

# On-Demand Severe Weather Forecasts Using TeraGrid via the LEAD Portal

Keith A. Brewster<sup>1</sup>; Daniel B. Weber<sup>2</sup>, Suresh Marru<sup>3</sup>, Kevin W. Thomas<sup>1</sup>,  
Dennis Gannon<sup>3</sup>, Kelvin Droegemeier<sup>1</sup>, Jay Alameda<sup>4</sup>, Steven J. Weiss<sup>5</sup>,

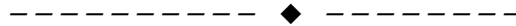
<sup>1</sup>Center for Analysis and Prediction of Storms – Univ. of Oklahoma, Norman, OK

<sup>2</sup>Tinker Air Force Base, Midwest City, OK

<sup>3</sup>Indiana University Department of Computer Science, Bloomington, IN

National Center for Supercomputing Applications, University of Illinois, Champaign-Urbana, IL

<sup>4</sup>NOAA – Storm Prediction Center, Norman, OK



## 1 INTRODUCTION

This work examines the use of the TeraGrid to produce on-demand severe weather forecasts as part of an experiment being conducted within the Hazardous Weather Testbed (HWT) spring program. This effort is a cooperative project between the members of the Linked Environments for Atmospheric Discovery (LEAD) project [1] – a National Science Foundation (NSF) Information Technology Research (ITR) project – and National Oceanic and Atmospheric Administration (NOAA) units, most notably the Storm Prediction Center (SPC) and the National Severe Storms Lab (NSSL). Among other responsibilities, the SPC issues the official Severe Thunderstorm and Tornado watches across the United States.

The HWT spring program is a 7-week program organized by NOAA meteorologists that brings in visiting scientists from operations, research institutions and the private sector in order to test and evaluate new weather forecasting tools designed to aide in prediction of the threat of severe and hazardous weather across the United States. [2]

Several groups produce special ensembles of high-resolution numerical weather prediction (NWP) products for the HWT effort. These products are used for guidance in experimental manual forecasts and are also evaluated for their own merit [3]. Most of these are initialized at 4 pm or 7 pm CDT the previous day and they are run on a fixed schedule over a large fixed domain. It is desirable to have numerical forecasts that adapt to the weather threat of the day and that utilize weather observation data from the current day, especially including the time when solar heating can affect the boundary layer. Thus LEAD proposed to provide on-demand forecasts covering a smaller, adaptable, target area that can be initialized with observation data from mid-morning (10 am CDT, 15 UTC) on the current day. The location of the domain is tailored to the needs of the HWT, based on input from the HWT participants.

On-demand forecasts were produced for the 2007 program and are currently being produced for the 2008 program. In a separate effort, LEAD also produced similar forecasts that were automatically generated based on operational severe weather forecast products.

The LEAD on-demand forecasts for the HWT were composed and submitted to the TeraGrid using the LEAD Portal. The LEAD Portal is the top tier of a service-oriented architecture that allows the seamless integration of data, numerical weather analysis and prediction tools, and grid computing resources using an intuitive web interface [4, 5, 6].

There are three primary goals of the LEAD on-demand forecast experiment: 1) to test and report on the LEAD Portal capabilities for providing on-demand high-resolution forecasts to severe weather forecasters, 2) to identify additional user needs for future development of the LEAD Portal, and 3) to identify other services or resource needs to support the portal services. It is important to highlight that this work is experimental from two perspectives: 1) the portal software, including the automated use of grid computing resources, is under continuous development and refinement and 2) the use of a real time adaptable convective-scale numerical prediction system in the operational forecast process is relatively new.

This paper will provide a summary of the operational and logistical aspects of the forecast process, briefly summarize the ongoing verification of the numerical predictions from 2007, and describe the spring 2008 effort.

## 2 THE LEAD PORTAL

As numerical weather modeling capabilities expand and additional remote sensing networks are deployed, there is an increasing need to manage the expanding volume of data available for use in meteorology research and education and to simplify the complicated process of using those data in weather prediction. Addressing this need represents a democratization of numerical weather analysis and prediction and as it eliminates the need for duplication of the effort to design, develop and maintain complex control scripts and software for data management and thus can provide such capabilities to a broad range of institutions.

