A COMPARISON OF MESOSCALE ANALYSIS SYSTEMS USED FOR SEVERE WEATHER FORECASTING

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ABSTRACT

The relative performances of several mesoscale analysis systems are evaluated with regard to severe convective weather forecasting, by exploring their ability to reproduce soundings collected in pre-convective and near storm environments observed during the Verification of the Origins of Rotation in Tornados Experiment 2 (VORTEX2) field phase. This was done to investigate a greater use of mesoscale ensemble forecasts in the operational setting. Soundings that matched the geographical locations and release times of the VORTEX2 soundings were extracted from datasets of the Rapid Update Cycle (RUC) model, the Surface Objective Analysis (SFCOA) developed by the Storm Prediction Center, and a Weather Research and Forecasting (WRF) mesoscale ensemble system, developed at the National Severe Storms Laboratory (NSSL). Parameters and characteristics important to severe weather forecasting are extracted from the systems' datasets at the observed sounding locations and compared to the observations. Results show that the mesoscale ensemble forecasts, in many cases, produce smaller errors than the other mesoscale analyses considered when calculating the planetary boundary layer height, surface based convective available potential energy, the surface based lifted condensation level, and near surface temperatures and dew points. Findings thus far display the potential of the mesoscale ensemble models to produce an accurate depiction of the mesoscale environment.

1. INTRODUCTION

An accurate depiction of the mesoscale environment is important to the forecaster in identifying the potential severe weather threat. Analyses of mesoscale observations from the surface and radiosonde networks provide valuable information about pre-convective and near-storm environments, but are too coarse in time and space. While not perfect, numerical weather prediction (NWP) model guidance compliments observations, as the same convective storm parameters [e.g., convective available potential energy (CAPE) and shear] important to severe weather forecasting can be calculated from the three-dimensional fields they generate (Coniglio 2012). Forecasters have a variety of mesoscale analysis systems to utilize, and as computer resources increase, ensemble based forecasts are gaining more consideration for operational applications. Since NWP models are staples for forecasters, it is important to evaluate these systems in order to understand their performance characteristics to assist the forecaster in providing guidance to the public during severe convective weather events.

One mesoscale analysis system used for the continental United States (CONUS) is the Rapid Update Cycle (RUC) model, developed by NOAA and the Earth Systems Research Laboratory and operated by NOAA and the National Centers for Environmental Prediction (NCEP) (Benjamin and Sahm 2012). This model provides single, deterministic analysis and forecasts out to eighteen hours (Benjamin and Sahm 2012). Resulting from this is a frequent (i.e., hourly) means of analyzing the variability of the atmosphere designed with the purpose to aid severe weather forecasters as well as those in aviation (Benjamin et al. 2010). This model serves as a first guess in the Storm Prediction Center's (SPC) mesoscale analysis system, the Surface Objective Analysis (SFCOA), also for the CONUS domain (Hart et al. 2012). (It should be noted

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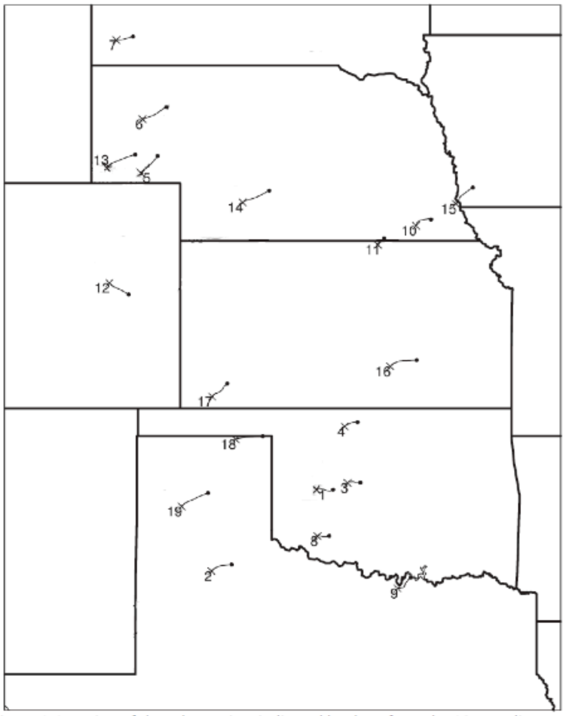

