--- DRAFT ---

RESEARCH-COMMUNITY PRIORITIES FOR WRF-SYSTEM DEVELOPMENT

Editor: Joseph Klemp, National Center for atmospheric Research (klemp@ucar.edu)

1. Introduction

The Weather Research and Forecasting (WRF) modeling project is a community effort intended to develop a next-generation mesoscale forecast model and data-assimilation system that will advance both the understanding and prediction of mesoscale weather, and accelerate the transfer of research advances into operations. The WRF model is state-of-the-art, transportable, and efficient in a massively parallel computing environment. It is designed to be modular, and a single source code is maintained that can be configured for both research and operations. It offers numerous physics options, thus tapping into the experience of the broad modeling community. Advanced data assimilation systems are being developed and tested in tandem with the model. The WRF model is well suited for a wide range of applications, from idealized research simulations to operational forecasting, and has the flexibility to accommodate future enhancements. Although the model is designed to improve forecast accuracy across scales ranging from cloud to synoptic, the priority emphasis on horizontal grid resolutions of 1-10 kilometers makes WRF particularly well suited for newly emerging Numerical Weather Prediction (NWP) applications in the non-hydrostatic regime.

WRF is maintained and supported as a community mesoscale model to facilitate wide use in research, particularly in the university community, and advances achieved in the research community will have a direct path to operations. The WRF software infrastructure currently supports two dynamical cores, the Advanced Research WRF (ARW), whose development has been led by the National Center for Atmospheric Research (NCAR), and the Non-hydrostatic Mesoscale Model (NMM) core developed by the National Centers for Environmental Prediction (NCEP). Since the first release of an early version of the ARW in December 2000, over 3800 users have registered to download the model code as of May 2006. Over half of these users are distributed across some 75 foreign countries. In the fall of 2005, the NMM core was also released to the community, and is experiencing a growing user base. Annual WRF users workshops and bi-annual tutorials are offered to assist a rapidly expanding community of users.

The research community is making significant use of WRF in advancing research objectives in a number of areas, such as convection-resolving NWP, hurricane forecasting, regional climate studies, and air chemistry/quality research. Community researchers have contributed strongly to evaluating the capabilities and limitations of the WRF system through real-time forecast experiments, model intercomparison studies, and case-study analyses. These researchers have also developed enhanced capabilities for WRF that are being incorporated back into the community release. These enhancements include new physics modules, Four Dimensional Data Assimilation (FDDA) capabilities, and even a global implementation of WRF suitable for simulation of planetary atmospheres. The breath of WRF user activities is illustrated by the wide range of papers presented at the Sixth WRF/MM5 Users Workshop in June 2005 (http://www.mmm.ucar.edu/wrf/users/workshops/WS2005/WorkshopPapers.htm) and the breadth of real-time forecasting experiments throughout the community (http://wrf-model.org/plots/wrfrealtime.php)

The WRF model is also transitioning into use in a number of operational forecast centers. NCEP is currently running versions of WRF in their High Resolution Window Domains, and as members of their Short-Range Ensemble Forecasts. NCEP is adapting WRF to become the basis for their North American Meso (NAM) Model in June 2006, and for the Rapid Refresh Model and Hurricane Forecast Model over the next year or two. The Air Force Weather Agency will transition to WRF for forecasting in their worldwide theatres beginning in June 2006. In addition to applications in the US, operational centers in South Korea, India, Israel, China, Taiwan, and Greece are implementing new forecast systems based on WRF.

As community researchers are investing significant energy and resources in the use of WRF, it is essential that the model's capabilities continue to advance to meet future research requirements as they evolve. Part of the charge to the WRF Research Applications Board (RAB) is to "review trends and emerging science and technologies and to identify and prioritize those elements representing the greatest opportunities for advancing the capabilities of the WRF modeling system for use by the research community." This assessment focuses on model technology having the potential for enhancing WRF-related research over a period extending five years or more into the future. In response to this directive, the RAB has solicited input from the research community and prepared this strategic planning document to identify the science challenges and opportunities that can be addressed with advanced modeling capabilities, and the specific new or enhanced model capabilities that will be required to enable this research. In the following sections, we outline the science issues, key model development areas, and action plan for eight research areas to meet future challenges.

2. Convection Resolving NWP

Section Coordinator: Ming Xue, University of Oklahoma (mxue@ou.edu)

The development of new high-resolution nonhydrostatic models and the rapid increase of computer power are making the explicit prediction of convective systems, including individual thunderstorms, a reality. Advanced remote sensing platforms, such as the operational WSR-88D Doppler radar network, are providing 3D volumetric observations that can provide high-resolution data for initializing convection resolving models. Here, convection-resolving NWP refers to models that explicitly treat moist convective systems ranging from organized mesoscale convective systems down to individual convective cells. For organized convective systems, skillful forecasts can often be obtained for strongly forced systems as far as 36 hours in advance using 2-4 kilometer horizontal grid resolutions (e.g., Xue et al. 2001, Done et al. 2004, Kain, et al. 2005). In comparison with coarser-grid models, these forecasts provide a much better indication of the likely mode of convection (bow echoes, mesoscale convective vortices, supercell lines) as well as the timing and location of convective initiation (Weisman et al. 2004). For individual storm cells, 1-2 km grid spacing is generally believed to be necessary (e.g., Xue et al. 2003), while even higher resolution is needed to resolve smaller non-supercell storms and the internal circulations within storm cells. Since the smallest scales in unstable convective flows tend to grow the fastest, the resolution of convective structures will always benefit from increased spatial resolutions (e.g., Bryan et al. 2003). Physics representations, including microphysics and subgrid turbulence, also need to be more accurate at higher resolutions. With the continued increase in computational power, we envision routine use of kilometer-scale resolutions covering continent-sized computational domains, with even higher-resolution nests over subdomains within 5 years. In fact, experimental real-time WRF forecasts at 2 km resolution over two thirds of the continental US have already been performed (Kain et al. 2005). Accurate characterization of convective systems is not only important for storm-scale NWP; it is also critical in properly representing scale interactions and the statistical/climatological properties of convection.

Key areas for WRF-model enhancement:

1) *Data assimilation for convection-resolving NWP.*

Data assimilation should be a top priority for improving convective-scale NWP. For convection-resolving NWP, accurate estimations of the state of convective storms themselves and their environment are both important. The environmental conditions surrounding convective storms, to a significant extent, determine the initiation and subsequent evolution of convection. In the absence of hydrometeor scatterers, the storm-environment is usually much more poorly sampled by remote sensing instruments. For these reasons, optimal assimilation of all available data, including surface mesonets, wind profilers, GPS water vapor measurements, clear air wind measurements and potentially available low-level refractivity data from radars, and high-resolution satellite observations, should be performed. For all these asynoptic observations, flow-dependent background error and the coupling with dynamic models are essential to extract maximum amount of information from the observations, which are always incomplete at this scale compared to the size of model state vector. Within the precipitation region of convective storms, the assimilation of Doppler radar radial velocity and reflectivity using advanced techniques, including the 4D-Var and ensemble Kalman filter (EnKF), are essential to obtain a complete and dynamically consistent state estimation. Research on the effective assimilation of radar data in more economical 3D-Var frameworks should be continued. The assimilation of additional parameters offered by future polarimetrically upgraded WSR-88D radars promises to improve the state estimation of precipitating systems and microphysicsand should therefore also be pursued.

Multi-scale capabilities for assimilating observations that represent the convective through synoptic scales must be developed. All data assimilation tools have to be scalable on distributed-memory platforms.

2) Physics improvements for convection-resolving NWP.

Even with perfect initial conditions, an inaccurate prediction model will lead to rapid growth of forecast error. Both 4D-Var and EnKF methods also depend on having accurate prediction models. The uncertainties and approximations in the physics parameterizations are believed to be the most significant contributors to model error. The cloud microphysics, in particular, contain significant sources of uncertainty for explicit prediction of convective cells; it is believed to have the most direct interaction with the convective-storm dynamics. Simulated thunderstorms have been found to be very sensitive to uncertain microphysical parameters that can significantly affect precipitation amount and the strength of low-level cold pool (e.g., Gilmore et al. 2004; van den Heever and Cotton 2004). Multi-species microphysics schemes with more accurate particle size distribution models and/or multiple moment schemes should be developed, refined, and verified against observations for different types of storms. Model microphysics should be integrated in a consistent manner into the assimilation of reflectivity data and the additional parameters from polarimetric radars.

Other parameterized physics are critical for establishing the storm environment, particularly for important features such as evolution of the planetary boundary layer (PBL) and the diurnal cycle. For the PBL parameterization, research should be focused on developing schemes suitable for kilometer-scale resolutions, where a significant portion of convective boundary layer mixing is achieved by resolvable eddies. Subgrid-scale turbulence closure models suitable for non-LES resolutions also require further research, as does the treatment of stable boundary layer fluxes. For the land-surface models, emphasis should be placed on acquiring and using the most up-to-date and near real-time, high-resolution land use and land cover data sets, and on accurate initialization of the soil state, including both soil temperature and moisture. Detailed verification should be performed against observations for all soil types and vegetation cover, and in situ observations should be combined with remotely sensed data. The improvement of radiation parameterization should focus on radiation and cloud interaction where multiple cloud and hydrometeor species should be adequately incorporated. While cumulus parameterization can be safely ignored at sub-kilometer resolutions, there may still be a need for improved treatment of shallow cumulus in the treatment of the PBL. For high-resolution deterministic forecasting, suites of compatible and well-tested physics schemes should be used instead of random combinations. The consistency of the constant physical parameters among different schemes should also be enforced.

3) Model numerics and computational infrastructure.

Flows on convection-resolving scales are highly turbulent and contain large amount of energy near the grid scale; such fine structures are an important component of convection-resolving NWP. Highly accurate numerical schemes with minimum damping are therefore strongly desirable, as are properties such as conservation and monotonicity (for e.g., positive definite fields) of the schemes. The schemes must be accurate with respect to all important processes, including advection, diffusion and wave propagation. Continuing priority should be placed on higher order schemes that provide a good balance between speed and accuracy, together with a proper subgrid-scale turbulence closure model and high-order numerical diffusion. Equally important is the distributed-memory support of all necessary pre-processing (data quality control and preprocessing, gridded background preparation, data analysis and assimilation, and boundary condition preparation) and post-processing (diagnostic calculations, visualization and forecast verification) software, and their scalability.

4) Convective-scale predictability study and probabilistic forecasting.

