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EVALUATING HIGH-RESOLUTION CONFIGURATIONS OF THE WRF MODEL THAT ARE USED TO FORECAST SEVERE CONVECTIVE WEATHER: THE 2005 SPC/NSSL SPRING EXPERIMENT

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1. INTRODUCTION

The NOAA Hazardous Weather Testbed in Norman, OK conducted its 6th annual Spring Experiment from April 18 through June 3, 2005. More than 60 forecasters, research scientists, and university faculty from around the country participated in the experiment, which was sponsored by the Storm Prediction Center (SPC) and National Severe Storms Laboratory (NSSL). The objectives of the experiment were to 1) evaluate the operational utility of several experimental high resolution versions of the Weather Research and Forecasting (WRF) model during severe weather episodes, 2) to identify characteristic behaviors and specific strengths/ weaknesses of the different WRF configurations, 3) enhance collaboration within the forecasting and research communities, and 4) accelerate the transfer of new science and technology to operations. This preprint will report on the second objective. Thus, it will provide a resource for model developers who continue to seek ways of improving the WRF model.

2. METHODOLOGY

The SPC and NSSL formed partnerships with three major modeling centers to ensure the generation of daily high resolution forecasts for this year's experiment. Specifically, numerical forecasts were produced by NCEP's Environment Modeling Center (EMC), the National Center for Atmospheric Research (NCAR), and the University of Oklahoma's Center for Analysis and Prediction of Storms (CAPS). The CAPS forecasts were generated at the Pittsburgh Supercomputing Center, while the EMC and NCAR forecasts were generated "in-house".

Table 1 summarizes the different model configurations used for these forecasts. The NCAR and EMC runs used approximately the same spatial resolution, but different dynamic cores and physical parameterizations. The CAPS run employed the same dynamic core and physical parameterizations as the NCAR forecasts, but it had twice the horizontal resolution and considerably higher vertical resolution as well, providing an unprecedented combination of high resolution over a large area in a daily forecast.

CAPS scientists sought to minimize any differences with the NCAR configuration other than spatial resolution, but other subtle differences were unavoidable. For example, CAPS was forced to use a smaller domain size (see Fig. 1). Their horizontal grid of 1500X1320 points placed extraordinary demands on computing resources, precluding the use of a larger domain. They were also forced to use a different interpolation routine to generate initial conditions because the standard WRF initialization package (WRFSI) could not accomodate the large number of grid points in a timely fashion. Finally, CAPS used the initial soil moisture field available in the Eta analysis while NCAR initialized soil moisture using HRLDAS (High Resolution Land Data Assimilation System - see Chen et al. 2004), an off-line soil model that incorporates observed surface variables, precipitation and radiation data (W. Wang, NCAR, 2005, personal communication).

As in previous SPC/NSSL Spring Experiments (e.g., see Weiss et al. 2004; Kain et al. 2003a), daily activities in 2005 were roughly evenly divided between experimental forecasting exercises and interrogation and evaluation of model output; the first half of the day was

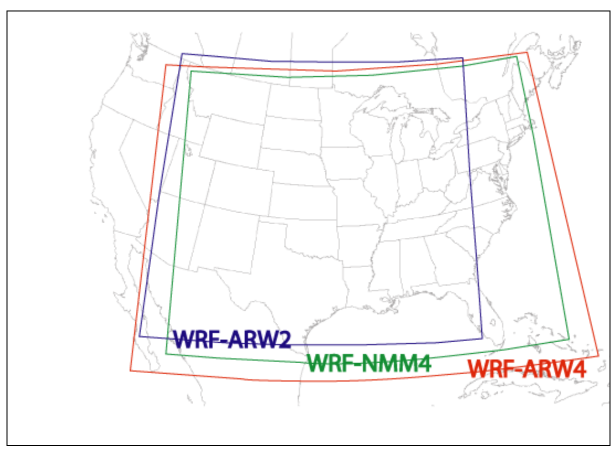

Fig. 1. Model integration domains for the CAPS (WRF-ARW2), EMC (WRF-NMM4), and NCAR (WRF-ARW4) forecasts.

