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Introduction: In 2007, the Intergovernmental Panel on Climate Change (IPCC) will publish its Fourth Assessment Report of the Scientific Basis of Climate Change (AR4). A significant portion of the AR4 will be the analysis of coupled general circulation model (GCM) simulations of the climate of the past century as well as scenarios of future climates under prescribed emission scenarios. Modeling groups worldwide have contributed to AR4, including three from the U.S., the Community Climate System Model (CCSM) project, the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Sciences, and the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL). This collection of model results is providing a wealth of new information that will be used to examine the state of climate science, the potential impacts from climate changes, and the policy consequences that they imply.

Our focus here is on the CCSM project. Although it is centered at the National Center for Atmospheric Research (NCAR), the CCSM version 3 (CCSM3) was designed, developed, and applied in a uniquely distributed fashion with participation by many institutions. This model has produced some of the most scientifically complete and highest resolution simulations of climate change to date, thanks to the teamwork of many scientists and software engineers. Their contributions will become obvious as a steady stream of peer-reviewed publications appears in the scientific literature.

Less obvious, however, is the largely hidden, unprecedented level of interagency cooperation and multi-institutional coordination that provided the direction and resources necessary to make the CCSM project successful. Contrary to the widely-held opinion that the US climate research effort in general, and the climate modeling effort in particular, is fragmented and disorganized (NRC 1998, 2001), the success of the CCSM project demonstrates that a uniquely US approach to model development can produce a world-class model.

History and Context: Prior to 1988, GCM-based climate modeling was primarily a research activity. In the U.S., several independent projects existed at federal research laboratories and universities that had access to the supercomputing resources necessary to perform the most comprehensive simulations, but there was no imperative for a national modeling strategy. In 1988, the IPCC was chartered to assess the potential for anthropogenic climate change. Less than a year later, the interagency U.S. Global Change Research Program (USGCRP) was established. One of its three overarching objectives was to "Develop Integrated Conceptual and Predictive Earth System Models (CES, 1989)." Four agencies, NASA, NOAA, the National Science Foundation (NSF) and the Department of Energy (DOE) emerged as the primary supporters of model development and application within the USGCRP. US participation in the 1990 IPCC Scientific Assessment demonstrated world leadership in climate modeling as the only transient CO_2 concentration experiments were carried out at NCAR through NSF and

DOE support, and at GFDL with NOAA support. Although climate modeling was central to the mission of both institutions, neither was focused exclusively, or even predominantly, on anthropogenic climate change.

With the publication of the IPCC Second Assessment Report in 1995, however, many believed that US leadership had been eclipsed by the Hadley Centre in the United Kingdom and Max Planck Institute for Meteorology (MPI) in Germany. Both centers had a well-defined mission to understand and predict century scale climate change and dedicated computing resources on which to build, test and validate their models. A letter to the four modeling agencies from senior climate researchers in 1995 discussed the "Crisis in US Climate Modeling" (NRC, 1998). This community attitude precipitated a series of high level studies between 1996 and 2001, (e.g. NRC 1998, 2001) on how to restore US leadership. These studies concluded that while the US remained a world leader in climate research it, paradoxically, lacked the structure and mechanisms to integrate that knowledge within a comprehensive modeling effort. The visionary and comprehensive solutions that the studies proposed required a wholesale restructuring and a reallocation resources that were impractical to implement within the USGCRP structure.

The Agency Perspective: While the USGCRP modeling agencies had a history of successful collaboration on large experimental campaigns, there was little experience on the coordination of longer-term ongoing research, such as model development and application. Nevertheless, the USGCRP established an interagency modeling working group composed of agency program managers and tasked it to define and fill gaps in a national program. Each agency brought its own strengths, weaknesses and perspective to the problem.

Scientific advances in the 1980s and early 1990s in the understanding of coupled atmosphere-ocean interactions had made seasonal prediction a realistic possibility with tremendous social and economic benefit. The USGCRP was instrumental in fostering this achievement, through efforts such as the interagency Tropical Oceans – Global Atmosphere program. A consequence of this remarkable success was that less attention was focused on longer term climate change and IPCC-type climate change simulations. Additionally, the culture in US climate research was dominated by a "bottoms-up" approach, whereby scientists and institutions proposed ideas to funding agencies, who then responded based on the merit of the proposal and its relevance to mission. "Top-down" direction was new to US climate researchers. A further complication arose from changes in US high-end computing encouraged by the federal High Performance Computing and Communications Program. Interconnected commodity-processor, massively-parallel designs replaced traditional shared-memory vector supercomputers that climate modelers had relied upon for the previous two decades. Machine architectures and software environments were not sufficiently consistent among computer vendors to ensure reasonable performance and portability among computers. While the long term benefit of this approach is still open for debate, it is clear that these changes resulted in a considerable increase in the cost and time required for code development and maintenance. It is worth noting that both the Hadley Centre and MPI use shared-memory vector systems as their primary production platforms.

