RESEARCH-COMMUNITY PRIORITIES FOR WRF-SYSTEM DEVELOPMENT

Prepared by the WRF Research Applications Board, December 2006

Executive Summary

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." 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, to identify the particular new or enhanced WRF-system capabilities that will be required to enable this research, and to recommend specific actions to help achieve these advancements.

This document is organized to focus on major community research and forecasting applications (convection-resolving forecasting, hurricane research, air-quality modeling, regional-climate modeling, ensemble forecasting, and forecast verification), as well as cross-cutting aspects of model development (parameterized physics, data assimilation, and high-performance computing). Our objective is to identify the most critical model-development requirements in each of these important areas, rather than attempt to determine which topic areas should be given highest priority.

In preparing this plan, we were impressed by the level of interest and motivation in the research community; with appropriate funding support and coordination of effort, we anticipate that rapid progress can be made in addressing the priority model-development requirements. Revitalized WRF working groups and more frequent topical workshops are recurring recommendations to better coordinate development efforts. The requirements for substantially improved parameterized physics, particularly for high-resolution applications, is emphasized in all of the major model application areas. Improved parameterization techniques are most critical for the PBL and surface layer, cloud microphysics, and radiation. Increased investment will be required to strengthen the cadre of researchers needed to develop the next generation of model physics. Another pervasive theme in the priority requirements for future weather-forecast and air-quality modeling is the need for enhanced data-assimilation capabilities, particularly at the mesoscale and cloud scale, and including the assimilation of chemical constituents. Data assimilation is also a powerful verification tool that can provide direct comparisons with observational data sets. Testbed facilities are recognized as important vehicles for testing potential improvements in data-assimilation and model-forecasting applications and for evaluating new techniques for model physics. The maintenance of comprehensive observational data sets over extended periods will be required to support this testing.

The WRF-system development emphasized in this plan is needed to achieve the advances in weather forecasting and related research desired by the broad community. We ask that the WRF-partner organizations and other funding agencies give serious consideration to providing both funding and organizational support to facilitate these proposed priority-development efforts.

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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 4200 users have registered to download the model code as of September 2006. Over half of these users are distributed across some 82 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 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 breadth of WRF user activities is illustrated by the wide range of papers presented at the Seventh WRF Users Workshop in June 2006 (http://www.mmm.ucar.edu/wrf/users/workshops/WS2006/WorkshopPapers.htm) and the real-time forecasting experiments throughout the world (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, as members of their Short-Range Ensemble Forecasts, and in their North American Meso (NAM) Model, and is adapting WRF-based implementations for the Rapid Refresh Model and Hurricane Forecast Model over the next year or two. The Air Force Weather Agency began operational use of WRF for forecasting in their worldwide theatres in July 2006. In addition to applications in the U.S., 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. To help identify the priority requirements for future model development and strategies for achieving these advances, the WRF Research Applications Board has solicited input from the research community and prepared this strategic plan for WRF-system development. We have identified a number of key model development and model application topics to help organize and focus the material in this document. The emphasis in this assessment is on model technology having the potential for enhancing WRF-related research over a period extending five years or more into the future. A description of the process established to encourage community participation in developing this plan is presented in the Appendix.

As might be expected, there are several cross-cutting areas of priority development that are emphasized in a number of different research and forecasting applications. The requirements for advancements in data-assimilation and model physics are particularly pervasive. In the following sections, we outline the important science issues, key model development requirements, and action plans to advance the WRF system to achieve the future research capabilities desired by the WRF community. The intent here is not to provide a rank ordering of the few most important requirements for future WRF development. Such an effort would be unlikely to achieve consensus given the diverse spectrum of interests in the research community. Rather, this plan is intended to provide a roadmap that outlines priority model development requirements in the major areas of interest to the research community that can be used to stimulate and justify the needed development efforts.

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 predictions 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., Weisman et al. 1997; Xue et al. 2001). In comparison to coarser-grid models, these forecasts provide a much better indication of the likely mode of convection (e.g., bow echoes, supercells, mesoscale convective vortices, squall 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. 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 and climatological properties of convection.

<u>Key areas for WRF-model enhancement and research:</u>

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 determine, to a significant extent, 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. 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 microphysics and should therefore also be pursued. Multi-scale capabilities for assimilating observations that contain information on convective through synoptic scales must be developed. Furthermore, more studies are needed to understand the optimal mix and information content of observations and identifying main deficiencies in current observation networks. OSSEs and OSEs and related data impact studies play important roles here.