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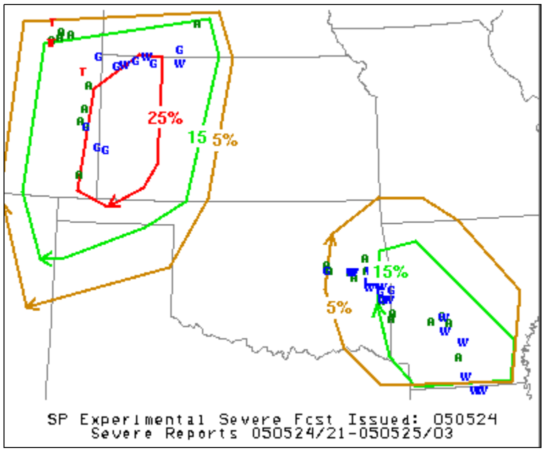


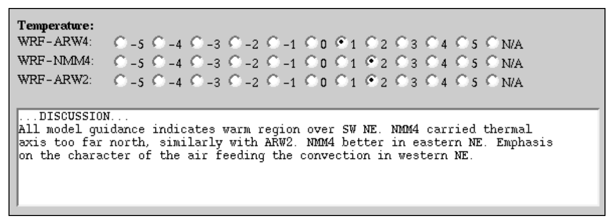
Fig. 2. Experimental severe-weather forecast valid 2100 UTC 24 May - 0300 UTC 25 May 2005. Contours denote probablility forecast of severe convection with 25 mi. of any point. Severe weather reports from this period are indicated by the letters **T** (tornado), **A** (hail ≥ 0.75 in.), **W** (wind damage), and **G** (wind gust ≥ 50 knots).

devoted to human forecasts while the WRF models were the focus of the afternoon time period. Model evaluation strategies involved a combination of descriptive documentation of model behavior and consensus subjective ratings of model performance, which lends itself to a qualititative comparison of different models (see Kain et al. 2003b).

Both the experimental forecasts and the model evaluations were conducted over limited regional domains and relatively short (6 h) time periods. For example, Fig. 2 shows the forecast/evaluation domain for 24 May. The size and aspect ratio of this domain were held constant throughout the experiment, but the window was relocated every day to focus on the area of greatest threat for severe convective weather for that day. Likewise, the focused 6 h time frame was shifted within the 18 - 30 h forecast period based on the expected timing of convective initiation and the first few hours of mesoscale convective development and evolution.

The first order of business each afternoon was to examine the previous day's model-forecast soundings, focusing on the convective boundary layer (CBL) and the convective inhibition layer (CIN). This focus was motivated by two factors. First, the structure of the CIN layer and the CBL are a primary concern for severe weather forecasters, so it is important to identify and document characteristic model behaviors in generating these layers. Second, these structures are strongly modulated by a model's physical parameterizations, especially those of the planetary boundary layer (PBL), so identification of systematic biases can provide valuable clues to help model developers improve physical parameterizations.

The next item on the agenda was an analysis of surface and surface-based fields. This included 2m temperature, dewpoint, and CAPE (convective available potential energy). In addition, specific elements of wind fields from the different forecasts were compared, including 0-6 km shear and 0-3 km helicity. These fields were all compared subjectively to locally derived 3-D objective analysis fields based on a 1 h RUC (Rapid Update Cycle - see Benjamin et al. 2004) forecast and all available


Temperature:
WRF-ARW4: -5 -4 -3 -2 -1 0 1 2 3 4 5 N/A
WRF-NMM4: -5 -4 -3 -2 -1 0 1 2 3 4 5 N/A
WRF-ARW2: -5 -4 -3 -2 -1 0 1 2 3 4 5 N/A

...DISCUSSION...
All model guidance indicates warm region over SW NE. NMM4 carried thermal axis too far north, similarly with ARW2. NMM4 better in eastern NE. Emphasis on the character of the air feeding the convection in western NE.

