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LESSONS LEARNED FROM THE DTC WINTER FORECAST EXPERIMENT

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1. INTRODUCTION

The Weather Research and Forecasting (WRF) model Developmental Testbed Center (DTC) is a new distributed facility consisting of nodes at NCAR and FSL in Boulder, Colorado, and at the Naval Research Laboratory (NRL) in Monterey, California. The research and operational communities interact at the DTC to test and evaluate new Numerical Weather Prediction (NWP) models and techniques having promise for operational implementation at some point in the future. A blend of idealized, retrospective, and real-time forecast methods are used for testing. The first DTC Winter Forecast Experiment (DWFE) was a real-time NWP experiment conducted from 15 January to 31 March 2005. Two variants of the WRF model were run for the duration of the DWFE over the entire CONUS domain: the NCAR Advanced Research WRF (ARW) model and the NCEP Nonhydrostatic Mesoscale Model (NMM). The design, conduct, and evaluation of DWFE were performed in close consultation with operational forecasters, modelers, and researchers. The objectives of DWFE were to:

- Provide experimental model guidance for winter weather forecasting over a large domain using two variants of the WRF model run at 5-km grid spacing with explicit convection only (no convective parameterization scheme).
- Expose forecasters to the nature and behavior of the WRF model at very high-resolution prior to the first scheduled implementation of the WRF.
- Using objective verification methods, determine whether encouraging results seen earlier from 4-km WRF runs in the warm season provide forecast value during winter for lead times out to 48h.
- Determine the extent to which various mesoscale phenomena, such as gravity waves, lake-effect snow, and coastal fronts can be skillfully forecast.

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The ARW and NMM versions of WRF run during DWFE utilized different sets of physics. The ARW model used the WSM 5-class microphysics scheme, the YSU boundary layer scheme, the NOAH 5-layer land-surface model (LSM), and Dudhia shortwave and RRTM longwave radiation. The WRF-NMM model used the Ferrier microphysics scheme, MYJ 2.5 closure scheme for the boundary layer, NOAH LSM, and the Lacis-Hansen shortwave and Fels-Schwartzkopf longwave schemes (all of which are used in the Eta model). No cumulus parameterization was invoked for either WRF model. A horizontal resolution of 5 km and 38 vertical levels were configured for each WRF model, which used the same Eta grid 212 (40-km) boundary conditions and 0000 UTC EDAS initial conditions. Forecasts were made once daily out to 48 h, with the goal to have the complete forecast cycle completed and distributed to the NWS by no later than 1430 UTC. Greater details about the model configuration and experimental design are provided by Bernardet et al. (2005).

FSL distributed the model forecasts in four different ways to NWS users: 1) a web site run jointly with NCAR, 2) FX-Net for full interactive control of the model fields, 3) Local Data Manager (LDM) via the regional wide-area networks for ingest and display of selected two-dimensional grids (mostly surface and precipitation) on AWIPS, and 4) full-resolution GRIB data via ftp for viewing on NAWIPS. Bandwidth limitations, which are especially severe for such large three-dimensional datasets as these 5-km CONUS-wide models, were addressed by FX-Net using wavelet transform data compression techniques and multithreaded client-side processing and communication. FX-Net is a request-based, client-server system for providing access to the basic display capability of an AWIPS workstation via the Internet (Wang et al. 2002). The FX-Net server is a modified AWIPS workstation, and the client runs as a Java application on a PC or Mac. The application of this relatively new compression technique was critical to the success of delivering very large-size model forecast imagery via the Internet in a reasonable amount of time.

DWFE provided valuable experience for the DTC in learning how to run complex, multi-organizational real-time, numerical forecast experiments. Although these high-resolution models predicted enticingly realistic-looking mesoscale phenomena, DWFE provided an unforeseen challenge in presenting such detailed forecast fields to forecasters. The DTC adapted quickly to this challenge by creating novel product displays (discussed below). Another challenge was to reconcile the difference between codes and databases that had initially produced disparity in some results emerging from alternative verification packages, as discussed by Demirtas et al. (2005). One of the biggest challenges was to attempt to balance the desire of the model developers at both NCEP and NCAR to make improvements to model configurations *during* the course of the experiment, while not compromising the statistical integrity of the verification results as required by the NWP researchers, nor causing too much disruption for the forecasters. We discuss how lessons learned from DWFE might benefit future NWP experiments from the planning stage to improving the value of two-way feedback with forecasters and model developers.