Convective-scale predictability should be a key area of fundamental research that would provide important guidance for convection-resolving data assimilation and NWP. Error-growth dynamics should be studied along with the sensitivity of forecasts to initial and boundary condition uncertainties. Probabilistic forecasting using the ensemble approach at the convective scale is only beginning and requires much attention (e.g., Kong et al. 2005). The highly nonlinear nature and relatively low reliability of convective-scale NWP render the probabilistic information of the forecast even more desirable for practical purposes. The most promising approach is perhaps to integrate the ensemble forecasting with ensemble-based data assimilation techniques (e.g., EnKF), and in the process carefully calibrate the forecast error variance and take into account model uncertainties. Physics perturbations may also prove to be an important component of the ensemble system; for this reason, it is desirable to support multiple but carefully tested physics options in the WRF model system.

Proposed Action Plan:

1) Promote and seek community and funding agency support, through workshops, conferences, and publications, for more in-depth analysis and diagnostic studies of state of the art physics packages, and the development of more advanced physical parameterization schemes designed specifically for the convection-resolving scales.

2) Promote the training of next-generation scientists specialized in atmospheric physics, and in advanced data assimilation, and in effectively applying statistical theories and methods to atmospheric data assimilation, verification and probabilistic prediction.

3) Continue to provide an efficient and flexibility modeling and data assimilation framework that facilitate rapid experimentation.

Other Section Contributors: ...

3. Hurricane Research and Prediction

Section Coordinator: Shuyi S. Chen, University of Miami (schen@rsmas.miami.edu)

While hurricane track forecasts have improved significantly over the last a few decades, progress in storm intensity forecasts has been very slow (DeMaria 2005). The lack of the skill in the intensity forecasts may be largely attributed to deficiencies in the current prediction models: insufficient horizontal and vertical resolution, inadequate surface and boundary layer as well as precipitation physics, insufficient observations over the ocean, less than optimal utilization of available data, and the absence of full coupling with the ocean. The key factors controlling hurricane intensity are the inner core dynamics and interaction with the environmental conditions such as vertical wind shear and water vapor distribution. To resolve the hurricane eye and eyewall structures crucial for intensity forecasting, the horizontal grid resolution may need to be at least ~1-2 km (Tenerelli and Chen 2001, Braun 2002, Rogers et al. 2003, Chen and Tenerelli 2006). The extreme high winds, intense rainfall, large ocean waves, and copious sea spray push the surface-exchange parameters for water vapor, and momentum into new untested regimes. The air-sea interaction in the eyewall region is largely unknown as there are few available observations. While hurricanes draw energy from the ocean surface, they cool the ocean by wind-induced surface fluxes and vertical mixing. The enthalpy and momentum exchange coefficients under the high-wind conditions are difficult to determine. The stress is supported mainly by waves in the wavelength range of 0.1-10 m, which are unresolved by wave models. Rapid increases in computer power and recent advances in technology in observations from field programs such as the ONR supported Coupled Boundary Layer Air-Sea Transfer (CBLAST) (Black et al. 2006, Chen et al. 2006) and the NSF supported Hurricane Rainband and Intensity Change Experiment (RAINEX) (Houze et al. 2006), are important factors in developing a strategy for the next generation of high-resolution hurricane prediction models.

Key areas for WRF-model enhancement:

1) Improving numerics and physical parameterizations for high-resolution modeling.

An important enhancement to the WRF system for hurricane applications has recently taken place; a vortex-following movable, two-way interactive nested grid has been implemented in the basic WRF framework that can work with both the ARW and NMM cores. This allows the model to resolve the high gradient regions, convective cells, and vortex-Rossby waves related to the eyewall mixing events that are important for the rapid inner core structure and intensity changes. However, some of the physical parameterizations in the current WRF are not adequate for the grid resolution at 1 km. As the grid meshes shrink, the nature of the subgrid scale processes changes. Subgrid turbulence and microphysical processes are two areas in particular where improved parameterization schemes are needed for the very high-resolution model applications.

2) Developing a fully coupled atmosphere-wave-ocean modeling system.

Several new coupling parameterizations, including the wind-wave coupling and sea-spray parameterization, have been emerging from the CBLAST-Hurricane science team (Andreas and Emanuel 2001, Donelan et al. 2004, Chen et al. 2006). These parameterizations are designed to work with various atmospheric, surface wave, and ocean circulation models. It is desirable to develop numerical couplers that are general enough to allow users to select various atmospheric or ocean model components according to different application needs (Zhao and Chen 2005)..

3) Initialization and data assimilation for hurricane research and forecasting.

The lack of accurate initial conditions for high-resolution hurricane modeling is a major limiting factor in hurricane research and prediction. Improvements in initial conditions rest on the use of more airborne and remotely sensed observations in high-resolution assimilation systems and on the application of advanced assimilation schemes to hurricanes. On the observation side, recent studies have indicated that assimilating surface vector winds from scatterometer data (Leidner et al. 2003) and combining those with satellite-retrieved tropospheric temperature profiles from the microwave data (Chen et al. 2004) have a great potential to improve the model initial conditions. Airborne dropwindsonde and radar data continue to be a challenging issue for data assimilation because of the limited spatial coverage. Furthermore, the airborne data is usually not available in the tropical cyclone genesis regions over the eastern Atlantic and other ocean basins. Advanced assimilation schemes such as the EnKF or 4DVar also have great potential to improve hurricane initial conditions. In simpler schemes, such as 3DVar, the influence of a single observation on the analysis is independent of the presence of the hurricane vortex. The EnKF and 4DVar, in contrast, use dynamical information from the forecast and their analysis increments depend on the presence of the vortex. For example, they can effectively shift the vortex given limited observations (Leidner et al. 2003, Chen and Snyder 2006).

Proposed action plan:

1) Form a working group representing the interests of the research community to develop a detailed implementation plan and integrate the existing efforts in hurricane modeling from various universities and research institutes.

2) Organize group meetings and special sessions in the annual WRF workshop specifically targeted in the hurricane related modeling issues.

3) Promote the development of new physical parameterizations needed to advance their validity in the tropical hurricane environment.

4) Develop specific plans by the working group and scientists at DTC to test and evaluate the research products at DTC for transition to operational hurricane forecast models.

Other Section Contributors: ...

4. Regional Climate Modeling

Section Coordinator: Ruby Leung, Pacific Northwest Natl. Lab. (Ruby.Leung@pnl.gov)

In past decades, global climate modeling has played a significant role in advancing our understanding of the climate system and its sensitivity to perturbations. Although computational power has increased tremendously since three-dimensional climate modeling began, the spatial resolutions of Global Climate Models (GCMs) have only increased three to five fold to the now typical horizontal resolution of 150-300 km with 30-50 vertical layers. Much of the enhanced computational resources have been utilized to incorporate more sophisticated physics parameterizations, interactive earth-system components, and ensemble simulations of extended lengths. To date, major model biases remain in global climate simulations that challenge their ability to provide climate information with sufficient fidelity and spatial specificity for societal use (e.g., McAvaney et al. 2001, CCSP 2003). Perhaps the most persistent and pervasive biases are related to the depiction of the hydrological cycle. With the spatial distribution and phase changes of moisture predominantly controlled by the wide-ranging atmospheric motions, the resolution or physical parameterization of the scale interactions necessary to describe the environments for clouds/precipitation and their feedbacks remains a grand challenge. The consequences of a distorted hydrological cycle are far reaching in fully coupled models of the climate system since water integrates across the physical, biological, and chemical components.

Resolving scale issues is a major key to significant progress in reducing biases in climate models. Regional Climate Models (RCMs) have traditionally been used as a downscaling tool to simulate regional processes under imposed large scale conditions. To represent scale interactions, both upscaling and downscaling are clearly important. With the capability of simulating atmospheric processes of any scale from large-eddy modeling to hemispheric simulation, WRF provides a useful framework for advancing scale-interaction research. It has already been adapted for downscaling research and application (e.g., Leung et al. 2005). A WRF Regional Climate Modeling Working Group has been established to provide a community nested climate model that enables process studies, downscaling and upscaling research, and facilitates multi-disciplinary research that promotes understanding of climate and societal impacts.

In March 2005, a workshop on “Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM” was organized to engage the regional and global climate modeling communities to define research needs for the development of a next generation community RCM (Leung et al. 2006). The workshop identified three areas of model development needs summarized below.

Key areas for WRF-model enhancement:

1) Model coupling to include regional earth system components.

To enable simulations of regional climate processes from seasonal to decadal time scales, WRF needs to include earth system components including the atmosphere, ocean, land, cryosphere, and biogeochemical cycle to represent their interactions, which could be strongly modulated by forcings (e.g, orography) and feedbacks at the regional scale. To function as a regional earth system model, WRF needs to include ocean coupling and sea ice, more comprehensive land surface and hydrological components such as river routing, sub-surface flow, lake, land use, fires, and land ice, and fully couple chemistry and aerosol processes to the water cycle for representing chemistry-aerosols-clouds-radiation feedbacks. While some individual efforts are underway to address different aspects of model coupling, a coordinated effort is needed to ensure that different components are interacting properly (e.g., conservation of fluxes at the interface, using common input datasets across the component models), to collectively evaluate the coupled model, to address computational efficiency of the coupled model, and to document the sensitivity of the coupled model to climate forcing. This coupled system should first be implemented and tested within the WRF software framework, with the expectation that the coupling mechanism may be modified in the future to make use of Earth System Modeling Framework (ESMF) features as they become available.

2) *Model numerics and physics for high-resolution applications.*

High-resolution modeling (1-20 km resolution) may improve the fidelity of climate simulations and provide climate information at the scales needed for resource management and impact assessment. The non-hydrostatic dynamical cores and high-order, conserving numerical techniques specially designed in WRF for high-resolution modeling should be exploited in regional climate research. More studies are needed to assess and improve model skill at high resolution. These include developing and testing physics parameterizations such as cloud microphysics, turbulence, and shallow convection that are highly scale dependent, and representations of processes such as terrain sloping effects on the planetary boundary layer and radiation and urban effects that are important at high resolution. However, a balance must be maintained between complexity and computational efficiency for climate applications. Long term cloud resolving simulations should be performed with WRF to understand its capabilities and limitations for climate applications.

