krueger	Ongoing
	Develop and test improved turbulence parameterizations	**Moeng**, Krueger, Randall	Ongoing
	Develop and test improved radiation parameterizations	Pincus, Collins, Ackerman	Ongoing
3. Application of CMMAP models to study multiscale interactions of the atmosphere and land-surface	Land-atmosphere interactions in the current climate	**Denning**, **Bonan**	Ongoing
	Changing roles of biogeochemistry and land-use change in future climates	Denning, Bonan	Ongoing
4. Application of CMMAP models to study the coupled climate system	Studies of cloud feedback	**Bretherton**, Blossey, Stevens, C. DeMott	Ongoing
	Studies of the MJO	**Maloney**, Waliser, Schubert, Randall	Ongoing
	Climate simulations using the MMF in a coupled model	Stan, C. DeMott, Randall	Ongoing
5. Community-based evaluation of results produced by CMMAP models, through the use of diverse observations	Participation in Intercomparisons	**C. DeMott**, Randall	Ongoing
	Experimental NWP using the GCRM	**Konor**, Randall	Start in Year 6
6. Management, analysis, and visualization of very large model output datasets -- creation of infrastructure	Resource procurement and distribution	**Helly**, Randall	Ongoing
	Data management	**Schuchardt**, Heikes	Year 6
	Analyzing and visualizing model results	Konor, Schuchardt, Heikes	Ongoing

Table R1: A summary of CMMAP's Research Objectives for Years 6-10, including required actions, key scientific participants, and a timeline. The Objectives are listed in order of priority. The scientists listed in bold face are the Objective Leaders.

this larger community, is to take advantage of its academic setting, sustained funding, and talented research team to attack important research problems that are too risky to undertake in a mission-oriented center or laboratory that is constrained by operational or quasi-operational deadlines and commitments. Specifically, CMMAP:

- Draws on a broad cross-section of the Atmospheric Science research community to create qualitatively new types of global atmospheric models that can flexibly and realistically represent the effects of clouds on weather and climate, across a wide range of scales;
- Evaluates the new models by systematic comparison with observations;
- Applies the new models to investigate how clouds influence the multiscale interactions of the atmosphere with the vegetated land surface and the oceans, including climate change scenarios.

Goals and Objectives

CMMAP's Research Objectives for Years 6-10 are summarized in Table R1. In the following Sections, with red section headings, each Objective is briefly described.

1. Further development of global models with diverse representations of cloud processes

Continue work with the prototype MMF

Until about ten years ago, conventional general circulation models (GCMs) were the only global

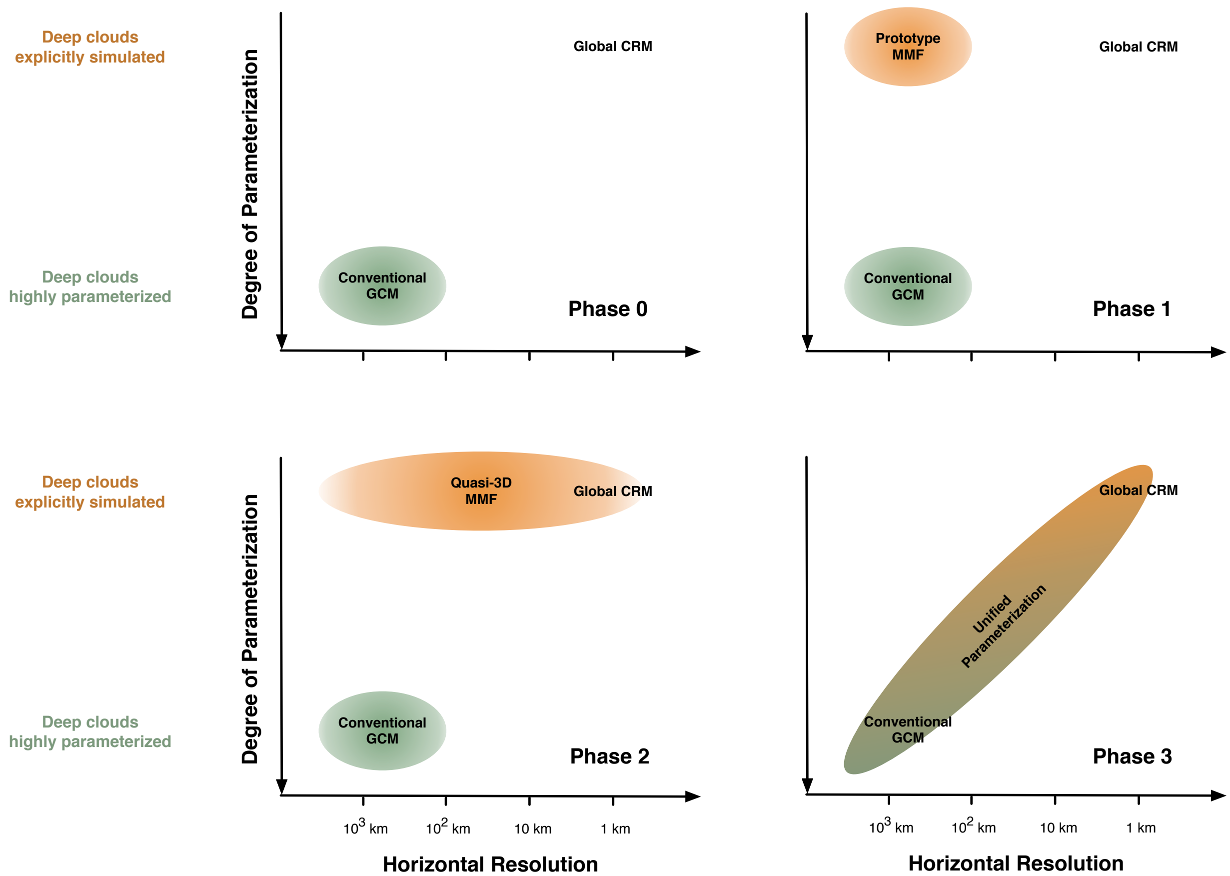

Fig. 1: Sketch showing the relationships between horizontal resolution (horizontal axis in each panel) and degree of parameterization (vertical axis, increasing downward), for various model types. See text for explanation.

atmospheric models. As shown in the upper left panel of Fig. 1, labeled "Phase 0," conventional GCMs have coarse horizontal resolutions and highly parameterized representations of deep convection. In the figure, the abscissa is the horizontal resolution and the ordinate is the degree of parameterization, increasing downwards.

In the prototype MMF, the cloud parameterization of a GCM is replaced by a 2D cloud-resolving model (CRM) embedded in each GCM grid box. Thus the prototype MMF uses the CRM physics while staying with the conventional resolution for the GCM as shown in the top right panel of Fig. 1, labeled "Phase 1. " Largely through the work of CMMAP, prototype MMFs have been extensively explored and exploited over the past ten years, and important results have been obtained. This work will continue in Years 6-10, focusing on:

- The effects of improved parameterizations of microphysics, turbulence, and radiation, which have been developed during Years 1-5, and are discussed in Section 2 below;
- Multiscale interactions of the atmosphere and the land-surface, as discussed in Section 3 below; and
- The Madden-Julian Oscillation (MJO), atmosphere-ocean interactions, and low-cloud feedbacks on climate change, which are discussed in Section 4 below.

Complete development of the Q3D MMF, and perform climate simulations with it

Limitations of the prototype MMF arise from the two-dimensionality and periodic boundary conditions of the embedded CRMs. As a result, important dynamical interactions between convection and the mean flow, including convective momentum transports, cannot be represented even approximately. CMMAP has developed a second-generation MMF, called the Quasi-3D (Q3D) MMF, which is an attempt to overcome these limitations of the prototype MMF without necessarily using a fully three-dimensional CRM. This is accomplished by using a "gappy" grid in the Q3D CRM, which allows a partial representation of 3D processes, following the "vector vorticity" approach of Jung and Arakawa (2008). The Q3D MMF converges to a fully 3D global CRM (GCRM) as the GCM's resolution is refined. Consequently, the horizontal resolution of the GCM can be freely chosen depending on the objective as shown in the bottom left panel of Fig. 1, labeled Phase 2. Preliminary results from the Q3D CRM are very encouraging, and we are confident that it will become a useful framework for climate modeling by the end of CMMAP's Year 6.

Complete development of the GCRM, and perform short climate simulations with it

CMMAP's GCRM (discussed in the section on Prior Accomplishments) and the Q3D MMF have many common elements. The GCRM will be used in part as a benchmark for the global Q3D MMF. During Years 6 - 10, we will use CMMAP resources to perform simulations with the GCRM, and to test it with improved parameterizations of microphysics, turbulence, and radiation, discussed in Section 2 below.

Work towards the development of a unified parameterization

Deep cumulus convection is a multiscale phenomenon with narrow, cloudy, precipitating updrafts surrounded by very broad, unsaturated sinking regions. At present there are only two ways to represent deep clouds in climate models: statistical parameterization, which must be used when the entire cumulus circulation is subgrid-scale; and explicit simulation, in which the entire cumulus circulation, incuding the convective updrafts, is resolved.

The left panel of Fig. 2 schematically shows a typical vertical profile of moist static energy source inferred from $Q_1 - Q_2$, where Q_1 and Q_2 are the "apparent heat source" and "apparent moisture sink" (Yanai et al., 1973) obtained as the residuals in observed *large-scale* heat and moisture budgets, and currently simulated by large-scale models using conventional parameterizations. These profiles are dominated by the effects of vertical transports. The right panel, on the other hand, shows vertical profiles of the moist static energy source expected from the *local* cloud microphysics, which are explicitly simulated in a GCRM. Any space/time/ensemble average of the three profiles in the right panel does NOT give the profile in the left panel. This means that the physical parameterizations of a large-scale model must be qualitatively different from those of a fine-scale model.

Ideally, as the horizontal resolution is refined, a global model's physics should continuously transition, in a physically based way, from the highly parameterized GCM physics to the CRM physics. This ideal can be called a "*unified parameterization*. " It is shown in the bottom right panel of Fig. 1, labeled Phase 3. In the unified parameterization, the degree of parameterization varies smootly and continuously with the horizontal resolution of the model. No unified parameterization currently exists, and as far as we know, none is under development. We do not interpret Phase 3 in Fig. 1 as the second

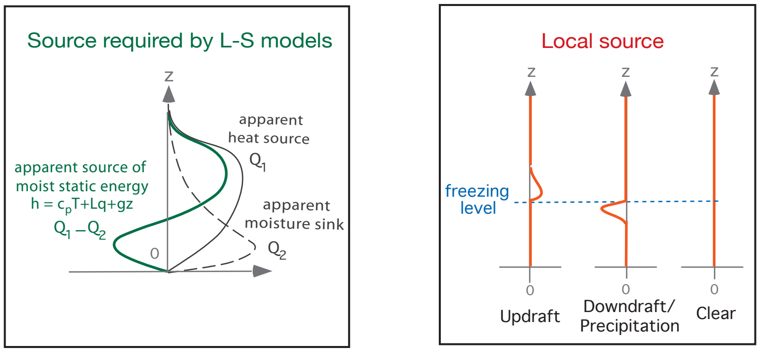

Fig. 2: The left-hand panel schematically shows the vertical distributions of the parameterized source of moist static energy (green line) required by large-scale (L-S) models. The contributions from the apparent heat source and apparent moisture sink are shown by the solid and dashed black lines, respectively. The right-hand panel shows the local source of moist-static energy due to freezing and melting.

five years of CMMAP; it merely refers to a future time at which a unified parameterization exists.

A future global model with a unified parameterization will be a very flexible and efficient simulation tool. It will be a good complement to the Q3D MMF, which has more explicit model physics but is naturally more expensive. Both the Q3D MMF and a global model with a unified parameterization can converge to a GCRM as the horizontal resolution is refined. More importantly, the scientific work required to create a unified parameterization will yield major improvements in our fundamental understanding of the interactions between cumulus cloud systems and larger-scale circulations. CMMAP boldy proposes to work towards the goal of a unified parameterization, with the understanding that complete success cannot be achieved within the lifetime of the Center as an STC.