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 data assimilation 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, contains significant sources of uncertainty for explicit prediction of convective cells. 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) or even tornadogenesis (Snook and Xue 2006). 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 additional polarimetric-radar parameters. Microphysics-aerosol interactions may also need further study.

Other parameterized physics are critical for establishing the storm environment, particularly for important features such as 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 both in situ and remotely sensed observations for all soil types and vegetation cover. The improvement of radiation parameterization should focus on radiation and cloud interaction, incorporating multiple cloud and hydrometeor species. 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. More resources should be devoted to in-depth diagnostic analyses of existing schemes in controlled settings and to verifications against observations.

3) Model numerics and computational infrastructure.

Flows at convection-resolving scales are highly turbulent and contain a 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 at resolvable scales 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, etc.) and post-processing (diagnostic calculations, visualization and forecast verification) software, and their scalability. All computer codes should be readable to facilitate research and understanding.

4) Convective-scale predictability study and probabilistic forecasting. Convective-scale predictability is poorly understood and varies significantly with the type of convective systems; it therefore should be a key area of fundamental research that would provide important guidance for convection-resolving data assimilation and NWP. Error-growth dynamics, in the presence of model error, 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.

5) Forecast verification at convective-resolving scales and model evaluation. Because of the high spatial and temporal intermittencies of convective-scale phenomena, most traditional verification scores have limited value. New skill scores, such as feature-based ones, that assess errors in both space and time need to be developed. Some of these involve quantification and standardization of forecast skills identified subjectively. Direct verification should be performed against indirect observations utilizing the capabilities of data assimilation systems. Ideally, verification scores can help reveal the skills and deficiencies in the handling of physical processes by the model. Model behavior should be analyzed in a holistic way where all aspects of the model system are evaluated together.

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 specializing in advanced data assimilation and atmospheric physics, and in statistical approaches to atmospheric data assimilation, verification and probabilistic prediction. Promote collaborations between physical scientists and statisticians.

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

Other Section Contributors: Morris Weisman (NCAR), Stan Benjamin (NOAA/ESRL/GSD), George Bryan (NCAR), Yi Jin (NRL), Richard Farley (SDSMT), Jason Otkin (UW-Madison), Kate LaCasse (UAH/NASA), Tetsuya Takemi (Tokyo Int. Tech.), George Grell

(NOAA/ESRL/GSD), and the convection-resolving forecasting breakout group at June 2006 WRF Users Workshop.

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) Improved 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) 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).

<u>Proposed action plan:</u>

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 the DTC for transition to operational hurricane forecast models.

Other Section Contributors: Hurricane research and prediction breakout group at June 2006 WRF Users Workshop.

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, capturing 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 (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 to understand 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 on a fully coupled model 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 its behavior, to address its computational efficiency, and to document its sensitivity 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 nonhydrostatic 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. In addition to high resolution physics, sustained efforts are needed to address current physics parameterization issues, such as boundary layer physics, effects of subgrid orography, cloud fraction, and cumulus convection, in mesoscale 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, matching the top level of the regional and global models and improving the treatment of the upper atmosphere in WRF 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 in a manner that eliminates artificial sources/sinks.

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.

Research in the above four key areas can proceed in parallel with prioritization and planning. On the near term, the priorities are to:

- Develop a framework for coupling earth system models
- Develop a framework for coupling WRF and the Community Atmosphere Model (CAM)
- Develop and implement improved physics parameterizations for regional climate applications
- Implement earth system components from existing community models
- Test global WRF and physics parameterizations towards an atmospheric GCM

On the longer term, the priorities are to:

- Develop and evaluate a more complete regional earth system model
- Develop and evaluate a fully functional two-way coupled WRF/CAM within the respective regional and global earth system models
- Address high resolution physics for the nested and global WRF

<u>Proposed Action Plan:</u>

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, and to establish stronger ties to the Community Climate System Model (CCSM).

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 benchmarks for comparison with 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, and the regional climate breakout group at the 2006 WRF Users Workshop.