3) *Nesting RCMs within global models.*

A major weakness in climate modeling is the artificial separation of scales that limits a model's ability to simulate scale-interactions that are the dominant features of climate processes. One approach to resolve scale interactions is two-way coupling of regional and global climate models. In this approach, downscaling is achieved through regional modeling, and the effects of regional processes are upscaled through feedbacks from the regional to the global climate model. To accomplish this, more general coupling capabilities are needed in WRF for two-way nesting within GCMs as well as coupling with other earth system components discussed above. Model compatibility issues between WRF and the host GCM must be identified and examined. For example, to match the top level of the regional and global models, treatment of the upper atmosphere in WRF needs to be improved for processes such as gravity wave drag and stratospheric physics. An important aspect of coupling regional and global climate models is to maintain conservation in the host GCM. This issue must be addressed using carefully designed techniques to apply large scale forcing and feedback between the models to eliminate artificial sources/sinks generated by the feedbacks from the regional model.

4) Global WRF

In the longer term, having a global version of WRF in which to nest regional climate domains would be of great benefit. This capability would ensure compatibility of the numerics, physics, and grid structures of the regional and global domains, and would provide significantly enhanced efficiency by running the grid nesting within a single executable module. In designing a global implementation of WRF, alternative grid structures should be evaluated to determine the most efficient techniques for integrating the model equations on a grid that is nearly uniform over the globe. For the global WRF to function as a host GCM, however, more testing is required to ensure global conservation and realistic surface and top-of-the-atmosphere radiative budgets at a range of spatial resolution intended for global applications.

Proposed Action Plan:

1) Establish an advisory group built on the existing WRF RCM working group to develop an action plan to prioritize and implement model development activities.

2) Promote and coordinate community efforts in regional climate research using WRF, and integrate model components from community regional climate model development efforts into the WRF single-source code.

3) Promote interactions between the regional and global climate modeling communities to define research needs and priorities, and identify opportunities to support collaborative model development efforts that take advantage of the expertise and experience from both communities.

4) Participate in community model intercomparison projects to establish a benchmark against other regional climate models applied to different geographical regions and climate regimes.

5) Coordinate with other WRF model development efforts that address model physics for high-resolution applications and coupling with other earth-system component models.

Other Section Contributors: This section is based on discussions at the Workshop on Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM that was held on March 22-23, 2005, at NCAR, Boulder, CO.

5. Air Quality and Chemistry Modeling

Section Coordinator: Georg Grell, Earth System Res. Lab. (Georg.A.Grell@noaa.gov)

A fully coupled air-quality modeling capability should be considered an important component of a future state-of-the-art nonhydrostatic modeling system for both research and forecasting applications. Many of the current environmental challenges in weather, climate, and air quality are strongly coupled, and a modeling system such as WRF/Chem represents an opportunity to include these coupled interactions in future research. Coupling of atmospheric chemistry with regional climate in a multi-scale model will enable new issues to be addressed that improve our understanding of how climate change will affect local air quality, how local point, mobile, and area sources of pollutant emissions modify regional and global climate change, and how megacities affect regional air quality and climate. While regional climate and air quality have evolved as separate disciplines, the WRF system will enable strong interactions between them in the near future. Currently, regional climate models are used to better resolve cloud processes, but they neglect aerosol chemistry and subsequently the feedbacks of aerosols on radiation and clouds. The meteorology and chemistry in current air-quality models are not coupled so that the aerosol-radiation-cloud feedback processes cannot be simulated. Neglecting aerosol-radiation-cloud feedback processes may be appropriate for multi-day simulation periods that focus on impact of pollutants on human health, but they cannot be neglected for longer simulation periods.

Research utilizing a fully coupled WRF/Chem will not only improve understanding of climate and air quality problems, but may also in return lead to improved prediction and simulation of the weather, as well as to better data assimilation systems. Three major areas have been identified where future WRF developments may lead to significant scientific opportunities: (1) direct and indirect aerosol effects, (2) data assimilation, and (3) the application of generalized chemical mechanisms, which are discussed below.

Key areas for WRF-model enhancement:

1) Direct and indirect effects of aerosols in climate simulations.

Global climate model predictions contain major uncertainties associated with the direct and indirect effects of aerosols. Our understanding of the life cycle of aerosols, including the distribution of particulate mass, composition, size distribution, physical characteristics, and the connection between the physical and optical properties of suspended particulate matter, needs improvement to more accurately simulate aerosol radiative forcing. The coarse spatial resolution employed by global climate models may be a significant source of uncertainty in estimating direct and indirect forcing that may lead to erroneous conclusions regarding spatial variations of future climate change . While cloud modeling studies such as Haywood et al. (1997) have estimated the uncertainties in clear-sky and cloud-sky direct radiative forcing resulting from spatial resolution, analogous studies that quantify the influence of spatial resolution on predictions of aerosol direct and indirect forcing have not yet been done. A multi-scale model, such as WRF, that can resolve local and regional atmospheric processes that affect the life cycle of aerosols, can be used to improve our understanding of those processes in which aerosols play an important role. A multi-scale meteorology-chemistry-aerosol model that has been evaluated and improved using a wide range of field campaign measurements will be a powerful tool to test new parameterizations for global climate models.

An advantage of the WRF framework in developing new aerosol treatments is that the strengths and weaknesses of various aerosol process modules can be determined using the same model framework, meteorology, transport, and primary pollutant emissions. Current aerosol modules suitable for operational air-quality forecasting have been implemented into the existing WRF framework; however, the framework must also be augmented to efficiently handle the computational burden associated with atmospheric-chemistry research that require hundreds to thousands of additional transported variables.

In contrast to the modal approach in which the aerosol size distribution is approximated by several modes (typically three), the sectional approach divides the aerosol size distribution into discrete size bins. A large number of size bins can theoretically better represent the size distribution of various aerosol constituents, gas-aerosol partitioning, solid-liquid partitioning, and scattering and absorption of radiation that is a function of particle diameter. Organic carbon constitutes a large fraction of the total particulate mass exported from urban areas, yet our understanding of the processes associated with secondary organic aerosol formation and the properties of organic aerosols is limited. The complex hydrocarbon chemistry involved with gas-aerosol exchange requires a large number trace gases and organic carbon aerosols to adequately represent the wide range of processes that may also vary from region to region. Most models underestimate the amount of organic carbon mass (e.g. Zhang et al., 2004; Tsigaridis and Kanakidou, 2003) that subsequently affects the magnitude of the direct radiative forcing (e.g. Fast et al. 2006). Recent research has also shown that some types of organic aerosols are hydrophilic and may affect the development of clouds (e.g. Novakov and Penner, 1993; Chung and Seinfeld, 2002). Cloud-aerosol interactions effectively double the number of transported variables in order to differentiate interstitial aerosols from those that are activated in cloud drops. Additional variables are needed for a prognostic treatment of aerosols in the ice and precipitation phases and to account for connections between aerosol and droplet size distributions.

A major computational challenge in the future is to determine how to best represent in models the mixture of aerosols having different properties, since this will impact how radiative forcing is calculated. Most models currently employ an *internal mixture* approach in which all the particles of a given size have the same composition, physical properties, and optical properties. Although such an approach may be appropriate far from primary particulate sources, in near source regions particles are frequently found to be an *external mixture* in which particles of a given size can have different composition, physical properties, and optical properties. To treat the transition of external mixing to internal mixing, a more general internal-external representation is required that would also require a significantly larger number of transported variables.

While the gas-phase and aerosol-chemistry mechanisms represent a significant computational cost in a simulation, the main computational challenge is associated with the advection of chemistry variables and the related communication. For this reason, more computationally efficient techniques for advection that conserve mass and are locally monotonic are needed for atmospheric chemistry applications.

Additional modifications to the WRF framework should also be considered to accommodate atmospheric chemistry needs. Pointers that group aerosols by their characteristics such as composition, size bin, type, and phase would simplify the handling of the larger number of chemistry transported variables in the model. For regional climate applications that include chemistry, WRF will need to be able to employ time-varying boundary conditions of trace gases and aerosols from larger-scale models or analyses in a method similar to that employed for the meteorological quantities. The large number of chemistry variables can also produce difficulties related to the 2 Gb addressing limits of 32-bit computer architectures so that the next generation of aerosol treatments in WRF may require the use computers that employ 64-bit addressing and large amounts of memory.

2) Data assimilation of chemical constituents.

Chemical transport models (CTMs) play a critical role in air quality science and environmental management. CTMs are designed to describe the fate and transport of atmospheric chemical constituents associated with the gas and aerosol phases. CTMs have become an essential element in atmospheric chemistry studies, including important applications such as providing science-based input into best alternatives for reducing pollution levels in urban environments, and assessments into how we have altered the chemistry of the global environment.

Quantitative aspects of model-based atmospheric-chemistry and air-quality analyses and forecasts are hampered by deficiencies in CTMs arising from a variety of sources, including incomplete emissions information, lack of key measurements to impose initial and boundary conditions, missing science elements, and poorly parameterized processes. However, improvements in the analysis capabilities of CTMs require them to be better constrained through the use of observational data. The close integration of models and observational data through data assimilation has been successfully applied in meteorology and oceanography, but is only just beginning to be used in nonlinear atmospheric chemical models. When chemical transformations and interactions are considered, the complexity of the implementation and the computational cost of the data assimilation are highly increased.

There is also a compelling need for chemical data assimilation applications testbeds to stimulate the advancement of chemical data assimilation techniques and tools. This has been recommended by several national studies (e.g., recommendations from the USWRP Workshop on Air Quality Forecasting, and from the NOAA Workshop on Chemical Data Assimilation and Data Needs for Air Quality Forecasting. These test beds should: 1) explore and enhance advanced data assimilation systems (i.e., 4D-Var); 2) develop full adjoints for air quality forecast models (i.e., WRF/Chem) building upon previous developments; 3) explore techniques for targeted observations and field experiment design; 4) explore data assimilation techniques based on model ensembles; and 5) utilize the system for inverse applications (to improve emissions estimates, and other key parameter estimation).

Thus it is recommended that a coordinated effort focused on data assimilation utilizing WRF/Chem be initiated. As outlined above, a key early step is to build an adjoint of WRF/Chem. An adjoint of this model will allow the application of chemical data assimilation in fully coupled dynamics and chemical setting, which can be used to explore the feedbacks (e.g., radiative). This can build upon the WRF/Chem community and efforts in building adjoints of the chemical elements for which some new general tools are available (e.g., the Kinetic Preprocessor (KPP)).

3) Application of generalized chemical mechanisms

With the evolution of computer power, air-quality models have become increasingly complex, incorporating explicitly more physical and chemical processes with each new model generation. However, while groups in developed countries are obtaining remarkable results with these models, developing countries lag behind. The World Meteorological Organization (WMO) has recognized this deficit, and they have established the Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) program (http://www.cgrer.uiowa.edu/people/carmichael/GURME/GURME.html) to help enhance the capabilities of these developing countries to handle meteorological and related aspects of urban pollution.