Fig. 3. Sample evaluation form used for subjective evaluation of surface-based thermodynamic and wind fields.

observations (Bothwell et al. 2002). These objective analysis fields, collectively called SFCOA, were treated as reference points for assessing the relative magnitudes of each of the forecast fields. Specifically, model forecast fields were assigned a value from -5 (much lower) to 5 (much higher), indicating their relative magnitudes compared to the corresponding SFCOA field (see

	EMC	**NCAR**	**CAPS**
Dynamic Core	NMM	ARW	ARW
Horiz. Grid Spacing (km)	4.5	4.0	2.0
Vertical Levels	35	35	51
PBL/Turb. Param.	MYJ	YSU	YSU
Microphysical Param.	Ferrier	WSM6	WSM6
Radiation Param. (SW/LW)	GFDL/GFDL	Dudhia/RRTM	Dudhia/RRTM
Initial Conditions	00Z 32 km Eta	00Z 40 km Eta	00Z 40 km Eta

Table 1. Model configurations used for the high resolution forecasts. NMM: Nonhydrostatic Mesoscale Model (Janjic et al. 2005); ARW: Advanced Research WRF (Powers and Klemp 2004); MYJ: Mellor-Yamada-Janjic (Janjic 2001); YSU: Yonsei University (Noh et al. 2003); Ferrier: Ferrier et al. (2002); WSM6: WRF single moment, 6 class microphysics; GFDL: Geophysical Fluid Dynamics Laboratory (Tuleya 1994); Dudhia: Dudhia (1989); RRTM: Rapid Radiative Transfer Model (Mlawer et al. 1997; Iacono et al. 2000).

Fig 3). As with the sounding analysis, these assessments focused on areas that were not contaminated by ongoing or recent precipitating convection - ideally in the preconvective or convective inflow environment. This strategy proved to be quite useful for documenting the relative biases of the different configurations in predicting selected fields that are frequently examined by severe-weather forecasters.

As a separate component of the surface analysis, low-level air mass boundaries were analyzed in observational data and in each of the model forecasts. Boundary positions were compared and the association between boundaries and convective initiation was assessed. Results from this component of the surface analysis are being compiled and will be presented in a later paper.

The third major element in afternoon activities involved observed and model-predicted precipitation fields. For this element, equivalent reflectivity factors were derived from the model-predicted hydrometeor fields (see http://www.atmos.washington.edu/~stoeling/RIP_sim_ref.pdf for a description of the reflectivity algorithm, developed by M. Stoelinga, University of Washington, 2005) and compared to observed reflectivity fields from WSR-88D radar data. Specifically, model-derived reflectivity based on hydrometeor fields at Z = 1 km AGL were compared to observed base (lowest elevation angle) reflectivity. The reflectivity fields were used to infer characteristics of convective initiation and evolution. Each model forecast was given a separate rating (on a scale of 0 to 10) for initiation and evolution, based on its correspondence with observed reflectivity.

Additional activities also took place each afternoon. For example, model output fields were interrogated using algorithms similar to the National Weather Service's mesocyclone detection algorithm (MDA - see Stumpf et al. 1998). Mesoscale circulation centers detected in model output were compared to operational MDA alerts. Analysis of this comparison is just getting underway and will be the subject of a future paper.

3. RESULTS

3.1 *Sounding Analysis*

Since the EMC and NCAR forecasts used approximately the same resolution, but provided a distinct contrast in physical parameterizations, model-sounding analysis focused on output from these two runs. The 24 h forecast time (0000 UTC) was emphasized because observed soundings were available for comparison. Sounding locations in close proximity to developing or ongoing convection were favored, but a top priority was to select locations where none of the soundings (simulated or observed) was contaminated by ongoing or recent convective activity. In practice, this meant that many of the model soundings that were compared to RAOBs came from locations in the warm sector, sometimes far removed from convective activity. Since the sounding sites were confined to the regional forecast/evaluation domain, only 2-3 sounding sites were examined each day. We also had the ability to compare model-forecast soundings over a fairly dense spatial network on an hourly basis. This capability was useful for direct comparisons between models and for achieving better proximity to active convection.

Comparisons with observed soundings were quite revealing, sometimes favoring the NCAR configuration, other times the EMC package. For example, Fig. 4 shows a forecast favoring the NCAR run, valid 0000 UTC 24 May at Dodge City, KS. The NCAR configuration produced a CBL that was slightly shallow and cool compared to observations, but the moisture profile in the CBL verified well (Fig. 4a). The model did not reproduce the sharpness of the CIN layer and it was relatively lacking in small-scale structure at all levels, but the general shape of both the temperature and dewpoint curves was reproduced well by the model. (Note, however, that the model's moisture profile appears to be shifted downwards relative to observations. This would result in significant errors in a level-by-level assessment in spite of the good agreement in profile shape. This is one reason why subjective assessment of profiles is so important.)

