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MODEL DEVELOPMENT AND ENHANCEMENT PDT

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1. Introduction

For purposes of flight planning and routing, it is necessary to provide accurate and useful forecasts of aviation weather hazards. This requires a combination of improved model guidance and development of algorithms to convert from atmospheric “state variables” (temperature, winds, pressure, humidity, precipitation types) predicted directly from a Numerical Weather Prediction (NWP) model to “aviation impact variables” (turbulence, icing, convective storm development, cloud ceiling, and visibility). Except for a few products that can be generated from observations alone, the entire aviation weather enterprise depends upon analyses and forecasts that have resulted from the efforts of the Model Development and Enhancement (MD&E) Product Development Team (PDT) under FAA Aviation Weather Research Program (AWRP) support. These efforts have resulted in the generation, improvement, and maintenance of models running operationally at the NOAA National Centers for Environmental Prediction (NCEP).

The goals, organizational structure, and accomplishments of the MD&E PDT are presented in this paper. The four-stage process whereby research advancements are eventually implemented into operations at NCEP, and the efforts of the MD&E PDT to entrain the other PDTs into the design, testing, evaluation, and execution phases of new modeling developments are also discussed. A concise history of model development supported by the AWRP, including ensemble model forecasting, and plans for improving model capabilities, including the assimilation of WSR-88D data, are presented.

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2. Goals and Organization

The goal of the AWRP is to increase the scientific understanding of atmospheric conditions that cause weather hazardous to aviation. The research is aimed toward producing weather observations, warnings, and forecasts that are more accurate and more accessible. The goals of the MD&E PDT are to:

- Exploit available observations to improve the analysis of meteorological fields. This is a *data assimilation* problem.
- Define the detailed wind, temperature, and cloud features required to forecast turbulence, icing, convection, visibility and cloud ceilings. This is a *modeling* problem.
- Improve model internal representation of cloud processes, including convective storms. This is a *physics* problem.

In summary, these requirements dictate state-of-the-art data assimilation, numerics, and physics. Better aviation weather products require improvements to rapidly updated, high-resolution numerical weather prediction (NWP) systems. The two models running currently at NCEP under many years of AWRP support are 1) the Rapid Update Cycle (RUC) model, developed by the Forecast Systems Laboratory (FSL, now the Global Systems Division (GSD) of the NOAA Earth Systems Research Laboratory (ESRL), and 2) the North American Mesoscale (NAM) model, formerly known as the Eta model, developed by the Environmental Modeling Center (EMC) of NCEP. The NAM currently runs four times daily on a full North American continental domain at 12-km resolution, whereas the RUC runs hourly on a more limited domain at 13-km resolution.

The RUC model forms the backbone for aviation weather forecast guidance, as its ability to successfully use the latest observations in a 1-h update cycle results in accurate 1-h forecasts of meteorological variables both at the surface and aloft that are useful for flight planning. Also, its use of a hybrid isentropic-sigma coordinate system is well suited to the problems of forecasting clear-air turbulence in the upper troposphere, as well as the distribution of clouds and hydrometeors of importance to many of the other PDT groups. Specifically, the RUC is used in CONUS Current Icing Potential (CIP) and Forecast Icing Potential (FIP), whereas the NAM model is used in Alaska CIP and FIP (because the RUC domain does not extend that far north). RUC is used alone for the Graphical Turbulence Guidance (GTG) and National Convective Weather Forecast (NCWF) products. Weighted averages of the RUC and NAM forecasts are used in the CONUS National Ceiling and Visibility (NCV) forecast product, but neither model's analysis products are used, as the NCV analysis product is derived directly from METAR and satellite data.

The MD&E PDT consists of model developers at ESRL/GSD, NCEP/EMC, the National Center for Atmospheric Research (NCAR), and the Center for the Analysis and Prediction of Storms at the University of Oklahoma (OU/CAPS). The primary PDT points of contact for these institutions are Stan Benjamin (GSD), Geoff DiMego (EMC, who also acts as the Co-Lead of the PDT), Jordan Powers and Roy Rasmussen (NCAR), and Ming Xue (OU/CAPS).

Figure 1 illustrates how MD&E fits into the overall AWRP in terms of a matrix. The columns of the matrix describe the progression of aviation weather information from researchers (who discover it) through operational meteorologists (who use it in numerical prediction and for advisories, watches, and warnings) to the end users (who require it tailored in the form of specific products). The rows of the matrix represent the chronological use of weather information, first in the form of raw observations or analyses (diagnosis) and then as input for numerical forecasts (prediction). The arrows represent the direction of information flow. MD&E activities lie within the shaded region. Except for a few products that can be generated from observations alone, the entire aviation weather enterprise depends upon analyses and forecasts from computer models.