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. Advanced research capabilities will lead to an improvement of the understanding of complex interactive processes that are of great importance to regional and urban air quality, global climate change, and also weather prediction. The resulting improved predictive capabilities will lead to more accurate health alerts, to a larger confidence when using the modeling system for regulatory purposes, and to better capabilities in predicting the consequences of an accidental or intentional release of hazardous materials. Such advanced research capabilities may also facilitate the design of future chemical observing networks. Finally, 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.

Three major areas have been identified where future WRF developments may lead to significant scientific opportunities: (1) direct and indirect aerosol effects, (2) chemical data assimilation, and (3) the application of generalized chemical mechanisms, which are discussed below.

<u>Key areas for WRF-model enhancement:</u>

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 contributing to erroneous conclusions regarding spatial variations of future climate change. 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. 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. However, to accommodate future needs the framework must also be augmented to efficiently handle the computational burden associated with atmospheric-chemistry research that requires hundreds to thousands of additional transported variables.

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.

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, and have become an essential element in atmospheric chemistry studies. 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, to significantly improve the analysis capabilities of CTMs, they must be closely integrated with observational data through data assimilation, which is only just beginning to be used in nonlinear atmospheric chemical models. When chemical transformations and interactions are considered, the complexity and 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; 5) utilize the system for inverse applications (to improve emissions estimates, and other key parameter estimation); and 6) conduct Observing System Experiments (OSE's) and Observing Systems Simulation Experiments (OSSE's) with the modeling system to aid in the design of future chemical observational networks.

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 all KPP capabilities.* A state-of-the-art tool to generate chemical mechanism modules and their adjoints – such as KPP – should be fully integrated into the WRF software infrastructure. This will require close collaboration of the software group and members of the WRF/Chem working group.

2) *Development of advanced data assimilation methods*. A coordinated effort between the developers of the meteorological advanced data assimilation methods and members of the air quality community should be initiated to develop a next-generation data-assimilation system for air quality applications. A key early step is to build an adjoint of WRF/Chem, which 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).

3) *Enhancement of WRF-system efficiency 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, time-varying boundary conditions of trace gases and aerosols from larger-scale models or analyses will be needed.

4) *Increased compatibility with the Community Multiscale Air Quality (CMAQ) Model.* CMAQ is an active open-source development project of the U.S. EPA Atmospheric Science Modeling Division (http://www.epa.gov/asmdnerl/index.html) that consists of a suite of programs for conducting air quality model simulations. Because of its widespread use in the regulatory community, compatibility of the chemical capabilities between WRF/Chem and CMAQ would be very beneficial in enabling the use of WRF/Chem for regulatory purposes.

Other Section Contributors: Jerome Fast (PNL), William Gustafson, Jr. (PNL), Richard Easter (PNL), Steve Ghan (PNL), Gregory Carmichael (U Iowa), Rainer Schmitz (U Chile), John Nielson-Gammon (TAMU), and the WRF chemistry breakout group at June 2006 WRF Users Workshop.

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 because 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 variability of physical parameterization schemes 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 as they relate to different ensemble applications.

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 highly desirable.

Key areas for WRF-model enhancement:

1) Integration of ensemble applications into data assimilation software. Ensemble initialization and data assimilation methods share many common needs, such as background error covariances, adjoint models, and singular vector calculations. The explicit incorporation of ensemble applications into data assimilation tools is strongly desired.

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 and verification 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 implement.

Proposed action plan

Short-term goals:

1) Organize ensemble-related scientific workshops and special sessions in the annual WRF workshop specifically targeted at ensemble studies and applications. Specifically, organize a WRF ensemble forecasting tutorial as part of the regular WRF tutorials beginning in 2007 (Josh Hacker, lead).

2) Promote the development of needed tools and their sharing through the WRF ensemble forecasting web page (David Stensrud, lead). Encourage ensemble forecasting working group members to collaborate on proposal submissions.

Longer-term goals:

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

4) Establish better contacts with members in the data assimilation, model physics, and verification working groups.

Other Section Contributors: Stan 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), David Stauffer (Penn State), Josh Hacker (NCAR), Fuqing Zhang (TAMU), Patrick Hayes (NGC), Nelson Seaman (NOAA), Rob Fovell (UCLA), Brent Shaw (WNI), Brian Colle (Stonybrook), and Xuguang Wang (NOAA), and the ensemble forecasting breakout group at June 2006 WRF Users Workshop.

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 is the modularization and interoperability of the physics packages so they could be easily exchanged between multiple cores, impediments remain in achieving this interoperability between the existing WRF cores.