Many cities in the developing countries are characterized by a very complex topography. Examples are Mexico City, Quito, La Paz, or Santiago de Chile. In order to describe the meteorological fields in such cities adequately, a state-of-the-art nonhydrostatic meteorological modeling system is required. WRF is such a modeling system. Chemical modules have been added to produce WRF/Chem, which deals with the gas-phase chemistry as well as with aerosols by means of fairly sophisticated modules. However, the detailed chemistry results in relatively high computational costs. Tools are available within the atmospheric chemistry community that can generate chemical mechanisms according to the needs and specifications of the modelers. These tools (such as KPP), are extremely flexible, and also generate adjoints of the code. If implemented properly within the WRF Common Infrastructure, the use of such tools could streamline the configuration and application of WRF/Chem for specific applications. Predicting air quality of mega cities in the most efficient way is only one example. Implementation of these tools may also play a major role in the development of data assimilation systems.

Proposed Action Plan:

1) *Inclusion of KPP*

A state-of-the-art tool to generate chemical mechanism modules and their adjoints – such as KPP – should be fully integrated into the WRF Common Infrastructure. This will require close collaboration of the software group and members of the WRF/Chem working group. The implementation of this tool may require significant changes to the CI, such as automatic generation of the Registry.

2) *Development of advanced data assimilation methods*

A coordinated effort between the developers of the meteorological advanced data assimilation methods and some members of the air quality community should be initiated to develop a next-generation data-assimilation system for air quality applications. This should greatly benefit the chemistry community, but will also feed back to the meteorological community.

3) *Efficiency related changes within the WRF modeling system important for chemical applications*

More computationally efficient techniques for advection that conserve mass and are locally monotonic are needed for atmospheric chemistry applications. Additional modifications to the WRF framework should also be considered to accommodate atmospheric chemistry needs. Pointers that group aerosols by their characteristics such as composition, size bin, type, and phase would simplify the handling of the larger number of chemistry transported variables in the model. For regional climate applications that include chemistry, WRF will need to be able to employ time-varying boundary conditions of trace gases and aerosols from larger-scale models or analyses in a method similar to that employed for the meteorological quantities.

Other Section Contributors: Jerome Fast, William Gustafson, Jr., Richard Easter, Steve Ghan, Gregory Carmichael, Rainer Schmitz

6. Ensemble Forecasting

Section Coordinator: David Stensrud, Natl. Severe Storms Lab. (David.Stensrud@noaa.gov)

Model simulations starting from slightly different initial conditions are known to diverge and eventually have little relationship to one another (Lorenz 1963). The realization that the atmosphere has a sensitive dependence upon initial conditions has led to the exploration of approaches that provide information on forecast uncertainty (Epstein 1969; Leith 1974). Since at any time the true atmospheric state can only be known approximately, the atmosphere prediction problem should be expressed in terms of the time evolution of a probability distribution function (pdf) for the atmosphere. One method to produce an estimate of this pdf is to create an ensemble of different initial conditions, all within the range of the uncertainty in the analysis (Leith 1974). Each of these initial conditions then is used to start a separate model forecast. Assuming that the atmospheric pdf can be determined from the statistics of the resulting forecasts, this ensemble of forecasts can be used to provide probabilistic forecast information. The use of ensembles alters the way in which we view numerical guidance from a deterministic (single realization) perspective to a probabilistic perspective, providing richer information for a variety of weather information users to use in making weather-related decisions. Murphy and Winkler (1979) further argue that uncertainty information, as can be provided by ensembles, must be available if one is to make the best use of forecast information.

Unfortunately, the computational cost of ensembles is high as each additional ensemble member requires its own computer time and resources. This situation has led to the desire to provide an estimate of the forecast pdf with as few ensemble members as possible. Techniques to strategically sample the forecast pdf have been designed, ranging from the breeding of growing modes (Toth and Kalnay 1993) to singular vectors (Molteni et al. 1996), with an emphasis on sampling the fastest growing modes that should dominate the ensemble variability. Other approaches focus more upon providing a representative sample of the analysis errors (Errico and Baumhefner 1987; Houtekamer et al. 1996). Questions remain as to which type of initial condition perturbation approach is most useful, and the answer may depend upon the forecast time range. It may be that perturbations for short-range forecasts (0 to 2 days) need to have different characteristics than perturbations for medium-range (7 to 14 day) or seasonal forecasts. In addition, the roles of model differences and physical parameterization scheme variability in ensembles have yet to be addressed fully. Initial results across a variety of forecast time scales all indicate that variability in forecast models and/or parameterization schemes within a model produce improved probabilistic forecasts from ensembles (Atger 1999; Stensrud et al. 2000; Ziehmann 2000; Wandishin et al. 2001; Hagedorn et al. 2005). More work clearly is needed to understand better the role of model and model physics uncertainty in ensemble prediction.

Ensembles often are viewed as being in competition with the resources needed for high-resolution numerical weather prediction. However, this need not be the case. There may be ways to merge ensembles with high-resolution weather prediction and provide improved guidance on both forecast uncertainty and forecast details to end users. Another operational need related to ensembles is post-processing, an often overlooked aspect of numerical weather prediction. Recent studies indicate that post-processing can increase the accuracy and skill of ensemble forecasts (Hamill et al. 2004; Stensrud and Yussouf 2005), and may help us understand the influence of model error in the creation of ensemble initial conditions. From a research perspective, ensembles may be a very useful tool in exploring the limits of small-scale and mesoscale predictability. Improved understanding of the predictability limits for a variety of atmospheric phenomena will help forecasters and other end users of model forecasts use these data more appropriately and to a greater advantage. Ensembles also may be a key component of data assimilation using ensemble Kalman filter methods (Evenson 1994; Snyder and Zhang 2004).

While there remain numerous important scientific issues related to the creation and use of ensembles, providing probabilistic guidance to users of weather information from ensembles has increased dramatically in the past 10 years. Ensembles are now being used over time scales ranging from a few hours for short-range forecasts through hundreds of years for research on global climate change (Elmore et al. 2002; Brooks et al. 1994; Hamill and Colucci 1997; Toth and Kalnay 1993; Palmer et al. 2004; Staniforth et al. 2005). Operational forecast centers are running ensembles for both short-range and medium-range forecasts, and NCEP is currently utilizing WRF-based forecast members as part of its operational Short-Range Ensemble Forecasting system. Therefore, continued and expanded use of the WRF modeling system for the study of ensembles in both research and operations is shighly desireable.

Key areas for WRF-model enhancement:

1) Capability for an ensemble to be run as a single WRF executable. This capability could streamline communication and parallel efficiency for ensemble Kalman filter procedures that require access to data from all ensemble members while they are running.

2) Readily accessible parameters in physics schemes. Parameters within physics schemes are generally hardwired in the respective subroutines. To perturb these parameters in constructing ensemble members, the parameters need to be defined, reasonable ranges for the parameter values specified, and the user must be able to access the parameter settings easily. Perhaps these features for parameters should be included as part of the standard physics interfaces.

3) Enhanced analysis products for ensemble output. This includes both improved diagnostic and verification tools for the evaluation of ensemble forecasts and new techniques that would convey ensemble forecast information more effectively to end users.

4) Script for generating a set of initial conditions for an ensemble. This script would utilize one or more of the more widely accepted techniques for generating initial conditions, and would require reaching a consensus on the best techniques to use before this would be implemented.

Proposed action plan:

1) Organize ensemble-related scientific workshops and special sessions in the annual WRF workshop specifically targeted at ensemble studies and applications.

2) Promote the development of needed tools and their sharing through WRF organization and proposal submissions when appropriate.

3) Establish testbeds for evaluating ensemble forecasting techniques that would contribute to the optimal design of ensemble systems.

Other Section Contributors: Stanley Benjamin (NOAA), Craig Bishop (NRL), Kelvin Droegemeier (OU), Tony Eckel (AFWA), Brian Etherton (UNC Charlotte), Tom Hamill (NOAA), Steve Mullen (U_Ariz), Michael Sestak (FNMOC), Chris Snyder (NCAR), Steven Tracton (ONR)

7. Model Physics Development

Section Coordinator: Cliff Mass, University of Washington (cliff@atmos.washington.edu)

As noted in several of the major research priorities discussed above, model physics represent a major challenge for WRF and other mesoscale modeling systems. Advancement on many of the model physics issues is not merely a technological or development challenge, but will require progress in fundamental understanding of a number of atmospheric processes on a wide range of scales. Recent WRF/MM5 workshops continue to highlight a number of major problems regarding key physics parameterizations. Although a major goal of WRF was the modularization and interoperability of the physics packages so they could be easily exchanged between multiple cores, impediments remain in achieving this interoperability within the existing WRF cores.

Key areas for WRF physics enhancements:

1) PBL parameterizations and LSMs.

There are serious deficiencies with all boundary layer parameterizations and land surface models, including poor characterization of boundary layer heights and an inability to maintain shallow stable layers (reference?). In addition, significant biases are often noted for surface and 2-m temperatures (reference?).

2) Cloud microphysics.

As documented in the IMPROVE field experiment and other studies, there are substantial discrepancies between observed fields of clouds and their constituent microphysical species and those produced by model parameterizations (reference?). Furthermore, mesoscale models generally produce too much precipitation on the windward slopes, and higher resolution does not appear to ameliorate the problem (reference?). It is not clear whether bulk parameterizations can provide satisfactory microphysical simulations or whether higher moment schemes are a necessary next step.

3) Cumulus parameterization.

It is still not clear at which resolutions cumulus parameterization is required and how the answer to this question may vary with the size of nested domains. The interaction of the cumulus parameterization scheme on one nest and the convection on another without such parameterization is poorly understood. In addition, all available cumulus parameterizations have significant deficiencies (reference?).

4) Ultra-high resolution physics.

A major issue deals with design of parameterizations suitable for ultra-high resolution

(100m-5km) applications in which key physical processes, such as cumulus convection and boundary-layer eddies, are no longer subgrid scale, but are only partially resolved in the model.

5). Uncertainty of physical parameterizations.