2. UNCONVENTIONAL DISPLAYS OF FORECAST MESOSCALE PHENOMENA

Some of the traditional ways of looking at model forecasts (e.g., unsmoothed geopotential height, vertical velocity, frontogenesis and quasi-geostrophic forcing) were found to be of relatively little use in DWFE. An example of the extraordinary level of detail over the national landscape provided by these 5-km resolution models is presented in Fig. 1, which shows a WRF-NMM forecast of absolute vorticity at 700 hPa over the complex terrain of the western U.S. The “streamers” of vorticity parallel to the flow may have been caused by the tilting of horizontal vortex tubes generated baroclinically by the flow of stratified air past three-dimensional mountains. Alternatively, differential drag may have retarded the flow in the boundary layer near the mountains, creating streamers of shear vorticity. Numerical problems related to handling of the pressure gradient force over steeply sloped terrain might also have contributed to the streamers. In any case, such extreme level of detail made it nearly impossible for a forecaster to be able to discern quasi-geostrophic vorticity advection.

The DTC attempted to respond to these problems of interpreting such detailed fields by creating innovative displays of the forecast fields. One such experimental product is shown in Fig. 2: a nonlinearly scaled absolute vorticity field. This field is intended to show both the superb mesoscale detail forecast by the WRF models, and at the same time, the vorticity field associated with synoptic-scale cyclones. This attempt was only partially successful, however, since the amplitudes of the smaller scales strongly dominated the pattern.

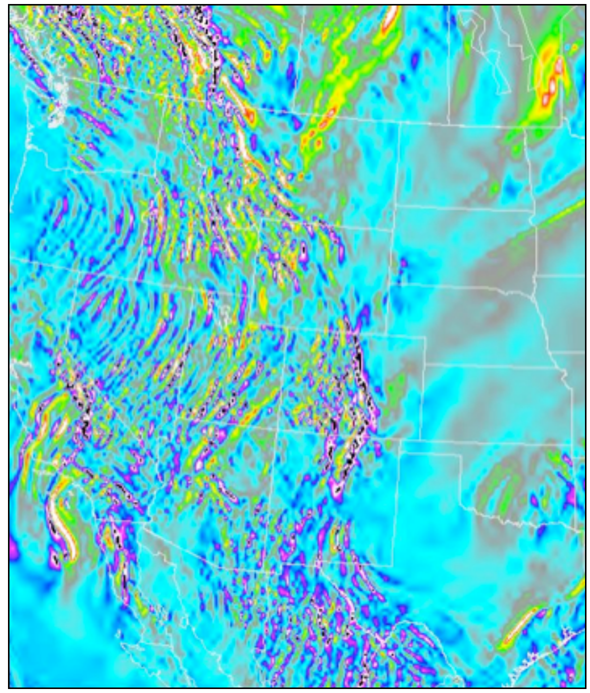

Fig. 1. FX-Net display of WRF-NMM model 12-h forecast of 700 hPa absolute vorticity (blue, negative; yellow and orange, positive values) showing complex streamers of vorticity parallel with the mid-tropospheric flow. Maximum vorticity is 25 x 10-5 s-1. Forecast is valid for 1200 UTC 02 February 2005.

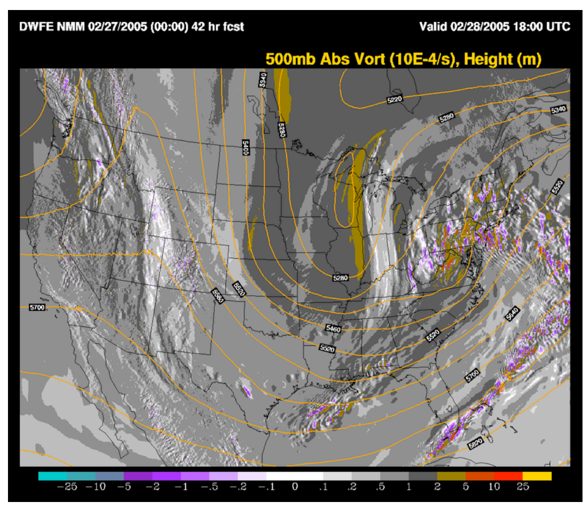

Fig. 2. An experimental product: nonlinearly scaled absolute vorticity at 500 hPa (shading) and smoothed 500-hPa geopotential height fields from 42-h WRF-NMM forecast valid at 1800 UTC 28 February 2005. Vorticity contours are ±25, 10, 5, 2, and 1 x10^{-4} s^{-1}.

