Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM

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WORKSHOP ON RESEARCH NEEDS AND DIRECTIONS OF REGIONAL CLIMATE MODELING USING WRF AND CCSM

What: 60 members of the regional and global climate modeling community discussed science issues and model development needs using WRF and CCSM to address downscaling and upscaling issues in climate modeling

When: 22-23 March 2005

Where: National Center for Atmospheric Research, Boulder, CO

Climate varies across a wide range of temporal and spatial scales. Yet, climate modeling has long been approached using global models that can resolve only the broader scales of atmospheric processes and their interactions with land, ocean, and sea ice. Clearly, large-scale climate determines the environment for mesoscale and microscale processes that govern the weather and local climate, but, likewise, processes that occur at the regional scale may have significant impacts on the large scale circulation. Resolving such scale interactions will lead to much improved understanding of how climate both influences, and is influenced by, human activities.

Since October 2003, the National Center for Atmospheric Research (NCAR) has supported an effort through the Opportunity Fund to develop regional climate modeling capability using the Weather Research and Forecasting (WRF) model (http://www.wrf-model.org/index.php) and the Community Climate System Model (CCSM) (http://www.ccsm.ucar.edu/models). The goal is to develop a next generation community Regional Climate Model (RCM) that can address both downscaling and upscaling issues in climate modeling.

Downscaling is the process of deriving regional climate information based on large-scale climate conditions. Both dynamical and statistical downscaling methods have been used extensively in the last decade to produce regional climate change scenarios; however, their resolution and physical fidelity are regarded as inadequate. Hence, at a workshop (http://www.climatescience.gov/events/workshop2002/) to review the Climate Change Science Program plan, the global change community expressed a strong demand for improved regional climate information to develop climate scenarios for exploring the implications of adaptation and mitigation as well as assessing climate change impacts.

Upscaling encapsulates the aggregate effects of small-scale physical and dynamical processes on the large-scale climate. One form of upscaling is the use of physical parameterizations such as that for deep convection that represent the gross properties of subgrid scale processes. These are also considered to be inadequate, as much of the uncertainty in model sensitivity to greenhouse gas is now known to be associated with cloud parameterizations in climate models. Another form of upscaling is to explicitly include the effects of regional processes to the large-scale environment, both locally and remotely. Since its inception in the late 1980s, RCMs have been used predominantly to address downscaling issues through one-way coupling with global analyses or climate models. A few studies have used RCMs as testbeds for parameterization development and evaluation to address upscaling issues.

As part of the NCAR project, WRF has been adapted for simulating regional climate at the seasonal to decadal time scales. Seasonal simulations over the U.S. showed realistic features including the low-level jet and diurnal cycle of rainfall in the Central U.S. (Leung et al. 2005), and orographic precipitation in the western U.S. (Done et al. 2005). A WRF Regional Climate Modeling Working Group has been established to coordinate RCM research activities.

To help define the next steps, a workshop on "Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM" was organized on March 22-23, 2005, at NCAR to engage the regional and global climate modeling communities. The workshop was attended by about 60 invited U.S. and international participants. The workshop aimed to: (1) define research needs for the development of a next generation community RCM based on WRF and CCSM; (2) define upscaling and downscaling research that can be addressed by RCMs; and (3) develop a plan of actions that would meet the research needs. This article summarizes the research issues and recommendations discussed at the workshop. More information about the workshop including the agenda and presentations can be found at http://box.mmm.ucar.edu/events/rcm05/.

DOWNSCALING RESEARCH.

During the last decade, research in regional climate modeling has demonstrated that RCM is a useful downscaling tool for providing climate information at the scale appropriate for societal use. The ability of RCM to downscale depends on the large-scale boundary conditions provided by global analysis or global climate simulations, and regional scale forcings such as orography, land cover and land use, lake, and urban effects. Near regions with high terrain, for example, Mesoscale Convective Complexes (MCCs) are often found in association with nocturnal low level jet that occurs over sloping terrain (Laing and Fritsch 1997). RCMs can more realistically simulate the meso-α-scale features of the convective environments because of their ability to resolve the orography and the prominent baroclinic zones typically found in the MCC synoptic scale environment. Some studies have shown that RCMs can produce realistic simulations of the life cycle of MCC and the associated hydrological cycle (e.g., Anderson and Arritt 2005).

