16A.1 **E-4DWX: An Operational Mesoscale Ensemble Modeling System**

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1. INTRODUCTION

This paper describes an operational mesoscale ensemble weather forecasting system used at the Dugway Proving Ground (DPG) to support testing operations, and uses a case study to show the operational benefit provided by the ensemble compared with a traditional deterministic forecast. The ensemble is based on the Four-Dimensional Weather (4DWX) system developed by the National Center for Atmospheric Research (NCAR) and the U.S. Army Test and Evaluation Command (ATEC) Meteorology Program. 4DWX uses the WRF and MM5 mesoscale weather models coupled with a robust data assimilation process, resulting in a system known as Real-Time Four Dimensional Data Assimilation (RT-FDDA). A system known as E-4DWX, consisting of a 30-member ensemble of WRF and MM5, is run four times each day over the DPG area, using a computer system provided by the High-Performance Computing Modernization Office. This paper shows how E-4DWX can provide better operational forecast guidance for DPG test operations than any single forecast could do.

2. WEATHER REQUIREMENTS FOR DPG TESTING MISSION

The primary mission of DPG is to conduct testing to support development of chemical and biological systems such as detectors and protective equipment. Many tests require accurate calculation of the dispersion of a simulant of a chemical or biological agent released in the open air, and such detailed dispersion calculations require very accurate weather predictions. In addition, many tests require specific weather conditions to be present, for example, a particular temperature range or wind speed, and these considerations add to the requirement for accurate weather predictions.

A typical outdoor test scenario for a hypothetical detector illustrates the utility of E-4DWX to support testing at DPG. This test is designed to challenge a detector to measure the concentration of a simulant with properties similar to a biological agent. In this scenario, the test is conducted at a DPG location known as the Horizontal Grid. Table 1 is a list of desired environmental conditions during a typical dissemination, and Table 2 lists weather safety thresholds that cannot be exceeded during the testing period. A weather and dispersion forecast is provided 6 to 12 hours before testing, and test officers may make go/no go decisions based on that forecast. Small forecast errors (e.g., 10° wind direction errors or 2 ms^{-1} wind speed errors) can result in test delays or cancellation, which are expensive in both money and time and which prevent mission accomplishment. Understanding the amount of uncertainty in forecast model predictions can assist the forecaster in determining the likelihood of desired conditions occurring during a test period. The forecaster communicates the probability of desired conditions to the test officer, providing assistance in scheduling and execution decisions.

Desired Atmospheric Conditions	
Parameter	**Values**
Wind Direction	130-190° or 310 – 10°
Wind Speed	2-8 ms^{-1}
Temperature	5°C
Precipitation	<1mm hr^{-1}
Inversion	Mixed Layer 0-100 m
Visibility	>16 km

Table 1. List of desired atmospheric conditions for proper testing.

Safety Thresholds	
Parameter	**Value**
Lightning	Within 15 km of test grid
Wind Gusts	15 ms^{-1}
Snowfall	>Trace

Table 2. List of safety thresholds during testing.

3. FORECASTING CHALLENGE AT DPG

Weather forecasting at DPG requires consideration of the local terrain and surface conditions.

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DPG is located at the southern end of the Great Salt Lake Desert, about 75 miles southwest of Salt Lake City, Utah (see Figure1.) DPG is located primarily on the lake bed of the ancient Bonneville Lake, and most of the test grids lie in this region, which now includes the Great Salt Lake Desert. Narrow mountain ranges rise up to 1000 meters above the ancient lake bed. Test locations near the base of these mountain ranges experience gap winds and upslope or downslope winds driven by diurnal temperature changes.

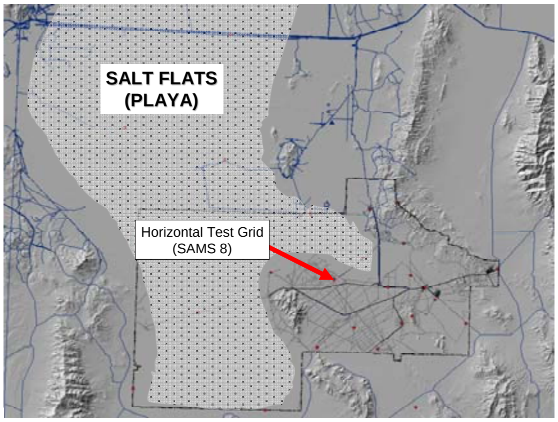

Figure 1. This map shows the topography around DPG along with the Salt Flat area as a dotted gray shading. DPG boundaries are a dot-dash line. The Surface Automated Measuring System (SAMS) 8 is a local mesonet weather station at Horizontal Test Grid.