LEAD is charged with developing an easy-to-use web-based interface designed for meteorology students, researchers and educators to advance scientific discovery in mesoscale meteorology. The LEAD project has two overarching goals: 1) to

democratize the use of complex numerical weather prediction systems to enhance our understanding and prediction of mesoscale weather, and 2) to dynamically interact with mesoscale weather phenomenon. One deliverable of the project is the LEAD

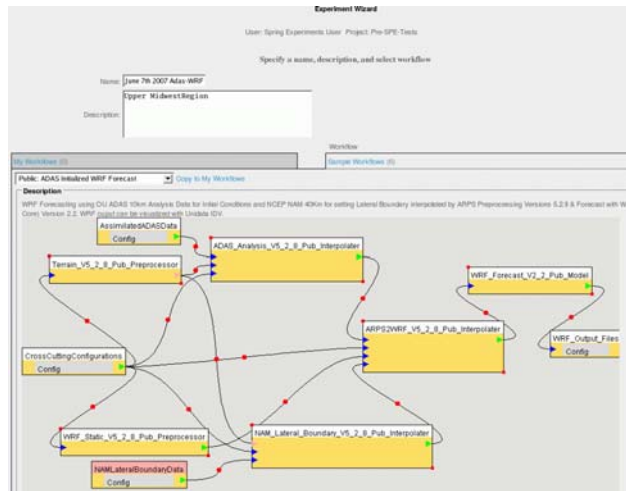


Fig. 1. Screenshot of the Experiment Builder page on the LEAD Portal

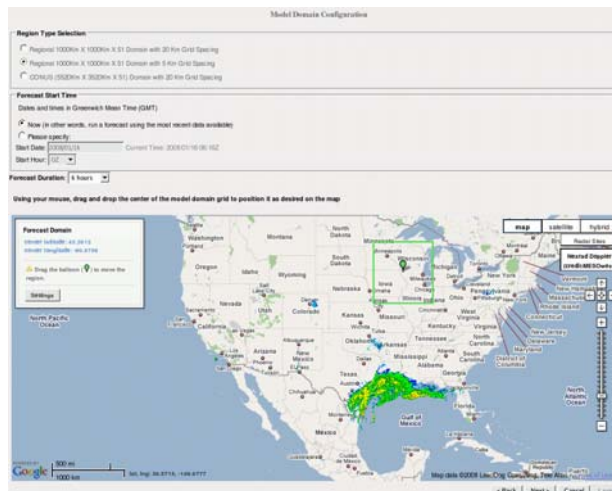


Fig. 2. Domain selection GUI from the LEAD Portal.

Portal (<http://www.leadproject.org>), a web-based system that uses service oriented architecture [7] to provide users with the ability to prepare, conduct, monitor, and verify Weather Research and Forecasting Model (WRF) [8] forecasts as well as explore and analyze meteorological datasets, including NEXRAD radar data [9, 10].

Applications are run through workflows which can be built on-the-fly by the user or might be pre-generated and saved for repeated use. A workflow composer with web GUI is provided as shown in Fig. 1. The application programs have been precompiled and installed on LEAD infrastructure as well as on some TeraGrid computers. Shell executable programs are wrapped into web services using the Generic Service Toolkit (GFac) [11]. GPEL [12], a workflow enactment engine based on the industry standard Business Process Execution Language [13], sequences the execution of each computational task based

on control and data dependencies. When the workflows are invoked they are sent to TeraGrid resources and monitored using Grid computing middleware provided by the GLOBUS toolkit [14].

The workflow for the LEAD On-Demand HWT forecasts consists of linking and orchestrating the 10-km CONUS operational ADAS [15, 16] analysis of current weather data or output from the NOAA/NCEP operational North American Mesoscale Model (NAM) for initial conditions, preparation of the boundary conditions from the NAM, interpolation of terrain and the land-surface data, and submission of the WRF numerical weather forecast model to the TeraGrid for processing. The LEAD Portal provides an interactive GUI which allows the user to easily specify the forecast domain (Fig. 2). Furthermore, the LEAD system manages the resultant forecast files in the users workspace and provides some built-in fault tolerance.