Because physical parameterizations may be the largest source of error in many simulations, accounting for and quantifying the uncertainty in parameterizations is crucial to progress in high-resolution ensemble forecasting and data assimilation. Recently, there has been increasing interest in various approaches to account for uncertainty in physics parameterization. In one technique, stochastic parameterization, uncertainties in the physical processes are addressed by stochastically perturbing terms in which uncertainty is present. An important question regarding this approach is whether such stochastic perturbation makes sense when there are large errors in the parameterizations: is it meaningful to perturb around the wrong attractor or use a stochastic approach if important processes are not being properly treated? Another suggested direction is using parameter estimation through data assimilation as a tool for estimating key parameters in physical parameterizations. If parameterizations are reasonably faithful to the atmosphere, this approach has the appeal that it can potentially provide both systematic tuning of physical schemes and estimates of the uncertainty in each parameter, and thus in the overall parameterization. But again, if the basic equations are incomplete or inadequate the applicability of this method is uncertain. The other alternative is to rely on the spread among multiple, distinct parameterizations of a given process as a measure of the uncertainty in the parameterization of that process. This approach is certainly expedient when multiple physical parameterizations are already available, yet it is not clear the differences between existing parameterizations are representative of the errors in the parameterizations.

6) Suites of physics packages.

Another issue regards the necessity of physics “suites”, collections of physics options that work well together. This is not a trivial issue, since suites suitable for one application (e.g., active mesoscale convection), might not be appropriate in differing environments (e.g., orographic precipitation), just as individual parameterizations may be more suitable for one application or another. Should substantial effort be placed in testing and recommending certain physics suites, where compensating errors can obscure fundamental problems, or should each physics parameterization be evaluated on its own against observational data for cases where its performance can be isolated (e.g., evaluating boundary layer or surface schemes for cloud-free periods)? On the other hand, can we ignore the fact that the flows of most interest involve interactions between various parameterized processes, so that tuning of physical parameterizations as a suite is always necessary even when the individual schemes have each been rigorously evaluated in isolation?

Proposed action plan:

Significant and sustained progress on model physical parameterizations will only be realized when sufficient personnel and observational resources are applied in a coordinated fashion. Historically, this has not been the case. To improve model physical parameterizations requires:

1) Trained scientific experts in the important areas of model physics. In the U.S. in general there appears to be a shrinking cohort of scientists with the background and interest in improving key parameterizations. For example, only a handful of scientists are working on boundary layer parameterizations, with few working on this problem even at national centers. Increased investment by NSF, NOAA, and other agencies is needed to strengthen the cadre of researchers needed to develop the next generation of model physics.

2) Observational data for physics development and verification. Comprehensive observational data that describe the basic physical processes underlying each parameterization as well as the environment in which the processes are occurring are generally lacking and have only been partially available during a few field experiments (e.g., IMPROVE for microphysics). Process-verifying observational data needs to be available in two modes: short-period field experiments with comprehensive observations, and long-period testbeds with sufficient resources to determine whether the parameterizations are doing a reasonable job for a wide variety of events and seasons.

3) Organization and funding to support more comprehensive efforts in model physics. The WRF effort should refocus and reorganize its efforts in model physics and provide the rationale for acquiring additional resources to improve model physics parameterizations. The WRF community should begin by establishing WRF working groups for the major physical parameterizations (boundary-layer physics, cumulus parameterization, radiation, cloud and precipitation processes, and land-surface processes (existing)). They should be populated by a varied group from academia, national laboratories, national prediction centers, and the private sector. To be successful, these groups will need to be standing and active, conducting regular conference calls and physical meetings, convening timely (perhaps once every two years) community workshops on their respective topics, coordinating a semi-annual review of the state of model physics, and updating recommendations on major priorities for future work..

4) Testbed facilities for model physics. The Developmetal Testbed Center (DTC) should play a central role in facilitating the testing and improvement of model physics. It should prepare and maintain suites of cases for testing proposed new or improved physics packages, serve as a repository for the observational data sets used to document model behavior, and assist researchers in the process of verifying the model physical processes. The DTC could also be the venue of workshops on physics parameterizations.

5) The interoperability of physics packages across dynamic cores. This is an important capability that permits systematic intercomparison of WRF-system components and provides flexibility to accommodate a broad range of research and operational interests. Although the standard physics interface in WRF facilitates this interoperability, impediments remain that have limited the realization of this objective. More effort and resources will be required to insure that an acceptable level of interoperatibily is achieved. It must be recognized that all physics packages may not be adaptable to all dynamic cores and that certain combination of physics packages may be inherently incompatible. To address these issues, the DTC should lead a process to define the requirements and procedures for the designation of physics packages as "reference code" that emphasize suites of physics options that work well together, and includes the stipulation that all reference-code physics be interoperable across all supported dynamic cores. In adapting/testing physics packages for reference-code consideration, the DTC should strive to provide appropriate diversity to satisfy both operational and research-community interests. The DTC should carefully evaluate the value of current or proposed new (replacement) dynamic cores and their interaction with supported physics to insure effective use of the substantial resources required for maintaining them.

Other Section Contributors: ...

8. WRF Data-Assimilation Development

Section Coordinator: Chris Snyder, Natl. Center for Atmospheric Research (chriss@ucar.edu)

A recurring theme in the research priorities discussed above is the trend toward numerical weather prediction at very high resolution and the requirements for enhanced data-assimilation capabilities in WRF at smaller scales, from mesoscale through convective scale. For hurricane prediction, there is a clear need for assimilation schemes that can initialize the vortex with the correct position, intensity and structure (including perhaps its asymmetric components) and minimize spurious transient evolution in the subsequent forecast. Other high-resolution applications, such as atmospheric chemistry or dispersion problems through WRF/Chem, are also becoming increasingly important.

In-situ observations are typically much too sparse to characterize flows at small scales and thus data assimilation at small scales often must rely on remotely sensed observations and the ability of data-assimilation systems to project limited data onto structures dynamically relevant to the range of scales resolved in the model. Since remotely sensed observations in many cases have a complicated and indirect relation to the prognostic variables carried in the WRF model, data-assimilation algorithms for small scales must be capable of utilizing observations, such as radial velocity and reflectivity from Doppler radars, that are not model variables.

Beyond numerical weather prediction, WRF will also be used to simulate specific flows of scientific interest, such as convective systems related to tropical depressions, and hurricane genesis or trade cumulus and their associated transports. At present, numerical simulations for such problems are compared against observations only qualitatively.
A robust and advanced data-assimilation system for WRF allows direct comparisons between simulations and the special observation sets obtained in field experiments, often

at great expense.

Data assimilation is, in essence, the process of combining information from observations with information from a previous forecast, often termed the “background.” Estimation theory provides a rigorous basis for this process (e.g., Cohn 1997) and requires as input knowledge of the statistical properties of errors in both the observations and the background forecast. Two classes of assimilation schemes within the framework of estimation theory are currently being developed for WRF: variational methods (3D- and 4D-Var) and ensemble-based approximations and extensions of the Kalman filter (which, for simplicity, can be termed the ensemble Kalman filter, or EnKF).

Variational methods compute the analysis as the model state that minimizes a cost function measuring the fit to the observations and to the background, where the two terms are weighted by the inverses of the observation- and background-error covariances, respectively. In 3D-Var, observations are processed sequentially in time and, typically, the background covariance is assumed not to vary in time. 4D-Var generalizes this method by considering all the observations within a given time window and incorporating the forecast model into the observation operators (which then map the state at the beginning of the window to the observations). A 3D-Var system for WRF has been released to the community (Skamarock et al. 2005); the system is also operational in Korea and Taiwan using forecast models other than WRF and is undergoing final testing at AFWA. Development of 4D-Var is underway.

The EnKF approximates the required background-error covariances directly from an ensemble of forecasts. Like 3D-Var, it processes observations sequentially in time, but unlike typical implementations of 3D-Var, the EnKF allows the background-error covariances to evolve in time as the flow evolves. As part of the assimilation process,the EnKF produces an ensemble of analyses consistent with the analysis uncertainty, which then provides initial conditions for an ensemble forecast to the time of the next available observation. Ensemble Kalman filters for WRF have been implemented at the University of Washington, where the EnKF is the basis for a real-time assimilation and ensemble-forecasting system (http://www.atmos.washington.edu/~enkf); at NCAR, where the EnKF is available to the community as part of the Data Assimilation Research Testbed; and at Texas A&M.

Both 4D-Var and the EnKF offer the ability to assimilate any observation that can be related to the model's variables or to assimilate asynoptic observations, that is, observations that are distributed throughout a time interval. Both approaches also alleviate the need, as in the existing WRF three-dimensional variational system, to specify a priori relations between model variables before the assimilation. Finally, they both also produce analysis increments that are flow-dependent (Thepaut et al. 1996, Hamill and Snyder 2000), which has been demonstrated to improve analyses significantly when observations are sparse (Whitaker et al. 2004). The EnKF and 4D-Var are equivalent when errors are Gaussian and both the forecast error evolution and the observation operators are approximately linear (e.g., Lorenc 1986). Moreover, Caya et al. (2005) show that performance of 4D-Var and the EnKF are broadly similar for assimilation of Doppler radar observations at high resolution; what differences there are appear to arise from practical details of the implementation of each method rather than fundamental differences in the two methods.

Key areas for WRF data-assimilation enhancements:

1) Further development of advanced assimilation algorithms.

Though both approaches have shown promise for high-resolution applications (Sun and Crook 1998, Dowell et al. 2004), neither 4D-Var nor the EnKF is yet mature for small-scale flows, and a significant research effort will be required to realize their potential. Since 4D-Var and the EnKF are computationally intensive, the development and implementation of scalable codes is crucial to progress for high-resolution applications.

Other priorities for enhancements of 4D-Var for WRF are:

a) Background covariances models suitable for meso- and smaller-scale flows. The covariance models employed in existing 4D-Var systems rely on geostrophic or gradient-wind balance.

b) Adjoints for additional physical parameterizations. The adjoint employed in the initial prototype of WRF 4D-Var includes only a simplified vertical diffusion scheme and no moist processes.

c) Additional terms in the cost function to control the lateral boundary conditions and to limit spurious inertia-gravity waves by penalizing rapid temporal variations over the assimilation window.

For the EnKF, the key research issue is to improve and generalize techniques for ameliorating the effects of sampling error in ensemble estimates of the background covariances. At present, most EnKFs assume that state variables at a sufficient distance from an observation have no covariance with that observation; this greatly reduces the deleterious effects of noise in estimates of small covariances. Such an approach, however, ignores the possibility that cross-variable covariances may be small even at zero separation or that decorrelation lengths may vary both spatially and temporally. Problems with sampling error can also be reduced by identifying and assimilating only those observations that are most influential (i.e. most correlated) with the state.