Land surface characteristics include contrasting areas of salt flats and surrounding basalt soil. The salt flats have high albedo due to a thin layer of salt that appears white at the surface. These areas also retain more moisture than the surrounding soil. For these reasons, the local air temperature varies more slowly through the day. Also, the surface roughness is low because the salt flats are devoid of any vegetation. The basalt soil is drier and darker, causing more rapid temperature changes, and is rougher, with various shrubs up to one meter in height over most of these areas. These contrasts can drive a “salt breeze” with characteristics similar to a sea breeze. In particular, it is common in winter to see cold northerly flow over the salt flats to the north, with warm southerly flow over the surrounding basalt area, creating a convergence feature known locally as a salt front.

Another common wind feature is nocturnal drainage flow over the central part of DPG, which occurs frequently under high-pressure weather patterns. As the land cools at night, a strong stable boundary layer develops, and steady drainage winds driven by a gradual elevation difference consistently occur.

Synoptic scale forcing, summertime thunder-storms, and clouds can disrupt all these flow patterns (mountain breezes, the salt breeze, and the nocturnal drainage flow), presenting a complex forecasting challenge well suited to ensemble forecasting. At the local scale, advanced mesoscale numerical weather models account for most of these effects. However, various models are configured to represent physical processes differently, and there are resulting differences in predictions. No single forecast configuration has been shown to out-perform the others consistently. At larger scales, where the mesoscale model is driven by larger-scale models, different input weather patterns can cause quite different mesoscale predictions. No available larger-scale model provides consistently superior predictions. Therefore, it is not desirable to select a single model configuration *a priori*.

4. E-4DWX

The E-4DWX modeling system includes both the WRF and MM5 mesoscale models, the RT-FDDA data assimilation system, the High-Resolution Land Data Assimilation System (HRLDAS), and other system components developed at NCAR. E-4DWX runs on three computational domains (30, 10, and 3.3 km horizontal grid spacing). (DPG also generates traditional deterministic forecasts, with an additional inner domain at 1.1 km horizontal grid spacing.) All the nested model domains use the same vertical grid structure, with 37 vertical levels. Forecasts are produced every 6 h (00, 06, 12, 18 UTC), and have a forecast period of 30 h. There are 30 ensemble members; the set includes 15 WRF and 15 MM5 members, with lateral boundary conditions initialized by the North American Model (NAM) or the Global Forecast System (GFS), various physics parameterization, and two control members of WRF and MM5 for reference. After completion of the 30 model runs, post processing of the data generates a suite of probabilistic forecast products for the forecast period. These products can be viewed through the local 4DWX website, which is publicly accessible at https://dpg-ingest.dpg.army.mil

5. E-4DWX Example Products

Actual E-4DWX forecasts on 14-15 April 2009, focusing on the testing period around 06 UTC or local midnight, show the benefit of an ensemble approach. Forecasts from 24 or 36 hr before the testing period indicated a cold front would pass the range, but the timing of the frontal passage was in question. The cold front’s impact on testing would be significant because wind direction, wind speed, and temperatures would be quite different if the front had passed; and if the front was passing during the test period, high winds, lightning, and precipitation could create hazardous conditions.

Figure 2 shows the location of the cold front at 06 UTC on 15 April 2009, predicted by two selected 18 h forecasts from the E-4DWX runs initialized at 12 UTC on 14 April 2009. The WRF prediction shows the cold front on the west side of DPG. The forecast conditions would be an optimal testing environment. The MM5 prediction shows the cold front already passed to the south and east of the test location, with unfavorable