Once the forecast files are returned, the UNIDATA Interactive Data Viewer (IDV) can be launched from the LEAD Portal and used to view the results. The Center for Analysis and Prediction (CAPS) also has a custom script to generate images and web pages from the WRF output for display of the results on the CAPS website for further dissemination, URL: <http://www.caps.ou.edu/wx/spc/>

### 3 WRF FORECAST PREPARATION

The LEAD on-demand forecasts are prepared daily (Monday through Friday) during the spring by a LEAD project scientist (either DW or KB in 2007, KB in 2008) after consultation with the scientists participating in the HWT. During the daily weather briefing and forecast discussion the HWT scientists specify the area for which they will be composing forecasts describing the probability of several severe weather events, including severe wind gusts, large hail and tornadoes. This region is used to specify the location of the on-demand forecast domain for the 9-hr WRF model forecasts, consisting of grids with 2-km resolution approximately 1000 km x 1000 km. This interaction and decision process is illustrated schematically in Fig. 3.

Once the forecast region is identified, the forecast/workflow building and submission process is completed using the LEAD Portal. The on-demand forecast workflows were submitted to the TeraGrid computing resources. For most of the 2007 project, the Tungsten machine at the National Center for Supercomputing Applications (NCSA) was used. Toward the end of the 2007 spring program the University of Chicago/Argonne National Lab resources were used via SPRUCE [17, 18].

Due to the load on Tungsten, including other 2007 HWT computing resource needs, the workflow often waited for several hours in queues to run, before 80 Tungsten processors were available to be allocated to the workflow. For 2008 we have secured access to more resources for the forecaster-initiated on-demand forecasts, allowing for more real-time use and evaluation of the forecast data.

The entire process, from login to workflow submission, required less than 5 minutes to complete and represents a

huge savings in terms of manpower when compared to other real time forecast scripting systems that can require significant development overhead and maintenance by the user.

The current LEAD portal has a modest workflow

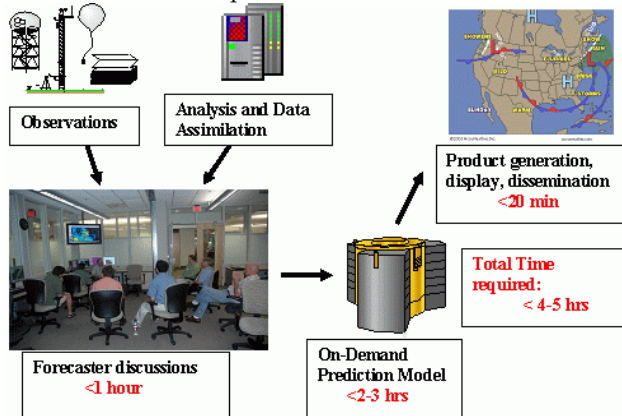


Fig. 3. Schematic of the on-demand forecast process, including the collection and analysis of data, forecaster discussions, creating and completing the on-demand WRF forecast.

library available for users becoming familiar with the workflow environment. Users can also build WRF workflows using the workflow composer, but during this experiment the workflow library was used in conjunction with the domain selector.

The on-demand forecasts were initialized using the 10 am CDT (15 UTC) LEAD 10-km ADAS analysis or 3-hr NAM forecast initialized at 12 UTC. The ADAS analysis included radar data and other observations to update the 3-hour NAM forecast from the 1200 UTC initial time. One advantage to the ADAS-initialized on-demand forecast configuration is the updating of the early morning operational forecast with mid-morning observations. The period selected, from 15 UTC to 00 UTC overlaps with the primary 2007 HWT WRF forecast and verification period for the larger-scale 4-km grid spacing ensemble forecasts and the 2-km deterministic forecasts, all produced the previous evening.

## 4 FORECAST EVALUATION

Automated verification from within a real time workflow is a difficult in part due to the complex nature of discrete precipitation systems, and the automation is further complicated by the delay in receipt of all verification data. At present, CAPS and LEAD are developing verification applications for the portal forecasts to compare surface data and rainfall observations to the gridded forecast data. As a result, we will present only subjective verification results for some of the cases during the spring experiment, while continuing to work on the objective verification services.