Formulation of the resolution-dependent "convective eddy transport," i. e., vertical transports that are not resolved in coarse-resolution models, is a key to the development of a unified parameterization. Such transports play a crucial role in coarse-resolution models, but should vanish when convection is explitly resolved! The latter requirement is not satisfied by conventional parameterizations. In the large-scale cumulus parameterization of Arakawa and Schubert (1974), for example, the fractional area covered by updrafts is assumed to be small. A consequence is that the effects of convective eddy transport can be expressed in terms of the subsidence and detrainment effects in the cloud environment, which are independent of the fractional area and therefore independent of the resolution. The convective eddy transport is related to the fraction of the entire convective circulation (cloudy updraft and unsaturated environment subsidence) that occurs within a grid box (Krueger, 2002). As this fraction goes to zero, so does the convective eddy transport. What we must do in a unified parameterization is formulate the convective eddy transport in such a way that it vanishes when the resolution is sufficiently high. To do this, we obviously need idealizations, as is true for any parameterization, but as long as the formulation satisfies the above requirement, convergence to an explicit simulation is guaranteed.

Another important issue is the statistical nature of the parameterization problem. As a model's horizontal grid spacing becomes finer, the number of clouds within a GCM grid box becomes smaller, so that the statistical significance of the grid-box average is lost (e. g., Xu et al., 1992). For this reason, a parameterization should include a stochastic component, generally becoming stronger as the resolution increases. In the limit as the resolution becomes high enough to resolve individual clouds, however, the model itself tends to play the role of a random-process generator, so that the role of the stochastic component decreases (Krueger, 2002).

Global weather prediction models are now running with ~30 km grid spacings. There are plans for climate change simulations with comparable grids. These high-resolution models benefit from well-resolved topographic forcing and a broad spectrum of fluid dynamical scales, but at present there is no strong empirical or theoretical basis to use cloud parameterizations with 30 km grid spacings. Our studies of unified parameterizations will help to provide such a basis.

We recognize that the development of a resolution-dependent formulation of the convective eddy transport is a very challenging task, requiring multiple approaches, including data analysis. The required data must be very comprehensive, covering the almost continuous space-time spectrum of many coupled variables. There is little hope that observations can meet these requirements, but results from CRMs and LES (large-eddy simulations) can be very useful for inspiring, evaluating, and refining ideas. Jung and Arakawa (2004) provide an example of how this can work. They compared CRM results, with microphysics, to a low-resolution model without microphysics. They showed that, as the resolution changes, a transition takes place between a composite of the three profiles shown in the right panel of Fig. 2 and a profile similar to that shown in the left panel. In their analysis, a control simulation was performed first, using a CRM with full physics or a component of the physics. Then a low-resolution version of the same model without physics was run starting from a particular realization of the control simulation for a certain time interval. The difference between the results of these two runs, accumulated over the time interval, gives the parameterized source needed by the low-resolution model. To obtain useful statistics, this procedure is carried out for many realizations of the control simulation under the same external conditions (e. g., at the same local time of day). The ensemble/domain average is computed, along with the associated standard deviation. This is repeated for different low-resolution model grid sizes and different time intervals.

In Years 6 -10, we will follow three approaches based on the method outlined above, to work towards a unified parameterization:

Approach I: Guide unification of the GCM physics and the CRM physics through an analysis similar to that of Jung and Arakawa (2004). Analysis of the resolution-dependent stochastic component of the convection should also be emphasized this time.

Approach II: Guide unification of the CRM physics and the LES physics, including resolution-dependent formulations of shallow clouds and cloud-PBL interactions. LES data for a relatively small domain (a few hundred kilometers across) can be used for this task.

Approach III: Obtain a broad coherent view of the multiscale transitions from the GCM physics all the way to the LES physics, using data from an LES with a horizontal domain size of at least 1,000 km. This huge but necessary task is a natural undertaking for CMMAP.

1. Further development and testing of improved parameterizations of microphysics, turbulence, and radiation

The parameterizations discussed in this Section can be used in the prototype MMF, the Q3D MMF, and the GCRM. Many of them can also be used in conventional GCMs.

Develop and test improved microphysics parameterizations

Aerosols and microphysics play an important and still poorly understood role in the Earth's climate (e. g., Solomon et al., 2007). Cloud microphysics governs the formation, growth and fallout of water and ice particles in clouds, while aerosols act as cloud condensation nuclei or ice-forming nuclei. Two-moment schemes can represent the evolution of cloud and precipitation particle size distributions and the effects of nucleating aerosols. CMMAP is collaborating with an ambitious DOE-sponsored effort led by S. Ghan (PNNL) to implement cloud-aerosol interactions into the MMF. We propose to design and test both warm-rain and ice schemes (e. g., Grabowski 1998, 1999; Morrison et al., 2003, 2005a, 2005b; Morrison and Grabowski 2007, 2008a, 2008b, 2009; Morrison and Gettelman 2008). We will use tests in which simulations are compared to observations of individual cloud systems, through participation in community-based intercomparisons (cf. Section 5). Detailed bin-microphysics schemes will be also used as benchmarks. Simplified formulations (e. g., Phillips and Donner, 2007) will be explored to find the best balance between cost and accuracy. Specific tasks are as follows:

- We will couple warm-rain microphysics with prognostic aerosol in the MMF and GCRM to simulate aerosol indirect effects in liquid clouds. This work will involve coupling of our two-moment warm-rain scheme with a prognostic aerosol scheme and PDF (probability distribution function)-based representations of subgrid-scale variability.
- We will develop and test a scheme to represent the effects of entrainment and mixing on cloud droplet spectra in warm convective clouds (e. g., Chosson et al., 2007, Slawinska et al., 2008).
- We will couple ice microphysics with improved formulations of ice particle nucleation that are based on field and laboratory studies. This will enable CMMAP models to simulate aerosol effects in ice clouds, which may be important for global climate (e. g., Lohmann and Feichter, 2005).
- We will continue development and testing of a two-moment, three-variable ice scheme with a predicted rime mass fraction (Morrison and Grabowski, 2008 b), including an improved representation of graupel/hail density based on detailed observations, and an explicit treatment of crystal habit (shape).

Develop and test improved turbulence parameterizations

Advanced turbulence parameterizations have been developed by several CMMAP researchers during Years 1- 3, and continuing in Years 4 - 5. These include the schemes of Golaz et al., (2007), Cheng and Xu (2009), Lappen and Randall (2009), Firl (2009), and Bogenschutz and Krueger (2009). All of these make use of assumed multivariate PDFs with predicted second and/or third moments, following the approach of Randall et al., (1992) and Lappen and Randall (2001). These advanced parameterizations are being tested the CRM called SAM (Khairoutdinov and Randall, 2003), developed by M. Khairoutdinov, and also in the vector vorticity model of Jung and Arakawa (2008).

Meanwhile, R. Marchand has endowed SAM with an adaptive vertical grid scheme designed to better simulate stratocumulus clouds. The scheme has been tested using idealized cases for trade cumulus and nocturnal stratocumulus. Marchand and Blossey will test Marchand's adaptive gridding algorithm in the MMF. We will evaluate the results of these tests based on the realism of cloud cover over the subtropical oceans, as measured by cloud radiative forcing and the vertical distribution of cloud cover, along with a suite of standardized global climate model metrics (e. g., Park and Bretherton 2009) and output from satellite simulators (e. g., CloudSat and Calipso).

By the beginning of CMMAP's Year 7, we will create a version of the prototype MMF that combines enhanced grid resolution and improved subgrid turbulence parameterization. The improved parameterizations will also be implemented in the Q3D MMF and the GCRM. These models will be used in the studies discussed in Sections 3 - 5 below.

We will generate additional Giga-LES benchmark simulations of various convection systems including mid-latitude storms, to understand the complex interactions across physical scales from turbulence, shallow clouds, to deep convection (Khairoutdinov et al., 2009; Moeng et al., 2009). This work also supports the plans described at the end of Section 1.

Develop and test improved radiation parameterizations

We have developed an improved radiative transfer approach called Monte Carlo spectral integration (McSI; Pincus and Stevens, 2008), which replaces the temporally sparse, spectrally dense calculation of broadband fluxes at discrete times with temporally dense, spectrally sparse calculations. The method converges to a full radiative transfer calculation as the model's spatial and/or temporal resolution increases. McSI has been combined with RRTMG (Mlawer et al., 1997; Iacono et al., 2008), a widely used, state-of-the-art radiation parameterization. McSI is both less expensive and more accurate than earlier methods. We are at the point now of testing McSI in the prototype MMF. We propose to test McSI in conventional climate models, including the Community Climate System Model (CCSM).

CMMAP scientist W. Collins and collaborators have submitted a Climate Process Team proposal to enhance RRTMG by increasing its physical realism and incorporating emulators of satellite sensors. If their CPT proposal is funded, we will work to incorporate these improvements into the CMMAP models.

2. Application of CMMAP models to study multiscale interactions of the atmosphere and land-surface

Exchanges of heat, water, momentum, and trace gases are important determinants of atmospheric circulation and climate. These exchanges modulate surface climates and have direct impacts on human welfare, and are in turn strongly affected by human intervention such as land-use change, irrigation, and other management. It has long been recognized that mesoscale circulations driven by spatially-organized landscape patterns (e. g., agriculture, urban/suburban development, topography) can organize clouds and precipitation at regional scales (e. g., Avissar and Pielke, 1989; Schar et al., 1999; Weaver et al., 2002; Silva Dias et al., 2002). Regional field experiments investigating these interactions and the numerical experiments that have been used to interpret them have been confined to limited areas and require specification of lateral boundary conditions from larger-scale models or analyses. We propose to extend these analyses to the global scale using the multiscale modeling environment provided by CMMAP.

Current state-of-the-science land-atmosphere coupling in climate models allows heterogeneity of the land surface using non-spatially-explicit "tiles" to represent fractional areas with different states or parameters that all share the same overlying atmosphere: that is, they all share the same weather (e. g., Dickinson et al., 2006). A separate instance of the parameterized land surface is integrated once for each "tile" using forcing (e. g., radiation, temperature, precipitation) from the overlying atmosphere, and the resulting fluxes of heat, water, momentum, and carbon are weighted by the subgrid-scale areas of each tile before being passed back to the atmospheric model as a grid-scale mean. Subgrid-scale tiles may be organized by plant functional type (Bonan et al., 2002), or by hydrologic units such as catchments Koster et al., 2000; Chen and Kumar, 2001;) or the depth of the water table (e. g., Wood et al., 1992, Gedney et al., 2003; Decharme and Douville, 2006). Global models represent subgrid-scale heterogeneity based on variations in vegetation or topographically-distributed soil moisture, but none have considered the covariance of these effects. Although it is clear from field experiments and from numerical experiments with limited-area models that these variations affect precipitation (e. g., Schar et al., 1999, Silva Dias et al., 2002), it has hetetofore been impossible to include the feedbacks between heterogeneous landscapes and the overlying organization of clouds and precipitation.

Early experiments with the prototype MMF turned the logic of current climate models upside down: we simulated many interacting atmospheric columns in the SAM that interacted with only a single underlying land surface. In the second phase of CMMAP, we will explore the interactions between heterogeneous land surface vegetation, topography, soil moisture, and snowpack with the circulation, radiation, and hydrologic cycle of the overlying heterogeneous atmosphere, at multiple scales. These new experiments will be focused on two goals: (1) to better understand the role of land-atmosphere coupling in the current climate; and (2) to improve quantitative treatment of the roles of biogeochemistry and land-use in anthropogenic climate change.

Land-atmosphere coupling in current climate, hydrology, and the carbon cycle

We have coupled the Simple Biosphere model (SiB, Sellers et al., 1996; Baker et al., 2008; Denning et al., 2008;) to the cloud-resolving model (SAM) used in the prototype MMF. This allows treatment of heterogeneous clouds, radiation,precipitation, infiltration, runoff, soil moisture, and evapotranspiration within a single CAM grid column. Preliminary numerical experiments with the coupled model at the ARM Southern Great Plains site show improved timing of precipitation and simulation of surface fluxes relative to the more traditional couopling mode. We will use the coupled model to study boundary-layer turbulence and clouds in a Giga-LES experiment over land.

Extending the heterogeneous land surface to global simulations in the prototype MMF will require two innovations: (1) topographic variations within a single atmospheric model will have to be simulated in such a way that energy, water, mass, and other key quantitiareaes can be conserved; and (2) the heterogeneous land surface will have to be "sampled" and parameterized under each column of the global model. These problems are not independent, because vegetation type, soil moisture, and topography are highly correlated. Furthermore, representation of mesoscale circulations and fluxes will require that not only the fractional areas but also the covariance length scales (i. e., the "clumpiness") of the different sub-areas in each column be represented. We will experiment with a combined representation of vegetation and hydrological variations. Sellers et al., (2007) have shown that complex distributions of soil moisture can be represented with a fairly limited sample.

