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An Operational Mesoscale Ensemble-Based Forecast System Using HPC Resources

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Abstract

The US Army Test and Evaluation Command (ATEC) currently is responsible for providing operational meteorological support to research, development, test, and evaluation (RDT&E) activities at eight Army installations. The Four-Dimensional Weather (4DWX) meteorological support system used to provide that support was developed by the National Center for Atmospheric Research (NCAR) in collaboration with ATEC meteorologists. A high-resolution (mesoscale) numerical weather prediction (NWP) model is a major 4DWX component in operational use at seven ATEC test centers. This paper describes current 4DWX NWP capabilities and discusses how the new Department of Defense (DoD) Dedicated High Performance Computing Project Investment (DHPI) at Dugway Proving Ground (DPG) will enhance NWP forecast support to ATEC field and virtual tests.

1. Current 4DWX NWP Capabilities

1.1. The 4DWX Modeling System

The 4DWX system provides information about meteorological processes in both the three space dimensions and time. The 4DWX NWP modeling system has two closely related components: one assimilates meteorological data and the other produces the forecasts. Both components are based on the same meteorological model—the Pennsylvania State University (PSU)/NCAR mesoscale model version 5 (MM5, Grell, et al., 1995), although the transition to the next-generation community Weather Research and Forecast (WRF) model is underway. The 4DWX real-time four-dimensional data assimilation (RT-FDDA) engine ingests meteorological data as they become available, producing model-assimilated data sets that both define the current

conditions of the atmosphere and serve as initial conditions for the model forecasts. The other 4DWX NWP component produces forecasts of up to 48-h duration, with the forecast length depending on the specific need and the computer resources available.

Data assimilation is done by Newtonian relaxation, which involves adding nudging terms to the model predictive equations. These terms force the model solution at each grid point to observations in proportion to the difference between the model solution and the observations. This approach was chosen because it is robust, relatively efficient computationally, allows the model to ingest data continuously rather than intermittently, and the full model dynamics are part of the assimilation system, which means that analyses contain all locally-forced small-scale features. Additionally, the nudging methodology does not unduly complicate the structure of the model code.

1.2. Example Applications of the 4DWX Modeling System

Examples are provided below of the use of the current 4DWX NWP system for various applications that require HPC resources. The first compares warm-season rainfall predictions by the White Sands Missile Range (WSMR) 4DWX system with (1) observations, and (2) forecasts by coarser-resolution operational models of the National Weather Service (NWS). The second example is application of the 4DWX-system to define the fine-scale climate over regions where observations are not available because of small data voids between observations or data denial over large areas of the world.

1.2.1. Warm-Season Rainfall in the Southwest US

Precipitation can have important impacts on test and other operations at any of the ATEC ranges. The White

Sands Missile Range (WSMR) 4DWX forecast system was chosen for evaluation of the performance of the 4DWX system in predicting precipitation because of the prevalence of summertime convection from the North American monsoon, the importance of predicting the lightning hazards associated with this convection, and the proximity of the WSR-88D Doppler weather radar at Holloman Air Force Base for use in the evaluation. Additionally, the fact that the precipitation is related to the combined effects of the large-scale North American monsoon and modulation by the local orography provided an opportunity to evaluate the model's ability to correctly render both large-scale and small-scale processes.

We compared the WSMR 4DWX precipitation forecasts for August 2005 with those by the NWS's North American Model (NAM) and Rapid Update Cycle (RUC) model. The WSMR 4DWX model has three nested computational grids, and the one that we used for model evaluation was the middle one, which has a 10-km horizontal grid increment. This resolution is similar to those of the NAM and RUC, which have horizontal grid increments of 12 and 13 km, respectively. Evaluation of convective precipitation forecasts is well known to be especially problematic because it is difficult to measure the large spatial variations in convective precipitation. We compared the precipitation forecasts with the National Centers for Environmental Prediction (NCEP) Stage-IV analyses, which are constructed by compositing WSR-88D radar and rain gauge estimates. Only a subjective evaluation is reported on here. The Stage-IV analyses in the Southwest US tend to underestimate the actual precipitation amounts because the higher terrain blocks the radar beam and there is a paucity of rain gauges in some areas. The forecasts were evaluated for the entire month of August 2005, a period during which the North American monsoon was active in the Southwest US. With eight 4DWX forecast cycles per day, the evaluation was based on over 200 forecasts, most of which had some rainfall.

Figure 1a shows the observed (Stage-IV analysis) monthly mean precipitation accumulation for the 3-h period from 2100–0000 UTC (1400–1700 Local Time [LT]). The higher precipitation amounts generally are restricted to areas of terrain elevation greater than 2,000 m above mean sea level (MSL), the “altitude oases” that are well known in arid areas. For example, the north-south-oriented area of higher precipitation in eastern New Mexico is related to the Sacramento Mountains, while the northwest-southeast-oriented feature in eastern Arizona and western New Mexico coincides with the Mogollon Plateau in Arizona and its extension into New Mexico. For this 3-h time period, there was at least some moist convection over this area on 26 days of the month. Figures 1b–d show the monthly mean precipitation forecasted for this 3-h period by the NAM, RUC, and

WSMR 4DWX models. All three models capture the observed dryness in the southwest part of the area and the observed north-south oriented strip of dryness in the Rio Grande Valley in west-central New Mexico. Recalling that the observational data are expected to under-estimate precipitation, the WSMR 4DWX forecasts appear to better capture the correct spatial scales and amplitudes of the rainfall over most of the area.