In contrast, the EMC configuration produced a CBL that was much too shallow, cool, and moist (Fig. 4b). Analysis of hourly soundings leading up to this time revealed that the EMC sounding contained a cloud (saturated) layer at the top of a very shallow mixed layer up until about 2200 UTC. It appeared that incoming shortwave radiation was blocked, limiting surface heating and

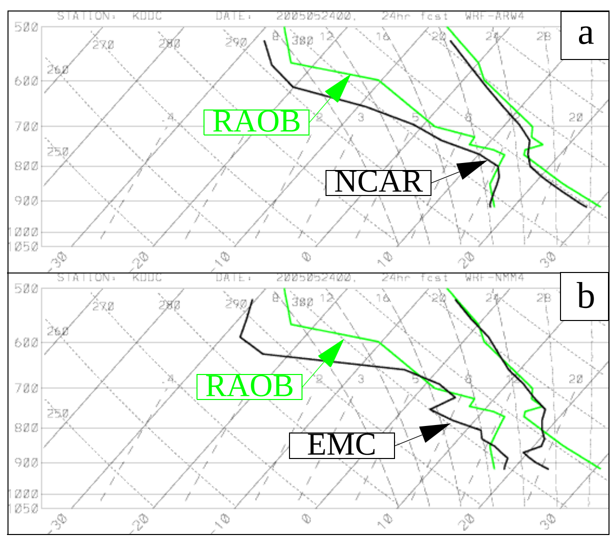


Fig. 4. 24 h model forecast soundings overlaid on the observed sounding, valid 0000 UTC 24 May 2005 at DDC. a) NCAR forecast, b) EMC forecast

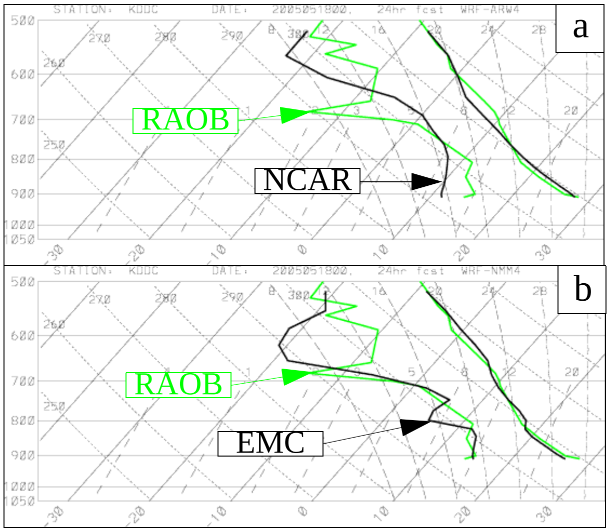


Fig. 5. 24 h model forecast soundings overlaid on the observed sounding, valid 0000 UTC 18 May 2005 at DDC. a) NCAR forecast, b) EMC forecast

inhibiting the growth of the CBL. Similar behavior was noted on other days as well.

However, the NCAR soundings had their own set of problems. For example, some of the undesirable tendencies from the NCAR run were evident one week earlier at the same location (Fig. 5a). In this case, the NCAR moisture profile was much too dry in the CBL and too moist just above. This pattern was repeated on other days, suggesting that the YSU PBL parameterization was mixing over a much deeper layer than the quasi-adiabatic layer in contact with the ground. Although the temperature profile looked quite good below ~800 hPa in this sounding, the stable layer above this point was considerably weaker than in observations, again suggesting that the PBL scheme was mixing over a much deeper layer. In this case and in others, the YSU PBL seemed to blur the distinction between the PBL, any shallow convection layer, and the free atmosphere.

