The NCAR Earth System Model (NESM): A Recommended Approach to Formulating a Structured Development Plan

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Development of the NESM will require a delicate balance between visionary goals and hard-nosed practicalities, and between internal and external contributions. The NESM will build off a very substantial existing NCAR climate, weather and air quality modeling enterprise, one that involves literally thousands of collaborators and users around the world and across a wide range of disciplines from societal impacts to fluid dynamics. NESM is also made possible by major advances in computing infrastructure, such as the NCAR Wyoming facility and the model development will provide a major program focus for much of the NCAR research activity.

This document lays out a recommended approach to a structured development plan that will enable us to build on our existing modeling system and expertise to convert the vision to reality. We start with an overview of the current modeling system, the vision and NCAR's leadership role, then move to interim activities and finally to a recommended structured approach to the NESM development.

1. Background and Vision

Recent major advances in petascale computing, especially the NCAR Data Center in Wyoming, coupled with rapid advances in scientific understanding are rapidly moving us toward the ability to simulate a wide range of physical and dynamical phenomena with associated physical, biological and chemical feedbacks that collectively cross the traditional weather-climate divide. Such simulations and predictions are essential to a society that is becoming much more sophisticated in its requirements for weather, air quality and climate predictions and that is able to make useful economic and social use of such improvements. Moreover, fundamental barriers to advancing such prediction on time scales from days to years, as well as long-standing systematic errors in weather and climate models, are partly attributable to our limited understanding and capability to simulate the complex, multiscale interactions intrinsic to atmospheric and oceanic fluid motions. In order to address such challenges, a sophisticated software framework must be developed to provide the ability to flexibly deal with phenomena across a wide range of scales of motion, for different levels of complexity, and across many time scales.

The scientific and societal questions and issues to be addressed with this system are many. A very limited sample includes better understanding of:

- The water cycle and its predictability;

- The limits of weather, air quality and climate predictability;
- Chemical weather and its prediction;
- The interaction of hydrological and biogeochemical cycles;
- How biogeochemical cycles of nitrogen, iron, and sulfur influence carbon/climate feedbacks;
- How land use, land cover change, and water use modify biogeochemical processes;
- The mechanisms by which solar variations influence the chemistry and dynamics of the upper atmosphere, and how these effects are manifested in the lower atmosphere;
- The role of hurricanes in climate;
- How climate change affects ENSO and other natural modes;
- The mechanisms of abrupt climate change;
- The impact of weather and climate on food production;
- The advantages and disadvantages of living in mega-cities;
- The capacity of the Earth to sustain both population growth and quality of life requirements; and
- The limitations of available water.

We are moving into a decade of prediction across scales, covering phenomena ranging from local convective elements to regional water and chemical cycles to long-term changes in extreme weather, droughts and hurricanes and learning to live with Megacities. NCAR is well positioned to take a lead in coordinating the extremely complex task of designing and developing a hierarchical modeling strategy and framework that will allow these scientific challenges to be met.

The NESM framework should recognize that some applications will not require the full complexity possible. Flexibility in the modeling framework should provide for the hierarchical treatment of the core physical system with increasing levels of complexity that include chemical, biogeochemical, and other modeling capabilities, as well as connections to extensions like population and disease models and space weather. Another important attribute of the NESM framework will be the ability to readily exploit observational opportunities (e.g., HIAPER and NASA’s A-Train; field campaigns). In this regard, data assimilation capabilities will be an important component.

This NESM modeling environment will require a high-performance, flexible software infrastructure to allow for increased ease of use, performance portability, interoperability, and reuse of various modeling applications. Based on careful and thorough requirements analysis, a design employing technologies that support development of multi-component applications -- for example, the Earth System Modeling Framework -- will be developed.

We emphasize that the NESM will be much more than a modeling exercise. Our vision is that it will:

- Provide an integrator of diverse activities across NCAR and into the broader community;

- Be the key focus for research and development across pretty well all components of the physical and societal sciences;
- Be a major driver of future developments in supercomputing; and,
- Support the evolution of innovative approaches to providing critical weather, air quality and climate information to an increasing complex and vulnerable society.

2. Leadership

This is a project that will be led by NCAR but has to be developed as a community activity from the very beginning, building on, merging and adapting the existing highly successful CCSM and WRF programs.