The global coupled model will be applied to studies of the impact of land-atmosphere coupling in current climate in the western US (with special emphasis on topographic control of snow cover and drought stress), in monsoon climates (emphasizing coupled onset and proagation), and in the Amazon (emphasizing fine-scale deforestation). Previous experiments have demonstrated the sensitivity of precipitation and circulation in the Amazon to the treatment of soil moisture dynamics (Baker et al., 2008, Harper et al., 2009). Field experiments and numerical experiments with limited area models have shown that fine-scale deforestation and land-use change affects organization of precipitation in that region (Silva Dias et al., 2002). Short expermments with the GCRM will be used to evaluate the multiscale coupled model of land-atmosphere interactions.

Quantitative Treatment of Biogeochemistry and Land Use in the 21st Century

We will also use the coupled land-atmosphere MMF to study the effects of land-use change and biogeochemistry in simulations of future climates. These simulations will use land-use change scenarios being developed using the IMAGE model. Historical and projected future land-use change scenarios are currently available on a 0. 5° grid. These will be downscaled using topographic controls and run in the coupled MMF. Coupled experiments will be performed ass part of the studies of anthropogenic climate change described under Objective 4.

3. Applications of the MMF to study the coupled climate system

Studies of cloud feedback

Over half of the globe is typically covered by shallow cumulus and stratocumulus cloud systems. CMMAP scientists have used the MMF to study low cloud feedbacks (Wyant et al., 2006, 2009), as well as the "semi-direct" effects of increased CO_2 on low cloud. Vertical transports in these cloud systems involve turbulent eddies, a few hundred meters across, that are not resolved on the MMF's 4-km grid grid. This may explain why the MMF produces too much low cloud cover over the warmer tropical oceans and too little over the cool oceans (Wyant et al., 2006). The improved parameterizations and increased CRM resolution discussed in Section 2 above are expected to reduce these errors. We will use the improved MMF to simulate the global response of low clouds to changes in greenhouse gases, aerosols, and sea-surface temperatures.

Studies of the Madden-Julian Oscillation

CMMAP has made major progress towards understanding the physical nature of the MJO,. We propose to continue this work in Years 6-10:

- We will study the sub-grid-scale cloud regime simulated by the MMF as a function of MJO phase.
- We will perform experiments to investigate the importance of zonally-asymmetric basic states for MJO formation, with special attention to feedbacks involving surface winds and radiative heating.
- We will examine the intraseasonal moist static energy (MSE) budget of the MMF, focusing on 1) the tropical gross moist stability, 2) the ability of surface fluxes and radiative feedbacks to destabilize the MJO, and 3) the role of horizontal MSE advection. Results will be compared with ongoing MSE budget analyses using conventional GCMs (Hannah, 2009) and observations.
- We will analyze the MMF's ability to simulate the mean state and intraseasonal variability of monsoon systems in Asia and the Americas during boreal summer, including the ability to support northward propagation. Preliminary analyses are intriguing.
- We will analyze MMF results to determine whether tropical synoptic waves and depressions affect the momentum budget (Majda and Stechmann, 2009) and the moisture preconditioning process (Maloney, 2009) of the MJO.

- CMMAP will participate through membership and diagnostic activities in the nascent WCRP/WWRP MJO Task Force, a successor to the MJO Working Group. A focus is developing and applying process-oriented diagnostics. Links will also be forged to a proposed Climate Process Team (led by E. Maloney) aimed at improving parameterized convection in global models.
- W. Schubert and colleagues will use MMF results to guide the incorporation of moisture into shallow water models of tropical circulations, so as to enable a coupled representation of diabatic heating. The goal is to create very simple analytical models of the MJO, which are key to physical understanding.

Climate simulations using the MMF in a coupled model

The results of Stan et al., (2009), briefly discussed in the accomplishments section under Knowlwedge Transfer, have encouraged us to pursue coupled ocean-atmosphere simulations with the MMF. In the near future, we will conduct a new coupled simulation using higher-resolution dynamical cores for both the atmosphere and ocean GCMs. This coupled model is called the SP-CCSM. After preliminary tests, we will pursue two longer-term goals:

- A "Climate of the Twentieth Century" simulation using the SP-CCSM, following the protocols of CMIP (the Coupled Model Intercomparison Project), and with atmosphere and ocean GCM resolutions identical to those used by the CCSM project itself
- At least one "future climate" scenario with the SP-CCSM, following the protocols of the ongoing Fifth Assessment of Climate Change being carried out by the IPCC (Intergovernmental Panel on Climate Change).

Although it is not practical for CMMAP to offer the planned SP-CCSM results as an "official" contribution to the Fifth Assessment, we do intend to collaborate actively with the National Center for Atmospheric Research (NCAR) and other modeling centers that are officially contributing. In this way, we hope to provide useful input for the Assessment.

Sea ice coverage and thickness vary on both large and small scales. Nearly all of the leads (open water channels) in sea ice are sub-GCM-grid-scale. During the Arctic winter, leads can produce convective plumes that penetrate hundreds of meters into the extremely stable Arctic boundary layer and produce extensive areas of low clouds that have strong radiative impacts on the surrounding sea ice and can potentially produce a positive feedback that tends to reduce sea ice thickness and coverage. In the summer, there are small-scale variations in ice albedo, temperature, and roughness. We propose to enhance the coupled model by including the sea-ice component within the CRM, so that the small-scale structure of the sea ice can be explicitly simulated.

4. Community-based evaluation of results produced by CMMAP models, through the use of diverse observations

Participation in intercomparisons

It is useful to test new physical parameterizations in SAM before running them in the MMF or GCRM. To this end, CMMAP will continue to participate in a variety of community-based intercomparisons with our cloud-resolving models and single-column models.

As one example, CMMAP will participate in the VOCALS Assessment (VOCA), in which regional and global atmospheric models will simulate the Southeast Pacific stratocumulus region (which encompasses a variety of vertical structures and aerosol loadings and has a strong diurnal cycle with extensive offshore drizzle cells) during the period October -November 2008, when airborne and shipborne cloud, aerosol and chemical data was gathered. We will use SAM to simulate a 100 km x 100 km doubly-periodic domain embedded in this study area, forced by analyses of vertical motion and horizontal advective tendencies from the ECMWF global weather prediction model over the month. The challenge for SAM will be to simulate the day-to-day cloud variability better than a conventionally parameterized weather forecast model. This will allow definitive attribution of errors to specific physical processes.

CMMAP will also conduct process-oriented diagnoses of the MJO in the MMF using YOTC (Year of Tropical Convection) datasets and simulations. Through the work of M. Khairoutdinov, the MMF will participate in a YOTC-based intercomparison of experimental forecasts.

Experimental NWP using the GCRM

Because of their computational expense, early tests of our GCRM will focus on short-range global weather prediction, starting from high-resolution analyses produced by operational weather prediction centers. Foci will include tropical cyclones and other extreme weather events.

5. Management, analysis, and visualization of very large model output datasets -- creation of infrastructure

Resource procurement and distribution

We use supercomputers at NCAR, NERSC (the National Energy Research Supercomputer Center), and NCCS (the National Center for Computational Sciences), and on the BlueGene machine owned by the State of New York. In 2011, we expect to obtain access to BlueWaters, the Track 1 supercomputer to be installed at the National Center for Supercomputing Applications. In collaboaration with NCAR and COLA, we have been successful in obtaining a Petascale Computing Resource Allocations (PRAC) award from NSF, which will help us to prepare for efficient use of BlueWaters. Additional, emerging assets include some within the Teragrid, and the Triton Resource at the San Diego Supercomputer Center. CMMAP will propose to NSF's MRI (Major Research Instrumentation) program for dedicated hardware.

We have adopted a Teragrid community account approach to make CMMAP models more widely usable. This enables "occasional" access for researchers and students, and simplifies the support requirements, but it creates additional accounting and security burdens, including a user registry and a gateway authentication mechanism. Those already exist within the CMMAP Digital Library, and will be adapted to support the community account.

Data management

Up to now, global atmospheric models have relied almost entirely on serial output. With the GCRM, highly parallel output is essential; we cannot rely on a single "pipe" to send all of the model output to disk. Parallel I/O technology, such as parallel netCDF, will be designed into new CMMAP models, and retro-fitted into existing models. To accomplish this, we are collaborating with Karen Schuchardt's group at the Pacific Northwest National Laboratories.

We have to move CMMAP model output from where they are generated to where they are archived and analyzed. We will of course use network communications whenever it is practical to do so, but for the forseeable future it will be necessary to mail large volumes (terabytes or more) on physical media.

Analyzing and visualizing model results

In the GCRM, the range of scales involved (in one dimension) is roughly 10,000 to 1. Displays, printers, eyes, and brains cannot handle that all at once. Filtered data can be used to depict the larger scales, but full-resolution data are needed to study local weather systems. To develop visualizations of appropriately sampled model output, we are collaborating with the VisIt team at the Lawrence Berkeley National Laboratory. VisIt is an open-source, extensible visualization and analysis tool. We will also explore use of the TViz system, which is supported through the Teragrdid.

Discussion

The output, data management, and analysis/visualization issues listed above are faced by all groups working with very high-resolution global models. CMMAP's work in these areas will contribute to new infrastructure that will made available to other modeling groups.

(3d) Narrative Description of the Education and Human Resource Development Objectives of the Integrated Center

Vision Statement for Education

CMMAP works to enhance science literacy and awareness of climate for students, teachers, policymakers, and the general public. We provide high-quality educational experiences at all levels, and seek to infuse the next generation of climate scientists with a sense of the role of science in the larger culture.

Objectives Years 6-10	Actions Required	Key Personnel	Timeline
1. Enhance K-12 Science Education	Little Shop of Physics (LSOP) school visits	Foster, **Jones**	Ongoing
	Everyday Science TV Show		
	Weather and Climate for Teacher's Course		
	Windows to the Universe website		
	Web-based seminars and dissemination		
	Spin off nonprofit enterprise		
2. Improve undergraduate climate education	Curriculum infusion initiative	**Burt**, Calderazzo, Campbell, Drossman	Ongoing
	Course development at CSU and Colorado College		
	CMMAP summer internship		
3. Train next-generation climate scientists	Support 25 graduate students	**Burt**, Denning, Drossman	Ongoing
	Summer workshops for graduate students		
	Graduate student teaching fellowships		
4. Engage the larger culture regarding climate	Public outreach to stakeholders	Betsill, Calderazzo, **Campbell**, Lacy	Ongoing
	Science writing in popular outlets		
	Short video productions		

Table Edu 1: A summary of CMMAP's Education Objectives for Years 6-10, including actions required, key personnel, and a timeline. The personnel listed in bold face are the Objective Leaders.

Goals and Objectives

CMMAP's Education Objectives for Years 6-10 are listed in Table Edu 1. In the following Sections, with red section headings, each Objective is discussed. During Years 6-10, CMMAP's Education Team will continue our highly successful activities, focus on refinement and testing, and launch an exciting new intiative to engage the larger cultuure.

1. Enhance K-12 Science Education

The Little Shop of Physics (LSOP) team will continue to visit over 60, K-12 schools each year to present a hands-on science program consisting of 100+ interactive demonstrations of science principles. A major focus of our activities in the second phase of CMMAP will be the development, refinement and testing of curriculum materials for schools. We will develop specific activities, guides and materials to provide teachers with the tools they need for their classrooms. Schools selected for these visits, targeting schools with populations that are historically underrepresented in the sciences, will allow us to meet with teachers to get their opinions and ideas for development of instructional materials, and to test our instructional materials in a classroom. We have worked with and fostered a unique "two-way" relationship with Native American populations (e.g., Wind River and Pine Ridge reservations), and will extend our work in urban areas (Denver and Colorado Springs) and rural areas with diverse populations (such as the San Luis Valley). Our evaluation work for this activity will focus on formally testing the technical accuracy, and feasibility and utility of classroom use of these materials for scaled up use, as well as developing/adopting outcome assessments focusing on understanding of science processes and attitudes towards science (i.e. George, 2000).