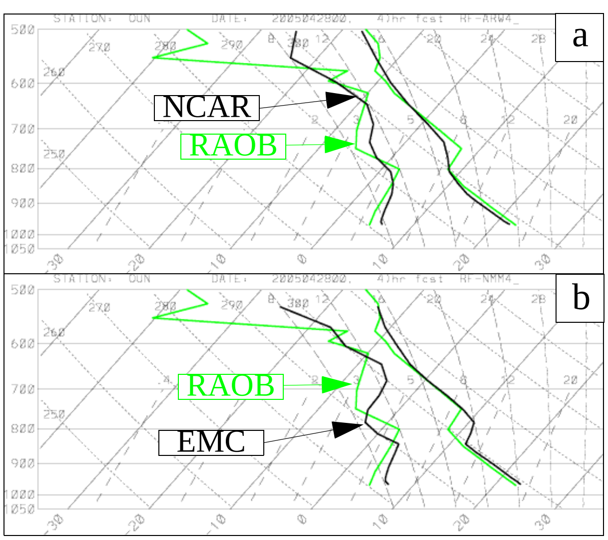


Fig. 6. 24 h model forecast soundings overlaid on the observed sounding, valid 0000 UTC 28 April 2005 at OUN. a) NCAR forecast, b) EMC forecast

Meanwhile, the EMC forecast showed much better agreement in both the CBL and CIN structure on this day (Fig. 5b). The temperature and moisture profiles in the CBL were just slightly cool and moist and the top of the PBL was clearly discernible in both profiles.

Variations of these characteristic behaviors were noted on other days. For example, on 28 April the NCAR run reproduced the CBL temperature and moisture profiles from Norman, OK quite well, but the CIN layer was much too weak (Fig. 6a). The EMC forecast captured the sharpness and strength of the CIN layer well, but its CBL was too shallow (Fig. 6b).

It is tempting to say that these differences can be explained by arguing that the YSU scheme mixes too strongly at the top of the CBL, leaving the layer too deep, warm, and dry, while the MYJ scheme entrains too weakly at the top of the CBL, resulting in the opposite biases in temperature, moisture, and CBL depth. While these general tendencies may be operative, the Spring Experiment assessment suggests that many other factors are important as well. Since results of the sounding analysis were documented primarily by descriptive summaries, a quantitative assessment of systematic biases is not available. However, a preliminary assessment of general tendencies, based on the written documentation

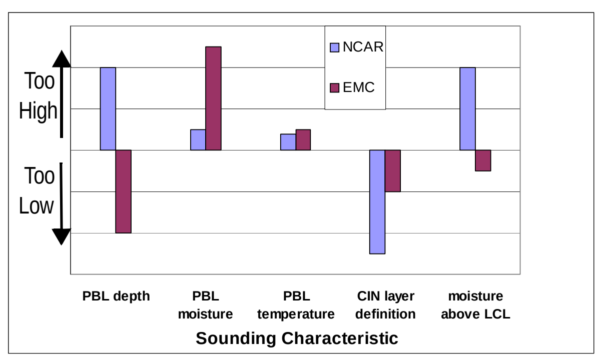


Fig. 7. Subjective assessments of sounding structures based on the interpretations and observations of the authors.

and the interpretations and observations of several of the authors, is presented in Fig. 7. As this figure indicates, for the sounding locations examined during the program, the NCAR forecast tended to deepen the convective PBL too much, while the EMC run left it too shallow; boundary layer moisture was often overpredicted by the EMC forecasts, sometimes substantially, while the NCAR run seemed to have a slight moist bias; on average, both forecasts did quite well with PBL temperatures; the EMC run predicted the sharpness and strength of the CIN layer more accurately, and it did not appear to mix excessively with free troposphere.

These results suggest that sounding structures are modulated by numerous physical parameterizations, such as those for the the land surface, long-wave and short-wave radiation, and microphysics, in addition to PBL/turbulence. Furthermore, the interactions between these different parameterizations can be highly non-linear and complex. Comparisons with observed soundings provides a particularly challenging test for any modeling system and improving the WRF model's prediction of sounding structures is a significant challenge for model developers.

A comprehensive collection of observed and model-forecast soundings is available online at URL http://www.spc.noaa.gov/exper/Spring_2005/sndgcomp/. This site provides links to plots of model soundings overlaid on observed profiles for 0, 12, and 24 h forecasts from all 3 models for the entire period of the Spring Experiment. Furthermore, it contains plots and tables of differences between many observed and predicted fields.