Figure 1. Location of the release sites indicated by the x from the 19 soundings used as well as their path with their termination of the collection of data displayed by the circle. Numbers by x's indicate sounding number (Coniglio 2012).

that recently the Rapid Refresh (RAP) system has replaced the RUC model as first guess to SFCOA). These analyses are generated by merging objectively analyzed surface data with the RUC pressure level fields above the surface, valid at the same time. The SFCOA is used by the SPC with the purpose of forecasting severe convective weather for CONUS (Stensrud et al. 2003).

A mesoscale ensemble system that has not been used in operations largely but shows potential in reproducing mesoscale environments, is an ensemble based on the Advanced Research and Weather Research and Forecasting Model (ARW-WRF) (hereafter, ENS) (Wheatley et al. 2012). Fujita et al. (2007) display the ability of using this model system with the ensemble Kalman filter (EnKF) technique on predicting the planetary boundary level (PBL) height, which in NWP models can influence near surface conditions (Kain et al. 2005). Shear and moisture near surface conditions (under one kilometer above ground level (AGL)) can be a factor in differentiating supercell thunderstorm classes (Thomson et al. 2002). This finding by Thomson et al. (2002) exhibits the importance of accurate PBL heights (Wheatley et al. 2012).

An ensemble system consists of a collection of analysis/forecasts, from each constituent ensemble member, which are then averaged to form an ensemble mean for the final product (Wheatley et al. 2012). The EnKF can be used in conjunction with this technique to assimilate observations at the time of analysis, which has shown the potential to improve severe convective weather forecasts (Wheatley et al. 2012). These ensemble members have varied physical parameterization schemes (listed in Section 2) to account for model physics uncertainty (Wheatley et al. 2012). In addition, each member has slightly perturbed initial conditions to account for the relatively unknown state of the atmosphere (Wheatley et al. 2012). This type of system is being explored as a component to the current NOAA/NSSL project “Warn-on-Forecast,” which has potential to increase warning lead times of severe convective weather (Stensrud et al. 2009).

These mesoscale analysis systems are evaluated using vertical atmospheric profiles (of temperature moisture and winds) collected by radiosondes during the field phase of the Verification of the Origins of Tornadoes Experiment 2 (VORTEX2) (NSF/NOAA). Radiosonde data was collected prior to and during storms in order to obtain information on environments supportive of tornadic supercells (Atkins et al. 2012). The purpose of this study is to expand upon Coniglio (2012) considering the potential use of ENS products in mesoscale forecasting by analyzing their ability to reproduce VORTEX2 soundings from May and June of 2009. Coniglio (2012) considered the models already in use in operations.

Section 2 presents the methodology used to verify the model products. Errors and performance evaluations of the models are discussed in Section 3. Section 4 summarizes the findings and concludes the work.

2. Methodology

a. The Models

As stated in the introduction, three mesoscale analysis systems are considered as part of this research: the RUC model, the SPC's comprehensive

Table 1. Case number, dates, locations in latitude and longitude, and release times of the 19 soundings that were used from May and June of 2009 from VORTEX2 (Coniglio 2012)