2) Assimilation of new observation types.

The assimilation of existing, remotely sensed, observation types, particularly observations of radial velocity and reflectivity from Doppler radars and satellite radiance observations at high spatial or spectral resolution and in the presence of cloud and precipitation, is crucial to improve the characterization of smaller-scale structure in analyses. Preparations should also begin for assimilation of next-generation observations that are not yet routinely available, including the polarimetrically upgraded WSR-88D radars, GPS networks, radar-based refractivity measurements of refractivity, and new satellite-borne instruments such as CloudSat . Research is needed into the forward operators (which map the WRF model variables onto observations) for all of these observations, the error characteristics of both the measurements and the forward models, and automated quality control.

3) Assessment of model error.

Deficiencies in the WRF model itself, which of course lead to forecast errors, limit the the effectiveness of any assimilation scheme. Model errors are an especially significant limitation for advanced assimilation approaches, such as 4D-Var and the EnKF, that rely on dynamical information produced by the forecast model. The assessment of model error in WRF, and the proper representation of such errors in either 4DVar or the EnKF are thus important steps if we are to realize the potential of these approaches.

Proposed Action Plan:

1) Testbeds. Assembling high-quality observation sets for assimilation experiments can consume substantial effort, especially for individual investigators. This overhead also often leads to experiments covering single case studies rather than the extended test periods that can provide statistically significant results. Moreover, comparison among different assimilation schemes is difficult or impossible unless the schemes are applied to identical domains, resolutions and observation sets. Establishing several test problems for which comprehensive observation sets are available for extended periods, would help alleviate these difficulties. Test problems should span scales and phenomena of interest for WRF simulations and prediction, such as winter storms, hurricanes, air quality and transport, and moist convection, both severe and benign. Test problems that capitalize on special observations from field experiments may be advantageous in many cases, though the planning and design of the field experiment should carefully address the needs of the testbed from the outset. It would also be usefule for these testbeds to include assimilation experiments with nudging and/or 3D-Var as benchmarks for the more sophisticated (and more expensive) schemes.

Other Section Contributors: ...

9. Forecast Verification Capabilities

Section Coordinator: Chris Davis, Natl. Center for Atmospheric Research (cdavis@ucar.edu)

The ability to systematically evaluate the quality of forecast information produced by the WRF model is essential to the development and refinement of the modeling system. Since verification information “drives” forecast development, it is critical to evaluate the performance of the most relevant variables in an appropriate and meaningful way. While it is not possible to formally verify the results of a numerical forecast model (since it is an open system and results are non-unique), agreement between model predictions and observations can provide a substantive body of confirmatory evidence documenting the quality or “accuracy” of the modeling system. As forecast models move into the high-resolution nonhydrostatic regime, however, traditional pointwise verification measures (such as RMS errors and skill scores) no longer adequately reflect the quality and value of the forecast information provided by the model. Thus, new techniques are needed for high-resolution applications that test the quality of important information provided by the forecast model and that provide linkages, where possible, between forecast deficiencies and specific inadequacies in the model formulation. Three principle areas have been outlined as being vital aspects of verification as it pertains to future research efforts with WRF.

Key areas for forecast-verification enhancement:

1) *Expanded data sets for verification to include non-traditional model variables.*

One of the major problems with many current verification systems is that they are limited mainly to either state variables of the model, or precipitation. The totality of observational information available is much greater, but it is difficult to tap effectively. Furthermore, there have traditionally been few targeted efforts to gather new observations for the purpose of verification of weather models, yet this practice has been done for decades in the context of climate models. As research NWP transitions to longer time-scales and at high resolution, it will be essential to correctly diagnose the balance of processes in physical parameterizations. Making full use of existing data and therefore knowledgably targeting the collection of additional data are keys to improving the information content of verification as it pertains to diagnosing model errors. This effort requires participation from model developers, data-assimilation experts, and possibly instrument designers and manufacturers. It also requires collaboration between research and operational communities to get the most information about model performance. Several key efforts are required.

a. Expand the data available for verification through collaboration of research and operations. This would allow the research community to be more involved in use of satellite data for verification.
b. Improve diagnostic information content derived from WRF. This must not come at the expense of dramatically decreased parallel efficiency or increased data storage. Numerous fields such as surface energy balance terms, tendencies from convective, PBL and microphysics parameterizations would be insightful. Assistance from the climate community may help focus this effort for longer integrations.
c. Incorporate forward operators to place data in observation space. Many of these have been constructed for 3D-Var in the research or operational communities.
d. Collaborate with organizers of field campaigns to include the collection of observations specifically for verification of short and medium-range prediction using WRF.

2) *Event-based verification methods applicable to a variety of spatial and temporal scales.*

The fundamental limitations of traditional, measures oriented verification approaches (e.g. root-mean-square-error, equitable threat score, etc.) are that they are highly sensitive to even small forecast errors and are generally non-diagnostic. The former is not necessarily undesirable, but when spatial and temporal scales of predicted phenomena decrease, realistic forecasts (with potentially valuable spatial or temporal information) often are scored inferior to even random forecasts. These factors and the increasing emphasis on particular weather events in forecasts motivate creation of so-called object-based techniques. These techniques are designed to identify features of interest in models and observations, decide which model and observation pairs of features correspond, and develop statistics of the discrepancies of matched and unmatched features. By allowing for finite skill even for features that have little or no overlap in time or space, these approaches give credit to forecasts with realistic spatial or temporal structures. By relating the attributes of features to physical processes, these approaches become diagnostic of model errors in such processes.

Significant work in the area of object- or event-based verification is needed to allow meaningful intercomparison of fine-scale forecasts and for the full potential of diagnostic information to emerge. Specific goals are:

a. Compare existing object-based techniques to understand their relative behavior.
b. Advance object based methods for satellite data (e.g., verification of objects defined from radiances). Couple object-based methods with forward operators from 3D-Var.
c. Adapt object-based methods to “sparse” observation networks. This work emphasizes, for instance, surface observations that are non-uniformly distributed within complex physiography.
d. Investigate the application of statistical spatial modeling techniques (geostatistical models) for evaluation of model fields.
e. Extend event-based techniques by considering both temporal and spatial dimensions, identifying time-coherent objects (evolving weather features, trajectories, etc.)
f. Quantify uncertainty in verification metrics including that arising from observation errors. This is vital for developing confidence metrics in the intercomparison of forecasts using object-based approaches, for instance.
g. Explore improved quantification of forecast value using event-based verification metrics.

3) New strategies for probabilistic forecasts.

While several methods of evaluation of probabilistic forecasts have seen wide use in recent years (e.g. reliability diagrams, Talagrand diagrams, etc.), there are more that should be explored further. Collaboration with researchers in ensemble prediction is crucial. New areas of emphasis include:

a) Adapt object-based methods to ensemble forecasts. This is straightforward and could be highly beneficial for display and interpretation of ensembles in cases where the feature of interest is less isolated than, say, a hurricane, for which this type of verification is already performed.

b) Use spatial/temporal variance to estimate uncertainty. This is best applied to an ensemble, but can be applied to a single forecast. This approach can extend to model trajectories, by quantifying the uncertainty of parcel paths and the conservation (or lack thereof) of constituents along such paths.

c) Compute cost-loss ratios as an additional verification metric. Investigate other approaches for estimating forecast value and utility of forecasts in different applications.

Proposed Action Plan:

1) Actively research and develop new forecast evaluation methods. Engage the statistics community in designing and developing techniques, including spatial modeling approaches.

2) Quantify hardware and software requirements for processing large volumes of model output needed to perform verification on large samples of large model grids. Advance software for manipulating large model grids.

3) Couple traditional and new verification approaches to variational data assimilation systems to maximize the use of remote sensing observations.

4) Work with model developers to extract model data for verification during run time to (a) take advantage of every time step of the model (critical for trajectory budget analysis) and (b) reduce demands for postprocessing. Not everything can be output as WRF is running, hence the need for (2) above.

Other Section Contributors: Mike Baldwin (U Oklahoma), Barb Brown (NCAR), Brian Colle (SUNY Stonybrook), Brian Jewett (U. Illinois), Cliff Mass (U Washington), Jason Nachamkin (NRL), Paul Roebber (U Wisconsin), …

10. Advanced Computing, Data Analysis, and Visualization

Section Coordinator: Robert Wilhelmson, University of Illinois (bw@ncsa.uiuc.edu)

Advanced WRF enabled research requires components that include data assimilation, modeling, data management, data analysis/mining, and visualization. The implementation of an integrated, tested, stable, robust, and modifiable computational software environment that includes all of these components remains incomplete. Further, the time, energy, and resources required for carrying out very large simulations (higher spatial resolution or more variables), moderate sized simulations (but many of them associated with large ensembles), and/or analysis/visualization of the very large model data sets are often beyond that possible for most researchers or research groups. As the complexity of the model and associated components grows, it is imperative that efforts be undertaken to plan for and provide these capabilities for productive use by the WRF user community.

Behind the challenges ahead are changes in computer architecture, advances in grid technologies, and the push to petascale computing. The doubling of processor speed every 18 months (Moore's Law) is no longer viable due in large part to the associated increase in heat output. Substantial speed increases will come from the use of larger numbers of processors (>100,000). Further, these processors will be grouped on dies with a multicore chip containing as many as 32 or more processors. Memory bandwidth to each of these cores will need to be monitored as it may not increase as fast as the number of cores on a chip. These architectural changes may impact code performance and modifications may be needed to WRF to obtain reasonable performance.

WRF developers and users will be faced with additional challenges. Load balancing for the physics calculations will be more challenging as the network distances between chip cores expand. With ten's of thousands of processors, I/O will need to be parallel on the subdomains and whenever full three-dimensional arrays are needed, they will need to be built from these subdomains on other resources since this process is not highly parallel. Ensemble simulations involving 10's to 100's of simulations will require workflow technologies (or a graduate student spending there time monitoring simulations). Kalman filtering requiring frequent communication among many simulations will depend on careful programming and minimizing serial operations. Further, large simulations should be carried out with a WRF model that is tolerant to failures of individual processors without total model shutdown. Further, coupling of models such as WRF with an ocean model for studying hurricanes will require careful subdomain layout to minimize data transfers between models.