A rigorous four-stage process is followed by GSD and EMC to bring new modeling and data assimilation capabilities into operations at NCEP:

1. Chronologically, the first stage designated "*research quality*" reflects the point in the overall process when development efforts produce code that is stable and reflects the new capability or effects the desired changes. Efforts then switch from development to periodic case study testing and fine-tuning. It is at this time that the implementation process is invoked – i.e. a charter is written and submitted to NCEP Central Operations (NCO) and a schedule of subsequent events is laid out. Developers work with NCO throughout the remaining steps until the process culminates in implementation or, if results don't merit it, cancellation of the particular upgrade.

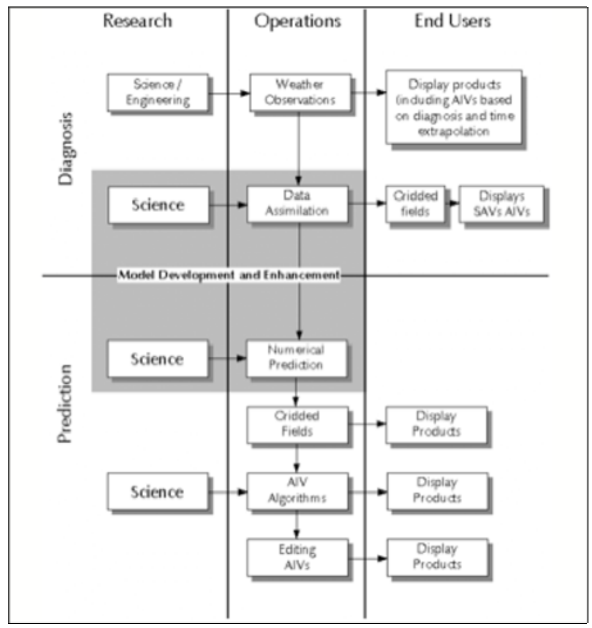

Fig. 1. The matrix relationship of the MD&E PDT to the overall AWRP (see text).

2. The second stage designated "*experimental*" reflects the point at which refinements performed during case study testing have produced a stable code whose results warrant that the level of testing is elevated to a parallel status. Parallel testing includes both retrospective testing and extensive case studies usually involving cycled data assimilation over extended periods of at least three weeks duration.

3. The third stage designated "*Pre-implementation*" indicates that the parallel testing has produced consistent results that are positive and stable enough to justify elevation of the code to pre-implementation status. This status normally involves real-time testing at the resolution targeted for implementation. This testing also involves

combination with other mature upgrades to both the prediction model and the assimilation system into a single package or bundle of changes that are tested together. This phase of testing is used to perform timing tests to assure the bundle/package will fit into the prescribed production time window at NCEP. It is during this stage that results are made available for customers to evaluate usually for roughly a 30-day period. This stage includes major preparation steps to prepare documentation of the changes included in the bundle, summaries of the objective (internal only) and subjective (internal and external) evaluations of the pre-implementation parallel runs, composition and distribution of advance notices, and briefings to the EMC, NCO, and NCEP Directors.

4. The fourth and final stage designated "*Operational*" signifies the culmination of the overall process with the new or upgraded codes being implemented into the NCEP operational production suite. The new system must beat the current operational system in at least some aspects of performance.

The other Product Development Teams in the AWRP are important participants in the design, testing, and evaluation of new modeling and data assimilation capabilities. During the design phase, which is prior to the first stage of the four-stage NCEP implementation process, the researchers at the various institutions work together to discuss the most viable and productive scientific approaches and to formulate the requirements. During the testing phase, the other PDT groups are provided access to the "experimental" model code and help in the evaluation of the parallel model runs (with and without the new changes), insofar as the new capabilities affect their PDT products (e.g., the Graphical Turbulence Guidance or the Forecast Icing Potential products). As the model development process progresses to the third stage, the expected behavior of the aviation impact variable algorithms is analyzed statistically in real-time and feedback is provided to the model developers about the impact of the new changes upon the algorithms' performances. Once the new model is implemented at NCEP, the PDT developers continue to oversee the performance of the new products and interact with the Aviation Weather Center and the Verification PDT to assure high quality is maintained.