	Date	Time (UTC)	Lat (°N)	Lon (°W)
1	11 May 2009	2201	35.501	98.986
2	12 May 2009	2151	33.954	101.359
3	13 May 2009	2200	35.625	98.296
4	15 May 2009	2138	36.667	98.358
5	19 May 2009	2002	41.156	102.935
6	20 May 2009	1915	42.096	102.901
7	22 May 2009	2055	43.420	103.481
8	25 May 2009	2336	34.636	98.966
9	26 May 2009	2231	33.650	97.170
10	31 May 2009	1833	40.255	96.748
11	1 Jun 2009	1926	39.929	97.613
12	4 Jun 2009	1818	39.264	103.670
13	5 Jun 2009	1808	41.219	103.661
14	6 Jun 2009	2048	40.663	100.648
15	7 Jun 2009	2046	40.639	95.858
16	9 Jun 2009	1912	37.761	97.336
17	10 Jun 2009	2133	37.197	101.339
18	12 Jun 2009	2028	36.440	100.803
19	13 Jun 2009	2002	35.188	102.010

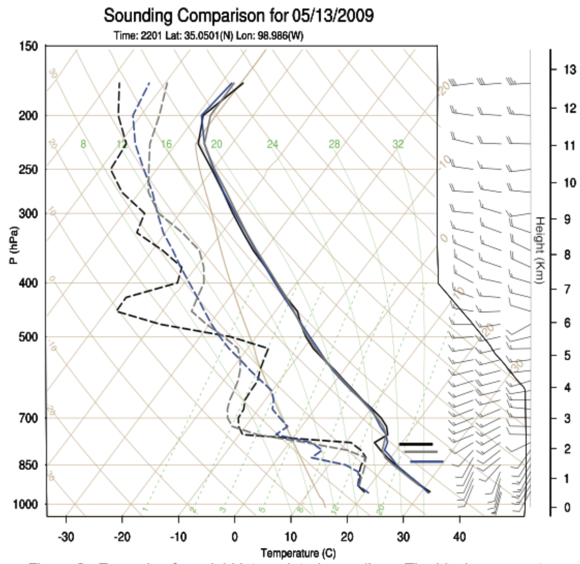

Figure 2. Example of overlaid interpolated soundings. The black represents VORTEX2, grey is ENS00 and blue represents RUC00. Dew point temperatures are depicted by dashed lines and solid lines are temperature profiles. Planetary boundary layer heights are indicated by the bars in the lower left.

analysis scheme, SFCOA, and the WRF mesoscale data assimilation. Each model system examined has distinctive characteristics in their operational design as well as the data assimilation technique employed, which can lead to slight variations in their final products. The latter ensemble system was developed at the National Severe Storms Laboratory (NSSL), and in this study is based off of the WRF-ARW version 3.3.1 (Skamarock et al. 2008). The ENS utilizes a CONUS domain with horizontal grid of 15 km and 51 vertical levels. The physical parameterization schemes were varied to account for model physics uncertainty, such as planetary boundary layer physics options, cumulus parameterization schemes, and shortwave radiation schemes. In addition, each member has slightly perturbed initial conditions to account for the unknown actual conditions of the atmosphere (Wheatley et al. 2012). The EnKF technique is used within this system to assimilate the observations available described by Wheatley et al. (2012 see p. 1543).

The RUC model uses 13 km horizontal grid spacings with fifty vertical levels. It uses a single prescription of physical parameterizations to produce single analyses and forecasts, and assimilates observations using three-dimensional variational technique (3DVAR) described in detail by Benjamin et al. (2004; 2010). The SFCOA objectively analyzes the surface observations using a two-pass Barnes Scheme on 40 km horizontal grid spacings (Barnes 1973). Both the RUC and SFCOA have a CONUS domain as well.

b. Verification

Radiosondes collected over the Great Plains (Fig. 1) during the field phase of VORTEX2 during May and June of 2009 (Table 1) are the primary tools for evaluating of the relative performance of the models. These soundings provide vertical profiles of the temperature, dew point temperature, winds, and pressure heights. These variables are crucial in themselves, in addition to their use in calculations of parameters forecasters use for severe convective weather. It is important to note that these soundings are independent from the model data sets, as the VORTEX2 sounding data has not been assimilated into the models. The VORTEX2 soundings are quality controlled by the National Center for Atmospheric Research/Earth Observing Laboratory (NCAR/EOL) to assure reliable means of comparison as well as additional means (see Coniglio 2012 pg 10).

