

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

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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 a 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 to develop regional climate modeling capability using the Weather Research and Forecasting (WRF) model (see information online at [www.wrf-model.org/index.php](http://www.wrf-model.org/index.php)) and the Community Climate System Model (CCSM) (information online at [www.cesm.ucar.edu/models](http://www.cesm.ucar.edu/models)).

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

**WHAT:** Sixty regional and global climate modelers discussed science issues and development needs using the WRF and CCSM models to address downscaling and upscaling issues in climate modeling

**WHEN:** 22–23 March 2005

**WHERE:** National Center for Atmospheric Research, Boulder, Colorado

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 to produce regional climate change scenarios; however, their resolution and physical fidelity are considered inadequate. Hence, the global change community has expressed a strong demand for improved regional climate information to explore the implications of adaptation and mitigation and assess climate change impacts (see information online at [www.climatescience.gov/events/workshop2002/](http://www.climatescience.gov/events/workshop2002/)).

Upscaling encapsulates the aggregate effects of small-scale physical and dynamical processes on

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the large-scale climate. One form of upscaling is the use of physical parameterizations, such as that for deep convection. These are also considered to be inadequate, because much of the uncertainty in model sensitivity to greenhouse gases is now known to be associated with cloud parameterizations. Another form of upscaling is to explicitly include the effects of regional processes on the large-scale environment, both locally and remotely. Since their inception in the late 1980s, RCMs have been used predominantly to address downscaling issues through one-way coupling with global analyses or climate models.

As part of the NCAR project, WRF has been adapted for simulating regional climate. Seasonal simulations over the United States have shown realistic features, including the low-level jet and diurnal cycle of rainfall in the central states (Leung et al. 2005) and orographic precipitation in the West (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, NCAR hosted a workshop on “Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM” to encourage the climate modeling community 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 an action plan that meets research needs. This article summarizes the research issues and recommendations discussed at the workshop. There is no implied order in the research priorities listed below. The workshop agenda and presentations can be found online at <http://box.mmm.ucar.edu/events/rcm05/>.

**DOWNSCALING RESEARCH.** During the last decade, research has demonstrated that an RCM is a useful downscaling tool for providing climate information at the scale appropriate for societal use (Leung et al. 2003). The ability of RCMs to downscale depends on large-scale boundary conditions and regional-scale forcings, such as orography, land cover and land use, and lake and urban effects, which influence not only local climate but also may have far-reaching effects. RCMs can also be used as regional climate analysis tools to elucidate mechanisms of climate variability and change. For example, RCMs were used to understand, quantify, and attribute the projected European summer drying (e.g., Pal et al. 2004) in the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change

Risks and Effects (PRUDENCE) project (available online at <http://prudence.dmi.dk>).

At the workshop, the modelers discussed a wide range of scientific investigations that can be addressed using RCMs. For downscaling, these included how climate change affects extreme events, such as the frequency and intensity of hurricanes, heat waves, floods, and droughts, and how to improve seasonal prediction of warm-season precipitation. In addition, the effects of land surface initialization on forecasts, the influence of large-scale climate on the characteristics of convective systems, and how the subtropical eastern boundary regimes respond to climate forcing were discussed.

For climate analysis, discussion included 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 their 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.

The following two areas of model development needs emerged: regional Earth system and high-resolution modeling. These areas were considered high priorities because they are timely and essential for addressing the scientific investigations discussed above that require high-resolution modeling (e.g., hurricanes, urban effects) and model coupling (e.g., air–sea interface and aerosol effects). Furthermore, 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, which are important drivers of regional climate. 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. Biases in simulating regional precipitation, for example, can have far-reaching consequences in fully coupled models of the climate system, because water integrates across the physical, biological, and chemical components.

Workshop participants strongly recommended the development of WRF toward a regional Earth system model to address a wide range of science questions specific to regional-scale processes, and forcing and

response. Examples include interactive coupling of the RCM with sea ice and ocean models to represent air–sea interactions; chemistry and aerosol models, including dust, to represent chemistry–aerosol–cloud–radiation feedbacks; and marine and terrestrial ecosystem models to represent biogeochemical cycling processes. Additionally, developing more comprehensive treatments of land surface and hydrological processes, including river routing, subsurface flow, lake, land use, fires, and land ice, will enable a more dynamic representation of land–atmosphere feedbacks. 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. Building data assimilation capabilities for the coupled model will enable the development of regional analyses of the Earth system; an example is an ocean and land data assimilation system. Finally, to facilitate model coupling, participants recommended accelerating the transition of WRF to the Earth System Modeling Framework (ESMF) (Hill et al. 2004).