3. Recent (4-year) history of MD&E activities and accomplishments

A brief summary of the major accomplishments made by the MD&E PDT since November 2001 is provided here. The emphasis in this summary is naturally on those technical developments that have found their way into operational implementation. However, basic research on model physics, numerics, and new methods for data assimilation has provided the necessary scientific foundation for these advances, and will continue to do so.

3.1. Accomplishments in FY02

Two important milestones were attained during FY 2002. First, on 27 November 2001, NCEP implemented a new, higher resolution version of the Eta NWP model, giving it 12-km horizontal resolution and 60 levels in the vertical, as compared to the former 22 km and 50 levels. This upgrade came with an improved "Three-Dimensional VARiational (3DVAR)" analysis, which allowed the use of microwave moisture channels (AMSU-B) from the NOAA15 and NOAA16 polar orbiting satellites.

Second, a major upgrade to the operational version of the Rapid Update Cycle (RUC) model was implemented at NCEP on 17 April 2002. With increased horizontal resolution (going from 40 km to 20 km) and more vertical levels (increased from 40 to 50), the new RUC provided improved prediction of clouds and precipitation, winds and temperature near the surface, and icing (Benjamin et al. 2004a, b). It is interesting to note that the very first version of the RUC model (implemented in 1994) had a 60-km grid spacing and used a 3-hourly data cycle, and that the next significant enhancement occurred in 1998, when the 3-h cycle was replaced with a 1-h cycle, the resolution was increased from 60 km to 40 km, and both cloud physics and land surface modeling components were added to the RUC. Thus, major improvements to the RUC model occurred every four years over the 1994 – 2002 time frame. The rate of improvements has accelerated since then.

3.2. Accomplishments in FY03

The operational RUC modeling system was enhanced on 27 May 2003 by the replacement of the former Optimum Interpolation (OI) analysis system with a full 3DVAR system (Devenyi and

Benjamin 2003). The 3DVAR avoids known problems with OI (truncation of the analysis increment from observations) and produced improved divergent wind analysis (important for the prediction of turbulence and convection). Perhaps most importantly, 3DVAR introduced the capability for future assimilation of radial winds from the WSR-88D radar and radiance data from satellite into the RUC.

The Eta model benefited on 8 July 2003 from the development of a better cycling of total condensate in the grid-scale cloud and precipitation schemes, along with improvements to its microphysics and cloud–radiation interactions. The Eta 3DVAR analysis began including direct analysis of WSR-88D radial velocity from NWS Multicast data. Radiance data from the NOAA-17 satellite started being used. The Eta Data Assimilation System (EDAS) now incorporated GOES cloud top pressures, which together with the use of Stage IV instead of Stage II hourly precipitation fields, resulted in demonstrable improvement in the forecasts of precipitation. Other improvements included the addition of a new precipitation type diagnostic to the Eta system, extension of the "off-time" (06/18Z) runs out to 84 hours, and hourly output on selected grids out to 36 hours.

During FY04, the NCEP Short Range Ensemble System (SREF) added 5 new Eta members using the Kain-Fritsch cumulus parameterization scheme to the 10 Eta and Spectral model members already being used. At the same time, the resolution of the SREF was increased from 48 to 32 km. Additional enhancements were made to the SREF output product stream upon request by the Aviation Weather Center and other NCEP centers. The SREF products are available at:
http://wwwt.emc.ncep.noaa.gov/mmb/SREF/SREF.html

3.3. Accomplishments in FY04

Most of the FSL effort in FY04 was focused on testing new capabilities for a 13-km version of the RUC that would become operational the following year. An improvement was made to the RUC system on 14 April 2004 with the implementation of a method whereby METAR surface data influences a much larger depth of the planetary boundary layer in the model. This reduced surface warm biases formerly seen in the RUC at night in the eastern U.S. and surface dry biases in the western U.S. Both biases have direct consequences for the prediction of cloud ceilings and visibility. Use of the PBL depth in the assimilation cycle resulted in better depiction of the potential for convection (CAPE) and surface fields.

Changes were made to the Eta/EDAS system on 16 March 2004, including use of daily gauge data as a bias adjustment for precipitation assimilation (soil moisture had been too dry), use of GOES-12 cloud top radiances instead of the cloud top product added just the year before to EDAS, and use of the Eta model microphysics predictions to influence the state of the Land Surface Model (LSM). In particular, the Eta LSM had previously diagnosed precipitation type based only on the air temperature in the lowest model layer, whereas in the new procedure, the fraction of frozen precipitation predicted by the grid-scale cloud and microphysics scheme was used. This improvement led to warmer surface temperatures in freezing rain events and cooler surface temperatures when snow is falling and the surface layer is above freezing.