Data for RUC was provided on constant pressure levels at 25hPa increments from 1025 hPa – 100 hPa. Soundings from the other mesoscale analysis systems are interpolated to match these levels, including the VORTEX2 soundings. These mesoscale analysis systems are then interpolated to match the radiosondes' path temporally and spatially. This was done since on average, the balloon had a time lapse of 40 minutes and a horizontal path of 55 kilometers. Since the ENS is a collection of forecasts, the ensemble mean forecast is interpolated and used, in order to have a single product to analyze in comparison to the single model datasets from SFCOA and RUC. These interpolated soundings (Fig. 2) are then used to calculate environmental characteristics important to severe storm forecasting as well as other soundings parameters, including the planetary boundary layer height which is defined as the height at which the virtual potential temperature exceeds the average virtual potential temperature of the lowest 25 hPa by .5 K. Calculations of characteristics and parameters are matched to Coniglio's calculations to ensure a fair comparison. Relative performances on the characteristics and parameters calculated are assessed by model errors calculated by subtracting the observation from the forecast. These are further analyzed by finding the error magnitude, or root mean square difference (rmsd), and by calculating the bias, or mean error. Comparisons will be made especially between the SFCOA, RUC01, and ENS01 to display the potential usage of the ENS01.

3. Results

Vertical profiles of the rmsd are presented for vector wind, temperature, and relative humidity for the 0-h forecasts from RUC and ENS (Fig. 3). In general, the trend is a smaller rmsd for ENS00. For vector wind, ENS00 has a smaller error magnitude in the upper and lower troposphere, including the near surface. In the mid-troposphere the error magnitudes are comparable, both on the order of 3-4 m/s. Otherwise, the difference in error magnitudes between the two is approximately 1-2 m/s, with ENS00 possessing smaller errors. The vertical temperature errors depict a comparable performance between the RUC00 and ENS00 with both error magnitudes under 2 K. Smaller magnitudes