We emphasize that the NESM is not starting from scratch. WRF, CCSM, WRF-Chem and WACCM are well-developed, complex systems in their own right and many of the components will be directly transferable to, or will form the basis for the NESM. NCAR also has invested heavily in the Nested Regional Climate Model (NRCM), which provides both a valuable test bed and an interim means of undertaking urgent research activities on regional climate as a more complete hierarchical modeling system is developed.

CCSM and WRF have established community structures, including steering and advisory panels, external collaborators, and very large external user groups. These are well-oiled structures that have a lot of community support and, thereby, provide a solid foundation for moving forward. The WRF and CCSM communities also have major continuing commitments to, for instance, the IPCC assessments and operational forecasting in a number of centers, which must be accommodated in the development of the NESM.

3. Interim Progress and Continuation of Current Programs

NCAR has already devoted substantial resources to the coupling of weather, climate, chemistry and upper-atmosphere models. New efforts are emerging investigating scale interactions and producing higher resolution, shorter-term simulations of weather and climate. There is therefore a wealth of continuing work that cannot be neglected in moving towards a NESM. Indeed, this work will provide a substantial and necessary basis for the development of the NESM. Examples of such work vary across the whole spectrum of disciplines, from the IPCC and NARCAP to MILAGRO and to hurricane and severe storm forecasting.

The tropical channel version of the NRCM forms an excellent example of current developments. This, initially, has involved close interactions between MMM and CGD scientists and software engineers, but is rapidly expanding into interactions with, and contributions from other NCAR and external community members. The initial NRCM program has been a success in both demonstrating capacity and in generating a community of involved scientists from universities and other government laboratories. Valuable lessons have also already been learned from the marriage of these well-established weather and climate models. There is much more to be gained from continuation and expansion of this process, however, and there is a lot of very valuable research that can be undertaken along the way. It is recommended that the NRCM form a founding basis for the NESM and that it be extended to a fully coupled WRF running within CAM together with global (POP) and regional (ROMS) ocean models to enable a hierarchical treatment of climate and forecast phenomena that span a wide range of space and time scales. Initially, the relevant physics, chemistry and biological modules will be transferred as a part of the package, but further development, substantial testing, and extensions to the initial framework will be required.

WRF and CCSM represent the current status of modeling the Earth system. Moreover, these complex models are being expanded to encompass chemical and biological aspects of the Earth system, including models of atmospheric chemistry and the carbon cycle, with dynamic vegetation modules and interactive marine ecosystems.

Other Earth system Models of Intermediate Complexity (EMICs) offer a complementary approach for long-term simulations, and more holistic, exploratory models are being developed (outside of NCAR) for the investigation of the interaction of human societies with the other components of the Earth system. Improvement of the present modeling capability at NCAR thus requires a coordinated hierarchical approach with a suite of different models. In particular, there is a need for:

- Continued experimentation with the current generation of CCSM, WRF and NRCM to provide, for example:
    - The material for IPCC and other international assessments through sensitivity studies, climate hindcasts and projections of future change;
    - A means to assimilate and predict the coupled system on intraseasonal to interannual (and eventually longer) time-scales;
    - Very high resolution forecasts of severe weather and chemical weather that is becoming of increasing concern;

- A continued major effort on data assimilation, with emphasis on both the very short (0-24 h) time scales and seasonal to interannual prediction, that includes innovative assimilation of observing systems, such as COSMIC, the NASA A-Train and ground and airborne Doppler radars;

- Continued development of the ability to perform more detailed global modeling of complex scale interactions, the carbon cycle, hydrology, dynamic vegetation, tropospheric and stratospheric chemistry, upper atmosphere processes and space weather requirements, ice sheets, ocean biology, lateral transport of elements and a range of other biogeochemical processes;

- Development of, and work with more holistic models (including EMICs) to:
    - Study the full range of interactive aspects of the natural system;

    - Enhance development of new societal and physical modules in response to community needs;
    - Simulate longer time-scales, e.g. Ice Age Cycles; and,
    - Compare to and validate the more complex models.

- Development of models of the interaction between the human and natural systems based on the more holistic models.