RCM can also be used as a regional climate analysis tool to elucidate regional mechanisms of climate variability and change. For example, RCMs have been used to project future climate change over many regions around the world. In the European PRUDENCE project (Christensen et al. 2002; http://prudence.dmi.dk), multiple RCMs were nested inside multiple GCMs to project future climate in Europe. Increases in the 95th percentile summer daily maximum temperature and decreases in summer rainfall were found in many regional climate simulations. Potential mechanisms of the summer drying include earlier decline of spring soil moisture, large-scale circulation changes, land-atmosphere feedback, local atmospheric response to radiative forcing, and reduced relative humidity due to greater warming over land in the future climate. By varying the inputs to the RCMs (e.g., lateral boundary conditions of temperature, winds, and humidity, surface boundary conditions such as soil moisture, and radiative forcing of greenhouse gases and aerosols) one at a time or in combinations, the regional models were used as an analysis tool to understand, quantify, and attribute the projected European summer drying to the different mechanisms.

The workshop participants represented a wide range of research interests in using RCMs for downscaling and process studies. They discussed many scientific investigations that can be addressed using RCMs. For downscaling, these include investigations of how climate change affects extreme events such as frequency and intensity of hurricane, heat wave, floods and droughts, how to improve seasonal prediction of warm season precipitation and examine the effects of land surface initialization on the forecasts, examine how large scale climate influences the characteristics of convective systems, and how the subtropical eastern boundary regimes respond to climate forcing.

For climate analysis, they discussed scientific investigations including the use of RCMs to understand the mechanisms of diurnal variations, scale interaction processes in warm season rainfall, monsoon processes and predictability, orographic processes and influence on synoptic scale phenomena, coastal air-sea coupling and processes that establish the structure of winds at the air-sea interface, urban effects on climate, and interactions between aerosol and precipitation processes.

Through discussion of research interests represented by the group, two areas of science issues and model development needs emerged. They can be categorized into two main themes: regional earth system modeling and high resolution modeling. These areas were considered high priorities because of their timeliness. Furthermore, new capabilities in these areas provide new and diverse research opportunities that can significantly advance the use of RCMs in climate modeling research.

Regional Earth System Modeling

The role of the ocean and cryosphere in regional climate is not well understood because most RCMs are atmospheric models. They do not represent the interactions between the atmosphere and other earth system components that are important drivers of regional climate. As examples, air-sea interactions play an important role in the initiation and propagation of the Madden-Julian Oscillation, which influences mesoscale processes such as convection and tropical cyclone activities. Interactions of the atmosphere with the cryosphere produce large uncertainty to how the polar climate responds to greenhouse warming. Interactions of the atmosphere with other earth system components such as chemistry and aerosols, and the terrestrial and marine ecosystems are also important for investigating regional climate response to anthropogenic perturbations. Although more and more of these interactions are now represented in GCMs, global models lack the spatial resolution to represent regional scale processes and feedbacks. Workshop participants strongly recommended the development of WRF towards a regional earth system model. Such a modeling system can be used to address a wide range of science questions specific to regional scale processes and forcing and response. The following research priorities were recommended:

- Develop interactive coupling with sea ice and ocean models to represent air-sea interactions.

- Develop interactive coupling with chemistry and aerosol models, including dust, to represent chemistry-aerosols-clouds-radiation feedbacks.
- Develop more comprehensive treatments of land surface and hydrological processes including river routing, sub-surface flow, lake, land use, fires, and land ice. It was noted that some development efforts are already underway in the framework of the Community Land Model (CLM) and Noah Land Surface Model that have been implemented in WRF.
- Develop interactive coupling with marine and terrestrial ecosystem models to represent the effects of higher trophic-level organisms and ecological processes.
- Develop data assimilation capabilities for the coupled model that can be used to develop regional analysis of the earth system. Examples are ocean and land data assimilation system.
- Accelerate the transition of WRF to the Earth System Modeling Framework (ESMF) (Hill et al. 2004) to facilitate model coupling.