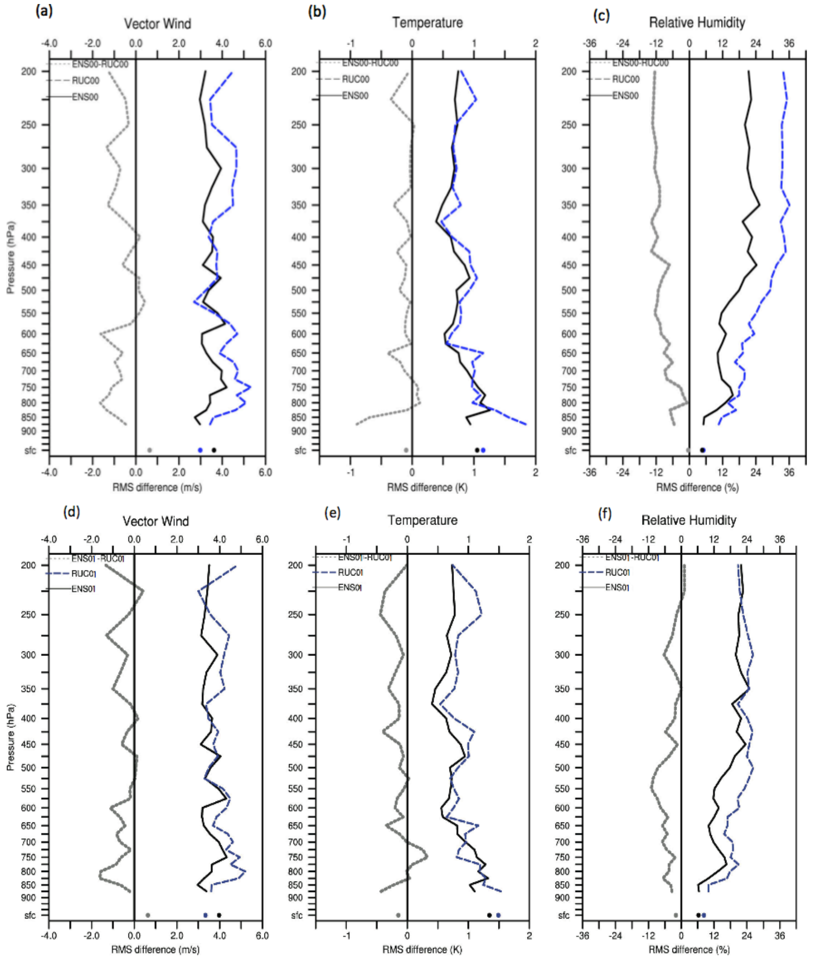

Figure 3. Vertical profiles of ENS and RUC average error magnitude (rmsd) for vector wind 0-h (a) and 1-h (d), temperature for 0-h (b) and 1-h (e) , and relative humidity for 0-h (c) and 1-h (f) are displayed from 875 hPa to 200 hPa as well as the surface rmsd values displayed by the filled in circles. The blue represents RUC, black indicates ENS, and the grey indicates the difference in performance.

of error are evident for ENS00 below 850 hPa (1 K for ENS00 and less than 2 K for RUC00 at 875 hPa). The relative humidity profile displays more of a difference in performance in ENS00 and RUC00, with error magnitude differences of 5% near the surface and as much as 15% near the tropopause. Both model datasets show an increase of error magnitude aloft. A greater error aloft for moisture has also been displayed by Coniglio (2012) Colle et al. (2003), Eager et al. (2007), and Rakesh et al. (2009). Nash et al. (2005) have noted that moisture content show greater heterogeneity in the mid- and upper troposphere.

Vertical error profiles for RUC01 and ENS01 (Fig. 3) display the same general trend as ENS00 and RUC00, with lower rmsd values for the ENS00. However, the performance between the two model datasets is more comparable. Vector wind errors calculated from ENS01 are smaller than those of RUC01 by 1 m/s, although this difference increases to 2 m/s in the lower and upper

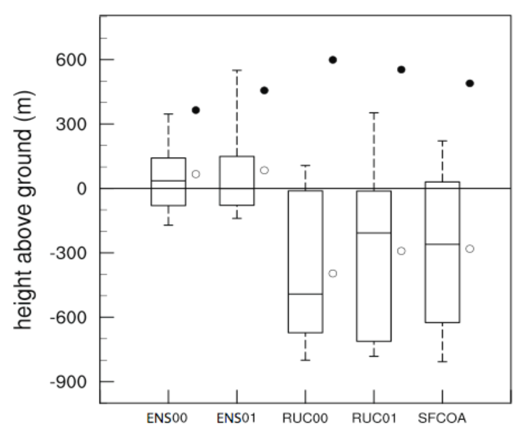

Figure 4. Boxplots of Planetary Boundary Layer (PBL) height error display the distribution of the errors (forecast-observation) for each model system product. The filled in circles display the rmsd and the outlined circles represent the biases for the systems products to its left. The middle 50 percent of error distribution is encompassed by the box with the bottom and top edge representing the 25th and 75th percentile. The median is represented by the horizontal line within the box. The dashed lines display the range of 15% of error as the bottom extends to the 10th and 19th percentiles.

troposphere. Temperature variables show error differences of about 1 K with lower errors in ENS01, but RUC01 has a smaller rmsd value from 700 hPa – 800 hPa. Relative Humidity has a difference in error magnitude of 0-10% with ENS01 having the minor error values.