3.2 *Surface Analysis*

Results from analyses of surface-based fields are consistent with those of the sounding analysis. Recall that the surface analysis focused on the pre-convective environment. Areas that were clearly contaminated by ongoing or recent precipitating convection were not considered. The output fields that were analyzed for these assessments are all available online, following the links to individual days from <http://www.spc.noaa.gov/exper/Spring_2005/archive/calendar.html>.

Compared to our benchmark SFCOA field, the 2 m dewpoint output from the EMC run was, on average, quite high (Fig. 8). In comparison, CAPS forecasts of this field had a considerably lower, though still positive bias, while the bias from the NCAR run was very small.

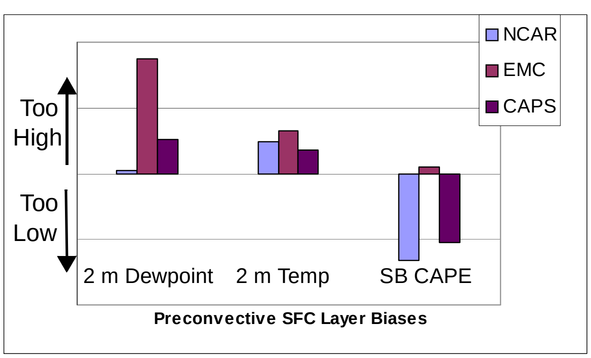


Fig. 8. Subjective assessments of pre-convective 2 m dewpoint, 2 m temperature, and surface-based CAPE relative to the SFCOA field.

Differences between all moisture biases are statistically significant at the 95% level.

Biases in the 2 m temperature field were much more similar (Fig. 8). All models had a weak warm bias and differences between the models were not statistically significant.

Comparative analysis of the surface-based CAPE field requires some explanation. The software used to generate the SFCOA field used virtual temperature in the computation of CAPE, whereas the model post-processing software did not. Thus, the CAPE field from the models was inherently lower than the corresponding SFCOA field. For example, the NCAR forecasts, which had small positive biases in both temperature and dewpoint, had a strong negative bias in CAPE. Presumably, if virtual temperature effects had been included in post-processing of model output, the NCAR run would show a small positive bias in the CAPE field. Similar adjustments would be appropriate for the CAPE results from the EMC and CAPS forecasts. With such an adjustment for all models, CAPE field biases would likely be similar to those of 2 m dewpoint. Regardless, it can be seen that the EMC runs produced significantly higher CAPE fields than either of the other two forecasts and the CAPS run is somewhat higher than the NCAR forecast. Differences between all models are statistically significant.

3.3 *Convective Initiation and Evolution*

As described previously, convective initiation and evolution from each of the forecasts were inferred from the simulated 1 km AGL reflectivity fields. Each forecast was rated on a scale of 0 to 10, according to its correspondence with observed base-reflectivity fields. The process of assigning ratings often generated considerable discussion; final ratings were decided by consensus of all participating forecasters and researchers on a given day.

Although there were sometimes significant differences in forecasts for a particular event, the models earned similar average ratings (Fig. 9). In fact, none of the differences in mean ratings is statistically significant. Ratings for individual forecasts, along with the images on which the ratings are based, are available from the web site given in the previous subsection.

A noteworthy general observation relates to differences between the NCAR and CAPS forecasts. Recall that these forecasts were generated using the same dynamic core and physical parameterizations. The primary difference in model configuration was spatial resolution. The CAPS run often initiated convection about an hour before the NCAR forecast and it earned higher ratings (significant at the 94% confidence level), suggesting the earlier initiation was usually more consistent with observations. Furthermore, detailed examination of

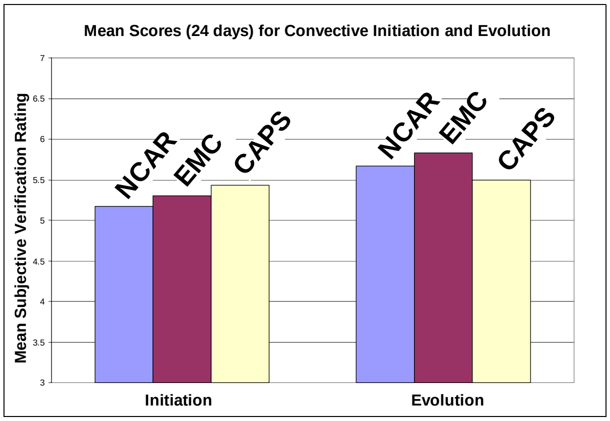


Fig. 9. Mean subjective ratings for convective initiation and evolution forecasts from all three high resolution models. Note that none of the differences are significant at the 95% level.