Key areas where WRF physics enhancements are required:

The priorities and strategies for improving model physics was discussed by the physics breakout group (approximately thirty individuals) at the June 2006 WRF Users Workshop. The consensus of the group was that the highest priority areas (in order of priority) are the planetary boundary layer (PBL) and surface-layer parameterizations, microphysics, and radiation.

1) PBL and surface-layer parameterizations. There are serious deficiencies with all boundary layer parameterizations and land surface models, including poor characterization of boundary layer heights, an inability to represent stable boundary layers, and uncertain estimation of surface fluxes over the ocean under high wind conditions. In addition, significant biases are often noted for surface and 2-m temperatures (e.g., Mass et al, 2002). A major challenge is to determine the horizontal scales for which current PBL schemes are valid and the scales at which 3-D turbulent processes become important. New approaches may be required for improving PBL parameterizations, and stronger interactions with the European community would be beneficial.

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. Further-more, mesoscale models generally produce too much precipitation on the windward slopes, and higher resolution does not appear to ameliorate the problem. It is not clear whether bulk parameterizations can provide satisfactory microphysical simulations or whether higher moment schemes are a necessary next step. Other major issues include the interactions of microphysics and dynamics at scales of 1 km and less, the impact of aerosols on clouds and precipitation, and the formation of stratiform regions in mesoscale convective systems.

3) Radiation. Improved treatment of radiation processes in high-resolution NWP models will require a better understanding and treatment of partial cloudiness in a grid volume, 3-D cloud effects, and the consistency of cloud optical properties and microphysics.

Other important issues in enhancing WRF physics include:

4) Cumulus parameterization. It is still not clear at which resolutions cumulus parameterization is required and how the answer to this question varies with the size of nested domains. The interaction of the cumulus parameterization scheme on one nest and resolved convection on another is poorly understood.

5) Quantifying uncertainty of physical parameterizations. Because physical parameterizations may be the largest source of error in many simulations, accounting for and quantifying the uncertainty in such parameterizations is crucial to progress in high-resolution ensemble forecasting and data assimilation. Recently, there has been increasing interest in developing approaches to account for uncertainty in physics parameterization using stochastic parameterization techniques. Another suggested direction is using parameter estimation through data assimilation as a tool for estimating key parameters in physical parameterizations. This approach can potentially provide both systematic tuning of physical schemes and estimates of the uncertainty in each parameter, and thus in the overall parameterization. An alternative approach 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. However, it is unclear if any of these methods provide reliable estimates of the uncertainty in physical parameterizations if there are significant deficiencies in the physics formulations or errors in parts of the modeling system.

6) Suites of physics packages. It is clearly important that the physics options selected for each area of model physics (physics suites) collectively 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. Weather systems of most interest involve interactions among various parameterized processes, so that tuning of physical parameterizations as a suite is required even when the individual schemes have each been rigorously evaluated in isolation.

<u>Proposed action plan:</u>

Significant and sustained progress on model physical parameterizations will only be realized when sufficient personnel and observational resources are applied in a coordinated fashion. 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 validation of existing and developing physics schemes. 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 include 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 (perhaps in tandem with WRF user workshops), convening timely (perhaps once every two years) community workshops on their respective topics, and updating recommendations on major priorities for future work. In the physics breakout group, two specific groups were proposed and two volunteers agreed to chair them: a Boundary Layer and Surface Processes Group, chaired by Wayne Angevine, and a Microphysics Working Group, chaired by Greg Thompson.

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 interoperability is achieved. It must be recognized that all physics packages may not be adaptable to all dynamic cores and that certain combinations 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. 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: Participants of the model physics breakout group at the June 2006 WRF Users Workshop

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. Other high-resolution applications, such as atmospheric chemistry or dispersion problems through WRF/Chem, are also becoming increasingly important. Beyond numerical weather prediction, WRF will also be used to simulate specific flows of scientific interest. At present, numerical simulations for such problems are compared against observations only qualitatively. Robust data-assimilation systems for WRF allow 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.” Observation-based nudging, in which additional terms are included in the model to relax the solution toward observations locally in time and space, is the simplest approach and has long been used on the mesoscale (e.g. Stauffer and Seaman 1990). Estimation theory provides a more rigorous basis for data assimilation (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).