Note that a significant portion of the workflows, 40 of the 65 cases, approximately 60%, encountered software and/or hardware problems. The failure points in the workflow system consisted of compute nodes failures at the supercomputing site (NCSA Tungsten) during an unusually unstable period in the aging Linux Cluster. In addition, the computing resources were limited for this

effort as most of the HWT resources were focused on the large scale 2-km and 4-km ensemble simulations, requiring approximately 65 times more computing resources than the LEAD On-demand forecasts (approximately 7600 CPU hours). Additionally, the workflows encountered file data transfer failures (GridFTP), due to Grid FTP implementation and configuration problems on file servers, job submission (WS GRAM) and control and LEAD cyberinfrastructure errors. In the following several months members of the LEAD team and TeraGrid systems engineers have addressed many of the infrastructure issues. Some of the forecast failures were due to unusually heavy loads on the supercomputer head nodes and long queue wait times in which the LEAD workflow submission wait time was exceeded. The LEAD portal continues to be evaluated and improved as the LEAD Portal and TeraGrid resources mature.

Thunderstorm prediction verification is an active area of research and both objective and subjective verification processes are challenging to design and accurately interpret. It has been shown that the use of traditional objective quantitative precipitation (QPF) verification methods for storm-scale forecasting is problematic. Small errors in the position of strong storms can lead to large errors in RMS, threat scores and other point-wise statistics and mask some of the other potential values of a storm-scale forecast such as revealing the mode and severity of convection [19,20,21]. The verification of the LEAD 2007 HWT WRF on-demand forecasts is presented herein using subjective verification methods.

### 4.1 Subjective Scoring

Several subjective scoring parameters were used to grade the WRF forecasts. These include the time of initial significant thunderstorm development, the speed and direction of storm movement, the location and intensity in terms of maximum estimated radar reflectivity, and the convective mode (squall lines, isolated long-lived cells (supercells), short-lived quasi-random cells, mesoscale convective clusters, etc). Table 1 contains the scoring parameters used in this study, and the point value assign to each level of skill, with higher points indicating a better forecast. These criteria were selected for use in comparing the NAM and ADAS initialized simulations with the observations and the HWT large scale 2 and 4km WRF forecasts started the night before the LEAD on-demand forecasts. Model generated composite reflectivity is compare to composite reflectivity from the on-demand WRF model output and to the composite observed reflectivity.

Table 1. Subjective Scoring Matrix..

Parameter/Points	4	3	2	1	0
Initiation Timing (hr)	< 1	1-2	2-3	3-4	>4
Location (km)	< 30	30-60	60-90	90-120	>120
Speed Error (km/hr)	< 9	9-18	18-27	27-36	>36
Direction Error	<5	5-15	15-25	25-35	>35

(+/- Degrees)					
Reflectivity	< 5	5-10	10-15	15-20	>20
Intensity (max dBZ)					