We will continue to produce "Everyday Science", a television program, developed in collaboration with Poudre School District Channel 10, and will distribute this program over the air—as before—but will also distribute them as podcasts. These podcasts will be posted on the Windows to the Universe site, through iTunes University and the iTunes Store, and on a dedicated LSOP podcast page. As we create each new episode we will produce a companion "behind the scenes" segment, that will show teachers how to incorporate this material and these activities in their own classrooms. These segments will be shared with local teachers, and will form one component of instructional materials that we will bring to market. During Year 6, we will initiate the process to create a non-profit enterprise that can distribute any and all materials that we develop, generating a continuing revenue stream to support the educational activities of Little Shop and our partners within CMMAP. As we evaluate the effects that LSOP has on science knowledge and attitudes, we will produce graphical, easy-to-understand representations of these LSOP effects and post these with the materials as well.

We will continue to develop and refine, our highly successful, Weather and Climate for Teacher's Summer Course, which has been instrumental, in our effort to work with teachers, locally, regionally and nationally. Our CMMAP graduate students will continue to have direct involvement in the development and presentation of this 5-day, 40 hour, course. This course will be more "two way", during our second phanse, giving teachers a chance to share ideas and to critique our instructional materials. Teachers in the summer course will be our "testers," trying out new activities with their classes. The teacher course will be integrated with our assessment efforts. We will do follow-up visits to see teachers implement the lessons they have learned. At these follow-up visits, we will conduct structured interviews using the Levels of Use (Hall & Hord, 2006) to assess the level at which teachers are willing and able to replicate these lessons. We will continue to offer this course to a broader, more diverse community, through our connection with the Colorado State Alliance schools, and our partners at Colorado College, who will offer this well-tested course with diverse schools in Southern Colorado.

The Education and Outreach team at UCAR will continue to develop levelized climate and atmospheric science content, illustrations, image collections, animations, and activities for K-12 students and teachers on the Windows to the Universe site. Science content is presented in three reading levels and translated into Spanish, to reach a broader community. Windows to the Universe, which reaches nearly 20 million visitors annually, has a specific interest in curriculum enrichment resources useful in middle and high school climate science courses. W2U content is updated on a regular basis and creates content focused on basic science concepts and more detailed information about clouds, weather, climate, and modeling in a manner and format appropriate for its audience of K-12 educators and students and the general public. The W2U team will integrate emerging information about CMMAP into this content so that visitors to the site can gain knowledge and appreciation of CMMAP's research mission, the scientists who can serve as role models of careers in the atmospheric sciences, and the challenge and importance of integrating cloud dynamics into global climate models. W2U educators will develop K-12 activities when content adapts well to such products, and will disseminate them in local to national teacher professional development workshops addressing climate and global change. Graphic images, animations, and interactives will be developed as needed to illustrate new concepts. They will collaborate with scientists and teachers in presentations at regional and national meetings of the AMS, AGU, National Science Teachers Association, to name a few, where the W2U workshops and the UCAR corporate booth also distribute information. Potential for collaboration with other programs include the NCAR Online Climate Discovery Online Course, NCAR Public Visitor Program at the Mesa Lab, as well as linkages with the National Earth Science Teachers Association (NESTA), GLOBE, and NSDL programs. We will offer a series of web seminars through NSTA, which teachers rely on for science education opportunities tailor-made to meet their needs. We will develop a new series of three web seminars per year to be offered in year six and updated in years seven through nine. In year nine, two of the three web seminars will be repeated for a total of 5 in that year. With all of our W2U activities, we will actively seek feedback from users focusing on extent of use of these materials and activities through the use of relatively simple web-based survey technology.

K-12 Curriculum Assessment

Much of our assessment will come before our next phase of development. We will focus our efforts on the topics and the skills that working scientists deem most important. We will meet with CMMAP and other scientists to determine what they think students should be learning. We have done this in an informal manner in the past; in the next phase of the grant, we will do this in a more formal fashion at team meetings and through individual contacts. We have recently met with science curriculum specialists for the local Poudre and Thompson school districts. Both districts are in the process of changing their science curricula to meet the new state science standards, which are aligned with national science standards. This is a unique opportunity to work with teachers in the two districts to develop exactly the materials they need. Once the materials are developed and in use, we will assess their effectiveness. Our long-term goal is to develop materials that are part of the curriculum of one or both districts. As these materials begin to be used in classrooms throughout the two districts we can rigorously assess their impact, looking at learning outcomes—and standardized test results—before and after their adoption. Ultimately, we can distribute these materials more widely with the backing of solid assessment data.

2. Improve undergraduate climate education

ChangingClimates@CSU, developed by Profs. John Calderazzo and SueEllen Campbell, will continue to develop and publish materials for use in college-level courses in different disciplines—materials that will include a library of very short, lively, tightly-focused videos on multiple climate change topics. We will produce and disseminate these with the help of CMMAP team members Little Shop of Physics and Windows to the Universe. We intend that these videos will help teachers feel more willing to introduce their students to this daunting subject without feeling that they must be expert in its every aspect. They will also allow teachers to supplement their own voices and points of view. We imagine that teachers might simply use the videos for their own study; might show them to their students during class sessions; or might refer their students to them for out-of-class time. We will share these videos with the NCSE organizers of the Climate Solutions Curriculum Initiative, new recipients of a large NSF climate change education grant who represent environmental deans and directors of 170 universities and colleges. We also plan to disseminate these in as many other ways as possible and appropriate: on our CC@CSU website, on YouTube and iTunes U, through Windows to the Universe, and on disks given to participants in the workshops described below. We will carefully coach and then film researchers and teachers with national and international credentials. We will check accuracy through relevant CMMAP experts and our own faculty advisory panel (which includes members of all eight CSU colleges). Because the Climate Solutions Curriculum Initiative group will also vet the teaching materials they post, they will provide another layer of review, and we will draw on their evaluation results as well as develop and refine our own evaluation system as we go along. This might include obtaining e-mail addresses from video users so we might contact them later to evaluate classroom effectiveness and to find out what needs there are for additional videos.

We will develop, edit, and publish a multidisciplinary climate-change reader to be called something like 25 Views of Climate Change. Our target readers will be upper-division undergraduate students in classes on climate change, though we will make the material accessible enough for lower-division students and sophisticated enough for graduate students. Such classes could be either multidisciplinary (e.g., Introduction to Climate Change or a capstone seminar), in which case our reader could be a primary text, or focused on one or two disciplines (e.g., Climate Change and Ecology), in which case our reader would offer a larger context for part of the term. Assessment will follow the usual publishing protocols of peer and editorial board review; in addition, we will track course adoption numbers and overall sales figures.

We will also continue to develop, pilot, and run intensive multidisciplinary seminars on the climate problem, seminars that might last a single day or a week. We will target several kinds of participants: college-level faculty interested in stimulating cross-campus conversation, teaching, and research at their institutions; middle- or high-school educators interested in adapting such information for their curricula; policy workers (for instance, aides to legislators) who want a fast, broad, high-level overview of the issue. These seminars will include core information from the physical sciences (especially atmospheric science), the natural sciences (especially biology and ecology), the social sciences (anthropology, sociology, economics, political science), the applied sciences (agriculture, human health), the humanities (ethics, religion, history, literature), and the arts (photography, film, and so on). Because we will be in close contact with the participants, we can assess effectiveness by pre- and post- tests and perhaps, following an interval of a year, interviews or questionnaires. With those middle-level, high school-level, and college-level faculty who attend our seminars, we will encourage each to document their subsequent implementation of what they have learned in their own teaching contexts. We will provide descriptions of different research designs they might use to assess the effects of their implementation, techniques to assure fidelity of implementation, and including a menu of outcome measures from which they might select for such efficacy testing. We will then use meta-analytic techniques (Ghersi, Berlin, & Askie, 2008, Sauerbrei & Blettner, 2003), harnessing the statistical power of meta-analysis to give us greater confidence in the causal links between implementation and effects. Finally, we will continue to recruit and supervise undergraduate interns working on a wide variety of climate science and policy research projects.

3. Train next-generation climate scientists

One of the best-developed aspects of the CMMAP education program remains our graduate degree programs which support 25 students at seven institutions. These include traditional M.S. and Ph.D. research assistantships, in which CMMAP's graduate students are inventing innovative methods for climate modeling, studying climate impacts and policy, and uncovering the reasons for the historical underrepresentation of diverse populations in climate science. Beyond their academic and research apprenticeships, CMMAP-supported graduate students participate in a deep range of professional development training. We organize an annual Summer Graduate Colloquium in which students have done workshops on reviewing manuscripts, writing research proposals, early career development for scientists, supercomputing, climate policy, and classroom teaching. In year 6, we will offer a semester-long course on academic career development for geoscientists. We plan to work with communication experts to provide training to both graduate students and the larger CMMAP research community on how to communicate with policymakers and stakeholders.

We plan to continue and expand the graduate student teaching fellow program that allows Colorado College faculty members to serve as teaching mentors for CSU graduate students by co-teaching undergraduate classes together at Colorado College. The graduate students who apply for this fellowship have a strong interest in teaching, so this mentorship is targeted to students who plan to teach as a significant part of their careers. Earlier studies on preparing future faculty funded by the NSF and others have indicated that mentoring is the most effective way to prepare future faculty, especially those interested in teaching (DeNeef, 2002). The mentoring program has been a success as judged by graduate student comments on the program's value, their continued interest in the fellowship and CC student comments on their positive experiences with the teaching fellows. In addition, we have compiled qualitative data from student reviews of some teaching fellows and quantitative data (SALG) on how well the courses have met their objectives. The collection of such data will be made more systematic so we can compare among courses and among mentors. In 2009, we started a qualitative analysis of what works to promote effective mentoring based on graduate fellows narratives in response to a directed set of questions. The data are being analyzed for a peer reviewed submission from a CC professor and three graduate teaching fellows (Drossman, 2009). CMMAP graduate students are currently co-teaching three Environmental Science courses: Air-Atmospheric Physics and Chemistry; Introduction to Global Climate Change; and Human Impacts on Biogeochemical Cycles. We also anticipate that opportunities will be available in our Environmental Synthesis class (a capstone class for majors) for both natural science and social science undergraduate students who are pursuing degrees related to climate change.

We will also develop, pilot, and run workshops on communication beyond disciplinary boundaries, for at least two kinds of participants, graduate students in atmospheric and other climate-related sciences and interested professionals in the sciences and elsewhere. We will focus on strategies to improve the clarity and relevance of communication to the public, to professionals in other academic disciplines, to policy makers, and to the media. As the number of participants increases over time, we can assess the effectiveness of these workshops with pre- and post-tests and perhaps a follow-up questionnaire.

4. Engage the larger culture regarding climate

Global climate change is not just a worry for atmospheric scientists. It's everybody's problem—an enormously complex series of challenges—and we will need a wide variety of approaches to best understand, tackle, and adapt to it. Where better, then, to improve citizen and student literacy and train a climate change workforce than at institutions of higher education that already offer the framework for exploring the thorniest of problems from multiple perspectives? Through the ChangingClimates@ CSU initiative, we plan to continue these efforts by improving citizen literacy about climate change (partly by making high-quality up-to-date information readily available and understandable, and partly by increasing the exposure of college students to aspects of the topic). We will work to broaden the multidisciplinary awareness of specialists (so that climate scientists, for instance, can better understand and deal with the political, economic, cultural, emotional and other challenges that are parts of this problem). We will work with specialists from various fields to communicate with the media, with the general public, with policy makers, and, so that they can better collaborate on solutions, with each other.

We will continue to disseminate climate science to the public and to climate stakeholders through both formal and informal outreach activities. CMMAP personnel give dozens of public presentations each year on climate and global change to communities across the region and the world. Colorado College offers several one-day summer classes and many seminars to the general public, including some by students in our classes. In the second phase of the Center, we plan to add formal participatory processes that bring together members of the CMMAP research community with policy makers/stakeholder groups, to explore how climate science is used in decision making and to identify needs for future research. As discussed under Knowledge Transfer (section 3f), we will develop and publish a web-based magazine on climate issues called Climate Sense. Finally, we will begin a partnership with science museums in Denver and Fort Collins through the "Future Earth Initiative" sponsored by NSF as a collaboration with five other "earth-focused" STCs.

(3e) Narrative Description of the Diversity Objectives of the Integrated Center

Vision Statement for Diversity

CMMAP's diversity activities are designed to broaden participation in climate science by creating a climate science worforce that incorporates the perspectives and human potential of the whole U.S. population.