Key issues for data assimilation at meso- and smaller scales are the often sparse and limited in-situ observations, the changes in or absence of the mass-wind balances that pertain at larger scales and the likely larger errors in the forecast model associated with the more prominent role of numerous physical process such as microphysics, surface fluxes and turbulent mixing. Because of the limited in-situ observations, remotely sensed observations become crucial and data-assimilation algorithms for small scales must be capable of utilizing observations, such as radial velocity and reflectivity from Doppler radars, that have a complicated and indirect relation to the prognostic variables carried in the WRF model.

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 unified 3/4D-Var system, known as WRF-Var (http://www.mmm.ucar.edu/wrf/WG4/wrfvar/wrfvar.htm), is being developed for WRF; the 3D-Var capability has already been released to the community (Skamarock et al. 2005), whereas the 4D-Var is still under development. The WRF-Var system is operational in 3D-Var mode at AFWA and in Korea and Taiwan using forecast models other than WRF.

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 (http://www.image.ucar.edu/DAReS/DART/); and at Texas A&M.

Variational methods and the EnKF both offer the ability to assimilate any observation that can be related to the model's variables and to account rigorously for uncertainty in the observations and background forecast. The EnKF and 4D-Var 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 for the mesoscale.* Though both approaches have shown promise for high-resolution applications (Sun and Crook 1998, Dowell et al. 2004), neither variational approaches nor the EnKF are yet mature for small-scale flows, and a significant research effort will be required to realize their potential.

Priorities areas for WRF variational techniques are: a) background-covariance models that are less dependent on geostrophic or gradient-wind balance and are suitable for meso- and smaller-scale flows, b) adjoints for additional physical parameterizations beyond the simplified vertical diffusion scheme developed to date, and 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 priority is to improve techniques for ameliorating the effects of sampling error in ensemble estimates of the background covariances. Most EnKFs assume that state variables at a sufficient distance from an observation have no covariance with that observation, but this ignores the possibility that cross-variable covariances may be small even at zero separation or that decorrelation lengths may vary both spatially and temporally.

Since 4D-Var and the EnKF are computationally intensive, the development of scalable codes is crucial to high-resolution applications. Hybrid techniques that combine ensemble-based background covariances and traditional covariance models from variational algorithms (e.g. Wang et al. 2006) are also a promising avenue for further development.

2) Nudging capability for WRF. Numerous implementations of observation-based nudging exist for mesoscale models such as MM5. Adapting one or more of these to WRF is important to allow a baseline capability in mesoscale data assimilation.

3) Forward operators and observation-error estimates. Research is needed into the forward operators that map the WRF model variables onto observations for a variety of observations, the error characteristics of both the measurements and the forward models, and automated quality control. Particular emphasis should be given to 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. Preparations should also begin for assimilation of next-generation observations that are not yet routinely available, such as polarimetrically upgraded WSR-88D radars, GPS networks, new satellite-borne instruments and others.

4) Assessment of model error. Deficiencies in the WRF model itself, which of course lead to forecast errors, limit the effectiveness of any assimilation scheme. Model errors and bias 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 and systematic bias 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.

<u>Proposed Action Plan:</u>

1) *Evaluation of various assimilation algorithms.* While nudging, variational techniques and the EnKF have each shown some success in mesoscale applications, their relative performance and computational costs are still unclear as are their strengths and weaknesses in specific applications. The growth of a data assimilation community using WRF provides

the opportunity for more rapid progress by sharing results and information between groups using various assimilation techniques. The WRF DA working group should act as a forum for exchange of experience on different mesoscale assimilation approaches and should encourage direct comparison for specific test problems.

2) *Data-assimilation 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.

Other Section Contributors: Dale Barker (NCAR), members of WRF working group 10 and the WRF data-assimilation breakout group at June 2006 WRF Users Workshop.

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. To implement new verification techniques, it is also clear that a verification framework must be developed in which traditional verification measures and new techniques coexist, providing both familiar statistics and new measures. This will facilitate interpretation of model performance and more directly assess the advantages of new techniques.

Key areas for forecast-verification enhancement:

1) A community verification system. WRF currently lacks a community supported verification package that provides even standard verification tools. Numerous candidate packages exist and there are statistical packages that have enjoyed wide use in the verification community. Key activities are

- Decide upon and build a community verification software system. 3D-VAR is a leading candidate because it already computes forecast-observation pairs in observation space, and performs quality control of the observations. It is also a supported code system. Other packages include the NCEP and RTVS systems. Resources prohibit building a community verification system from scratch.
- Design the system to allow new capabilities and identify a procedure to include new methods into community system.
- Make use of existing statistical analysis packages to the extent possible.