3.4. Accomplishments in FY05

A number of significant enhancements were added to the operational RUC model system on 28 June 2005. These included the increase of resolution from 20 km to 13 km, and the assimilation of GPS precipitable water, METAR clouds, visibility, and surface mesonet data (resulting in greatly improved cloud and moisture analyses). Also, an improved cloud and precipitation physics scheme, developed by the NCAR team, was delivered to FSL, where it was fully tested, and then implemented at NCEP with the rest of the bundle of changes. NCAR's introduction of a temperature-dependent slope intercept function in the equation for the snow-size distribution resulted in lower water vapor depositional growth rates and enhancement of freezing drizzle, which has important consequences for the prediction of aircraft icing. The moisture control variable in the RUC 3DVAR was changed to "pseudo-RH". The final part of this bundle of changes was that the Grell-Devenyi cumulus parameterization scheme (an ensemble-based scheme that accounts for numerous possible combinations of closures and feedback assumptions) underwent significant modification.

This past year, NCEP implemented, for the first time ever, two very high-resolution (5-6 km) versions of the Weather Research and Forecasting Model (WRF) model, in the so-called High Resolution Window (HRW) domains at NCEP. These two WRF versions are known as the Advanced Research WRF (ARW) model developed by NCAR, and the Nonhydrostatic Mesoscale Model (NMM) developed by EMC. The fundamental differences between the ARW and NMM versions of WRF are outlined below:

ARW

- Terrain following sigma vertical coordinate
- Arakawa C-grid
- Two-way nesting, any ratio
- 3rd order Runge-Kutta time-split differencing
- Conserves mass, entropy and scalars using up to 6th order spatial differencing equation for fluxes (5th order upwind diff. is default)
- NCAR physics package
- Noah unified land-surface model

NMM

- Hybrid sigma to pressure vertical coordinate
- Arakawa E-grid, 3:1 nesting ratio
- Adams-Bashforth time differencing with time splitting
- Conserves kinetic energy, enstrophy and momentum using 2nd order differencing equation
- Separate set of equations for hydrostatic vs. non-hydrostatic terms
- Eta/NAM physics
- Noah unified land-surface model

The WRF program is a collaborative multi-agency partnership between NCEP, FSL, NCAR, and CAPS (all supported by the FAA AWRP), the Air Force Weather Agency (AFWA), and the Naval Research Laboratory. WRF was developed in part to account for smaller-scale "nonhydrostatic" phenomena (i.e., producing strong vertical accelerations) important to aviation weather, such as mountain waves (turbulence) and convection, which can only be approximated in the NAM and RUC models. Another strong motivation for the development of WRF was the directive from NCEP to consolidate the various models running operationally in order to improve efficiency and to accelerate the transfer of new NWP technology into operations. WRF provides research-to-operations benefits: it offers operational forecasting a model that is flexible and efficient computationally, with NWP advances contributed by the research community. The WRF modeling system incorporates advanced numerics and data assimilation techniques, multiple relocatable nesting capability, and improved physics, particularly for treatment of convection and mesoscale precipitation systems.

Over the course of the past couple of years, MD&E members have produced experimental WRF forecasts at sufficiently high resolution to predict the fine-scale nature of weather-related events without recourse to a convective parameterization scheme. A comparison of 12-h and 36-h forecasts produced by the WRF ARW model run at 22 km (which is the grid resolution used by the Eta model 5 years ago) and at 4-km grid resolution (which is nearly the resolution that the WRF-NMM model is being run today in the HRW domains at NCEP) is shown in Fig. 2. Not only can today's models reproduce the kinds of *detail* that are evident in radar reflectivity displays, but also the *structure* of convective systems (e.g., a leading convective squall line followed by extensive stratiform precipitation as seen in northern Texas). CAPS has led the MD&E effort to be able to assimilate Level-II Doppler radar data from multiple WSR-88D sites into their data assimilation system known as the ADAS, which has also been ported (including quality control) to the WRF 3DVAR system.