*High-resolution applications.* Workshop participants recognized the potential benefits of high-resolution modeling using WRF as a next-generation RCM. With nonhydrostatic 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, more research is needed to assess and improve the skill of the model at high resolution.

The first step in this direction is to 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. Once the parameterizations are tested, representations of processes important at high resolution, such as terrain-sloping effects on the planetary boundary layer and radiation and urban effects, should be developed and implemented. More options for mesh refinement, such as multiple nesting, a stretch grid, and adaptive mesh refinement for high-resolution modeling, will need to be developed, and their performance evaluated. These model developments need to be systematically evaluated and compared against

mesoscale applications to establish the value of high-resolution modeling in regional climate modeling. Applying WRF as a cloud resolving model to explore its usefulness and limitations is timely because 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 previously mentioned, RCMs have not been applied in upscaling to the same extent as downscaling in the past decade. Recognizing that GCMs do not adequately resolve scale interactions, which are important for establishing certain key climatic features, the workshop participants strongly recommended that the climate modeling community undertake research on two-way coupling of regional and global climate models to represent the upscaled effects of regional processes.

A particular scale interaction problem discussed extensively at the workshop is the challenge in modeling the subtropical eastern boundary (STEB) regime off the coasts of southwest Africa, Peru–Ecuador–Chile, and Baja California–southern California. This regime is marked by marine stratus, equatorward alongshore winds, and ocean upwelling not well simulated by most, if not all, GCMs. 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 on the west coasts of North America and South America. They also do not represent the effects of coastal fog that influence nearshore ecosystems and hydrology. Recent studies (e.g., Large and Danabasoglu 2006) suggest that interactions of the atmosphere and ocean in the highly localized STEB regime 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 upscaled effects were also discussed, including monsoon regions with steep topographical gradients and the Maritime Continent (MC). Lorenz and Jacob (2005) performed a study of two-way coupling using the Max Planck Institute global and regional climate models over the MC. Preliminary results suggest that more realistic representations of the MC by the regional model have large and positive impacts on the tropospheric temperature and large-scale circulation in the global climate simulation.

The impacts of spatial resolution on climate simulations have been demonstrated by studies using both RCMs and GCMs. However, the significance of representing scale interactions in climate simulations must be more fully addressed using nonhydrostatic models capable of resolving dynamical processes at the 5–30-km spatial scale. Currently, this is not achievable with GCMs for a long-term simulation because of computational constraints and/or limitations of the hydrostatic formulation. The coupling of regional and global models to represent upscaled 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 models such as the WRF and CCSM.

To facilitate two-way coupling of WRF and CCSM, each modeling system needs to accelerate the transition to the ESMF standard. Because most of the intriguing scale interaction issues involve not only atmospheric processes, but also feedbacks between Earth system components at various scales, transition to the ESMF standard and development of more general coupling capabilities in WRF would be beneficial to its coupling with CCSM as well as other regional Earth system components, discussed previously. In addition, we need to develop and test different methodologies for coupling WRF and CCSM. These include testing different approaches and frequencies for applying feedback from WRF to CCSM (e.g., data assimilation versus direct updating of CCSM variables with the WRF variables).

With WRF and CCSM developed specifically for modeling processes at regional and global scales, model compatibility issues will likely arise in a fully coupled framework. We need to identify such issues, understand their impacts, and develop methods to achieve compatibility. Examples of compatibility issues between WRF and CCSM include the use of different model top levels, inadequate representation in WRF of the effects of gravity wave drag on the upper atmosphere, and a lack of stratospheric physics in WRF. 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. Pilot projects should be initiated to demonstrate the methodologies and impacts of two-way coupling on the regional and global climate simulations.

**SUPPORT OF COMMUNITY MODEL.** A substantial community exists that has contributed significantly to the development and application of RCMs based on the fifth-generation Pennsylvania

State University (PSU)–NCAR Mesoscale Model (MM5). This community can form the basis for a WRF climate modeling community to advance WRF development as a climate model. Workshop participants further recommended improving the infrastructure of a community RCM at NCAR through the following measures:

- Develop the spectral nudging capability in WRF for downscaling applications, exploring strategies for ingesting boundary conditions, and diagnosing model biases.
- Generalize the WRF preprocessor to ingest data from multiple sources, including GCMs and global analyses, and those needed to run component (such as chemistry and ocean) models.
- Develop and implement methods and software for regional climate model evaluation and diagnostics beyond the existing capacity for weather research and diagnosis.
- Develop guidance on the optimal treatment of lateral boundary conditions and the location of boundaries based on more systematic numerical studies.
- Provide modeling support such as code maintenance, software development, and workshops for the regional climate modeling community.

Last, 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 that symbiosis between the WRF and CCSM modeling efforts be created within NCAR and in the climate modeling community.

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