2) 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. Several key efforts are required:

- 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 instance, for verification.
- 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.
- Incorporate forward operators to place data in observation space. Many of these have been constructed for 3D-Var in the research or operational communities.
- Collaborate with organizers of field campaigns to include the collection of observations specifically for verification of WRF.

3) 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. The following activities are needed:

- Compare existing object-based techniques to understand their relative behavior.
- 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.
- Adapt object-based methods to "sparse" observation networks such as surface observations.
- Investigate the application of statistical spatial modeling techniques (geostatistical models) for evaluation of model fields.
- Extend event-based techniques by considering both temporal and spatial dimensions, identifying time-coherent objects (evolving weather features, trajectories, etc.)
- Quantify uncertainty in verification metrics including that arising from observation errors. This is vital for traditional metrics as well. A large uncertainty arises from sampling errors in turbulent flows.
- Explore improved quantification of forecast value using event-based verification metrics.

4) New verification 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:

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

<u>Proposed Action Plan:</u>

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.

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), and the forecast verification breakout group at June 2006 WRF Users Workshop.

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. For example, 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).

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 processors expand. I/O will need to be parallel or simulations will become I/O bound. Ensemble simulations involving 10's to 100's of simulations will require workflow technologies (or a graduate student spending considerable time monitoring simulations). Kalman filtering requiring frequent communication among many simulations will depend on careful programming and minimizing serial operations. 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 cores 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 with the increase in overall processing speed. In addition, communication between nodes in a parallel system has significant impact on performance. The WRF software must evolve as necessary to maintain efficient execution on new systems as technology advances.

In addition to processor speed, core architecture, and memory bandwidth, I/O is important. Parallel I/O techniques are needed 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. 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 (http://www.geo-prose.com/projects/petascale_science.html, http://www.geo-prose.com/projects/petascale_tech.html). Indeed, the Office of Cyberinfrastructure intends to deploy a petascale computer in 2011. 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.

2) Development of Cyberenvironment[1]. 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,

[1] 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.

assimilating, 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. 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. It is important that analysis tools be made available for common dynamical analyses of model results, including data mining software for automatic feature detection and classification as well as for statistical and precursor exploration. Further, 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). These analyses should make use of interactive parallel computing strategies, even for large data sets. 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 address 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) Continually monitor the impact of architectural changes in the computer industry and modify the WRF software as needed to effectively use these new systems, some of which will have 100's of thousands of processors.

2) Provide tools for parallel I/O, analysis/data mining, and visualization for all users including those carrying out very large simulations or ensembles.

3) Involve the WRF community 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.

4) Publish the process for contributing code modules more visibly.

5) Improve ease of use, ease of development (e.g. a build reworking, registry generation de-hacking), and coupling with other models.

6) Establish a "do no harm" policy for WRF code changes and additions through review by WG2 and active contributors, through standardized testing, and holding developers meetings.

Other Section Contributors: Tom Henderson (NCAR), Todd Hutchinson (WSI), Chris Harrop (NOAA/GSD), Wei Huang (NCAR), Joe Klemp (NCAR), Gerardo Cisneros (SGI)

Appendix

The Community Process for Preparing this Strategic Plan

At its, June 2005 meeting, the Research Applications Board agreed to prepare a document outlining the priorities for WRF-system development to meet the future needs of the research community. The board identified a range of important topic areas, and each Board member took the lead in preparing the material for one of the topics. In developing the material for each section, the coordinators solicited input from WRF working-group members and other scientists as appropriate to gain a community perspective. A first draft was completed in December 2005, which was then substantially revised to produce a second draft in May 2006. In early June 2006 the draft strategic plan was posted on the web and a message was sent to WRF boards and working groups, the WRF user community, and the WRF Users Workshop participants, asking for further in input that could be included in finalizing the document. At the June 2006 WRF Users Workshop, presentation sessions were organized around the topics areas of the plan and breakout groups reviewed each section and provided further input. The final content was then prepared by each of the section coordinators, leading to a final version of the strategic plan in December 2006. The community contributors to each topic area of the plan are listed at the end of each section.

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