Another way error was displayed and compared was through the use of box plots (Fig. 4) to show error spread, bias, and rmsd. Planetary boundary layer (PBL) height determines the height of which to mix properties such as temperature and moisture (Vogelezang and Holtslag 1996). Biases are low on the order of -300 m above ground level (AGL) for both the SFCOA and RUC products indicating PBL heights that are too shallow, Over 60% of the cases from SFCOA and RUC01 result in heights too shallow. Shallow PBL heights from NWP models can result in cooler surface temperatures as well as moister environments as a result of under mixing (Coniglio 2012). The error magnitude is slightly reduced from RUC01 being 550 m AGL to the SFCOA yielding a value of 500 m AGL with both products containing biases of approximately 300 m AGL too low. Both ensemble products produce smaller rmsd, as well as bias magnitudes (positive). The ENS products produce biases of approximately 100 m too deep, which result in over mixing within the model, potentially leading to warmer and dryer near surface conditions. The error distribution for ENS products is significantly smaller than the SFCOA, ENS01 is centralized between -100 m AGL and 150 m AGL compared to the SFCOA spread of 125 m AGL to -625 m AGL.

Surface temperatures and dew point temperatures (Fig. 5) error magnitude for the model products is less than 2 K. In both cases, SFCOA reduces the error magnitude when compared to RUC01. The SFCOA has rmsd value of 1.5 K for dew point temperature 1 K for temperature in comparison for RUC01 corresponding values of 2 K and 1.5 K. The ENS01 has a lower value being an error of 1.2 K for rmsd. The SFCOA bias is also lower for 2m dew point compared to the RUC01 by 1.6 K, although it becomes a dryer bias compared to a moist RUC01 bias. The ENS01 has a near zero bias in the 2 m dew point, and comparable but opposite biases in the 2m temperature, .2 for ENS01 and -.2 for SFCOA.

The lowest average 30 hPa temperature and dew point temperature (Fig. 6) are presented in order to lessen any adverse affects of undesirable launch conditions on the near surface temperatures, as optimal conditions and preparation for the radiosonde launch could not always be guaranteed (Coniglio 2012). As mentioned earlier, the potential effects of under and over estimating the PBL can be observed. Both ENS products have biases being dryer and warmer, corresponding with overestimating PBL heights, and vice versa for SFCOA and RUC products. Error magnitudes still remain under 2 K for both temperature values. The SFCOA has lower error magnitudes for

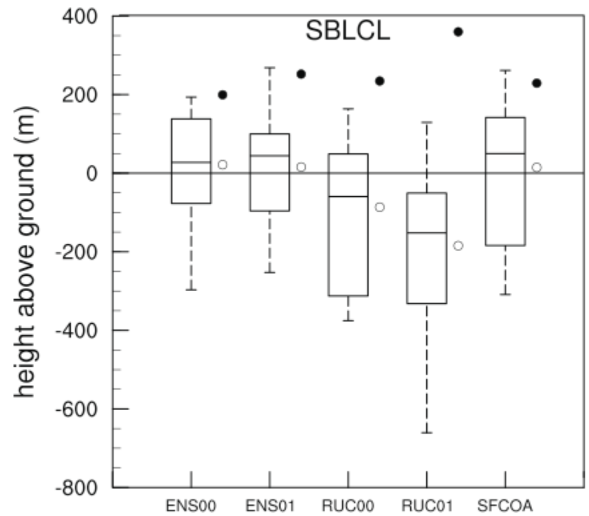

Figure 7. As in Figure 4, but for surface base lifted condensation level.

temperature and dew point temperature as well as the average 30 hPa dew point bias when compared to RUC01. The SFCOA's bias is 1 K compared to RUC01 error magnitude of 1.6 K. The bias is smaller than the RUC01 by .6 K . Error magnitudes for ENS01 are comparable to SFCOA, too large by .1 K in dew point temperature or lesser than by .4 K in temperature. ENS01 has an opposite, negative bias than SFCOA but of similar values varying by .2 K in average 30 hPa temperatures and .4 K in dew point temperatures.