Mode Accuracy (% matching cov)	>75	60-75	40-60	25-40	<25
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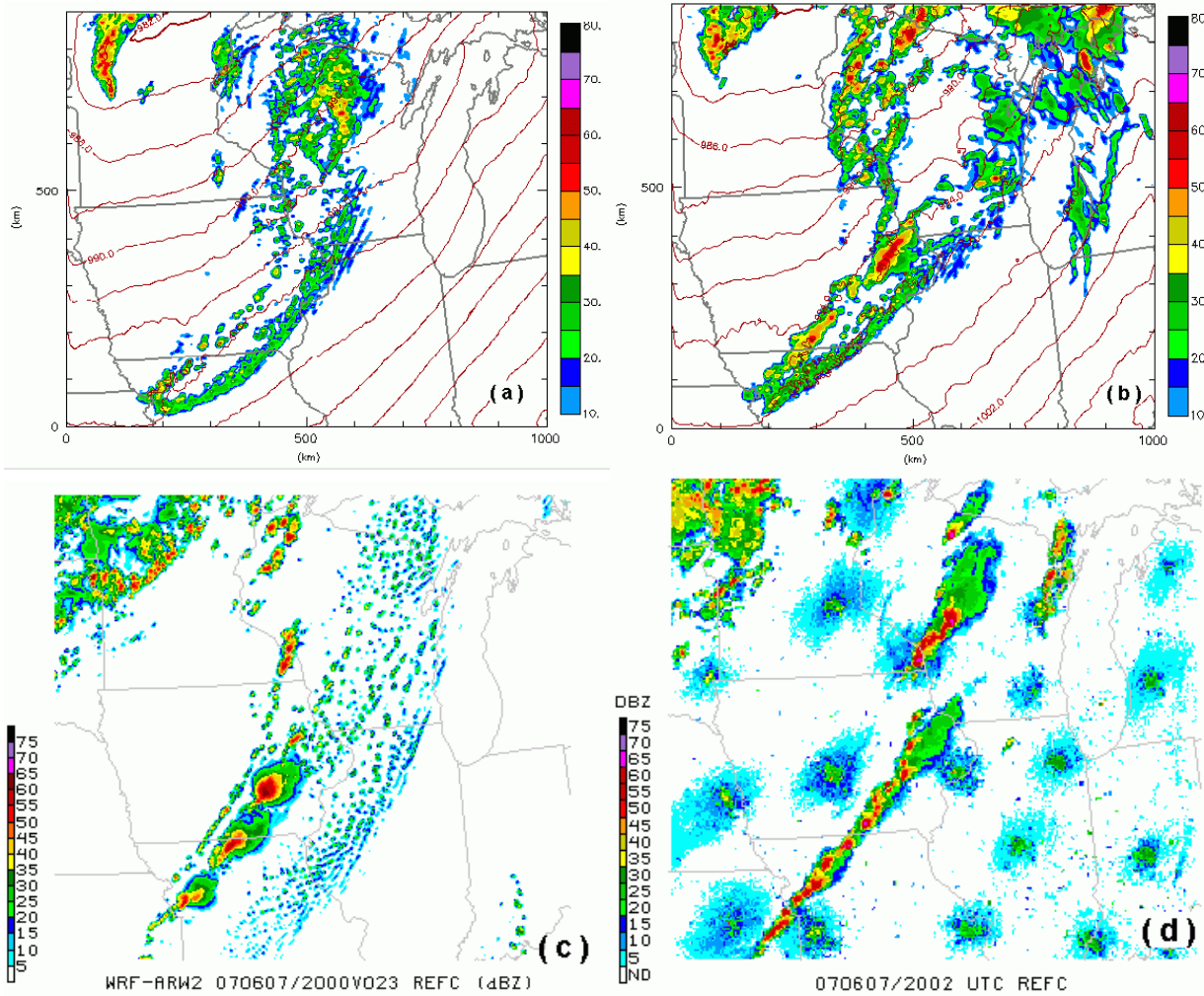


Fig. 4. Comparison of three forecasts of radar composite valid at 20 UTC 07 June 2007: a) LEAD 2-km WRF initialized from the 3h forecast of the 1200 UTC NAM, b) LEAD 2-km WRF initialized from the 15 UTC ADAS analysis, c) CAPS 2-km WRF initialized at 21 UTC 06 June 2007, d) Observed radar composite at 2002 UTC.

Table 2. Subjective scores for LEAD On-Demand WRF forecasts for 7 June 2007.

Date (2007) mm/dd	ADAS or NAM	Timing	Location	Speed	Dir	Inten sity	Mode	Sum
06/07	ADAS	3	3	2	4	3	2	17
06/07	NAM	2	2	1	4	2	2	13