The MD&E effort to assimilate Level-II Doppler radar data from multiple WSR-88D sites into the WRF model has been led by CAPS, either through their own data assimilation system known as the ADAS (ARPS Data Assimilation System) or directly through the GSI (Grid-point Statistical Interpolation) system, which is the operational version of WRF 3DVAR. In the spring of 2004, CAPS produced real-time 4-km forecasts using WRF-ARW for the NOAA Storm Prediction Center spring program (Weiss et al. 2004), and initialized WRF with its ADAS analyses, which included all WSR-88D radars in the model domain and a complex cloud analysis procedure. CAPS also participated in the SPC spring 2005 program, by running WRF-ARW at 2-km resolution over the eastern 2/3 of the CONUS. Results were compared with those from the 4-km version of WRF-ARW run by NCAR and those from the WRF-NMM HRW domain run by NCEP at 4.5-km resolution (Kain et al. 2005).

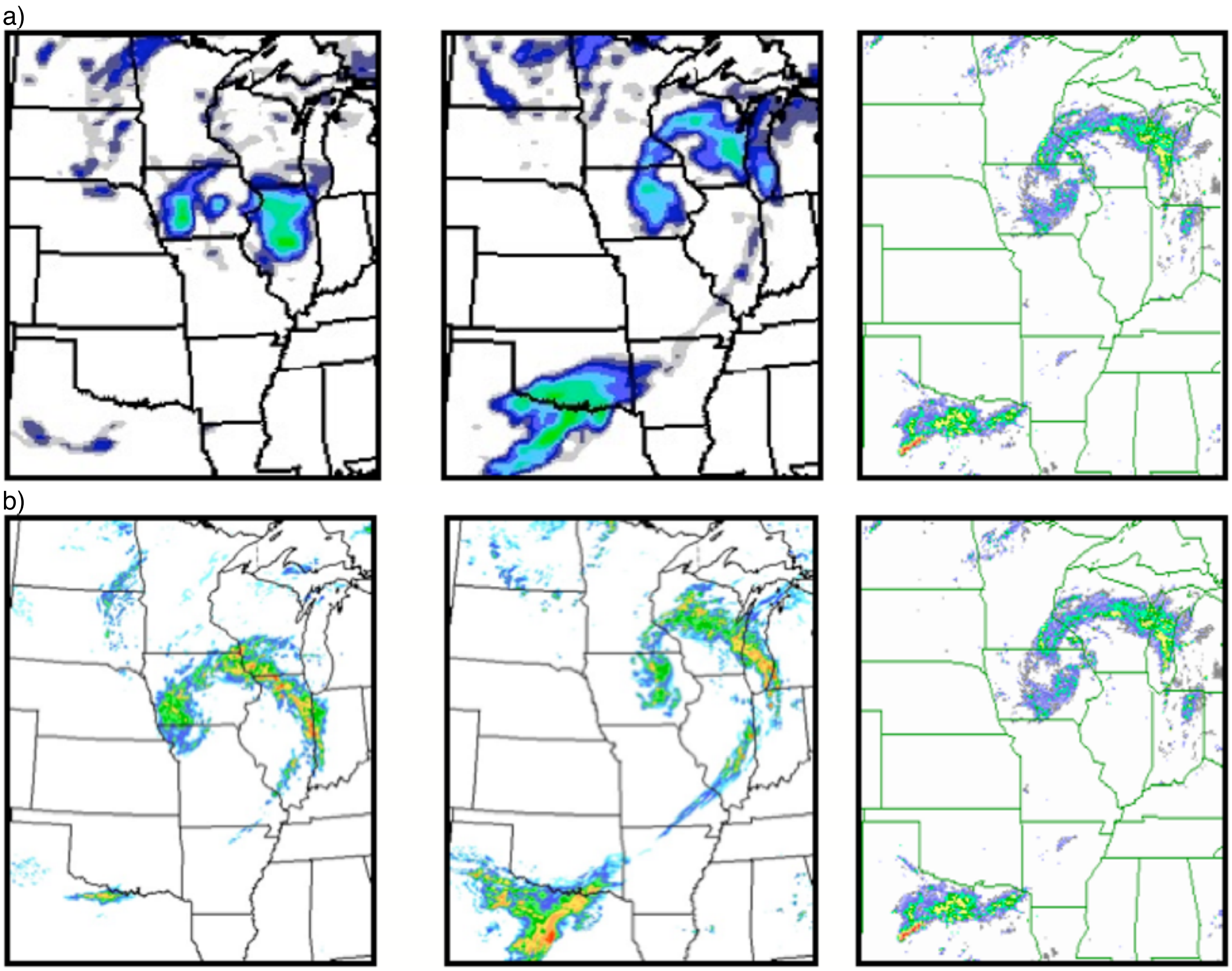

Fig. 2. Comparison of WRF-ARW model forecasts at varying resolutions: a) 22-km and b) 4-km grid resolutions. Left panels are 36-h forecasts, middle panels are 12-h forecasts, and right panels (identical) are the verifying composite radar reflectivity fields for 1200 UTC 8 June 2003.