Key areas for WRF-system development

1) WRF model code development and modification

Vendors such as AMD and Intel are now producing dies containing two processors, and this number will only increase in the future. Open questions remain on the impact of this change on code performance, particularly when memory bandwidth to the die may not increase proportionally to the increase in overall processing speed. Memory bandwidth is important to WRF. In addition, communication between nodes in a parallel system has significant impact on performance, and questions remain on how this will scale with current software technologies. The impact of architectural changes in the computer industry needs to be continually monitored and any needed changes to WRF be made to effectively use new systems. It is significant that WRF is being used as a key benchmark that is required in submitting responses to solicitations for new high performance computer acquisitions from the NSF Office of Cyberinfrastructure at NSF.

In addition to processor speed, core architecture, and memory bandwidth, it is important to note that future systems of value to the WRF community should be built with not only speed in mind but also with a balanced I/O capabilities. Rapid I/O can be achieved using parallel I/O techniques where the subdomains in a simulation are stored separately (not gathered into full three-dimensional arrays). However, most analysis and visualization software assume access to full three-dimensional arrays. This takes time to construct from the subdomains. Alternatively, it might prove beneficial and quicker to use the subdomains directly provided that parallel techniques are used for analysis and visualization.

There is a move toward petascale computing with technical and budgetary implications discussed in a new report, A Petascale Collaboratory for the Geosciences, sponsored by GEO-NSF[1]. Indeed, the Office of Cyberinfrastructure intends to deploy a petascale computer in 2010. Such a system could contain upwards of 1 million processors. If some WRF researchers intend to use such a system (most of them use significantly less than 1000 processors today), scalability issues including load balancing will need to be addressed – particularly in regard to fault tolerance. Even with just 10,000 processors, the chance of failure goes up significantly when making a simulation. It can be argued that the operating system and MPI implementations should account for such failures but this is idealistic and application code changes may be required for good performance and through-put.

There is increasing consideration being given to including specialized processors such as Field Programmable Arrays (FPGAs) in computational nodes for dramatically speeding up parts of an overall computation. Although not yet ready for speeding up some processes in the WRF model (FPGAs are currently too small and do not yet have full floating point), expectations are that such specialized processors may substantially improve code performance in the two- to three-year time frame. At the appropriate time in the next few years, this should be investigated in greater depth.

2. Development of Cyberenvironments[2]

The execution of the various software components in the WRF pipeline through the use of cyberinfrastructure is receiving considerable attention (this is also true in a number of other environmental areas). The Linked Environments for Atmospheric Discovery (LEAD) Project is a research and prototype project funded by the NSF for five years (it is in its third year) in partial response to this pressing need for a comprehensive national cyberinfrastructure in mesoscale meteorology, particularly one that can interoperate with those being developed in other relevant disciplines. It involves a multi-disciplinary effort that includes nine institutions and more than 100 scientists, students and technical staff in meteorology, computer science, social science, and education. It is addressing some of the fundamental IT research challenges, and associated development, needed to create an integrated, scalable framework for identifying, accessing, preparing, assimilating,

---

[1] http://www.geo-prose.com/projects/petascale_science.html
http://www.geo-prose.com/projects/petascale_tech.html

[2] A cyberenvironment is an integrated set of end-to-end tools and services needed to marshal the nation's resources and to model, analyze, and visualize interesting phenomena. These tools and services include scientific and engineering applications, graphical user interfaces and portals for easy interaction with the applications, and workflow software to support complex, collaborative projects.

predicting, managing, analyzing, mining, and visualizing a broad array of meteorological data and model output independent of format and physical location and in a dynamically adaptive and sometimes on-demand manner. Further, LEAD is working at providing advanced weather technologies for research and education, lowering the barrier to entry, empowering application in a distributed context, increasing the sophistication of problems that can be addressed, and facilitating rapid understanding, experiment design and execution. LEAD is using the WRF model in this effort.

The intent in LEAD and other similar projects is to provide a cyberenvironment tailored to the needs of the meso and cloud scale communities, enabling them to dynamically access computational resources at multiple sites to carry out the process of assimilation, modeling, analysis/mining, and visualization. The use of multiple sites in a grid (the TeraGrid is one example) is particularly valuable in carrying out large ensembles and in providing on-demand capabilities in a web services and application framework for handling severe events where additional computing power is needed. It is expected that the LEAD effort will provide a foundation for future developments and for hardening of relevant grid software. It is important that the WRF community be not only aware of this and other related activities, but contribute to it when appropriate, test the stability and usefulness of the cyberenvironment for research, education, and decision making, and help determine the most important capabilities they would like to have in production environments.

3. Data Analysis/Mining Challenges

Researchers have developed a variety of ways over the years to analyze model data, looking for processes and precursors that lead to selected events such as tornadoes. There now is a wealth of software that is directly useable or adaptable for use in automatic feature detection and classification as well as statistical and precursor exploration. This software can reduce substantially the number of simulations required in carrying out parameter or flexible (number of members) ensemble studies by identifying promising parameter combinations from smaller sets of simulations and exploring only those combinations. Mining can also be useful in automatically creating metadata - describing features found in assimilated or modeled data sets for later interrogation by other researchers.

It is important that analysis tools be made available for common dynamical analyses of model results. These analyses should make use of parallel computing strategies, particularly when analyzing large simulations or when interactive investigation of model data is desired. Too often this is done in batch mode and lengthens the period of analysis substantially.

Analysis tools for ensemble simulations should, in the future, be extended beyond the relatively simple analysis currently done in prediction (e.g. look at storm or hurricane tracks across all simulations, forecast of precipitation by looking at surface precipitation produced by each model with some simple weighting between model results to produce probabilities). This would involve the ability to adjust output from one simulation relative to another where time lag may be a strong factor. This could, in some cases, benefit from the availability of full three-dimensional data from multiple runs for interactive or batch analysis that is not sequential. This, in turn, would require a large memory system.

Finally, it should be recognized that some ensemble modeling requires sharing of data across simulations at frequent intervals during the simulations. There are various software strategies (e.g. using Python) being investigated for running such ensembles on a single machine but eventually, as such ensemble approaches are adopted more broadly, a common software framework for ensembles should be adopted and made available to the WRF community.

4. Visualization challenges

Flexible and sometimes interactive visualization of assimilated, derived, and mined data is an important part of the modeling enterprise. Visualization tools are often coupled with analysis/mining software to create an exploratory environment for understanding process relationships within or across simulations and for analyzing data mining results. To addressing future visualization requirements, parallel 2D and 3D visualization tools for very large data sets should be brought into WRF workflows such as the one being built by LEAD. It will be possible within the next five years for an increasing number of scientists to routinely carry out simulations that exceed 2000 x 2000 x 128 grid points. Many of these tools are not familiar to WRF users. Future simulations with WRF will also involve an increasing number of variables and ways to understand the time evolutionary relationship of these variables needs to be addressed both analytically and visually.

Analytic and visual comparison of modeled and observed event behavior beyond simple measures needs further emphasis to help determine the accuracy and limits of models in representing natural events. To aid in analyzing nested-grid simulations, visualization methods for looking simultaneously at all nested grids within a simulation are becoming available and accessible to the research community. Such techniques provide a way to detect problems that can occur at grid boundaries and eliminate the need to map model data onto a uniform single grid.

Proposed Action Plan:

1)_The impact of architectural changes in the computer industry needs to be continually monitored and any needed changes to WRF software be made to effectively use these new systems, some of which will have 100's of thousands of processors.

2) Tools for parallel I/O, analysis/data mining, and visualization need to be provided for all users including those carrying out very large simulations or ensembles.

3) The WRF community needs to become involved in testing capabilities of the prototype LEAD system and determining how to sustain and improve the LEAD cyberenvironment at the end of the LEAD award in the fall of 2009.

Other Section Contributors: …

References

Andreas, E. L. and K. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity. *J. Atmos. Sci.,* **58,** 3741-3751.

Atger, F., 1999: The skill of ensemble prediction systems. *Mon. Wea. Rev.*, **127**, 1941-1953.

Black, P. G., Eric A. D'Asaro, W. M. Drennan, J. R. French, T. B. Sanford, E. J. Terrill, P. P. Niiler, E. J. Walsh and J. Zhang, 2006: Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment. *Bull. Amer. Meteor. Soc.*, submitted.

Braun, S. A., 2002: A cloud-resolving simulation of Hurricane Bob (1991): Storm structure and eyewall buoyancy. *Mon. Wea. Rev.*, **130**, 1573-1592.

Brooks, H. E., M. S. Tracton, D. J. Stensrud, G. DiMego, and Z. Toth, 1995: Short-range ensemble forecasting: Report from a workshop (25-27 July 1994). *Bull. Amer. Meteor. Soc.*, **76**, 1617-1624.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution Requirements for the Simulation of Deep Moist Convection. *Monthly Weather Review*, **131,** 2394-2416.

Caya, A., J. Sun and C. Snyder, 2005: A comparison between the 4D-Var and the ensemble Kalman filter techniques for radar data assimilation. *Mon. Wea Rev.,* **133**, 3081--3094.

CCSP, 2003: *Strategic Plan for the U.S. Climate Change Science Program* – A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, 211pp (Available at http://www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-all.pdf).

Chen, S.-H., F. Vandenberghe, G. W. Petty, and J. F. Bresch, 2004: Application of SSM/I satellite data to a hurricane simulation, *Quart. J. Roy. Meteor. Soc.*, **130**, 801-825.

Chen, S. S., J. E. Tenerelli, W. Zhao, R. A. Foster, W. T. Liu, 2004: Improving tropical cyclone prediction using scatterometer surface winds in model initialization. *ENVSAT Symposium Abstract and Program Book, Salzburg, Austria,* No. 669.

Chen, S. S., and J. E. Tenerelli, 2006: Simulation of hurricane lifecycle and inner-core structure using a vortex-following mesh refinement: Sensitivity to model grid resolution. *Mon. Wea. Rev.*, submitted.

Chen, S. S., W. Zhao, M. A. Donelan, J. F. Price, E. J. Walsh, T. B. Sanford, and H. L. Tolman, 2006: Fully coupled atmosphere-wave-ocean modeling for hurricane research and prediction: Results from CBLAST-Hurricane. *Bull. Amer. Meteor. Soc*, submitted.

Chen, Y., and C. Snyder, 2006: Assimilating vortex position with an ensemble Kalman filter. *Mon. Wea. Rev.*, in revision.

Chung, S.H., and J.H. Seinfeld, 2002: Global distribution and climate forcing of carbonaceous aerosols, *J. Geophys Res.*, 107 (D19), 4407, doi:10.10292001JD001397.

Cohn, S. E., 1997: An introduction to estimation theory. *J. Meteor. Soc. Japan* (Special Issue), **75**, 257--288.