High Resolution Applications

Workshop participants recognized the potential benefits of high resolution modeling using WRF as a next generation RCM. With non-hydrostatic dynamics cores and high-order, conserving numerical techniques, WRF is designed for use at any scale from large-eddy simulations to hemispheric applications. High resolution modeling (1-20 km resolution) may improve the fidelity of climate simulations (e.g., more realistic simulation of extreme events) and provide climate information at the scales needed for resource management and impact assessment. However, to realize the potential of high resolution modeling, more research is needed to assess and improve the skill of the model at high resolution. This includes:

- Develop and test physics parameterizations suitable for high resolution applications. Examples include processes such as cloud microphysics, turbulence, and shallow convection that are highly scale dependent and must be parameterized even in cloud resolving simulations.
- Develop and implement representations of processes important at the high resolution. Examples are terrain sloping effects on the planetary boundary layer and radiation and urban effects.
- Develop more options for mesh refinement such as multiple nesting, stretch grid, and adaptive mesh refinement for high resolution modeling, and evaluate their performance.
- Systematically investigate the value of high resolution modeling in regional climate modeling through numerical experiments, model evaluation, and model intercomparison. Such studies have been done more extensively for weather forecasting applications, but less so for regional climate applications.
- Apply WRF as a cloud resolving model to explore its usefulness and limitations. Such research is timely as the climate modeling community is investigating approaches to global cloud resolving modeling. A limited-area cloud resolving model capable of ingesting real data is a useful framework for model evaluation and scientific investigations.

UPSCALING RESEARCH.

As noted above, RCMs have not been applied in upscaling to the same extent as downscaling in the past decade. Studies in the area of upscaling research are also mostly limited to using RCMs to develop and evaluate physics parameterizations for GCMs. Recognizing that GCMs do not adequately resolve scale interactions that are important for establishing certain key climatic features, the workshop participants strongly recommended the climate modeling community to undertake research on two-way coupling of regional and global climate models to represent the upscaling effects of regional processes.

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A particular scale interaction problem that was discussed extensively at the workshop is the challenge in modeling the Subtropical Eastern Boundary (STEB) regime. The STEB regime is marked by marine stratus, equatorward alongshore winds, and ocean upwelling not well simulated by most, if not all, GCMs. Large and Danabasoglu (2005) investigated the large positive sea surface temperature (SST) biases that occur in the STEB regime, most notably off the coasts of South West Africa, Peru-Ecuador-Chile, and Baja-Southern California, in CCSM3. Sensitivity experiments showed that the SST biases can be reduced by replacing the net solar radiation and surface wind stress in the coupled atmosphere-ocean model with observed values in the STEB regions. With relatively coarse vertical and horizontal resolution, GCMs do not adequately represent the boundary layer processes of the marine stratus and the offshore winds that are influenced by the narrow coastal mountains in the west coasts of North and South America.

A series of CCSM3 experiments were also performed by Large and Danabasoglu (2005) to determine the effects of STEB biases on the large scale circulation simulated by the coupled model. By restoring the ocean temperature and salinity to the observed values over the three STEB regions in the coupled simulation, the positive precipitation bias south of the Equator (or the double Inter-Tropical Convergence Zone (ITCZ) bias) is much reduced. These sensitivity experiments indicate that in the STEB regions, interactions of the atmosphere and ocean in the highly localized littoral zone can produce effects that propagate and strongly influence the large-scale climate system.