Goals and Objectives

CMMAP's Diversity Objectives for Years 6-10 are listed in Table Div 1. In the following Sections, with red section headings, each Objective is discussed. During Years 6-10, CMMAP's Diversity Team will continue our highly successful activities, refine others, and develop a new intiative to engage diverse communities in climate science.

1. Recruit and support students from underrepresented groups

The focus of SOARS® (Significant Opportunities in Atmospheric Research and Science) is to broaden participation in the geosciences by increasing the number students from underrepresented groups who enroll and succeed in graduate school in the atmospheric and related sciences. All participating agencies, national laboratories, universities, and other institutions will benefit from this increased pool of highly qualified, educated, and motivated people within the environmental sciences community at large.

Objectives Years 6-10	Actions Required	Key Personnel	Timeline
1. Recruit and support students from underrepresented groups	Sponsor & mentor SOARS Protégés and Fellows Relationships with Minority-Serving Institutions CMMAP summer internships CMMAP Diversity Scholarships	**Burt**, Denning, Pandya,	Ongoing
2. Encourage retention of underrepresented students in the science pipeline	LSOP visits to underserved and native schools Summer middle school Math-Science partnership program Climate course at Tribal Colleges	Burt,**Jones**, Pandya	Ongoing
3. Understand historical ethnic underrepresentation in climate science	Analyze interviews, surveys and institutional data from climate science departments	Canetto, **MacPhee**	Years 6, 7
4. Engage diverse communities in conversation about climate	Focus groups in diverse schools Meetings with community leaders Document and disseminate results	Calderazzo, **Denning,** Jones, Lacy, Pandya	Ongoing

Table Div 1: A summary of CMMAP's Diversity Objectives for Years 6-10, including actions required, key personnel, and a timeline. The personnel listed in bold face are the Objective Leaders.

In years six to eight, two SOARS student (protégés) will work with CMMAP or UCAR scientists and participate in all aspects of the ten-week SOARS summer research program. In years nine and ten, one protégé will participate in the summer research program. Each protégé's research effort will focus on the representation of cloud processes in climate models. This research may include field studies, laboratory experimental programs, computer simulations, and theoretical investigations. They will conduct a research project, prepare a written research report, and present their research findings and conclusions at a SOARS Colloquium and poster session held in Boulder, Colorado, during week 10 of the summer program. Each protégé will also benefit from institutional support associated with SOARS activities. These include: 1) a mentoring team comprised of a science research mentor, a scientific writing mentor, computing and a community mentor; 2) an eight-week scientific writing and communications workshop; 3) information, counseling, and guidance on education and career opportunities in atmospheric and related sciences; 4) support to present their summer research projects at regional and national science meetings and conferences. In addition, CMMAP will provide two fellowships each for one year and renewable for a maximum of two years to SOARS graduate students at CSU. The CMMAP 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. CMMAP scientists will also make presentations at the SOARS summer colloquium. In addition to two SOARS Graduate

Fellowships, CMMAP will support two Diversity Scholarships in years six through eight (and one in year nine), which will fund 50% of a Graduate Research Assistant at any participating CMMAP university.

SOARS and CMMAP will reach out to Minority Serving Institutions, helping to identity MSIs interested in opportunities that will be supported by CMMAP, including opportunities for teacher training. CMMAP has already established ongoing relationships with faculty at several MSIs, and will continue to develop these relationships. In addition to the SOARS protégés, CMMAP will host residential summer internships for 10 undergraduate students at CSU. These internships are structured following the SOARS model, including multiple mentorship by CMMAP faculty, research scientists, graduate students, and peers, but are intended to provide an intensive introduction to the research environment of CMMAP and the graduate student experience. Mentors attend an orientation workshop designed to insure uniform high standards of interaction with interns and sensitivity to diversity issues. Through our partnership with the Graduate School, CMMAP undergraduate internships are coordinated with other residential diversity programs at CSU, including recruiting, co-housing, transportation, meals and social activities.

2. Encourage retention of underrepresented groups in the science pipeline

During years 6-10, we will enhance LSOP connections with SOARS and other diversity and education efforts. For instance, SOARS protégés and CMMAP graduate students and interns will take part in outreach activities; and they will assist with development of instructional materials. Our annual summer course on Teaching Climate will focus on schools with populations of students that are underrepresented in science fields. We will continue to work with Native American populations, building on the relationships we have already established with schools on Pine Ridge, Navajo, and Mountain Ute lands. We will extend our work in urban areas (Denver, Colorado Springs) and continue our work in rural areas with diverse populations (San Luis Valley). A strong partnership with CSU's Alliance Schools program has already led to exciting relationships with school districts identified as underrepresented in CSU's admission data. CSU has committed resources to sustained engagement with these districts with the aim of building a sense of expectation of attending college throughout their communities.

We will continue to offer a one-week summer workshop on weather and climate as part of CSU's participation in the NSF-supported Math-Science Partnership. This residential workshop has been very successful in years two and three, and usually involves about 30 underrepresented middle-school students from the Denver metropolitan area, plus their counselors. We offer weather and climate content that is structured around the exciting hands-on inquiry activities developed and tested by LSOP during their interactions with tens of thousands of middle-school-aged students and their teachers.

CMMAP is participating in an NSF-sponsored initiative to develop a unique course on climate and global change to be taught at Tribal Colleges across the USA. Scott Denning and Raj Pandya attended a planning workshop for this activity in 2009, and will continue to participate in years one and two of the renewal. The course, developed by tribal college professors, is based on a Medicine Wheel concept, and is rooted in a sense of place, so that students, learn about climate processes as they are reflected in and affect the changing lands of tribes from the rainforests of the Pacific northwest to the arid southwest to the snowy northern Plains. The course will be taught at 16 Tribal Colleges, and has already led CMMAP scientists to think about climate change in new ways.

3. Understand historical ethnic underrepresentation in climate science.

We have designed and implemented a mostly qualitative study to track the experiences of women and men across ethnicities and nationalities from the undergraduate to the early postdoctoral years in Climate Science and related STEM fields. In-depth semistructured interviews and extensive written semistructured and structured survey data have been collected with nearly 100 participants at two sites, CSU and MIT. In years six and seven, we will analyze and publish results from semistructured interview study of CSU and MIT graduate students. We will study how the atmospheric/climate science "leaky pipeline" can be made less porous using existing institutional data sets (e.g., related to profiles of various "feeder" majors for Climate Science graduate programs) as well as new data collected from Geoscience graduate programs related to their graduate student and faculty composition (e.g., sex, ethnicity, degree discipline). Among the questions we are asking, using both structured and semistructured written surveys, and semistructured oral interviews, are:

- What factors are associated with choice and persistence in these fields for female and underrepresented ethnic minorities?
- What are the factors that lead to the decrease in the number of female and ethnic minority scientists at each higher level of education and career?
- What are the unique challenges (personal, familial, financial, cultural) faced by female and underrepresented ethnic minority students in these fields?
- What are the unique resources that female and underrepresented ethnic minority students bring to their education and careers, as compared to other students?
- What is common and what is unique about Climate Science students with regard to their choice, persistence and success in the field relative to the comparison graduate students?

4. Engage diverse communities in conversation about climate and global change

Besides the fairly traditional efforts to understand and enhance diversity discussed above, we plan an experimental approach to turn these questions around. Rather than ask why diverse people do not become climate scientists, we seek to learn about the concerns and needs of diverse communities regarding climate and global change. This will be accomplished through a transdisciplinary and multicultural conversation conducted over years six through ten. The conversation will occur following LSOP visits to diverse schools across our region, on native lands and in tribal colleges, in inner-city and rural farm communities, and with stakeholders and policymakers at various levels of government.

Political Science Professor Michele Betsill will coordinate workshops on the policy process for CMMAP students, interns, and scientists, and will lead meetings during which aspiring climate scientists learn about the needs of diverse communities and stakeholders. We will conduct focus group meetings to assess community attitudes, concerns, and questions about climate change. CMMAP graduate students and SOARS protégés will be engaged in developing these workshops, and trained for participating in them, in the hope that the experience deepens their understanding of the needs of our larger culture for climate science as they pursue their careers. Sociology Professor Michael Lacy will observe and document the process of engaging these young scientists and will disseminate their experience to social scientists through the academic literature. English Professor John Calderazzo will also study this process, and will document our findings about societal attitudes and needs regarding climate change through articles in Climate Sense, the Chronicle of Higher Education, and a book intended for the larger reading public. The results of this intense interdisciplinary engagement will also be shared through the video project and websites discussed above in Section 3d. Ideally, these activities will have a long-term impact on attitudes of climate scientists toward diversity, social perception of climate change, and help CMMAP trained scientists better connect their researrch to societal needs and concerns - including the needs and concerns of diverse communities.

(3f) Narrative Description of the Knowledge Transfer Objectives of the Integrated Center

Vision Statement for Knowledge Transfer

CMMAP engages in two-way knowledge transfer that benefits the Center, the public , and the academic and research communities, through technology transfer to modeling centers, and the creation of new publication channels for work on global environmental modeling.

Goals and Objectives

The Knowledge-Transfer Objectives of CMMAP for Years 6-10 are listed in Table KT 1. In the following sections, each Objective is discussed in turn.

1. Collaborate with CCSM on climate change simulations

CMMAP and NCAR have a strong partnership based on long-standing relationships that pre-date

Objectives	Actions Required	Key Scientists	Timeline
1. Collaborate with CCSM on climate change simulations	Perform simulations	**Randall**, Collins, Moeng	Year 8
	Analyze results		
	Communicate results to AR5		
2. Collaborations on global atmospheric model development	Continue interactions with NCEP, NCAR, and GFDL	Randall, **Krueger, Collins**, Donner	Ongoing
	Create new interactions with ESRL		
	Organize intercomparison of GCRMs		
3. Create a national training resource for global modelers	Create materials for both university classes and summer school	**Randall**, Schubert	Start by Year 6; ongoing thereafter
	Create summer school		
	Make class materials available nationally		
4. Foster *JAMES*, and wean it from CMMAP.	Establish financial self-sufficiency	**Schubert**, Ames, Randall	Year 8
	Establish managerial self-sufficiency		
	Hand-off to IGES		
5. Create an online magazine for public outreach	Create business model	**Ames**, Schubert, Randall	Year 7
	Organize content creation		
	Create web site		

Table KT 1: The Knowledge-Transfer Objectives of CMMAP for Years 6-10 (see narrative for explanation of acronyms).

CMMAP. NCAR Senior Scientist Chin-Hoh Moeng is CMMAP's Deputy Director. Several NCAR scientists participate in CMMAP research, especially in connection with parameterization development. This connection will continue to grow through a joint project, which is outlined below. The project has been discussed with and endorsed by James Hurrell, the Chair of the Community Climate System Model (CCSM) Scientific Steering Committee, and by Greg Holland, the Acting Director of the Earth and Sun Systems Laboratory.

We propose to work with CCSM scientists in connection with the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). AR5 will be completed in 2013. The proposed collaboration builds directly on the development and succesful tests of a version of the CCSM in which CMMAP's prototype MMF is used as the atmospheric component of the CCSM. This work was led by Cristiana Stan (Stan et al., 2009) of the Center for Ocean Land Atmosphere Interactions (COLA), and is summarized in Section 3g of this proposal, which deals with Prior Accomplishments. CMMAP will carry out simulations of direct relevance to AR5, using CMMAP computing resources, and CMMAP and CCSM will jointly analyze the results. The simulations will be a selected subset of those designed for the next iteration of the Climate Model Intercomparison Project (CMIP5; Taylor et al., 2008). These range from ten-year "time-slice" runs, to a simulation of the climate of the twentieth century (driven by prescribed time-dependent forcings), to simulations of future climate using the CMMAP-enhanced version of the CCSM. The particular simulation scenarios to be performed will be chosen through discussions between CMMAP and CCSM scientists. Analysis of the simulation results will provide a basis for evaluation of the cloud, lapse-rate, and water vapor feedbacks in the CMMAP-enhanced CCSM, in comparison with results from the standard version of the CCSM.

2. Collaborate on global atmospheric model development

As mentioned above, CMMAP has a strong modeling partnership with NCAR. We are also collaborating with GFDL, through the work of CMMAP scientist L. Donner. CMMAP will provide Donner with geographically and seasonally varying convective vertical velocity pdfs (probability density functions) that will be used his cumulus parameterization work. The pdfs will be based on results from the MMF, properly adjusted for coarse-grid-size effects.