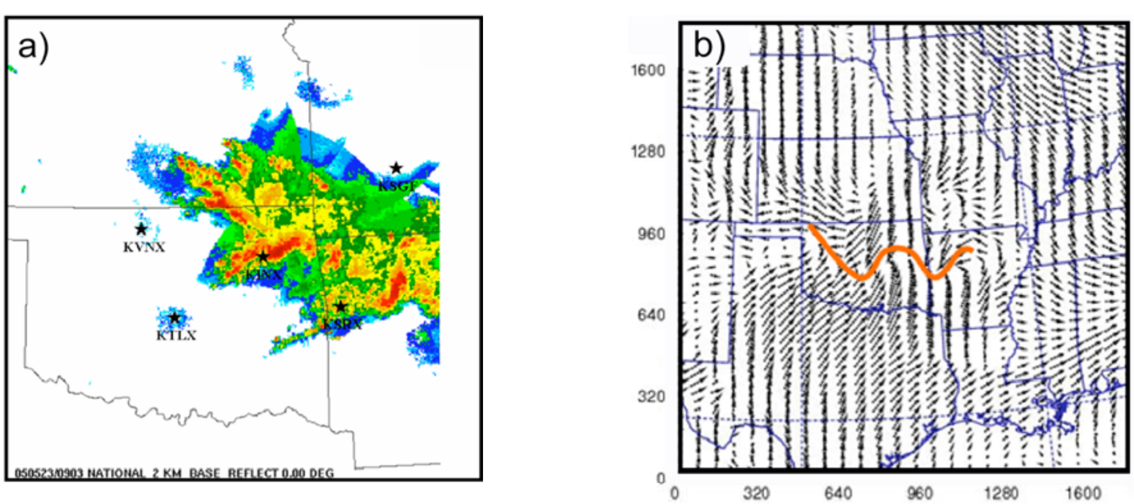

Fig. 3. (a) Mosaic radar reflectivity field at 0900 UTC on 23 May 2005 from the five WSR-88D radars indicated by stars, and (b) the GSI-analyzed vector wind field using a spatial background-error de-correlation length that is 1/4 of the standard NMC-method derived de-correlation length and a 0.05° resolution of super-obbed radial velocity. Analysis grid interval is 8 km.

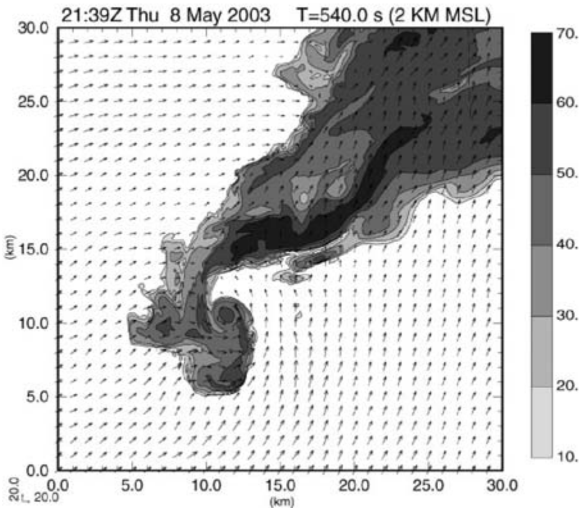

Fig. 4. Predicted reflectivity and wind fields at 2 km MSL 9 minutes into the 100 m forecast. Domain is 30 by 30 km2. A tornado is clearly indicated by the hook echo that contains reflectivity spirals into the circulation center.

In collaboration with NCEP, CAPS linked its Level-II data quality control and preprocessing packages with GSI and worked on testing and evaluating the impact of super-obbed radial velocity data on the analysis and prediction of WRF-NMM. An example from Liu et al. (2005) of a wind field analysis using five radars is shown in Fig. 3. The paper further discusses the impact of background error decorrelation lengths and the need for a multi-pass strategy for multi-scale analysis including radar data, as well as the impact of "superobbing" on the quality of analysis.