Other innovative forecast products developed during DWFE included simulated radar reflectivity fields derived from the model microphysics, precipitation type distributions, and integrated precipitable water fields.

The experimental reflectivity product deserves special mention. The composite radar reflectivity (the maximum reflectivity in the grid column) product was available for the WRF-ARW model by NCAR even prior to the beginning of DWFE (15 January), but did not become available for the WRF-NMM model until 28 February. This product was something new to look at for wintertime weather, not being available from the Eta or GFS models. The reflectivity product offered significant advantages over the conventional precipitation forecast displays. An important advantage is that radar reflectivity is easier to verify in real time by directly comparing with readily available observed reflectivity displays. The chief advantage of this product is that it allows one to more easily see the mesoscale structures forecast by fine resolution models, such as snowbands (Fig. 3) – structures that tend to get lost in precipitation fields (which are always accumulated over some length of time such as 1 hour or 3 hours).

The simulated equivalent reflectivity factor is computed from the forecast mixing ratios of grid-resolved hydrometeor species, assuming Rayleigh scattering by spherical particles of known density and an exponential size distribution. Perceptible differences appeared in the general nature of the simulated reflectivity fields from the two models run during DWFE, most notably, a greater coverage of reflectivity below ~25 dBZ and higher maximum reflectivities in the case of the NMM compared to the ARW for winter storms. These differences are most directly explained by the differences in physics packages, particularly the way various liquid water and ice species are treated in the model microphysics schemes. The WRF Single-Moment 5-class ("WSM5") microphysics scheme used for the WRF-ARW model during DWFE treats the cloud condensate in the form of cloud water and cloud ice as a combined category, and precipitation in the form of rain and snow also as a combined category. The WRF-NMM used the Ferrier microphysics scheme, which accounts for four classes of hydrometeors. The most important difference between the two microphysical parameterizations concerns the assumed size distributions for snow: for the same snow mass content, differences in radar reflectivity will scale with differences in parameterized snow number concentrations between the two microphysical schemes. These issues are discussed by Stoelinga (2005) and Ferrier et al. (2005).

There were instances when the strength and persistence of mesoscale phenomena were so pronounced that the precipitation forecasts were adequate in highlighting their existence. An example of stationary bands in mean sea level pressure and precipitation fields is presented in Fig. 4. The event is the severe New England blizzard of 23 January 2005, wherein hurricane-force winds and snow accumulations in excess of two feet occurred. Pronounced north-south bands were forecast by both WRF models to the north of the storm center (Fig. 4a). These bands were stationary, being fixed to the terrain (the Hudson and Connecticut River Valleys separated by the Adirondack and Berkshire Mountains) for 9h during the peak of the storm. The observations agreed with this prediction. Not only did the FSL 5-km resolution Space-Time Mesoscale Analysis System (STMAS, Koch et al. 2005) reveal similar features in the surface fields (Fig. 4b), but also the accumulated snowfall for this storm showed pronounced north-south bands, with the heaviest snowfall along the mountains and much less snowfall reported in the low-lying areas. This example serves to demonstrate the value of running high-resolution models over a large domain: since the ability to correctly represent the mesoscale forcing hinges on the ability of the models to also correctly forecast the synoptic scale, which is more likely to happen when the influence of boundary conditions does not dominate the forecast solution too quickly.

3. PARTICIPATION BY THE NWS REGIONS

The following regions of the National Weather Service participated in the DWFE: Eastern Region (ER), Southern Region (SR), Central Region (CR), and to a more limited extent, the Western Region (WR). The regions were involved with NCAR, FSL, and NCEP in the planning, execution, and evaluation phases of DWFE. Weekly coordination teleconferences held during the execution phase were a valuable component of the experiment, and these would be recommended for any future experiments involving the NWS. Participation by the NWS field offices varied greatly among the regions, primarily due to differences in available bandwidth (for FX-Net), flexibility in configuring new products into AWIPS, and commitments to ongoing operational activities. The NWS would always prefer to work on AWIPS. Since forecasters are familiar with this system, it should be faster, and any model data that is in AWIPS should be able to get into IFPS. Yet, since only a limited number of fields were available to display on AWIPS because of bandwidth limitations, FX-Net was attractive because it was the only way to look at more model fields.