The effective development and implementation of such a hierarchical modeling program at NCAR requires a range of separate but coordinated and collaborative activities. Including all of these in a single overarching NESM would not be appropriate, at least at this stage. Instead, the coordination of the various modeling activities above could be achieved at least initially through presentation, discussion and agreement among NCAR (and community) scientists periodically at appropriate venues (e.g., retreats). More dedicated mechanisms, procedures and forums will also be needed to make effective progress on the necessary cooperative efforts. Full consideration of how to best integrate with existing infrastructures, such as those associated with CCSM, WRF, WRF-Chem and WACCM, is required.

4. An Hierarchical Approach to NESM Planning and Development

The logical lead NCAR groups for the NESM modeling effort reside in ESSL and SERE. ESSL is currently providing effective leadership of the physical and modeling activities, while SERE should take the lead on the societal aspects. Initially, three parallel approaches are recommended:

- A series of specialist working groups be established in NCAR to develop white papers on relevant aspects of the NESM that will serve as both discussion points and a foundation for the full NESM strategic development plan. This must be a process driven by the scientific, societal and software engineering experts.

- The initial purpose of the white papers is to form the basis for a focused series of discussions on NESM at the next NCAR Director's retreat.

- All relevant NCAR groups and the WRF and CCSM communities must be brought into the planning process at the beginning. It is planned that the CCSM and WRF communities will consider the draft plans as part of the established communication and meeting schedules starting in June;

Each of these is elaborated below.

4.1 White Papers from Specialist Working Groups

Small specialist working group teams, led by 1-2 internationally renowned NCAR scientists, should be established to produce white papers in areas of importance to the NESM development. These white papers should be short (< 5-10 pages) and strategic in nature. They can outline the proposed NCAR-based efforts, existing and potential external collaborations, and resources needed to facilitate the development effort. The initial results are expected be used for developing concepts for the NESM to be used as the basis for the discussions at the NCAR Directors Retreat 31 May – 1 June 2007. Further development will then occur to provide the basis for the proposed discussions in conjunction with the CCSM and WRF community meetings. Lead scientists should formulate their working teams as they see fit. The suggested working groups include, but may not be limited to:

- ***Societal needs (SERE, ESSL, and RAL):*** This WG will be tasked with identifying the priority needs and methods for integrating social processes into the NESM. Requirements of impact, damage, mitigation, and solution studies have several common features, linked to the need to relate weather and climate processes to human concerns. These requirements relate to regional credibility, resolution of relevant scales, production of required variables, links between regional and global models, and impacts projections from regional climate variations and changes over decades to explicit predictions of damage from a hurricane landfall.
- ***Atmospheric model (ESSL):*** The atmospheric component is the most critical part of the entire model development, as everything else will couple into or be dependent on it. There are several aspects:
    - ***Dynamical core:*** Development of the next generation dynamical core has already commenced as a joint effort of CGD and MMM scientists and include development of suitable fine-scale meshes that are capable of efficient operation to provide simulations and forecasts from hours to decades and from global to regional scales.
    - ***Atmospheric Physics:*** Topics include representations of cloud and water substances in the atmosphere and precipitation, the processes that interact strongly with them (like aerosols and radiation), their influence on and interactions with other components of the earth system, and transport processes. All of this will involve improved parametric treatments of boundary-layer exchanges that deal with phase and chemical transitions more comprehensively, moist convection in terms of its initiation, temporal characteristics and interaction with stratiform cloud processes and the large-scale cloud field, and improved and more flexible treatments of radiative transfer.
    - ***Atmospheric Chemistry:*** These include both aqueous and dry processes, and interactions with the surface (land and ocean) to represent exchanges (natural and anthropogenic emissions and dry deposition). The explicitly calculated distribution of the chemical species, based on gas phase and heterogeneous chemistry, including aerosol interactions, is also necessary to calculate heating rates and radiative forcings fully compatible with the modeled chemical state.