CMMAP has worked to create and maintain a global modeling partnership with NOAA's National Centers for Environmental Prediction (NCEP), located in the Washington, DC area. NCEP scientists participate in CMMAP Science Team Meetings, and CMMAP scientists visit NCEP; this will continue. In Years 6-10, we plan to work with NCEP to develop and test parameterizations for use in models with horizontal grid spacings of ~ 4 km. Per discussions with Geoff DiMego, Head of the Mesoscale Modeling Branch at NCEP/EMC, NCEP is interested in collaboration with CMMAP on issues concerning NWP using a horizontal grid spacing of 4 km, which are under consideration for near-term operational use.

In Years 6-10, CMMAP plans to begin a collaboration with NOAA's Earth System Research Laboratory (ESRL), which is located in Boulder, Colorado. ESRL and CMMAP are both developing global cloud-resolving models (GCRMs) using similar modeling technologies, including geodesic grids, non-hydrostatic dynamical cores, and hybrid vertical coordinates, but with important differences central to CMMAP's research objectives. CMMAP's parameterization expertise will be useful to ESRL. In particular, CMMAP has supported the development of and is ready to deploy state-of-the-art parameterzations for microphysics, radiation, and subgrid-scale turbulence, all of which could substantially increase the capabilities of ESRL models. In return, ESRL's forecasting experience will be useful to CMMAP, especially as it relates to data assimilation on very fine spatial scales. Jin Lee of ESRL participated in CMMAP's July 2009 team meeting, and gave an invited presentation there. During the meeting, plans were made to pursue a partnership along the lines described above.

To extend this initiative to the larger community, CMMAP will organize an intercomparison of global cloud resolving models (GCRMs) to examine the strengths and weaknesses of alternative theoretical bases and implementations. We anticipate that the participants will include ESRL, NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), and NCAR, as well as the Frontier Resarch Center for Global Change, and the Max Planck Institute for Meteorology. All GCRMs are relatively new models. The modeling techniques used are still maturing. An intercomparison is therefore timely; it can reveal previously unrecognized weaknesses and suggest improvements, thereby accelerating progress across the entire field.

3. Create a national training resource for global modelers

The need to simulate possible future climates is creating a demand for modeling experts. Model developers are in especially short supply (Jakob, 2009). It is critically important to train a new generation of global model builders who will meet society's future requirements. CMMAP is currently supporting 25 graduate students at six institutions. Many of these students are being trained as modelers.

Center Director David Randall has recently begun working with NOAA to facilitate the training of future global modelers. The plan is to create instructional materials both for university graduate-level curricula, and for annual two-week summer schools. These will include classroom presentation materials, one or more textbooks, shorter instructional essays, model-derived computer codes, datasets, and analysis and visualization sortware. The content will include both the conceptual basis and the practical implementation of global models, with an emphasis on NOAA models such as NCEP's GFS, GFDL's AM

3, and ESRL's FIM. The inital focus of the NOAA-supported project is physical parameterizations, which fits very well with the research of CMMAP. This content will be made widely available online, although the textbook(s) may be published through traditional channels.

Although the training project has been started under NOAA support, which will be proposed for continuation, an expanded version of the project will be developed as part of CMMAP's Knowledge Transfer initiative for Years 6-10. To address the modeling workforce issue, CMMAP proposes to expand and accelerate the training project outlined above by broadening the curriculum and increasing the number of students. We will add a major focus on the evolving Community Atmosphere Model (CAM), which is a key component of the Community Climate System Model (CCSM) maintained at NCAR. We will include curricular materials on numerical techniques, as well as methods for testing models against observations. Instruction will be hands-on and inquiry-based, but will also include lectures. Instructors will be recruited by CMMAP from the university- and laboratory-based atmospheric science research communities. Our goal is to create a national training resource for global modelers. We will look for a way to sustain it after STC funding ends.

4. Foster JAMES, and wean it from CMMAP

As discussed in the section on Prior Accomplishments, CMMAP has successfully launched an all-electronic, open-access journal called the *Journal of Advances in Modeling Earth Systems* (*JAMES*). A journal requires constant attention. Submissions must be dealt with promptly, reviewers must be reminded of due dates, and Editors must make decisions. CMMAP will continue to foster *JAMES* as it grows and matures. Nevertheless, *JAMES* cannot be a creature of CMMAP forever. In CMMAP's 2004 proposal to NSF, we stated that, following its creation and initial subsidy by CMMAP, *JAMES* would become independent of CMMAP after several years. Following CMMAP's proposed renewal, we will follow through on this pledge. CMMAP and IGES will develop a plan through which *JAMES* will become independent of both CMMAP financial support and CMMAP management by not later than CMMAP's Year 8.

5. Create an online magazine for public outreach.

To increase outreach to policy makers and the general public, we propose to create a new non-technical online publication, with the working title *Climate Sense*, hosting non-technical articles on a range of topics related to climate science and climate policy. The mission of *Climate Sense* is to provide a venue for a multidisciplinary conversation surrounding the Earth's climate and climate change, and to promote Earth-Science literacy. The new publication is intended to appeal to authors and readers who want to understand current issues relating to climate change. The target audiences are students and members of the public who are educated at the university level, educators, and policy makers. The magazine will become independent of CMMAP before the end of STC support. A business plan is under development. A mock-up of *Climate Sense* has been created and is available online; we are not permitted to include the url here.

(3g) Prior Accomplishments

<u>Introduction</u>

This summary of CMMAP's accomplishments to date is being written in September 2009, about three months into CMMAP's Year 4. It is impossible to summarize more than three years of work by a large team in five pages, so we offer just a sample of what we have done. We are proud to say that CMMAP has already completed or made major progress towards all of its Objectives, across all components of the Center's work, i.e., Research, Education, Diversity, and Knowledge Transfer. Some of the activities proposed when CMMAP was created have been or soon will be wrapped up; an example is our book on the history of global modeling. Other activities are ongoing, and once put into place are intended to continue indefinitely; an example is the Teacher Training course. Finally, some CMMAP research has substantially achieved its original objectives, but has raised new questions and/or suggested new approaches; an example is the "unified parameterization" objective described in the section on proposed research. The remainder of this section lists the Center's Objectives for Years 1-5 under the headings of Research, Education, Diversity, and Knowledge Transfer, and briefly summarizes a few of our accomplishments in each area.

Research accomplishments

1. Extend, evaluate, and apply the prototype MMF.

- We have dramatically extended the prototype MMF by coupling the CRM to a land-surface model, and by coupling the MMF itself to a global ocean model (Stan et al., 2009). We have also incorporated new parameterizations of cloud microphysics, turbulence, and radiation.
- Evaluation of the prototype MMF is discussed under Objective 4 below.
- We have applied the prototype MMF to achieve major progress in understanding both the Madden-Julian Oscillation and low-cloud feedbacks on climate change (e.g., Benedict and Randall, 2007, 2009; Thayer-Calder and Randall, 2009; Wyant et al., 2006, 2009).

2. Develop a second-generation MMF and a GCRM.

- A. Arakawa and J.-H. Jung have created a second-generation MMF, which is really a completely new type of model. We call it the Q3D (Quasi-Three-Dimensional) MMF. The Q3D MMF includes important three-dimensional dynamical processes such as vortex stretching and tilting, and vertical transport of horizontal momentum, based on the 3D vector vorticity model developed by Jung and Arakawa (2008). The approach can be applied in GCMs of arbitrary horizontal resolution. When the GCM grid spacing becomes sufficiently fine, the Q3D MMF converges to a global cloud-resolving model (GCRM). Development of the Q3D MMF required re-thinking the problem of how to couple the large-scale circulation to the cloud-scale circulations, and invention of new numerical methods suitable for use on a "gappy" grid. The design of the Q3D MMF has been successfully demonstrated in a limited-area model, and will be transplanted to the global domain before the end of CMMAP's first five years.
- C. Konor, R. Heikes, H. Miura now have a working dynamical core for a global cloud-resolving model, and are close to having a second one based on the 3D vector vorticity model (Jung and Arakawa, 2008). The two cores share many design features, but differ in some important ways. They will be compared to judge their relative merits. Good scaling has been demonstrated on parallel machines. Parameterizations are now being added to the first core.

3. Develop and test improved parameterizations of microphysics, turbulence and radiation.

- We have modified the MMF to predict not only the mass of each hydrometeor species, but also the number of particles of each species (Morrison et al., 2005 a, b). This allows regional aerosol concentrations to affect cloud microphysics in a global model that resolves many important cloud-forming circulations.
- CMMAP has created and analyzed an unprecedented large-eddy simulation of deep convection on a domain 205 km square with a turbulence-resolving grid (Khairoutdinov et al., 2009; Moeng et al., 2009). As discussed in the section on proposed research, we believe that in the future such simulations will serve as indispensable benchmark database to allow exploration of nonlinear interactions across a wide range of scales and to develop improved SGS parameterizations. We are planning additional simulations of this type, for a variety of convection regimes; these will be carried out before the end of CMMAP's first five years.
- CMMAP has extensively evaluated the assumed PDF method for representing unresolved clouds and turbulence in CRMs (e.g., Cheng and Xu, 2009; Firl, 2009; Lappen and Randall, 2009; Bogenschutz and Krueger, 2009). We have tested the method for a range of grid sizes and PDF shapes, for a variety of cloud regimes, by comparison with results from large-domain large-eddy simulations, including the one mentioned above. CMMAP has also implemented and tested several versions of this approach in stand-alone versions of the CRMs used in current and future versions

of the MMF. This research has the potential to improve the representation of unresolved clouds and turbulence without the need to decrease the CRM grid size. It has applications to GCRMs and to mesoscale, convection-resolving NWP models, which face the same issues. It can also be used in conventional GCMs.

- Two improvements have been made to the radiation parameterizations used in CMMAP models. The first is the move from the older CAM3 radiation to the more modern, accurate, and flexible RRTMG (Mlawer et al., 1997; Iacono et al., 2008). CMMAP has created a generic interface for coupling cloud-scale models to RRTMG, and this code is now being used in international intercomparisons aimed at understanding cloud feedbacks on climate change. Concurrently, we are implementing a theoretical advance (Monte Carlo spectral integration, McSI) into RRTMG (Pincus and Stevens, 2008). We plan to use the RRTMG+McSI combination across all CMMAP models.

4. Analyze, evaluate, and interpret MMF results using emerging data sets.

- Benedict and Randall (2007) analyzed MMF-simulated characteristics of the MJO, utilizing TRMM 3B42 precipitation data averaged to a 1x1 degree grid (Kummerow et al., 2000). They emphasized the role of shallow cumulus clouds in MJO events. More recently, Benedict and Randall (2009) have examined MMF-simulated MJO results to the newly available ERA-interim reanalysis dataset (Simmons et al., 2006; Berrisford et al., 2009).
- Other recent studies have exploited the MMF's CRM-scale output for comparison to fine-scale satellite observations. S. Krueger and A. Kochanski of the University of Utah have compared simulated precipitation intensity as a function of column water vapor and temperature to corresponding observational analyses by Neelin et al. (2009) based on TRMM Microwave Imager (TMI) retrievals at 25x25 km resolution and ERA-40 temperatures. Pritchard and Somerville (2009) used the same dataset to analyze the MMF's diurnal cycle of precipitation over land, ocean, and coastal regions and found improvements in the simulated shape and horizontal inhomogeneity of the diurnal cycle.
- In a first-of-its-kind study, Marchand et al. (2009) compared simulated radar reflectivities calculated from 4-km CRM-scale model output to CloudSat reflectivities (Stephens et al., 2002). The MMF is ideal for this analysis, because the CRM grid-scale is comparable to the radar footprint.

5. Accelerate improvement of conventional parameterizations.

- The failure of current GCMs to simulate the MJO is believed to be due to inadequate parameterizations of convection and its interactions with other physical processes. Thayer-Calder and Randall (2009) analyzed the reasons for the failure of CAM 3.0 to simulate the MJO, and identified the convection parameterization's failure to link heavy precipitation rates with high column moisture content. In a complementary study, Hannah (2009) found a strong sensitivity of the MJO to the minimum entrainment rate used in the convection parameterization. These studies have led us to new ideas about conventional convection parameterization that, we believe, can enable successful simulation of the MJO. Work is under way to test these ideas.
- The new microphysics, turbulence, and radiation parameterizations discussed under item #3 above, in the context of CRMs, can also be used in conventional GCMs. Such tests are ongoing at both NCAR and GFDL (NOAA's Geophysical Fluid Dynamics Laboratory).
- S. Krueger of U. Utah is providing convective vertical velocity pdfs diagnosed from the CMMAP LES of deep convection (mentioned under item 3 above) to L. Donner of GFDL, who will use them to adjust the GFDL cumulus parameterization, which estimates vertical velocities for an ensemble of convective plumes. We will extend this effort with vertical velocity pdfs from the MMF.