1.2.2. Regional-Climature Downscaling

The 4DWX NWP model also can be used to provide high-resolution depictions of regional climates. Estimates of the fine-scale climate of a region can be useful for long range ATEC test planning, especially in data sparse regions. As one test of this capability, we considered the eastern Mediterranean and the adjacent countries of the Middle East, where the Mediterranean Sea is a large data void. Our objective was to use satellite estimates of rainfall to confirm that the model was reasonably replicating the small-scale aspects of the precipitation climate. We choose precipitation for this test because it is sensitive to many other variables and is an excellent single indicator that most other physical variables are being simulated correctly.

We ran the 4DWX NWP model in the analysis mode for six Januaries (2001 through 2006) using global analyses archived by the NCAR-NCEP Reanalysis Project for lateral-boundary conditions. Surface and upper-air observations were assimilated on the model grids to provide the best possible model climatology of the region. The left panel of Figure 2 shows the average January precipitation amount predicted by the 4DWX model simulations. Significant precipitation maxima over land are seen along the coastlines of the Levant, Turkey, and Greece. There also is significant precipitation over the Mediterranean to the south of Greece. The precipitation gradient is very large along the North African coastline. The gradient is somewhat less along the Levant and Turkey coasts, but it is still large. The satellite precipitation estimates in the right panel of Figure 2 are consistent with the model estimates, showing the greatest amounts along the coasts of the Levant, Turkey, and Greece, with large coastal gradients. However, the model predicted less precipitation over the central and southern Mediterranean than was derived from satellite imagery.

The model-defined fine-scale climate of the weather variables also can be used as input to coupled models to produce specialized climatologies. For example, Figure 3 illustrates the use of fine-scale climatology to assess the consequences of the release of hazardous material from a location in East Asia during the month of May. The model analysis for each day in the period of record included boundary layer winds and stability (heat fluxes). We used a DoD transport and diffusion model (Sykes, et

al., 2007) to calculate dosage (time-integrated concentration) resulting from the hypothetical release of hazardous material at a particular location. We then aggregated this ensemble of plumes into an analysis of the probability of the surface dosage exceeding a specified threshold. As shown in Figure 3, there are preferred transport corridors to the northeast and southeast of the hypothetical source. Higher-resolution plume displays illustrate fine scale orographic and coastal influences on the winds, which could only be defined with a model such as the ATEC 4DWX system.

2. Ensemble Prediction

All weather predictions are subject to uncertainty arising from imperfections in both the initial conditions for a forecast and in the model that propagates those initial conditions into the future. Initial condition (IC) uncertainty is inevitable because the discrete nature of atmospheric observations and the uncertainties in those observations prevent a perfect estimate of the state of the atmosphere at any time. Model uncertainty is equally unavoidable because the system of equations that describes atmospheric evolution requires numerical and physical approximations. The objective of the DPG DHPI is to enhance 4DWX NWP capabilities by developing an operational mesoscale (ensemble-based) probabilistic forecast system to quantify the uncertainty in 4DWX forecasts for major ATEC field tests wherever they occur.

The 4DWX probabilistic forecast approach is to replace a single NWP run with an ensemble of model runs, with the initial conditions and model physics of the ensemble members varied to bound the range of uncertainty. Major challenges include sampling error resulting from an inability to account for the number of degrees of freedom in the atmosphere, and also fundamental deficiencies in models that limit the representation of uncertainty in the prediction process. The 4DWX ensemble forecast is an attempt to account for uncertainties in both initial conditions and model physics parameterizations, and to ensure that the probabilistic forecasts adhere to the probability distribution of observations.

Initial-condition uncertainty is best handled with methods that consider both observational uncertainty and uncertainty in the forecast process. Currently, the best available methods are of a class of linear Monte-Carlo filters related to the Kalman filter. The ensemble transform Kalman filter (ETKF; e.g., Wang and Bishop, 2003), which is attractive because an ensemble of initial conditions can be obtained efficiently, is a Monte-Carlo sample of the spatially covarying distribution of error in the best estimate of initial conditions. Although it is an

approximation to the optimal linear Kalman filter, the dynamics of the model allow nonlinear temporal propagation of the uncertainty from one forecast cycle to the next. Because a computationally feasible ensemble cannot represent all of the degrees of freedom in a mesoscale prediction, sampling error can accumulate in any ensemble filter that runs over several forecast cycles. The new DoD high performance computing (HPC) platform being employed for this work enables development of an ETKF system with more ensemble members than are typically used, which should help to mitigate the sampling error problem.