Eastern Region. Forecasters in the ER preferred the AWIPS displays of the WRF model products, relative to FX-Net. The time it took for FX-Net to retrieve and produce requested information from these large data files on the FX-Net servers was prohibitively long for ER. Bandwidth problems were chiefly responsible for this region putting greater emphasis upon the AWIPS displays than the FX-Net capability, though in the early stages of DWFE, before the AWIPS functionality was working, FX-Net saw much greater use. Towards the end of the DWFE project, approximately ~60% of the offices in the ER were pulling in DWFE data via AWIPS. ER expressed a strong desire to keep the NMM 5-km model running at FSL even beyond the end of DWFE. FSL did continue to do so through the spring and early summer of 2005 to allow forecasters to gain experience with this model during the convective season.

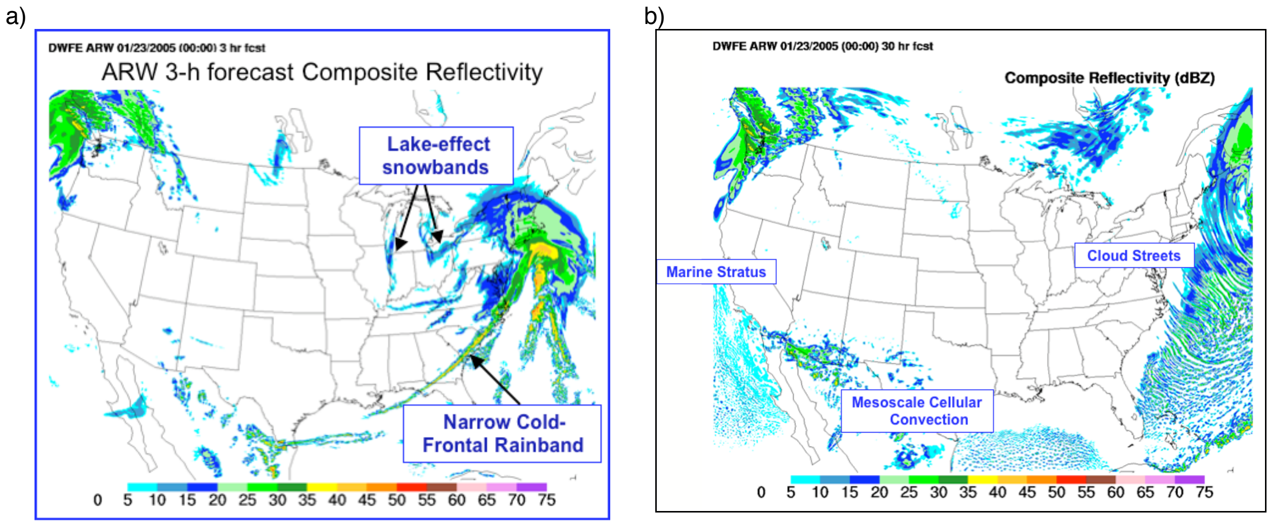

Fig. 3. Experimental composite reflectivity product showing examples of mesoscale phenomena forecast by the 5-km WRF models at a) 0300 UTC 23 January 2005 (3-h forecast) and b) 0600 UTC 24 January 2005 (30-h forecast). These phenomena were not nearly as obvious in conventional precipitation forecast field displays.