6. Optimize use of computational and data storage resources.

- CMMAP has obtained and is currently using approximately 5 million CPU hours per year, distributed over several supercomputer centers.

- CMMAP has created an online digital library that supports the use of large CMMAP-derived datasets by scientists at multiple sites.

Education accomplishments

1. Enhance K-12 science education.

- The Little Shop of Physics team (LSOP) continues to develop new hands-on classroom activities. We now have approximately 40 distinct activities, 10 being developed and tested with teachers in workshops and classrooms, and 30 completed activities that are being distributed via the web. Each year, the LSOP team presents programs to over 20,000 K-12 students from over 60 different schools. Students taking part in these programs do informal hands-on investigations with approximately 100 different experiment stations developed and constructed by LSOP interns.

  We have developed, in close consultation with CMMAP scientists and students, 4 new episodes of a television program, "Everyday Science", that is shown locally on Channel 10 and statewide on Rocky Mountain PBS. Our latest episode,"Wind," debuted in December 2009.
- The Education and Outreach team at UCAR continues to focus on developing climate and atmospheric science content based on CMMAP research for K-12 students and teachers on three reading levels in English and Spanish on the Windows to the Universe website. The number of visitors to content aligned with CMMAP related topics is quite remarkable.
- We have held three Colorado Global Climate Conferences for High School students. Over 1,000 students and their teachers from schools all over the Front Range have been in attendance. The one-day event features a representative from the Governor's Office, a keynote presentation, and breakout sessions on climate, energy, and sustainability.
- We have presented three one-week intensive summer courses titled "Clouds, Climate, and Weather for Teachers" to over 100 teachers. The class modeled effective pedagogy in addition to intensive instruction in atmospheric science content. The teachers are using these lessons with their students and sharing them with teachers in their schools.

2. Outreach to climate stakeholders and policy makers.

- We have begun laying the groundwork for future outreach activities with local, state and federal officials. Political Science professor Michele Betsill continues to develop a relationship with the City of Fort Collins through informal contacts and attendance at public climate change fora.
- Our students have participated in science-policy dialogue sessions with local, state and national policymakers. Most notably, Colorado Congresswoman Betsy Markey teleconferenced with two dozen CMMAP students and interns on recent legislative bills on climate policy and how Congress uses science in its decision making.

3. Improve undergraduate climate education.

- We have successfully developed, piloted and implemented two undergraduate courses at Colorado College (CC) related to Climate Change. EV128: Introduction to Global Climate Change, and EV211: Human Impacts on Biogeochemical Cycles. We have developed a new course on the Science of Global Change (ATS 150) at CSU. This course was recommended for inclusion in the All University Core Curriculum, which would allow hundreds of nonscience majors per year to satisfy science requirements by learning about climate.
- CSU English professors John Calderazzo and SueEllen Campbell have developed a science-outreach and education program that explores global climate change from the point of view of over two dozen academic departments. We are infusing climate science content throughout the undergraduate curriculum at CSU, insuring that every student graduates with some climate change literacy, including understanding how his or her field of study relates to the big picture.
- We have created a REU program and have supported 18 summer undergraduate interns thus far. Our interns work on innovative and cutting-edge research projects in atmospheric science and

climate policy with CMMAP faculty. Interns participate in professional development seminars, our summer graduate student colloquium, and present their research at the summer team meeting.

4. **Improve graduate research and education.**

- We currently support 25 graduate students, across seven institutions, and they have direct involvement with the Center's research. Each year, CMMAP hosts a summer Graduate Student Colloquium, an opportunity for CMMAP graduate students to develop contacts, collaborate and learn in a small group setting that is specifically designed to meet their needs.
- CMMAP students have the opportunity to integrate the Center's research by teaching undergraduate courses at CC. Our graduate students are acquiring the skills needed to become excellent educators of climate science and leaders in the Atmospheric Science community.

Diversity accomplishments

1. **Recruit and support undergraduate and graduate students from underrepresented groups.**

- We are actively involved with the SOARS program and have supported numerous proteges. More than half of these students have enrolled in graduate programs in Atmospheric Science and one in CMMAP related research at CSU.
- Our Diversity and Higher Education Manager is traveling to, and communicating with numerous majority and minority serving institutions (MSIs) recruiting and informing diverse students about research, internship opportunities and graduate programs at CMMAP. We have fostered a relationship with Morehouse College and hope to have a more defined partnership in the future.

2. **Implement programs that aid retention of underrepresented groups in the science pipeline.**

- We have developed a science mentoring program in a Native American reservation area. The Pine Ridge Reservation is very poor, but the schools are strong and the local Oglala Lakota College (OLC) has good ties to the schools and the community. OLC has the infrastructure for us to establish an "e-mentoring" program, through which classes at local schools are paired with CMMAP and other graduate students and communicate through regular video chats.

3. **Study diversity problems and solutions, and disseminate results.**

- We implemented a qualitative study to track the experiences of women and men across ethnicities from the undergraduate to the early postdoctoral years in STEM fields, in particular Atmospheric Science and other Geosciences. Data collection and analyses are in progress.
- We completed two studies on the McNair Mentoring Program. The first focused on self perceptions of high-achieving STEM students from underrepresented ethnic groups, and the second examined what attracts high-achieving socio-economically disadvantaged students to the physical sciences and engineering via an open-response survey.
- We studied the representation of female and male characters across ethnicities in elementary science materials. We found that the lack of representation of women and ethnic minorities in elementary science materials may be a factor in children's perception of science, and may contribute to the retreat of females and ethnic minorities from science careers. We are using this result to develop better K-12 materials for CMMAP.

Knowledge transfer accomplishments

1. **Provide climate modeling centers with improved tools.**

- Stan et al. (2009) coupled the prototype MMF to the other components of the Community Climate System Model (CCSM, Collins et al., 2006) to create what they call the SP-CCSM. The coupled model was not tuned. Results from a 20-year simulation produced with the SP-CCSM were compared with observations and also with a control simulation obtained from the standard version of the CCSM. Two remarkable results were obtained:

  First, the SP-CCSM produces a simulation of the atmospheric general circulation that is significantly better than that obtained with the prototype MMF driven by observed sea-surface temperatures (SSTs), especially for the Asian summer monsoon. This is surprising, because coupling with an ocean typically causes the results of an atmospheric model to become less realistic (Hurrell et al., 2006) until the model has been tuned.

The second major result is that the SP-CCSM produces much more realistic simulations of the El Niño-Southern Oscillation (ENSO) than does the CCSM. Stan et al. (2009) show that the improvement in the simulated ENSO is consistent with the SP-CCSM's ability to capture the correct structure of the equatorial cold tongue, which in the CCSM is too narrowly confined to the equator and extends too far into the western tropical Pacific.

2. Provide improved cloud parameterizations to numerical weather prediction centers.

- The results of Stan et al. (2009), discussed above, point the way to improved operational predictions of seasonal and interannual variability. These exciting results have been produced through a Knowledge-Transfer collaboration with the Center for Ocean Land Atmosphere Interactions(COLA), in which COLA scientists created a coupled ocean-atmosphere model using components provided by CMMAP.
- CMMAP has extensively evaluated the assumed PDF method for representing unresolved clouds and turbulence. This research has applications in numerical weather prediction models. We have shared our findings with NCEP's Environmental Modeling Center, which is evaluating it for use in their global forecast model.
- S. Krueger of U. Utah has provided convective vertical velocity pdfs diagnosed from the CMMAP LES of deep convection to L. Donner of GFDL. These are being used to test a new GFDL convection parameterization.

3. Create an edited book on the development of global atmospheric modeling.

- The book is nearly finished, and publication will occur during 2010.

4. Create a new all-electronic open-access journal.

- A new open-access online *Journal of Advances in Modeling Earth Systems* (*JAMES*) has been designed and successfully launched by CMMAP. Operating expenses are supported entirely through low page charges. Copyright is handled under a Creative Commons Attribution 3.0 license, which permits flexible use of an article so long as credit is given to its authors. The publisher of *JAMES* is IGES (the Institute for the Global environment and Society). IGES outsources layout services, and bills authors. *JAMES* is being evaluated for coverage by the *Web of Science*.

5. Create and maintain a CMMAP website.

- The CMMAP web site projects the Center's vision and accomplishments to the world, and is an essential tool for the conduct of the Center's business.

VI. References

Arakawa, A and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci*., **31**, 674 - 701.

Avissar, R., and R. A. Pielke, 1989. A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology. *Mon. Wea. Rev*., **117**, 2113-2136.

Baker, I. T., L. Prihodko, A.S. Denning, M. Goulden, S. Miller, and H.R. da Rocha, 2008. Seasonal Drought Stress in the Amazon: Reconciling Models and Observations. *J. Geophys. Res.,* **113**, G00B01, doi:10.1029/2007JG000644.

Benedict, J. J., and D. A. Randall, 2007: An analysis of the MJO based on TRMM rainfall data. *J. Atmos. Sci*., **64**, 2332-2354.

Benedict, J., 2009: *Madden-Julian Oscillation Structure in a Coupled and Uncoupled Version of the Superparameterized Community Atmosphere Model*. Ph.D. Dissertation, Colorado State University.

Benedict, J., and D. A. Randall, 2009: MJO Structure in the Superparameterized CAM. *J. Climate,* **66**, 3277-3296.

Berrisford, P., D. Dee, K. Fielding, M. Fuentes, P. Kallberg, S. Kobayashi, and S. Uppala, 2009. The ERA-Interim archive. *ERA report series No. 1*. European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire, United Kingdom. 20 pp.

Bogenschutz, P. A., S. K. Krueger, and M. Khairoutdinov, 2009: Testing Assumed Probability Density Functions as Turbulence Parameterizations for Shallow and Deep Convective Systems. Submitted to *J. Adv. Modeling Earth Sys*.

Bonan, G. B., S. Levis, L. Kergoat, and K. W. Oleson, 2002: Landscapes as patches of plant functional types: an integrating concept for climate and ecosystem models. *Global Dynamics*, **17**, 643-652.

Bony, S., and coauthors, 2006: How well do we understand climate change feedback processes? *J. Climate*, **19**, 3445-3482.

Chen, J. and P. Kumar, 2001. Topographic influence on the seasonal and interannual variation of water and energy balance of basins in North America. *Journal of Climate*, **14**, 1989-2014.

Cheng A., and K.-M. Xu, 2009: A pdf-based microphysics parameterization considering subgrid-scale variabilities for simulation of drizzling boundary-layer clouds. *J. Atmos. Sci*., in press.

Chosson, F., J.-L. Brenguier, and L. Schueller, 2007: Entrainment-mixing and radiative transfer simulation in boundary-layer clouds. *J.Atmos. Sci*., **64**, 2670-2682.

Collins, W. D. and Coauthors (2006), The Community Climate System Model version 3 (CCSM3), J. Climate, 19, 2122–2143.

Decharme, B. and H. Douville, 2006. Introduction of a sub-grid hydrology in the ISBA land surface model. *Climate Dynamics*, **26**, 65.78.

DeNeef, A. L., 2002: *The Preparing Future Faculty Program: What difference does it make?* Washington, D.C., Association of American Colleges and Universities.

Denning, A. S., N. Zhang, X. Yi, M. Branson, P. Bakwin, K. Davis, and J. Kleist, 2008. Evaluation of Simulated Boundary Layer Depth at the WLEF-TV Tower Site. *Agric. Forest Meteorol*., **148**, 206-215, doi:10.1016/j.agrformet.2007.08.012

Dickinson, R. E., K. W. Oleson, G. Bonan et al., 2006. The Community Land Model and its climate statistics as a component of the Community Climate System Model. *J. Clim*., **19**, 2302-2324.

Drossman, H., J. Benedict, et al., 2009: *Teaching Professors To Teach: What is the Role of a Constructivist Philosophy?* (in preparation).