Lifted condensation level (LCL) for surface based parcels is the height at which a parcel lifted from the surface reaches saturation (Fig. 7). This parameter can assist in identifying the potential of significant tornados (Coniglio 2012; Thompson et al 2003). The SFCOA improves upon the forecast of the SBLCL height by decreasing the error magnitude by 100 m AGL from RUC01 and minimizing bias magnitude to near zero from the negative bias of RUC01 of 200 m AGL. ENS01 has comparable values of bias and rmsd to the SFCOA, but has a more centralized spread around the zero error

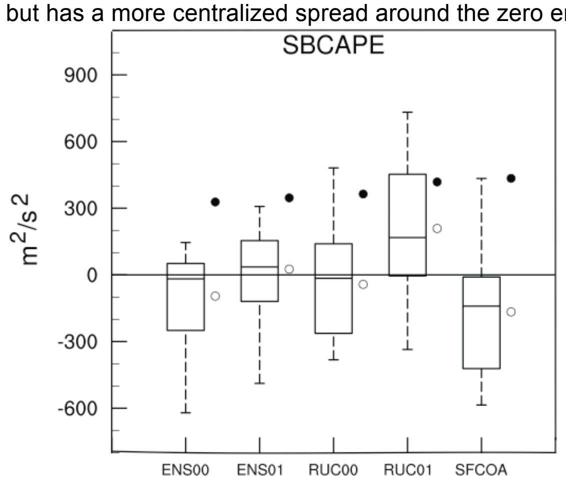

Figure 8. As in Figure 4, but for surface base convective available potential energy.

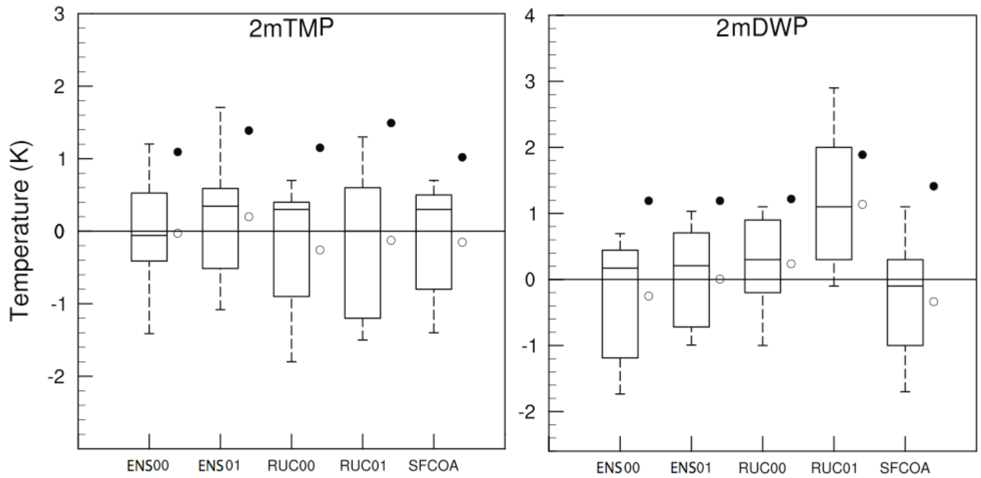

Figure 5. As in Figure 4, but for two meter temperature and dew point.