- ***Scale Interaction Processes (ESSL):*** A critical component that must be given priority attention is that of scale interactions. In particular, it is well known that a lack of ability to adequately simulate the main tropical modes and their interactions with higher latitude circulations is a significant limitation on both weather forecasting and climate projections. Nonlinear processes and turbulence across all scales is also a critical issue. This is a major focus of the THORPEX program, both international and national.
- ***Representation of the middle atmosphere (ESSL):*** This includes topics such as the mechanisms of stratospheric-tropospheric coupling, and the role dynamical forcing by waves propagating upward from the troposphere, radiative forcing by solar heating due to ozone, and smaller-scale gravity waves that propagate through the stratosphere into the mesosphere and lower thermosphere where they deposit momentum and affect the stratosphere through “downward control.” The WACCM activity is of prime relevance here.
- ***Upper Atmosphere and Space Weather Requirements (ESSL):*** Again WACCM is relevant, which sets an excellent foundation for ensuring that these important, and sometimes overlooked, aspects are properly incorporated into NESM, together with the Sun System model.
- ***Land model (ESSL):*** The land surface affects weather and climate through a variety of ecological, hydrological, and biogeochemical processes. Terrestrial biogeochemistry and the fluxes of carbon, nitrogen, mineral aerosols, and biogenic aerosols between land and atmosphere are important, as are land use and land cover change, the terrestrial hydrologic cycle and its feedback on the atmosphere.
- ***Ocean model (ESSL):*** A central question in oceanography is what role mesoscale ocean processes play in establishing the mean climate, its variability, and the response to climate forcing. Many others issues are important as well, such as ocean biogeochemistry, tropical instability waves, subtropical and tropical cell interactions, and atmospheric coupling from the diurnal to seasonal cycle. This should include current plans for ROMS nesting within NRCM.
- ***Cyrospheric model (ESSL):*** There are a number of issues related to cryospheric feedbacks and the role of the cryosphere in the global climate system, such as polar amplification, the role of the cryosphere in thermohaline circulation (THC) variability and change, including the role of changes in glacier and ice sheet mass budgets on the THC, thereby including ice sheet models.
- ***Data Assimilation (ESSL, CISL and RAL):*** The initial value problem is one of the great foci for weather forecasting (indeed it is considered more important than the modeling side by many). And as climate projections move to shorter scales and higher resolutions, it will become critical there as well.
- ***Diagnostics and model evaluation (ESSL, SERE, RAL, EOL, and CISL):*** A crucial question is how well we understand and simulate the full spectrum of natural variability in models and how well we represent the driving processes. Our ability to simulate the important variability forms the basis for how well we can make relevant forecasts and future projections. Simulating variability also requires proper recognition of predictability to determine appropriate measures of inherent uncertainty associated with chaotic aspects of the climate system.

- ***Field and Observing Program Support (EOL, ESSL):*** A major use of NESM will be in the form of "current" weather and climate, which can vary from directing an aircraft in real time, to assimilating data over several years and decades.
- ***Surface hydrology (RAL and ESSL):*** This is at best in its infancy, but a consideration of surface and subsurface hydrology should be included in the overall considerations for the NESM development and plans made to develop an appropriate system as part of the process.
- ***Software Engineering (ESSL and CSL):*** The complexity of the proposed system demands very close attention to application of the most advanced software techniques and a careful consideration of the framework within which the modeling system will operate.
- ***Education and Outreach (ASP):*** Following the substantial tradition of WRF and CCSM, the NESM will involve a strong role in E&O and this should be considered up front.

4.2 NCAR Directors' Retreat

The timetable for development of the above white papers is designed to enable a structured and substantial discussion on the NESM at the NCAR Directors' Retreat in late May. A recommended approach is for a small working group, led by the Associate Directors of ESSL and SERE, to coordinate a summary document covering the above white papers. This summary document, together with the above white papers as attachments, will be distributed to the retreat participants and several key presentations should be made by selected lead scientists. The outcome of the Directors' Retreat should then evolve into the draft of a comprehensive plan for NESM.

4.3 WRF and CCSM Community Inputs

The upcoming WRF and CCSM meetings provide an optimal opportunity to elicit community feedback on early planning and to gather support. The NESM goals and plans need to be carefully discussed with the relevant committees and involved scientists (many of whom are outside NCAR), so no details are provided here. The ESSL Directors are already discussing how this might best occur, with current plans to include overview presentations on the NESM Draft Plan at specific discussion sessions.

4.4 Wider Community Involvement

There are a number of international groups that are moving in the same direction as the NESM, and all are seriously considering the same issues. Their perspectives, therefore, would be of considerable value in the development of the NESM plans. It is recommended that following the initial concentrated planning development through June:

- A major NCAR white paper be prepared for circulation to relevant groups, including funding agencies; and,
- One or more meetings of experts be called to discuss the plans in detail, to solicit ideas on how to proceed, and to investigate potential major partnerships in the model development. Possible meeting venues are NCAR and a special session at a major conference, such as the AMS Annual Meeting.