Model physics uncertainty can be handled by including a distribution of models in an ensemble, where the distribution is populated by switching model options for subgrid scale physical parameterizations or by adding entirely different modeling systems. The implicit assumption is that, for any given forecast scenario, we cannot know *a priori* which model will perform the best according to a given metric, and that all of them are equally probable. While this assumption is not necessarily valid, the multi-model approach has proved to add potential value to a probabilistic forecast. Combined with the ETKF, the multi-model approach augments the initial-condition uncertainty with model uncertainty. The new HPC allows a large number of model configurations to be run operationally, and techniques such as self-organizing maps are being adopted to objectively remove model configurations that systematically perform poorly.

Finally, a large ensemble of model runs still cannot produce a probabilistic forecast that exactly matches atmospheric probabilities. Consequently, post-processing calibration is needed to provide a prediction with probabilities that agree with observed probabilities of weather events. Basic statistical techniques such as quantile regression show great promise in calibration, but huge samples of forecasts are needed. Accumulation of massive datasets of daily ensemble forecasts for a long record (a year or more) is necessary to tune the probabilistic forecasts. Daily minimum and maximum surface temperatures, which can be important for personnel safety and equipment performance at ATEC test ranges, are the first forecast parameters that will be subject to calibration in the 4DWX system.

The initial 4DWX ensemble forecast implementation consists of 55 members on the three computational domains (30, 10, and 3.3 km horizontal grid spacing) with a cycling ETKF and multiple models. Forecasts are launched from ETKF analyses every 6-h, and provide 24-h or greater forecasts for users. Lateral boundary conditions are obtained from the same sources as the deterministic (single) 4DWX NWP model runs. Probabilistic evaluation is ongoing, and calibration of daily minimum and maximum temperature forecast distributions with logistic regression is beginning.

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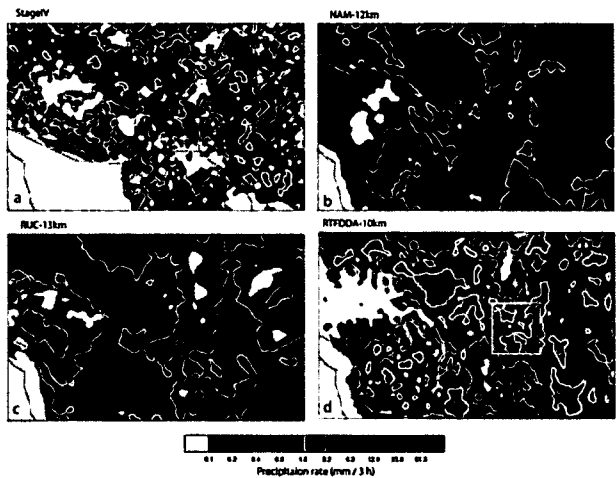


Figure 1. For August 2005, the monthly mean precipitation accumulation for the 3-h period from 2100–0000 UTC (1400–1700 LT) based on (a) the NCEP Stage-IV analysis, (b) the NAM model (12km grid increment), (c) the RUC model (13-km grid increment) and (d) the WSMR 4DWX model (10-km grid increment)

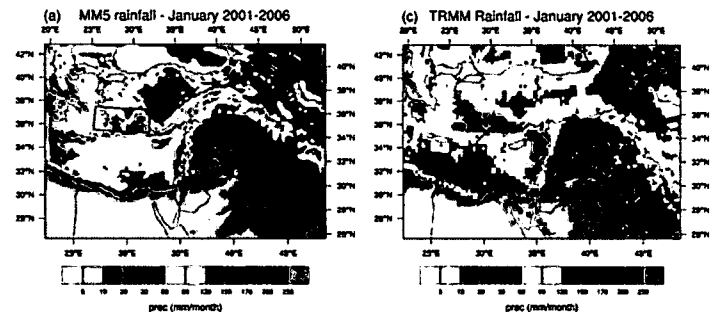


Figure 2. January precipitation for 2001–2006 based on 4DWX-model simulations (left) and data from the merged Tropical Rainfall Measurement Mission (TRMM) satellite and rain gauges (right)

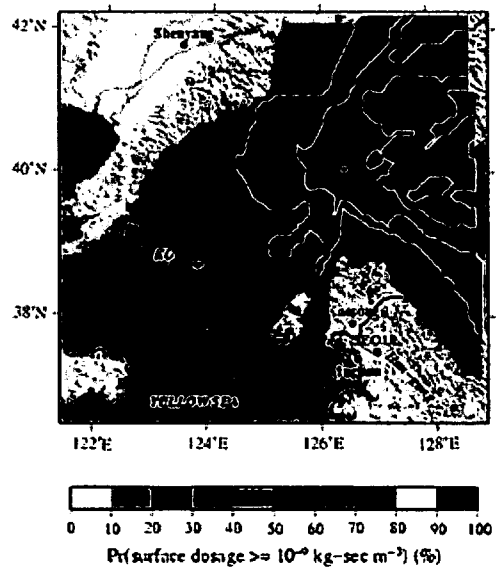


Figure 3. The gray shades indicate the probability (%) that the dosage from a release of hazardous material at 0700 local time in May in Korea will exceed a particular threshold