Against this backdrop, the interagency working group endeavored to build a distributed national program. In the early 1990s, its members unanimously agreed to use incremental funds dedicated to climate modeling to purchase additional high-end computing resources and thereby established the Climate Simulation Laboratory at NCAR, which provides computing for projects supported by all USGCRP agencies.

About the same time, both NSF and DOE developed multi-institutional collaborations within their programs that would later form the foundation for CCSM. The NSF initiated the Climate System Modeling Project (CSMP) at NCAR, with the goal of entraining the academic research community to build an NCAR-based climate modeling capability. Simultaneously, DOE expanded its program to bring together university, DOE laboratory and NCAR scientists to develop atmosphere, ocean and coupled GCMs that could run efficiently on the new massively-parallel supercomputers. Although both programs had NCAR involvement, there was little overlap among the scientists involved, because of the differing program objectives.

NSF and NCAR expanded the CSMP activity into the CCSM project in 1995 with the objective to develop a state-of-the-science climate model that would be used for a wide range of applications. Consistent with NSF's mission to support basic research involving the academic community, the CCSM strategy employed a deliberate, consensus approach to its model development enterprise. Through a system of working groups open to any scientist who wished to participate, ideas and plans were thoroughly debated so as to include the most recent scientific advances into the modeling system.   DOE, on the other hand, continued its more focused mission to simulate anthropogenic climate change using comprehensive coupled climate models. Climate change experiments were planned around the IPCC timetable. This situation raised the possibility of conflict between competing model development programs at NCAR.

Program managers at NSF and DOE agreed that their respective programs were more complementary than competing. They worked together to resolve conflicts and look for opportunities to increase collaborations. When the CCSM project produced CSM 1.0 in 1996, and DOE produced the PCM in 1997, the participants and the community were skeptical that interagency cooperation was working. Nevertheless, both models represented irreversible paradigm shifts toward a true distributed modeling capability. CSM was an open, accessible system that was freely available to any group who wished to use it, although the availability of computing resources represented a severe constraint. Community involvement in its development and analysis of its simulations was unprecedented. The DOE program, on the other hand, built a multi-institution collaboration that entrained the numerical methods and computational fluid dynamics expertise found at DOE laboratories and combined it with NCAR's experience in climate change simulation to build PCM, a state-of-the-science, computationally efficient coupled model that, unlike CSM, could be run on a variety of computers.   When the scientists recognized the complementary nature of their efforts, they fully supported the merger of the development efforts, resulting in CCSM2 in 2002, followed by CCSM3 in 2004. CCSM3 consists of an atmospheric model developed primarily at NCAR, an ocean model developed primarily at the DOE Los Alamos National Laboratory, with land and sea-ice components being largely developed as community activities. Major DOE contributions in software engineering and computational science enabled the model to be run on a variety of platforms with good performance.

Lessons Learned and Challenges for the Future: Advocacy for interagency activities is often difficult in the hierarchical federal budgeting process. Important high-priority national research activities may not map well onto individual department or agency priorities, for which agencies are held accountable by Congress and the Office of Management and Budget. The CCSM project demonstrates that sustained support by individual agencies for interagency research can have a large positive impact and should be used as an example to inform the budget making process.

Another key to the success of CCSM was the distribution of effort among universities and laboratories. It is clear that the human and computational infrastructure at NCAR and the DOE laboratories was essential. Complementing this infrastructure was the vast expertise in the academic community that contributed both directly and indirectly to the scientific development of the model. CCSM3 could not have been built through individual, single-PI scientific grants, or at a single laboratory. Funding for large laboratories is viewed by many as expensive “welfare” for their scientists, however, without the long-term dedication of resources to those laboratories, projects such at CCSM cannot succeed. The focused attention, creative research, and personal sacrifices of the core scientists at the modeling centers (including those not discussed here at NASA and NOAA funded institutions) over the past decade have lifted the U.S. to a world-class climate modeling nation.

With success comes a new set of challenges. The CCSM is now part of the national modeling strategy with obligations to both the scientific and science policy communities. Demands for support and computing resources far exceed what the agencies can provide. Additionally, continued development of the model to keep pace with advances in climate and global change science may require different expertise (e.g. chemists and biologists) and a new group of collaborators. A consensus has yet to emerge about the appropriate balance of priorities within realistic funding expectations. On the positive side, interagency and multi-institutional collaboration continues to grow in several areas, including model frameworks, numerical methods, and management of large volumes of model generated output. The agencies and the science community will continue to devise innovative and novel solutions to problems provided that it is encouraged and rewarded at high levels in the government. The example of CCSM will help make the case.

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