Based on a number of case studies by the CAPS group, a combined 3DVAR-cloud analysis has been shown to be efficient and effective for initializing convective storms. Rapid update cycles at 5–15 minutes intervals are typically used to achieve best results (Hu et al. 2005a,b). Recently, CAPS produced a short-range forecast at 100-m resolution, by interpolating a 1-km analysis obtained using the 3DVAR-cloud analysis procedure and obtained a tornado in the forecast that reaches F2 intensification (Fig. 4). We believe this is the first time that a tornado has been predicted by a numerical model initialized using real data (including radar) in the WRF 3DVAR system.

The NCAR and FSL teams have worked for several years under FAA sponsorship on the problem of optimizing microphysical schemes to predict freezing drizzle (Thompson et al. 2004). A complete description of the microphysical processes would require a prohibitive number of variables for forecast models to represent the water and ice particle spectra. Simplified parameterization of the microphysical processes is required. The work at NCAR in FY04 and FY05 culminated in the development of a hierarchy of improved microphysical parameterization schemes, including: a detailed bin model, a two-moment snow parameterization, single-moment snow parameterizations, and both single and two-moment cloud and drizzle parameterizations.

4. Plans for the future

Two different variants of the WRF model will be implemented at NCEP in the next couple of years to replace the RUC and Eta/NAM models. The NAM-WRF model scheduled for implementation in March 2006 will include an experimental diabatic initialization technique. The WRF-Rapid Refresh (WRF-RR) model is currently slated to replace the RUC model by mid-2008. In addition to replacing the RUC and Eta models, WRF models are also scheduled to replace two other atmospheric regional models running at EMC: the Short Range Ensemble Forecast (SREF) and the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane model. As more variants of the WRF model become tested and implemented at NCEP, probabilistic numerical weather prediction at increasingly higher resolution is quickly becoming a practical reality, allowing for measures of uncertainty to be attached to aviation weather forecasts.

There is always a trade-off between domain size and grid resolution for a fixed availability of computer resources. The RUC-13 model is near the grid resolution cutoff point (~10 km) below which the hydrostatic assumption used in the RUC becomes invalid. Future rapid refresh development will occur with the WRF nonhydrostatic modeling system. Tentative WRF-RR plans are to increase the duration of the 12-h forecasts made every third hour of the forecast cycle to 24h and to enlarge the domain to include Alaska, Puerto Rico, Canada, and Caribbean region (Fig. 6). The much larger oceanic territory being proposed for the WRF-RR model is an important argument for using satellite radiance data, and thus, the NCEP Grid-point Statistical Interpolation (GSI) 3DVAR scheme, since the GSI offers the capability of assimilating satellite radiances from both geostationary and polar-orbiting platforms, and is the 3DVAR system that has been chosen by NCEP for all future WRF-based systems.

A second key decision point for the WRF-RR application is the choice for the model dynamic core: both the ARW and NMM versions of WRF are presently being examined in this regard. Tests of the ARW version of WRF have been performed by FSL since February 2003. These tests have used RUC initial conditions, including the hydrometeor fields, to produce experimental twice-daily 48-h forecasts from this "WRF-RUC" system, at both 20 km and 13 km (the latter only since June 2004). Tests using the WRF-NMM are just about ready to be initiated at the time of this writing (November 2005). The results of these tests will determine which of the two WRF dynamic cores will form the basis for the WRF-Rapid Refresh model, to replace the current RUC. Note that the hybrid isentropic-sigma coordinate system that has provided the framework of the RUC model since its inception will not act as the framework for the WRF-RR model, but rather, one of the two "mass coordinate" systems underlying either the NMM or ARW will act in that capacity.

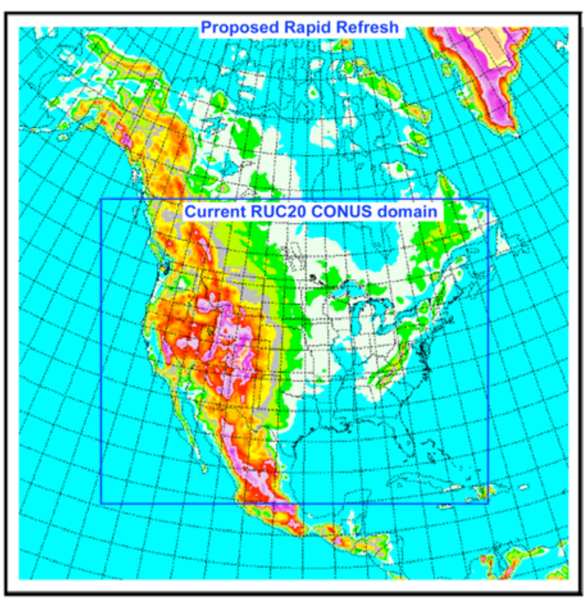

Fig. 6. Proposed domain for the WRF-Rapid Refresh model, compared to the current RUC model CONUS domain. Topographic contours are shown with color shading.