Firl, G., 2009: *Development of a Second-Order Closure Turbulence Model with Subgrid-Scale Condensation and Microphysics*. M.S. Thesis, Colorado State University.

Gedney, N. and P.M. Cox, 2003. The sensitivity of global climate model simulations to the representation of soil moisture heterogeneity. *Journal of Hydrometeorology*, **4**, 1265-75.

George, R. (2000). Measuring change in students' attitudes toward science over time: An application of latent variable growth modeling. *Journal of Science Education and Technology*, **9**, 213-225.

Ghersi, D., Berlin, B., & Askie, L. (2008). Prospective meta-analysis. In J. Higgins & S. Green (Eds.), Cochrane handbook for systematic reviews of interventions. New York: John Wiley & Sons. Retrieved from: http://www.mrc-bsu.cam.ac.uk/cochrane/handbook500/chapter_19/19_prospective_meta_analysis.htm.

Golaz, J. C., V. E. Larson, J. A. Hansen, D. P. Schanen, and B. M. Griffin, 2007: Elucidating Model Inadequacies in a Cloud Parameterization by Use of an Ensemble-Based Calibration Framework. *Mon. Wea. Rev.*, **135**, 4077–4096.

Grabowski, W. W., 1998: Toward cloud resolving modeling of large–scale tropical circula-tions: A simple cloud microphysics parameterization. *J. Atmos. Sci.*, **55**, 3283–3298.

Grabowski, W. W., 1999: A parameterization of cloud microphysics for long–term cloud–resolving modeling of tropical convection. *Atmos. Res.*, **52**, 17–41.

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.

Hall, G. E., & Hord, S. M. (2006). *Implementing change: Patterns, principles, and potholes*. (2nd ed.): Boston: Allyn and Bacon.

Hannah, W., 2009: *The role of moisture-convection feedbacks in simulating the Madden-Julian Oscillation*. M.S. Thesis, Colorado State University.

Harper, A., A. S. Denning, I. T. Baker, M. D. Branson, D. A. Randall and L. Prihodko, 2009: The effect of root-zone dynamics on climate in the Amazon rainforest. *Geophys. Res. Lett.*, submitted.

Helly, J, T. T. Elvins, D. Sutton, and D. Martinez, 1999: A Method for Interoperable Digital Libraries and Data Repositories. *Future Generation Computer Systems,* **16**, 21-28.

Hurrell, J. W., J. J. Hack, A. S. Phillips, J. Caron, and J. Yin (2006), The dynamical simulation of the Community Atmosphere Model version 3 (CAM3), J. Climate, 19, 2162–2183.

Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins, 2008: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *J. Geophys. Res.*, **113**, D13103, doi:10.1029/2008JD009944.

Jakob, C., 2009: Accelerating progress in global model development -- Challenges, opportunities, and strategies. Submitted to *Bull. Amer. Meteor. Soc.*

Jung, J.-H., and A. Arakawa, 2004: The Resolution Dependence of Model Physics: Illustrations from Nonhydrostatic Model Experiments. *J. Atmos. Sci.*, **61**, 88–102.

Jung, J.-H., and A. Arakawa, 2008: A Three-Dimensional Anelastic Model Based on the Vorticity Equation. *Mon. Wea. Rev.*, **136**, 276–294.

Khairoutdinov, M. F., and D. A. Randall, 2003: Cloud Resolving Modeling of the ARM Summer 1997 IOP: Model Formulation, Results, Uncertainties, and Sensitivities. *J. Atmos. Sci.*, **60**, 607–625.

Khairoutdinov, M. F., S. K. Krueger, C.-H. Moeng, P. Bogenschutz, and D. A. Randall, 2009: Large-eddy simulation of maritime deep tropical convection. Submitted to *J. Adv. Modeling Earth Sys.*

Koster, R.D., M.J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar, 2000. A catchment-based approach to modeling land surface processes in a general circulation model. 1. Model structure. *Journal of Geophysical Research*, **105D**, 24809-22.

Krueger, S. K., 2002: Current Issues in Cumulus Parameterization. *ECMWF Seminar on Key issues in the Parametrization of Subgrid Physical Processes*, ECMWF, Reading, 3-7 September 2001, 25-51.

Moeng, C.-H., M. A. LeMone , M. Khairoutdinov , S. Krueger , P. Bogenschutzc and D. A. Randall, 2009: The tropical marine boundary layer under a deep convection system: a large-eddy simulation study. Submitted to *J. Adv. Modeling Earth Sys*.

Kummerow, C., and coauthors, 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor.*, **39**, 1965-1982.

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.

Lappen, C.-L., D. A. Randall, and T. Yamaguchi, 2009: A higher-order closure model with an explicit PBL top. *J. Atmos. Sci.* (in press).

Lohmann, U., and J. Feichter, 2005: Global indirect aerosol effects: A review. *Atmos. Chem. Phys.,* **5**, 715-737.

Majda, A. J., and S. N. Stechmann, 2009: The skeleton of tropical intraseasonal oscillations. *Proc. National Acad. Sci.*, in press.

Maloney, E. D., 2009: The moist static energy budget of a composite tropical intraseasonal oscillation in a climate model. *J. Climate*, **22**, 711-729.

Marchand, R., J. Haynes, G. G. Mace, T. Ackerman, and G. Stephens, 2009: A comparison of simulated cloud radar output from the multiscale modeling framework global climate model with CloudSat cloud radar observations. *J. Geophys. Res.*, **114**, D00A20, doi:10.1029/2008JD009790.

Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102(D14)**, 16,663–16,682.

Morrison, H., M. D. Shupe, and J. A. Curry, 2003: Modeling clouds observed at SHEBA using a bulk microphysics parameterization implemented into a single-column model. *J. Geophys. Res.,* **108**, doi: 10.1029/2002JD002229

Morrison, H., and W. W. Grabowski, 2007: Comparison of bulk and bin warm rain microphysics models using a kinematic framework. *J. Atmos. Sci.*, **64**, 2839-2861.

Morrison, H., and W. W. Grabowski, 2008a: Modeling supersaturation and subgrid-scale mixing with two-moment bulk warm microphysics. *J. Atmos. Sci.*, **65**, 792-812

Morrison, H., and W. W. Grabowski, 2008b: A novel approach for representing ice micro-physics in models: description and tests using a kinematic framework. *J. Atmos. Sci.*, **65**, 1528-1548.

Morrison, H., and A. Gettelman, 2008: A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model (CAM3), Part I: Description and numerical tests. *J. Climate,* **21**, 3642-3659.

Morrison, H., and W. W. Grabowski, 2009: A new multicomponent detailed bin ice microphysics model: Toward an improved representation of rimed snow and graupel. *J. Atmos. Sci.* (submitted)

Morrison, H., and J. O. Pinto, 2005: Mesoscale Modeling of Springtime Arctic Mixed-Phase Stratiform Clouds Using a New Two-Moment Bulk Microphysics Scheme. *J. Atmos. Sci.*, **62**, 3683–3704.

Neelin, J. D., O. Peters, and K. Hales, 2009: The Transition to Strong Convection. *J. Atmos. Sci.*, **66**, 2367-2384.

Park, S. and C. S. Bretherton, 2009: The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the Community Atmosphere Model. *J. Climate*, **22**, 3449-3469.

Phillips, V. T. J., and L. J. Donner, 2007: Nucleation processes in deep convection simulated by a cloud-system-resolving model with double-moment bulk microphysics. *J. Atmos. Sci.*, **64**, 738-761.

Pincus, R. and B. Stevens, 2009: Monte Carlo spectral integration: A consistent approximation for radiative transfer in large eddy simulations. *J. Adv. Model. Earth Sys.*, 1, 1. doi:10.3894/JAMES.2009.1.1.

Pritchard, M. S., and R. C. J. Somerville, 2009. Empirical orthogonal function analysis of the diurnal cycle of precipitation in a multi-scale climate model. *Geophys. Res. Lett.,* L05812, doi: doi:10.1029/2008GL036964.

Randall, D. A., Q. Shao, and C.-H. Moeng 1992: A Second-Order Bulk Boundary-Layer Model. *J. Atmos. Sci.*, **49**, 1903-1923.

Sauerbrei, W., and M. Blettner, M., 2003: Issues of traditional reviews and meta-analysis of observational studies in medical research. In R. Schulze, H. Holling & D. Böhning (Eds.), *Meta-analysis: New developments and applications* (pp. 79-98). Cambridge, MA: Hogrefe & Huber.

Schar, C., D. Luthi, and U. Beyerle, 1999. The soil-precipitation feedback: a process study with a regional climate model. *J. Clim.*, **12**, 722-741.

Sellers, P. J., D. A. Randall, G. J. Collatz, J. Berry, C. Field, D. A. Dazlich, C. Zhang, and L. Bounoua, 1996: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 1: Model formulation. *J. Climate,* **9**, 676-705.

Sellers, P. J., M. J. Fennessy, and R. E. Dickinson, 2007. A numerical approach to calculating soil wetness and evapotranspiration over large areas. *J.. Geophys. Res.*, **112**, D18106, doi:10.1029/2007JD008781.

Silva Dias, M., S. Rutledge, P. Kabat, P. L. Silva Dias, C. Nobre, G. Fisch, A. J. Dolman, E. Zipser, M. Garstang, A. O. Manzi, J. Fuentes, M. O. Andreae, P. Artaxo, R. Gielow, and L. Gatti, 2002: Cloud and Rain Processes in a Biosphere-Atmosphere Interaction Context in the Amazon Region. *J. Geophys. Res.*, **29**, 10.1029/2000JD000335

Simmons, A., S. Uppala, D. Dee, S. Kobayashi, 2006: ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter*, No. 110 – Winter 2006/07, 25-36. European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, Berkshire, United Kingdom. Bob Riddaway, editor.

Slawinska, J., W. W. Grabowski, H. Pawlowska, and A. A. Wyszogrodzki, 2008: Optical properties of shallow convective clouds diagnosed from a bulk-microphysics large-eddy simulation. *J. Climate*, **21**, 1639-1647.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.), 2007: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Stan, C., M. Khairoutdinov, C. A. DeMott, V. Krishnamurthy, D. M. Straus, D. A. Randall, J. L. Kinter III, and J. Shukla, 2009: A global climate simulation with explicit clouds. Submitted to *Geophys. Res. Lett*.

Stephens, G. L., and coauthors, 2002: The CloudSat mission and the A-train: A new dimension of space-based observations of clouds and precipitation. *Bull. Amer. Meteor. Soc.*, **83**, 1771-1790.

Taylor, K., R. J. Stouffer, and G. A. Meehl, 2008: A summary of the CMIP5 Experiment Design. Available at https://cmip.llnl.gov/cmip5/docs/Taylor_CMIP5_design.pdf.

Thayer-Calder, K., and D. A. Randall, 2009: The Role of Convective Moistening in the MJO. *J. Atmos. Sci.*, **66**, 3297-3312.

Thayer-Calder, K., and D. A. Randall, 2009: The Role of Convective Moistening in the Formation and Progression of the MJO. *J. Climate* (in press).

Weaver, C. P., S. BaidyaRoy, and R. Avissar, 2002. Sensitivity of simulated mesoscale atmospheric circulations resulting from landscape heterogeneity to aspects of model configuration. Jour. Geophys. Res., 107D, 8041, 10.1029/2001JD000376.

Wood, E.F., D.P. Lettenmaier, and V.G. Zartarian, 1992. A land-surface hydrology parameterization with subgrid variability for general circulation models. *Journal of Geophysical Research***, 97D**, 2717-28.

Wyant, M. C., M. Khairoutdinov, and C. S. Bretherton, 2006: Climate sensitivity and cloud response of a GCM with a superparameterization, *Geophys. Res. Lett.*, **33**, L06714, doi:10.1029/2005GL025464.

Wyant, M. C., C. S. Bretherton, and P. N. Blossey, 2009: Understanding subtropical low cloud response to a warmer climate in a superparameterized climate model. *J. Adv. Modeling Earth Sys.*, **1**, Art. #7, 11 pp., doi:10.3894/JAMES.2009.1.7.

Xu, K.-M., A. Arakawa, and S. K. Krueger, 1992: The Macroscopic Behavior of Cumulus Ensembles Simulated by a Cumulus Ensemble Model. *J. Atmos. Sci.*, **49**, 2402–2420.

Yanai, M., S. K. Esbensen, and J. - H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large - scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611 - 627.6