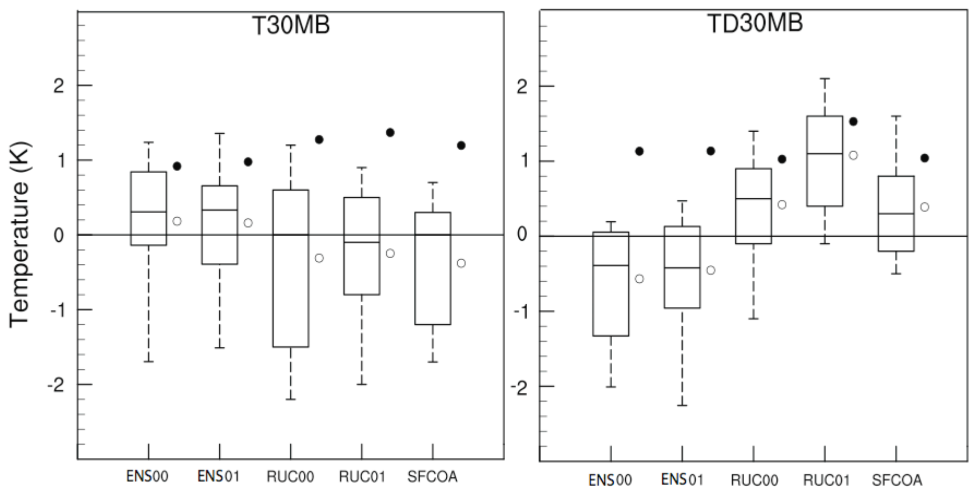

Figure 6. As in Figure 4, but for the lowest 30 mb average temerature and dewpoint.

ranging from 100 m too high to 100 m too low compared to the SFCOA of 150 m too high and 180 m too shallow.

The last computed parameter is surface based convective available potential energy (Fig. 8), which is a measure of the instability for a surface originating at the surface (Thompson 2012). The ENS01 has a lesser rmsd by 50 m^2s^{-2} than both SFCOA and RUC01. ENS01 also has a smaller 50 percentile error spread centralized around zero from 150 m^2s^{-2} too large to 125 m^2s^{-2} to low. The RUC01 and SFCOA contain 50 percentile spreads either above or below the null error. The ENS01 has a smaller bias magnitude being slightly too high, but in magnitude being 200 m^2s^{-2} less than SFCOA and RUC01.

4. Summary & Conclusion

This study expands upon the evaluation of RUC and SFCOA produced by Coniglio (2012) to include the WRF-based mesoscale ensemble system (referred to as ENS00 for analyses and ENS01 for 1h forecasts). This is done to display the model system's potential in severe convective weather forecasting, as it is being compared to mesoscale analysis systems already in use. These systems are staples for forecasters as they depict the mesoscale environment, which is crucial when identifying the threat of severe convective weather. Since these systems are heavily utilized, it is important to evaluate the relative performances of each to help forecasters provide guidance to the public. The relative performance of several parameters and environmental characteristics are computed, analyzed, and displayed in a way to allow for comparisons between the model datasets. Vector wind, temperature, and relative humidity vertical profiles of rmsd depicted a trend between the 0-h and 1-h forecasts. For vector wind, ENS00 and ENS01 contained smaller error magnitudes in the lower and upper troposphere. The temperature profiles displayed smaller rmsd errors for

ENS00 and ENS01 below 850hPa with similar performances aloft. Lastly, ENS00 and ENS01 rmsd errors were lesser than those of the RUC00 and RUC01 throughout the troposphere for relative humidity. These trends were more apparent in the 0-h forecasts and lessened in the 1-h forecasts since error magnitudes are more comparable. When error was analyzed by distribution, bias, and rmsd, it further showed the potential of ENS products, as the performances either produced smaller errors, or relatively comparable. The PBL height errors were smaller in the ENS00 and ENS01 with a slight overestimate in the height. With RUC products, there was a larger negative bias with larger spreads of error distribution favoring shallower PBL heights. SBLCL biases and rms errors were of similar magnitudes between SFCOA and ENS01, and lastly for SBCAPE, ENS01 has the lesser bias as well as rmsd error.

These results show the early potential of ensemble models using the EnKF to recreate an accurate depiction of the mesoscale atmosphere that is comparable to models already in use. To further this study, a total of 40 soundings from May and June of 2009 and 2010 are to be used to alleviate the effects of outliers. Also, more parameters and environmental characteristics need to be analyzed, such as the level of free convection, mixed layer and most unstable convective available potential energy and convective inhibition, shear and the significant tornado parameter. Statistical tests to determine the significant difference of errors will also be performed this study. Though more testing needs to be performed, ENS thus far has displayed its potential with the characteristics and parameters employed in this study.

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