The use of Level II WSR-88D radar data (radial winds initially) in the GSI will be a focused activity for both the WRF-NAM and the WRF-RR over the next few years. Methods for using this data for the purposes of diabatic initialization of the WRF model such that the cloud and thermodynamic fields are consistent with the wind fields will be explored by all members of the MD&E PDT over the next five years.

NCAR will continue to improve and evaluate the microphysical schemes in WRF for operational icing and drizzle forecasts. Cloud condensation and ice nuclei concentration will be added to the WRF model and tested with AIRS II and IMPROVE data. In a more general sense, NCAR is experimenting with development of a hierarchy of microphysical parameterizations with varying degrees of sophistication (e.g., one-moment vs. two-moment schemes, and gamma distributions vs. other kinds of hydrometeor size distributions), so as to select the parameterizations with the minimum necessary parameters to capture the phenomenon of interest (freezing drizzle, snow, etc.). These improvements to the microphysics will benefit many of the other PDT products:

- In-flight icing: Improved diagnosis and forecast of supercooled liquid water and freezing drizzle.
- Terminal and National Ceiling and Visibility: Improved depiction and diagnosis of ceiling and visibility through improved depiction of the size distribution and type of particles.
- Winter Weather Research: Improved forecasts of precipitation type and snow rate.
- Convective Weather: Improved production of gust front-producing downdrafts using an appropriate estimate of evaporation and melting of rain and snow, which in turn depends on the size distribution of the rain and snow particles.
- Turbulence: Low level wind shear and turbulence associated with gust fronts also heavily depends on the evaporation and melting of rain and snow particles.

NCAR and OU/CAPS will continue to work on convection-resolving applications with real-data simulation capabilities. The goal is to enable forecasts or simulations at high resolution to understand the fine-scale dynamics of weather-related events at convective and airport/aircraft scales. Extensions to existing verification techniques *appropriate* to validation of high-resolution numerical forecasts will be developed and merged with the NCEP verification package. These new techniques will include object-oriented verification of precipitation areas as well as techniques to isolate diurnal and propagating elements of rainfall.

The focus of the efforts at CAPS will continue to be the assimilation of Level-II radar data into the WRF 3DVAR and also the GSI. CAPS will continue performing very high-resolution model prediction studies. One goal is to evaluate the impact of radial velocity and reflectivity data assimilation on grids of approximately 2-km resolution. Other work includes advanced data assimilation techniques, such as the Ensemble Kalman Filter (EnKF) for the WRF model using Level-II WSR-88D radar data, and increasingly in future years, WRF 4DVAR technique development to improve the use of cloud, precipitation, turbulence, and icing observations in WRF model initialization. Relative accuracies and tradeoffs of 3DVAR, EnKF and 4DVAR methods will also be studied systematically.

8. Conclusions

The continued improvements in model physics, numerical techniques and model resolution, data assimilation techniques, as well as the addition of new observations in such schemes, all contribute to improvements in aviation products. Improved NWP products are the backbone for improvements in aviation products. The MDE PDT has benefited from increasingly strong collaborations with other AWRP PDTs including those for icing, turbulence, convection, and ceiling/visibility forecasts.

9. References

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Thompson, G., R. M. Rasmussen and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev.*, **132**, 519-542.

Weiss, S. J., J. S. Kain, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2004: Examination of several different versions of the WRF model for the prediction of severe convective weather: The SPC/NSSL spring program 2004. *22nd Conf. Severe Local Storms*, Amer. Meteor. Soc.

Refereed publications or manuscripts by the FSL group, related to the development of the RUC and WRF-Rapid Refresh models, under the full or partial support of FAA Aviation Weather Research Program, which are directly relevant to AWRP are listed below. Most of the papers are available at http://ruc.noaa.gov/RUC.pubs.html:

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