At the workshop, other examples of regions or "hot spots" with significant upscaling effects were also discussed. These include the monsoon regions such as India/Tibet and Central and South America where steep topographical gradients and mesoscale processes such as low-level jet and MCCs play an important role in the water and energy budgets locally and remotely. In the Maritime Continent, the presence of large islands has a significant impact on the distribution of convection and cirrus clouds in the region. Neale and Slingo (2003) have noted that the removal of these islands from a GCM has far reaching consequences for global dynamics. Lorenz and Jacob (2005) presented a study at the workshop of two-way coupling the Max Planck Institute global (ECHAM4) and regional (REMO) climate models over the Maritime Continent. Preliminary results suggest that more realistic representations of the Maritime Continent by the regional model have large and positive impacts on the tropospheric temperature and large scale circulation in the global climate simulation through two-way coupling of the regional and global models.

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The impacts of spatial resolution on climate simulations have been demonstrated by many studies using both regional and global climate models. However, the spatial resolutions tested in previous studies may not adequately address the model resolution issue. The significance of representing scale interactions in climate simulations must be more fully addressed using non-hydrostatic models capable of resolving dynamical processes at the 5 – 30 km spatial scale. Currently, such spatial resolution is not achievable with global climate models for long term simulation because of computational constraints and/or limitations of the hydrostatic formulation. The coupling of regional and global models to represent upscaling effects is considered by the workshop participants as the most expeditious path to addressing this science question because significant investments have already been made to develop the regional and global models such as WRF and CCSM. The following research priorities were recommended to address this coupling issue:

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- Accelerate the transition of WRF and CCSM to the ESMF standard to facilitate their coupling.
- Develop more general coupling capabilities in WRF for coupling with CCSM as well as other earth system components. Most of the intriguing scale interaction issues involve feedbacks between different earth system components.
- Identify and address model compatibility issues between WRF and CCSM. For example, WRF has a lower model top compared to CCSM. Coupling these models may require the use of a hybrid vertical coordinate in WRF to match the CCSM model top and issues of modeling the upper atmosphere such as gravity wave drag and stratospheric physics need to be addressed. Alternatively nudging of the WRF upper atmospheric variables towards the CCSM values may provide a more straightforward solution. Compatibility of model physics has been partly addressed with the implementation of the CCSM radiation and land surface model (CLM) in WRF through the NCAR regional climate modeling project.
- Develop and test different methodologies for coupling WRF and CCSM. These include testing different approaches to apply feedback from WRF to CCSM (e.g., through data assimilation versus direct updating of CCSM variables with the WRF variables), and determining the frequency for exchange of forcing and feedback between CCSM and WRF.
- Develop pilot projects to demonstrate the methodologies and impacts of two-way coupling on the regional and global climate simulations.

SUPPORT OF COMMUNITY MODEL.

Workshop participants further recommended the following activities to support the infrastructure of a community RCM based on WRF:

- Develop spectral nudging capability in WRF to enable research on the use of spectral nudging in downscaling applications. Such technique is also useful for diagnosing model biases related to large scale circulation versus physics parameterizations.
- Generalize the WRF preprocessor to ingest data from multiple sources, including atmospheric circulation from GCMs and global analyses, and data needed to run component models such as chemistry and ocean. This can also be used as a multi-driver interface to facilitate nesting of WRF within multiple GCMs for assessing uncertainty in climate projections.
- Develop and implement methods and software for regional climate model evaluation and diagnostics. There is an urgent need to understand systematic biases found in many RCMs such as negative rainfall bias in the Southeastern U.S. through comprehensive model diagnostics. It is also important to assess the skill of RCM

compared to GCM (or quantify the value added) in providing seasonal climate prediction and simulating tropical convection that has large impacts on mid-latitude prediction.

- Develop guidance on optimal treatment of lateral boundary conditions based on more systematic numerical studies.
- Provide modeling support such as code maintenance, software development, and workshops for the regional climate modeling community.

Lastly, the workshop participants recommended establishing an advisory group to be built on the existing WRF Regional Climate Modeling Working Group to develop a plan of actions based on research priorities recommended at the workshop. To facilitate downscaling and upscaling research using WRF and CCSM, it is strongly recommended to create some symbiosis between the WRF and CCSM modeling efforts within NCAR and in the climate modeling community.

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