Done, J., C. A. Davis, and M. L. Weisman, 2004: The next generation of NWP: explicit forecasts of convection using the Weather Research and Forecasting (WRF) Model. *Atmos. Sci. Let.*, **5**, 110-117.

Dowell, D., F. Zhang, L. Wicker, C. Snyder and N. A. Crook, 2004: Wind and thermodynamic retrievals in the 17 May 1981 Arcadia, Oklahoma supercell: Ensemble Kalman filter experiments. *Mon. Wea. Rev.*, **132**, 1982-2005.

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown, E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds, *Geophys. Res. Lett.,* **31***,* 4539-4542.

Elmore, K.L., D.J. Stensrud, and K.C. Crawford, 2002: Ensemble cloud model applications to thunderstorm forecasting. *J. Appl. Meteor***,** **41**, 363-383.

Epstein, E. S., 1969: Stochastic dynamic prediction. *Tellus*, **21**, 739-759.

Errico, R., and D.P. Baumhefner, 1987: Predictability experiments using a high-resolution limited-area model. *Mon. Wea. Rev.*, **115**, 488-504.

Evensen, G., 1994: Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics. *J. Geophys. Res.,* **99,** 10143-10162.

Fast, J.D., W.I. Gustafson Jr., R.C. Easter[1], R.A. Zaveri, J.C. Barnard[1], E.G. Chapman, G.A. Grell, and S.E. Peckham. 2006: Evolution of ozone, particulates, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology-chemistry-aerosol model. *J. Geophys. Res*., In Review.

Gilmore, M. S., J. M. Straka, and E. N. Rasmussen, 2004: Precipitation uncertainty due to variations in precipitation particle parameters within a simple microphysics scheme. *Mon. Wea. Rev.*, **132,** 2610-2627.

Hagedorn, R., F. J. Doblas-Reyes, and T. N. Palmer, 2005: The rationale behind the success of multi-model ensembles in seasonal forecasting - I. Basic concept. *Tellus,* **57A,** 219-233.

Hamill, T.M., and S.J. Colucci, 1997: Verification of Eta-RSM short-range ensemble forecasts. *Mon. Wea. Rev.*, **125**, 1312-1327.

Hamill, T. M., and C. Snyder, 2000: A hybrid ensemble Kalman filter/3D-variational analysis scheme. *Mon. Wea. Rev*., **128**, 2905-2919.

Hamill, T. M., J. S. Whitaker, and X. Wei, 2004: Ensemble reforecasting: Improving medium-range forecast skill using retrospective forecasts. *Mon. Wea. Rev.,* **132,** 1434-1447.

Haywood, J.M., V. Ramaswamy, and L.J. Donner, 1997: A limited-area-model case study of the effects of sub-grid scale variations in relative humidity and cloud upon the direct radiative forcing of sulfate aerosol. *Geophys. Res. Lett*., 24, 143-146.

Houtekamer, P. L., L. Lefaivre, J. Derome, H. Ritchie, and H. L. Mitchell, 1996: A system simulation approach to ensemble prediction. *Mon. Wea. Rev.*, **124**, 1225-1242.

Houze, R. A., S. S. Chen, and co-authors, 2006: The Hurricane Rainband and Intensity Change Experiment (RAINEX): Observations and modeling of Hurricanes Katrina, Ophelia, and Rita (2005). *Bull. Amer. Meteor. Soc*, submitted.

Kain, J. S., S. J. Weiss, M. E. Baldwin, K. K. Droegemeier, D. Bright, J. J. Levit, D. Weber, and K. Thomas, 2005: How much resolution is enough? Comparing daily WRF–ARW forecasts at 2 and 4 km grid spacing in severe convective weather environments during the 2005 SPC/NSSL Spring Program *11th Conf. Mesoscale Processes*, Albuquerque, NM, Amer. Meteor. Soc.

Kong, F., K. K. Droegemeier, and N. L. Levit, 2006: Multi-resolution ensemble forecasts of an observed tornadic thunderstorm system, Part I: Comparison of coarse and fine-grid ensembles. *Mon. Wea. Rev.*, **134**, 807-833.

Leidner, S. M., L. Isaksen and R. N. Hoffman, 2003: Impact of NSCAT winds on tropical cyclones in the ECMWF 4DVAR assimilation system. *Mon. Rea. Rev.*, **131**, 3-26.

Leith, C. E., 1974: Theoretical skill of Monte Carlo forecasts. *Mon. Wea. Rev.*, **102**, 409-418.

Leung, L.R., J. Done, J. Dudhia, T. Henderson, M. Vertenstein, and B. Kuo, 2005: Preliminary results of WRF for regional climate simulations. Presented at *Workshop on Research Needs and Directions of Regional Climate Modeling Using WRF and CCSM*, March 22-23, 2005, Boulder, CO.

Leung, L.R., Y.-H. Kuo, and J. Tribbia, 2006: Research needs and directions of regional climate modeling using WRF and CCSM. Bull. Amer. Meteorol. Soc., accepted. (Avail. at http://box.mmm.ucar.edu/events/rcm05/RCM_workshop_summary.pdf)

Lorenc, A. C., 1986: Analysis methods for numerical weather prediction. *Quart. J. Roy. Meteor. Soc.*, **112**, 1177-1194.

Lorenz, E.N., 1963: Deterministic nonperiodic flow. *J. Atmos. Sci.*, **20**, 130-141.

McAvaney, B.J., C. Covey, S. Joussaume, V. Kattsov, A. Kitoh, W. Ogana, A.J. Pitman, A.J. Weaver, R.A. Wood, Z.-C. Zhao, 2001: Chapter 8: Model Evaluation, In *Climate Change 2001, The Scientific Basis, Intergovernmental Panel on Climate Change*, Cambridge University Press, 473-523.

Molteni, F., R. Buizza, T. N. Palmer, and T. Petroliagis, 1996: The ECMWF ensemble prediction system: Methodology and validation. *Quart. J. Roy. Meteor. Soc.*, **122**, 73-119.

Murphy, A. H., and R. L. Winkler, 1979: Probabilistic temperature forecasts: The case for an operational program. *Bull. Amer. Meteor. Soc.,* **60,** 12-19.

Novakov T., and J.E. Penner, 1993: Large contribution of organic aerosols to cloud-condensation nuclei concentrations, *Nature*, 365, 823-826.

Palmer, T. N., and Coauthors, 2004: Development of a European multimodel ensemble system for seasonal-to-interannual prediction (DEMETER). *Bull. Amer. Meteor. Soc.,* **85,** 853-872.

Rogers, R., S. S. Chen, J. E. Tenerelli, and H. E. Willoughby, 2003: A numerical study of the impact of vertical shear on the distribution of rainfall in Hurricane Bonnie (1998), *Mon. Wea. Rev.,* **131**, 1577-1599.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF, Version 2. *NCAR Technical Note 468+STR*, National Center for Atmospheric Research, Boulder, CO.

Snyder, C. and F. Zhang, 2003: Assimilation of simulated Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.,* **131,** 1663-1677.

Stainforth, D. A., and Coauthors, 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature,* **433,** 403-406.

Stensrud, D. J., J.-W. Bao, and T. T. Warner, 2000: Using initial condition and model physics perturbations in short-range ensembles of mesoscale convective systems. *Mon. Wea. Rev*., **128**, 2077-2107.

Sun, J., and N.\ A.\ Crook, 1998: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part II: Retrieval experiments of an observed Florida convective storm. *J. Atmos. Sci.,* **55**, 835-852.

Tenerelli, J. E., S. S. Chen, 2001: High-resolution simulation of Hurricane Floyd (1999) using MM5 with a vortex-following mesh refinement. *Preprints, 18th Conference on Weather Analysis and Forecasting/14th Conference on Numerical Weather Prediction, 30 July-2 August 2001, Ft. Lauderdale, Florida, AMS*, J54-J56.

Thépaut, J.-N., P. Courtier, G. Belaud and G. Lemaître, 1996: Dynamical structure functions in a four-dimensional variational assimilation: A case study. *Quart. J. Roy. Meteor. Soc*., **122**, 53-561.

Toth, Z., and E. Kalnay, 1993: Ensemble forecasting at NMC: The generation of perturbations. *Bull. Amer. Meteor. Soc.*, **74**, 2317-2330.

Tsigardis, K., and M. Kanakidou, 2003: Global modeling of secondary organic aerosol in the troposphere: A sensitivity analysis, *Atmos. Chem. Phys. Discuss*., 3, 2879-2929.

van den Heever, S. C. and W. R. Cotton, 2004: The Impact of Hail Size on Simulated Supercell Storms. *J. Atmos. Sci.*, **61,** 1596-1609.

Wandishin, M. S., S. L. Mullen, D. J. Stensrud, and H. E. Brooks, 2001: Evaluation of a short-range multimodel ensemble system. *Mon. Wea. Rev.,* **129,** 729-747.

Weisman, M. L., C. Davis, and J. Done, 2004: The promise and challenge of explicit convective forecasting with the WRF Model. *Preprints, 22nd AMS Conference on Severe Local Storms*, 4-8 October 2004, Hyannis, MA, 11 pp. (Available at http://ams.confex.com/ams/11aram22sls/techprogram/paper_81383.htm)

Whitaker, J. S., G. P. Compo, X. Wei, T. M. Hamill, 2004: Reanalysis without radiosondes using ensemble data assimilation. *Mon. Wea. Rev.*, **132**, 1190-1200.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D. Wang, 2001: The Advanced Regional Prediction System (ARPS) - A multi-scale nonhydrostatic atmospheric simulation and prediction tool. Part II:

Model physics and applications. *Meteor. Atmos. Phys.*, **76,** 143-165.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, **82,** 139-170.

Zhang, Y., B. Pun, K. Vijayaraghavan, S.-Y. Wu, C. Seigneur, S.N. Pandis, M.Z. Jacobson, A. Nenes, and J.H. Seinfeld (2004), Development and application of the model of aerosol dynamics, reaction, ionization, and dissolution (MADRID), *J. Geophys. Res., 109*, doi:10.1029/2003JD003501.

Zhao, W., and S. S. Chen, 2005: A Coupled Atmosphere-Wave-Ocean Framework for High-Resolution Modeling of Tropical Cyclones and Coastal Storms, *Sixth WRF and MM5 User Workshop, Boulder, 26-30 June 2005,* (available at http://www.mmm.ucar.edu/wrf/users/workshops/WS2005/abstracts/Session5/5-Zhao.pdf).