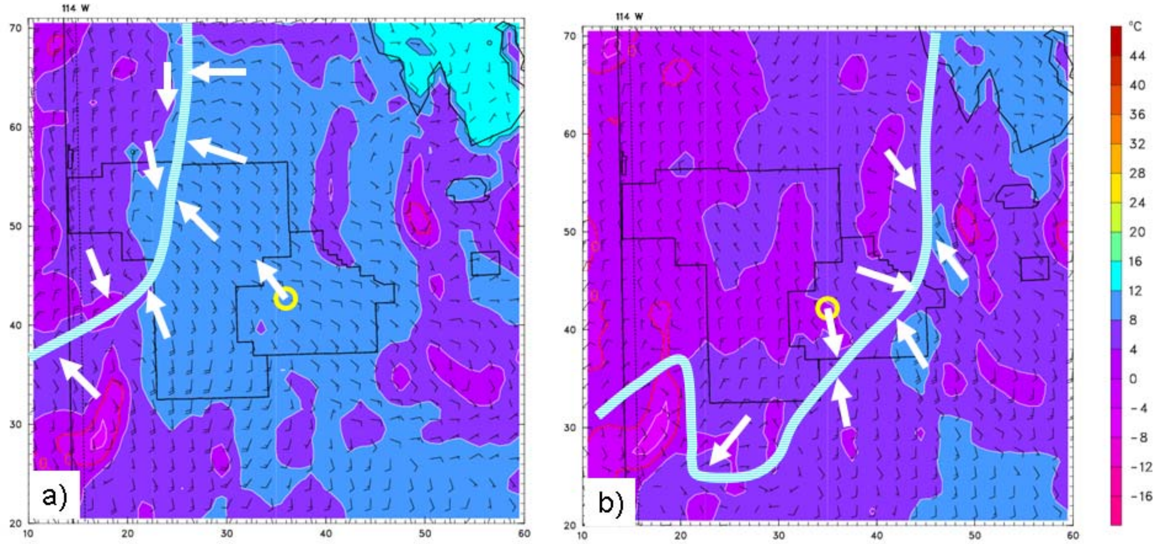

Figure 2. The WRF (a) and MM5 (b) 06 UTC on 15 April 2009 18-hr forecasts initialized at 12 UTC on 14 April 2009 of 10-m wind barbs and 2-m shaded temperature. A full-wind barb staff is 5 ms^{-1}. The light blue line is the cold front with the arrows indicating forecasted wind direction near the front. The yellow circle represents the location of Horizontal Test Grid.

conditions for testing. Thus, predicting the timing of the cold front passage results in very different guidance to the test officer. Note that the differences between these results, and the other 28 members of the ensemble set, could be due to a variety of factors, including the inherent differences between WRF and MM5, the selection of the larger-scale model, and selected options for physical process parameterizations. Our 30-member ensemble system assists the forecaster in determining the amount of uncertainty or possible scenarios in the model forecasts.

5.1 Wind Roses

Wind roses provide a useful illustration of uncertainty in wind predictions. The example in Figure 3 shows bins for a 16-point compass for a single location, based on 30 ensemble member 18 hr predictions all valid at 06 UTC on 15 Apr 09. Bins extending further from the center indicate that more ensembles predicted wind direction within that bin. The color coding indicates the wind speed in each prediction, with lowest speeds near the center. The number in each bin is the mean wind speed for that bin. In this example, the wind rose shows a slight majority of ensemble members (~55 percent) predicted that the front would not have passed through the test site at 06 UTC, which turned out to be correct. However, a substantial number of members predicted the front would have passed the test site, with much stronger post-frontal winds. For example, if the forecaster only had the MM5 control run, the wind direction prediction would have been off by 180 degrees at 06 UTC. These results, with no clear preference for one solution or another, indicate to the forecaster and the test officer that there was considerable uncertainty in this prediction. In other cases, we see a preponderance of forecasts in close agreement, which indicates the prediction has less uncertainty.

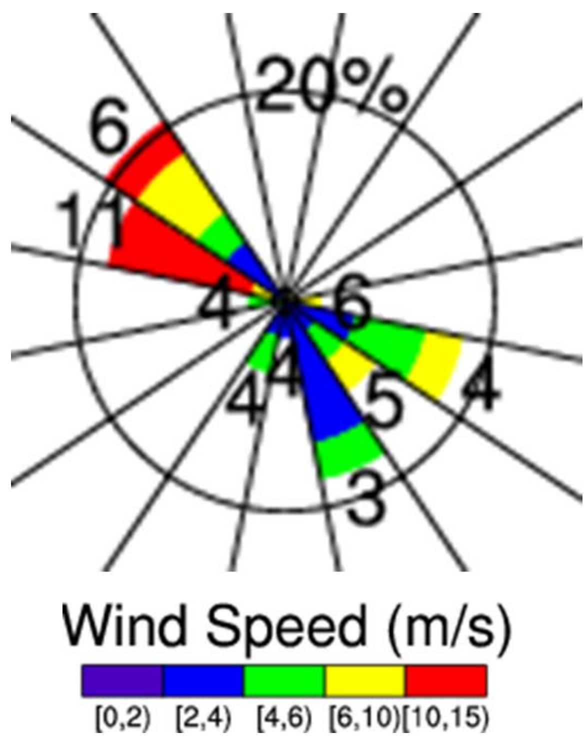

Figure 3. A wind rose plot broken down into 16 wind direction bins valid at 06 UTC on 15 April 2009 from the 18-hr forecasts initialized at 12 UTC on 14 April 2009. The wind direction is filled by the percentage of ensembles in each bin. The wind speed is color coded.