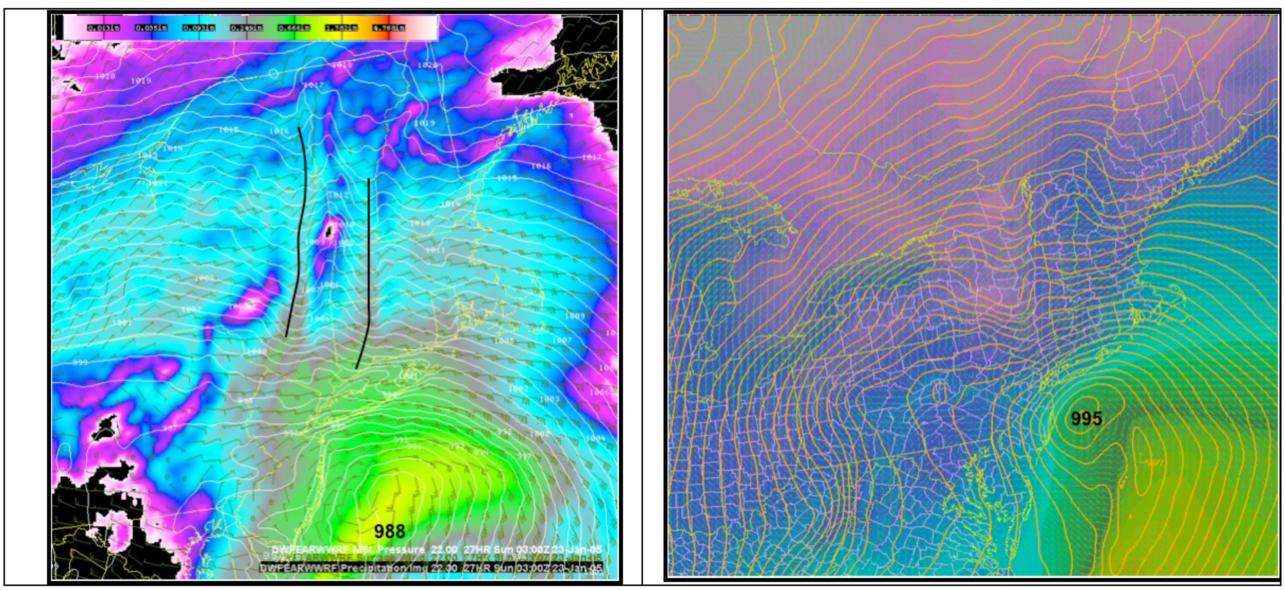

Fig. 4. Mesoscale bands in the mean sea level pressure (MSLP) and precipitation fields forecast by the WRF-ARW model for the New England blizzard of 23 January 2005: a) 27-h forecast of MSLP field (1 hPa intervals) and 3-h accumulated precipitation valid for 0300 UTC 23 January 2005 and b) STMAS mesoanalysis of isobars (1 hPa intervals) and isotherms (color-filled). Maximum precipitation forecast of ~2.0 in / 3h is east of the New Jersey coast. Thick north-south lines in (b) highlight the stationary bands. Minimum pressure in the cyclone at this time was observed to be 995 hPa (actually, the analysis over the oceanic regions reflects more the RUC model background analysis than pure observations), whereas the WRF-ARW forecast is 7 hPa deeper.

Southern Region. The SR developed a DWFE website on their Intranet, which included a description of the experiment, links to the VISITview training materials, the FX-Net software, and procedures developed to quickly display the output from the WRF models. The DWFE was promoted during the monthly SOO/DOH conference calls and in *Southern Topics*, the region's monthly newsletter. The DWFE model output was frequently shown during in the morning weather briefings at SRH. The SR staff also helped install the FX-Net software on PCs in the operations area during routine visits to various WFOs.

SR chose not to use the AWIPS display option for the DWFE because ongoing AWIPS hardware and software upgrades would have required different sets of installation instructions for each configuration, and local offices would have been required to repeatedly modify their AWIPS configuration after each hardware or software change. Because SR has greater Internet bandwidth than ER – through a service not available to ER – FX-Net was the preferred means of delivery for the DWFE model output. Forecasters especially appreciated the capability of the FX-Net software to overlay observations, radar and satellite imagery, and output from the various operational models directly on the WRF output. SR would like to see the FX-Net software used during future NWP experiments and for the evaluation of output from parallel model runs prior to planned changes to the operational forecast models.

Generally, SR field forecasters had limited time to devote to evaluation of the DWFE experimental model output. Forecasters did like the reflectivity product as a means for easily evaluating the nature of expected convection. As the time for the implementation of the WRF-NAM approaches, interest in the WRF will likely grow. SR joined with the other regions in requesting that the NMM 5-km model continue to run at FSL beyond the end of DWFE.

Central Region. The general impression about DWFE in the CR was the least positive among all the regions. Forecasters only looked at the DWFE products occasionally and when they did, they relied on the DTC web page for display. The primary reason for this lack of participation was that the CR has other high-resolution model options competing for their limited time in operations. FX-Net failed to perform adequately for CR, and most of the offices did not take the time to set up the AWIPS feed. Nevertheless, a poll taken of the CR offices strongly suggested a broad interest in continuing the high-resolution WRF model runs through the warm season, as with the other regions.