small-scale reflectivity features and mesocyclone signatures suggested that the CAPS forecasts generated supecell-like structures more frequently. But in terms of the mesoscale character, organizational tendencies, and evolution of convective systems, the two forecasts were remarkably similar on most days. Sounding structures were also very similar. These results suggest that there was not much added value in going from 4 km to 2 km grid spacing. It is not clear how general this result may be. Perhaps it is related to the fact that severe convective activity was anomalously quiet during this year's Spring Program.

4. SUMMARY

The 6th annual SPC/NSSL Spring Experiment was conducted in Norman, Oklahoma's NOAA Hazardous Weather Testbed from April 18 - June 3, 2005. As in previous years, the experiment had both forecasting and model-evaluation components. This preprint focuses on the latter. Specifically, it provides an overview of subjective assessments of high-resolution (convection-allowing) configurations of the WRF model.

The model evaluation had three separate foci, each related to the specific interests of severe convection forecasters: 1) model-forecast sounding structure, 2) near surface and surface-based instability and kinematic fields, and 3) precipitation fields. The evaluation was designed to provide forecasters with an early benchmark for the performance of these high resolution models and to give feedback to model developers related to specific strengths and weaknesses associated with different model physical and dynamical algorithms.

The sounding analysis emphasized structural differences between forecasts from NCAR and EMC. These runs used similar initial conditions and resolution, but very different physical parameterizations, so it was hoped that specific biases in soundings could be linked to different physical parameterizations, leading to eventual improvement of the parameterizations. For example, numerous systematic biases appeared to be linked to the PBL parameterization. The NCAR forecasts, using the YSU PBL scheme, tended to yield smooth transitions between the CBL and the free atmosphere. While this type of structure may help minimize absolute errors in sounding verification, it makes it difficult to link sounding structures to distinct processes and phenomena (e.g., shallow convection); it blurs the distinction between PBL, shallow convection layer, and free atmosphere. This is undesirable because forecasters at the SPC and elsewhere sometimes lose confidence in a model forecast when they cannot link the solution to identifiable physical processes. In contrast, the EMC forecasts produced relatively sharp transitions between convective boundary layer and free atmosphere, but entrainment at the top of the PBL appeared to be too weak with the MYJ scheme. Forecasted PBL depth was frequently too shallow and moist, while saturated layers at top of PBL were too persistent. Again, the characteristic profiles associated with shallow convection layers were not evident.

A separate analysis of broader scale temperature, moisture, and instability fields yielded results that were generally consistent with the sounding assessment. For example, this surface-based analysis showed that the EMC forecasts tended to have considerably higher low-level moisture values than those from NCAR (and CAPS), resulting in higher CAPE values as well. Yet, while some of these characteristics were consistent with known biases of the the YSU and MYJ schemes, it is likely that parameterizations of other physical processes also impacted model-forecasted sounding structures. More work is needed to isolate the impact of the different parameterizations.

Precipitation fields were also examined and compared, primarily as a means of inferring the characteristics of convective initiation and evolution predicted by the models. On most days, forecasts from the NCAR and CAPS runs were remarkably similar. The higher resolution of the CAPS forecasts produced intriguing differences in smaller-scale structures on some days, but subjective verification suggested that these differences provided little, if any, added value to forecasters. On many days the EMC forecasts were qualitatively different from the NCAR and CAPS runs. Sometimes they were rated higher, sometimes lower. However, on average there were no statistically significant differences between any of the three high resolution forecasts in terms of perceived value for convective initiation and evolution forecasting.

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We were fortunate to have many very talented and dedicated contributors from the SPC. Aside from the authors, Doug Rhue, Jay Liang, and Gregg Grosshans applied their expertise to find solutions to many different data flow and display challenges. Linda Crank and Peggy Stogsdill provided valuable assistance with many organizational and technical issues. Greg Dial, Steve Goss, Jeff Peters, and Jon Racy volunteered to give up a week of their springtime forecasting shifts to work with us. Bob Johns came out of retirement to do the same.

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