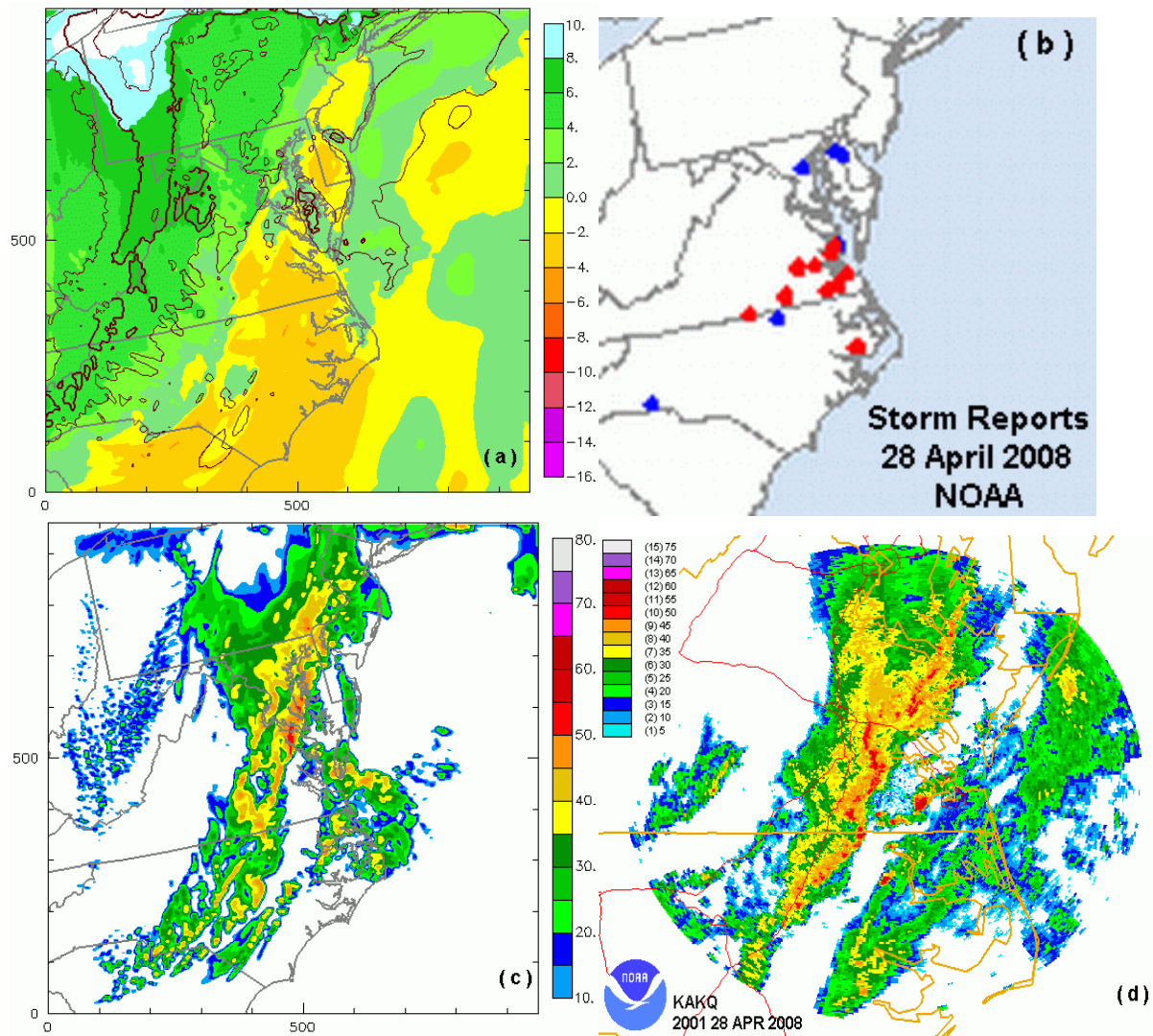


Fig. 5. Tornadoes in Virginia, on 28 April 2008. a) NAM-initialized WRF 5h forecast valid 20 UTC, Forecasted Lifted index ( $^{\circ}\text{C}$ ), b) preliminary storm reports for 28 April 2008, red dots are tornado reports, blue dots are large hail reports, c) WRF forecasted composite radar reflectivity (dBZ), d) Observed reflectivity (dBZ) from Wakefield, Virginia NEXRAD radar at valid 2001 UTC 28 April 2008.

## 5 SAMPLE FORECAST RESULTS

The 7 June 2007 case was selected due to numerous severe weather reports in the upper midwest and contained isolated supercells as well as convection organized in a line. For brevity of this paper, a sample time from this day, 2000 UTC, will be shown to highlight some of the differences typically seen among the forecasts.