Western Region. Participation by the WR was more scattered than in the other regions, primarily because WR was entrained into the planning at a very late stage, once FSL and NCAR could determine that they could extend the NMM model domain to the eastern Pacific Ocean on its supercomputer. Nevertheless, WR did express pleasure with the DWFE experience and stated that such experiments are important to the WRF development process – provided that the field evaluations are better organized in advance of the beginning of the test. This region preferred the FX-Net display to the AWIPS and web display options, though had it been possible to display all the fields in AWIPS, it is likely that WR would have preferred this mode of display to FX-Net.

4. IMPRESSIONS FROM THE FIELD

Here we discuss the general impressions made by the DWFE among the participating regions in the National Weather Service. The products that saw the greatest popularity were, by far, the MSLP/3-hourly precipitation and radar reflectivity products (Fig. 5). These two graphics products alone accounted for 64% of the total number of DWFE web downloads, which were substantial (totaling nearly 90,000 plots). An analysis of the originating hostnames revealed that 43% of the total number of downloads originated from NCEP and that the second-most frequent set of requests originated from NCAR and FSL – thus, indicating that DWFE was examined closely by modelers in both the research and operational communities. The next major set of users of this website included NWS/CR, NWS/WR, researchers at North Carolina State University, and commercial meteorological companies.

The results from the online forecaster evaluations indicated that the timing and location of snowbands were considered superior products of the DWFE model forecasts. Although the Eta model also often predicted precipitation bands, the WRF models provided a far more detailed indication of the structure of the snowfall as made evident in the simulated reflectivity displays. It is uncertain whether the actual forecast snowfall (precipitation) amounts were consistently better, though the results from the precipitation verification using conventional Equitable Threat Score and Bias skill scores (Demirtas et al. 2005) do not indicate that the DWFE models were superior to the Eta in this regard, except possibly for the heavier precipitation categories, where the Eta model was customarily too low. Yet, there were also examples of overprediction of snow by the DWFE models in heavy snow events, most notably for orographic snowfall.

A variety of factors limited the use of the high-resolution WRF model forecast fields by the NWS. Probably the biggest single factor was the Integrated Forecast Preparation System (IFPS), which the forecasters use to make their forecasts. As the weather became more complex, IFPS could become a *very* time-consuming task, which left the forecaster with limited time to look at the WRF forecasts. Moreover, since IFPS is in a constantly evolving mode, forecasters had to repeatedly learn new things, often making them less receptive to experimental model forecasts.

Another limiting factor was the fact that neither FSL nor NCAR could run these large-domain WRF models more than once per day. By comparison, the Eta and GFS are run four times per day, so a forecaster is more likely to use the latest guidance. In effect, the DWFE runs were only “new” for one of the three forecast shifts. This limitation was especially significant for the NCEP Hydrometeorological Prediction Center (HPC), whose greater participation was limited in part by the single run at 0000 UTC being usable for only ~33% of the forecast winter weather lead time (72 h), given that the DWFE runs only extended to 48 h and the output was not available until the next 1200 UTC cycle. Nevertheless, the detail presented by the WRF models "offered a tremendous advantage over the operational NCEP QPF product." The fundamental benefits noted were:

- DWFE allowed forecasters to gain experience with visualizing and using high-resolution WRF model output over a large domain in an operational fashion (recall that this was one of the chief objectives of the experiment).
- DWFE made it possible for HPC to gain technical expertise needed to establish data flow and storage paradigms for operational, high-resolution, model datasets in the future.
- HPC could view the entire three-dimensional model fields at full resolution at each forecast hour using NAWIPS/GRIB output; by mapping the fields to a 12-km grid, they worked around the problems caused by extreme levels of detail.