The bold number in each sector is the mean ensemble wind speed for that bin.

5.2 Exceedance Plots

When a particular weather parameter must be above or below some threshold to allow a test to proceed, a useful way to represent the likelihood of success is to use exceedance plots, which show the percent of members predicting values above or below that threshold over a map of the area. In this case, 5°C air temperature was a critical factor. The exceedance plot in Figure 4 shows the percent of ensemble members predicting temperatures below 5°C. The orange coloring over the central DPG test area indicates an approximately equal number of ensemble predictions warmer or colder than 5°C. Once again, there is considerable uncertainty in the model forecast guidance.

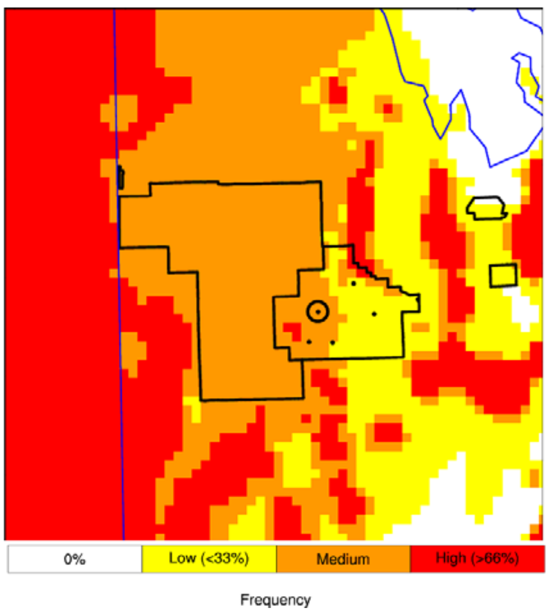

Figure 4. An exceedance plot of frequency of ensemble members having a temperature below 5°C. The black circle represents the location of Horizontal Test Grid. Valid at 06 UTC on 15 April 2009 from the 18-hr forecasts initialized at 12 UTC on 14 April 2009.

5.3 Wind Speed Maxima Plots

In some cases, we want to know the maximum (or minimum) value of a weather parameter, from all the 30 members, at a given location and time. For example, Figure 5 shows a plot of the largest 10-m wind speed at each grid point, predicted by any of the ensemble members, valid at 06 UTC on 15 Apr 09. These plots are useful in determining the possibility of weather conditions that may impact safety during testing. The wind speed maximum for the test area is between 10-15 ms^{-1}, which is within the safety constraint of 15 ms^{-1}.

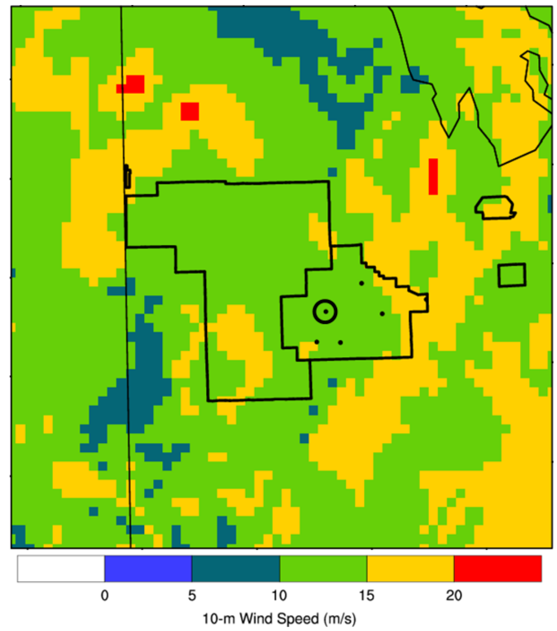

Figure 5. A plot of maximum wind speed of all ensemble members at each grid point. The black circle represents the location of Horizontal Test Grid. Valid at 06 UTC on 15 April 2009 from the 18-hr forecasts initialized at 12 UTC on 14 April 2009.

6. Summary

Weather forecasting in support of testing at DPG requires customized operational high-resolution meso-scale modeling to account for the variety of local-scale and large-scale weather influences. Having the capabilities of E-4DWX assists the forecaster in understanding the probabilities of desired atmospheric conditions that can result in the test officer making better go/no go decisions. Additionally, information about the possibilities of hazardous weather conditions helps test officers take preventative measures before testing begins.