Figure 4 is a comparison of the 20 UTC radar images for the HWT 2 km forecast (initialized at 21 UTC on 6 June) and the LEAD on-demand runs from 15 UTC on 7 June using the NAM forecast from 12 UTC (LEAD NAM) and the ADAS 10 km analysis at 15 UTC (LEAD ADAS). Note that the observed radar echoes (Fig. 4b) feature a line of individual supercell storms from which several severe weather reports were received

At 20 UTC the LEAD NAM and NSSL-4 km (not

shown) forecasted storms that were weaker than the observed storms, both in terms of coverage and intensity, over southeast Iowa and western Wisconsin. This bias is also present at a later time (00 UTC).

The LEAD-ADAS and the WRF ARW 2km forecasts were superior to the others in terms of intensity, location, and orientation of the storm over southeastern Iowa. However, over Wisconsin the LEAD-ADAS forecasts over-predicted the aerial coverage of precipitation.

Considering a comparison of just the two LEAD forecasts, the ADAS run does a better job handling the main line of convection during the period as the NAM-initialized run is a little slow in initiating convection on that line in Iowa and produces less intense thunderstorms. However, the ADAS-initialized run produces an area of spurious rainfall early in the run that started in NE Iowa and quickly moved northeast – the remains of that area of rain can be seen in the Upper Peninsula of Michigan at 20 UTC.

To date 14 forecasts from 2007 have been scored for the criteria in Table 1. The detailed scores for the

sample case day shown are indicated in Table 2. This is a very small sample size so we hope to have additional forecasts in 2008 to do a more complete statistical study. To date we can report a preliminary average forecast score sum of 14.1 (2.8 per element), the best scoring element is direction of movement, while the worst scoring element by our criteria is initiation location. On average, the LEAD ADAS initiated runs slightly outscored the LEAD NAM-initialized runs 14.8 to 13.0, consistent with the expected result from the addition of the 15 UTC observational data.

## 6 DISCUSSION AND ONGOING WORK

LEAD was successful in building and deploying a web-based portal from which forecasters, educators and students can seamlessly and quickly submit and manage on-demand high resolution numerical forecasts for severe weather. Some early technical difficulties with the data flow and queuing to the supercomputer centers have been addressed and we have greater confidence now in the robustness of the system for future use.

The system generates forecasts that were unique compared to the other high resolution forecasts being run for the Spring HWT operations, and we expect them to be valuable members of high-resolution ensembles numerical weather forecasts used as guidance for severe weather forecasts prepared manually.

All of the LEAD-generated forecasts will be verified objectively against quantitative precipitation estimates and subjectively using the criteria described here.

As mentioned, LEAD is also participating in the HWT Spring Program in 2008 which is underway at the time of this writing. For the 2008 season we aim to improve the success rate for return of a complete forecast. For 2008 the WRF forecasts are 6 h longer, out to 06 UTC, to better match the 2008 HWT forecast plans. TeraGrid machine BigRed at the University of Indiana is our primary computing resource for two forecasts per day, while utilizing SPRUCE at NCSA for backup and extra forecasts that the forecasters might request on special threat days.

Figure 5 shows the results from one of our 2008 forecast days. On April 28<sup>th</sup> there were several tornadoes in eastern Virginia that were spawned by relatively low-topped but vigorous thunderstorms. These storms were out ahead of another line of storms along a cold front. The models successfully forecasted the nature of the system showing the areas of convection out ahead of the frontal squall line. Although the model resolution is too coarse to forecast tornadoes themselves the forecasts did show an increase in instability as shown by the low values of Lifted Index in Fig. 5b and also forecasted high values of storm-relative helicity (not shown), an indicator of low-level wind shear favorable for developing rotation in storms.

Efforts have been made to integrate the evaluation of the forecasts in the HWT daily plan so that subjective feedback can be gained from all the participants. With a larger number of successful forecasts expected in 2008,

and combining those with the forecasts from 2007, we hope to have a database that is large enough that can be scored subjectively and objectively in a manner that will produce statistics that can be used to guide improvements in the analyses and forecasts and possible future use of such forecasts in operations.

## ACKNOWLEDGMENTS

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