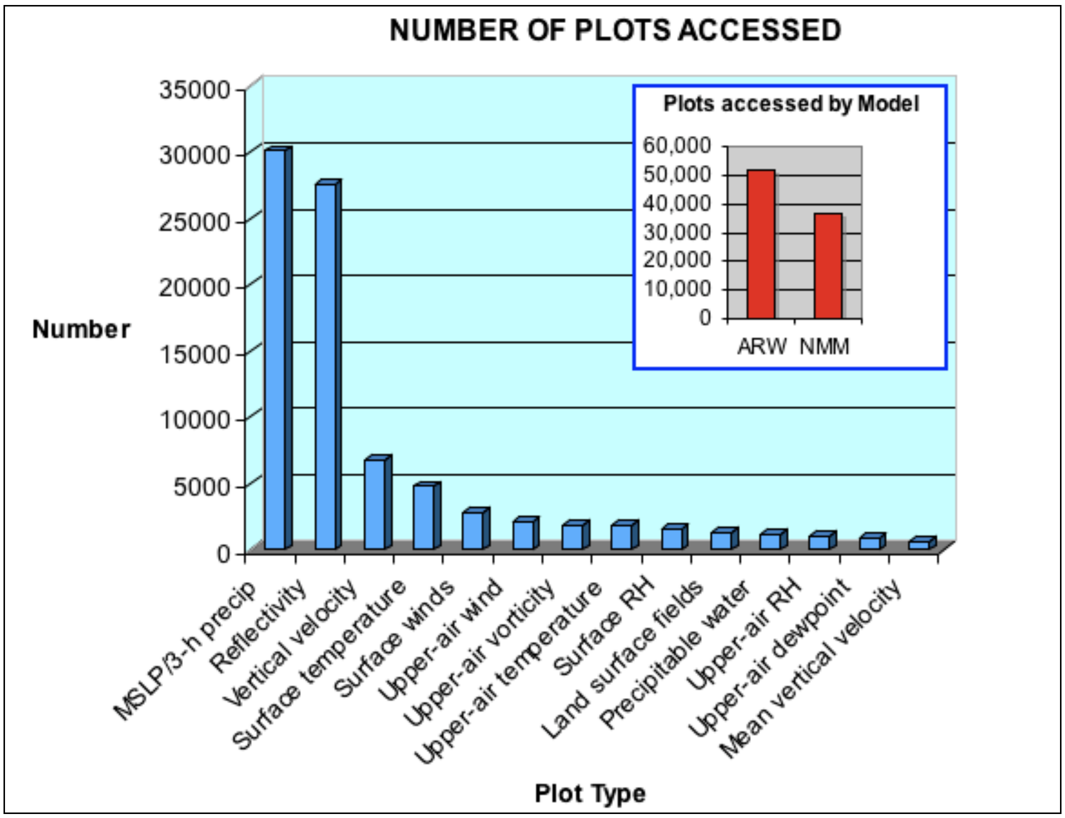

Fig. 5. Number of plots accessed during the entire DWFE project from the DTC web site. The most popular two products – mean sea level pressure with 3-h accumulated precipitation, and composite radar reflectivity – together accounted for 64% of the total number of plots downloaded. Land surface fields include a wide range of fields ranging from snow depth, to soil moisture and skin temperature. Total number of plots accessed was 89,924, of which 51,656 were for the WRF-ARW and 36,884 for the WRF-NMM model.

5. SUMMARY

A major success for DWFE was the development and popularity of experimental model output products – especially the radar reflectivity product, but also the precipitation type, full resolution surface wind and temperature fields, and precipitable water fields. Another innovative field that was only available on the DTC website for the WRF-ARW model was forecasts of total snowfall on the ground (which either increased or decreased through the 48-h forecast period). In the future, model hydrometeor and moisture fields could be converted (using "forward models") into satellite radiance displays to help forecasters compare model output to satellite infrared (water vapor and window channel) imagery. Such operationally attractive and inventive fields, especially if produced at hourly intervals instead of 3-hourly (which is all that the computers at NCAR and FSL could handle and get the fields out by 1430 UTC every day), are recommended for the future.

Perhaps one of the big surprises of DWFE was how difficult it was for forecasters to deal with the detail being predicted by the 5-km WRF models, particularly above the surface. Conventional fields such as vorticity and vertical velocity were found to be of little forecasting assistance, even after attempts to smooth the output fields using nonlinear filters (in an effort to retain the smooth, background fields while not losing the useful details present in some of the active mesoscale regions). More research is needed to find better ways to provide the most information possible from such extremely detailed upper-level fields, while retaining the true signals present. Perhaps a multiscale approach for displaying forecast grids (similar to what NCEP does with the Eta displays on AWIPS) would allow examination of both the larger-scale ("quasi-geostrophic") patterns of fields like vorticity and thermal advection, as well as the full resolution details associated with small-scale phenomena. The need exists to conduct basic research with the model forecast fields and mesoscale observations on the dynamics of mesoscale weather systems, as in the examples given above of lake-effect snowbands, vorticity streamers emanating from mountains, topographically fixed snowbands in major winter snowstorms, various structures in the marine boundary layer, and so forth.

FX-Net appears to have been too slow for general operational use, though this differed among the regions, depending mostly on the bandwidth differences. When the weather was potentially exciting, forecasters tended to quickly go to the web site and pull down a few of the more popular products, like the radar reflectivity and surface forecast fields. However, forecasters greatly preferred having the fields available on AWIPS, and given more time for preparation and coordination with all of the NWS offices, it is likely that eventually AWIPS would have turned out to be the most popular option.

One of the greatest challenges posed by DWFE was the need to try to balance the needs of three disparate groups of participants:

- ***Modelers*** want to make improvements to the models as bugs and other deficiencies are discovered during the course of the experiment, and wish to avoid displaying to the public results from models with known errors.
- ***Researchers*** at the DTC must have stable, meaningful statistical results from which informed recommendations can be made and published.
- ***Forecasters*** prefer to have only the most grievous model bugs fixed to improve model performance so they can conduct a meaningful evaluation and avoid forming lasting negative impressions about an experimental model destined for future operational implementation.

These same issues affect other high-resolution NWP field experiments, such as the annual Storm Prediction Center Spring Programs (Steve Weiss, personal communication). Short of ditching the experiment and trying again the following year, what else could be done if model bugs are discovered during the course of the experiment? In future DTC experiments, the model contributors will be asked to conduct thorough tests of stable model codes prior to the start of the experiment, in order to increase the likelihood that the models can be run in an unchanging configuration throughout the experiment. This was not really possible with the version of the NMM model running at FSL. This version had not been stabilized prior to the startup of DWFE, and literally months were spent porting software systems from EMC to the computer systems at FSL (and, to a lesser degree, also at NCAR). In the future, only if a "major" coding error (one that substantially affects the forecasts) is discovered at the beginning of the experiment, should model developers be encouraged to fix the code, since such experiments are typically of relatively short duration (couple of months).

In order that EMC can profitably use the results from NWP field experiments like DWFE, it is necessary that EMC have confidence in the verification results. We believe, along with EMC, that a common, universal verification system must be established at the DTC. The grid-to-point Real-Time Verification System (RTVS) developed by FSL and the grid-to-grid EMC system, both used during the DWFE, each offer certain useful points of view, and the data that feed these precipitation verification systems also differ. Making different scores public necessitates use of measures of confidence and a full disclosure about the nuances of each verification system. More on this subject can be found in the paper at this conference by Demirtas et al. (2005).

It might be argued that perhaps the DTC should only conduct rigorous "retrospective" tests and avoid real-time experiments until the model codes are fully mature and understood. Retrospective tests were the very first assignment that the DTC undertook. Last year, the DTC conducted thousands of model runs to help establish the configuration of the WRF High-Resolution Window (HRW), which was implemented at EMC in September 2004 (though the full six-member ensemble system recommended by the DTC experiment was not implemented). Retrospective tests are easier to control and interpret – yet, they are still quite difficult to set up, and most important, they do not involve the field forecasters, who can provide extremely valuable information about the performance of a model that is destined to be implemented in the future. Much was learned about the performance of both the ARW and NMM versions of WRF in the DWFE, and bugs were found and corrected as the result. Some of those corrections were made by both NCAR and NCEP right after the completion of DWFE, and DTC researchers and visiting scientists are still uncovering other bugs using the DWFE archived datasets.

In the future, the DTC will be operating under the guidance of an established Advisory Board, composed of members from both the research and operational communities to ensure that both groups are consulted. It was not possible to set up this Board in time to be of help for planning DWFE. As of this writing (June 2005), an Advisory Board has finally been established. The

DTC is committed to learn from experiences such as DWFE to move us to a point where we do not see ourselves as merely researchers and operational meteorologists collaborating together, but as scientists working together as partners.

6. ACKNOWLEDGEMENTS

The contributions of many hard-working individuals at NCEP, NCAR, and FSL enabled DWFE to take place. The host of characters includes numerical modelers, computer scientists, and website developers. The efforts of these people are acknowledged in other papers in this special conference session on DWFE. The authors would also like to express special appreciation to Jim Bresch (NCAR), who accumulated the DTC web site statistics during DWFE, and to Louisa Nance, for bringing these data to our attention. Discussion with Dave Dempsey at the DTC about sources for the "vorticity streamers" was helpful. The efforts of Nita Fullerton to edit this paper and improve its readability are appreciated. Finally, we wish to acknowledge the financial support for the DWFE obtained from the NWS/Office of Science and Technology (OST), the NOAA Office of Oceanic and Atmospheric Research (OAR), and the U.S. Weather Research Program (USWRP).

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