1. INTRODUCTION

A complex winter storm affected much of the eastern United States from 7 to 8 March 2008. The storm produced severe weather over the southeast on the 7th including tornadoes in Georgia and Florida and severe thunderstorms from Virginia to New on the 8th. Severe storm reports are summarized in Table 1. On the cold side of the storm, mainly north and west of the 850 hPa low track, the storm produced heavy snow. The heaviest snow was observed in the Ohio Valley from northern Alabama to northern Ohio. A records snowfall of 20.5 inches was observed in Columbus, OH, breaking a record that had stood for 98 years (Table 1). As much as 14 inches of snow was observed in the suburbs of Louisville, KY. On the warm side of the storm, heavy rainfall was observed from central Pennsylvania eastward into New Jersey and New York. Rainfall ranged from 1 to 3 inches across the region.

There is inherit uncertainty in weather forecasting due to the chaotic nature of the dynamical system (Lorenz 1960; Palmer 2005). Uncertainty in the initial conditions, computational representations of the basic equations, and the model physics can cause forecasts errors. There is also a flow-dependent impact on the forecast. Some regimes are more predictable than others.

Ensembles are best suited to forecast weather systems where there is potentially high uncertainty. Palmer et al. 2005 demonstrated that multi-model ensembles are superior to single-model systems.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wind</th>
<th>Hail</th>
<th>Tornado</th>
<th>Sum</th>
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<td>3</td>
<td>17</td>
<td>49</td>
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<tr>
<td>8-Mar</td>
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<td>54</td>
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<tr>
<td>Sums</td>
<td>79</td>
<td>7</td>
<td>17</td>
<td>103</td>
</tr>
</tbody>
</table>

Table 1. Storm Prediction Center summary of severe weather by date and by event. Events include wind, hail, and tornadoes.

Identification of areas of high uncertainty and arriving at a probabilistic forecast. A single deterministic model is a binary yes/no forecast. There, in areas of high uncertainty ensembles offer a practical means to address the range of potential outcomes and assess the most likely outcome (Toth et. al 2001). The practical use of ensembles and the economic impacts of ensembles have been demonstrated by Zhu et. al. 2002.

This event was relatively well forecast by the National Centers for Environmental Predictions (NCEP) Global Ensemble Forecast System (GEFS; Szunyogh and Toth 2002) 2-4 days in advance of the storm. There was considerable variation in the NCEP Global Forecast System (GFS) forecasts of this storm in the 3-8 range. The GFS is the model core of the GEFS. Thus, the NCEP GEFS has some limitations, relying on single model core, as outlined by Palmer et. al. 2008. To compensate for this single model limitation, NCEP has partnered with Meteorological Services of Canada (MSC) to share ensemble data between NCEP and the Canadian Meteorological Center (CMC). This allows for the production of a multi-model ensemble known as the North American Ensemble Forecast System (NAEFS).
For short-range forecasting, NCEP provides a high resolution Short-range ensemble prediction system (SREF: Du et al 2004, Grumm and Du 2005, Stensrud et al 1999). The SREF covers North America and has 4 model cores with varied model physics. The SREF has shown considerable value and skill in forecasting a wide range of short-term weather forecast problems from severe weather (Manikin et al. 2004) to heavy rainfall (Yuan et. al 2007).

This event was relatively well forecast by the NCEP Global Ensemble Forecast System (GEFS) 2-4 days in advance of the storm and the NCEP Short-range ensemble prediction system (SREF) 1-3 days before the storm. It will be shown that the GEFS forecast 8-14 inches of snow at least 48 hours in advance in the Louisville area.

The note will document the late winter storm of 7-8 March 2008. The focus will be on the impact in the Mid Atlantic region and the forecasts from the NCEP ensemble prediction systems. It will be shown that both the heavy rainfall and heavy snow along with strong winds behind the cyclone were well forecast by the EPS’s. There was some uncertainty with the track of storm in longer ranges, on the order of 4-7 days in advance of the actual event.

2. METHODS and DATA

Data for this study include re-analysis climatological data from the NCEP/NCAR global re-analysis project (GR: Kalnay et al 1996). The means and standard deviations were used to compute standardized anomalies, displayed in standard deviations from normal (SDs).

The 00-hour forecasts from the NCEP North American Meso-model (NAM) system and Global Forecast System (GFS) are used to provide an overview of the large scale pattern and the evolution of the “Clipper” system.

Ensemble data shown here were primarily limited to the NCEP GEFS and SREF. Displays focus on the storm system and the precipitation type issues.

The climatological data used to compute anomalies was restricted to those produced by the NCEP/NCAR GR data set (Hart and Grumm 2001). They will be presented in relation to both NAM and GEFS output.

All data was displayed using GrADS. Anomalies were computed as described Hart and Grumm (2001) and Grumm and Hart (2001). Shaded values show the standardized anomalies computed as:

$$ SD = \frac{F - M}{\sigma} $$ (1)
Where $F$ is the value from the reanalysis data at each grid point, $M$ is the mean for the specified date and time at each grid point, and $\sigma$ is the value of 1 standard deviation at each grid point.

Anomaly data were applied to GFS, NAM, and GEFS output. When anomaly data are used with EPS data it should be noted that the large anomalies are often a good indication of agreement between members. Thus, the large anomalies in the pressure and temperature fields, as well as indicating a significant event also indicated high confidence in the forecast.

For brevity times are presented in the format of 08/0000 UTC which signifies 08 March 2008 at 0000 UTC. Forecasts from both model and EPS initial and valid times are presented in this format.

Snow and ice reports were obtained from NWS public information statements and the National Weather Service Cooperative network. These data were shown in Figure 2. Tragically, these products are not always consistent and cobbling together maps can be difficult.

Large scale rainfall estimates were derived from the unified precipitation data set (UPD: Higgins et al. 2000). These data were shown in Figure 1.

3. RESULTS

i. event overview from analysis

Figure 1 shows the liquid equivalent precipitation from the UPD dataset for the 24 hour period ending at 08/1200 UTC and the 48 hour period ending at 09/1200 UTC. The precipitation shield to the west, from northern Louisiana into northeastern Ohio was primarily observed as snowfall (Fig. 2). Some of the higher snow totals were displayed in Table 2. Along the coastal plain, the precipitation fell as rain. Heavy rain was observed in northern Florida,
associated with the severe convection observed in that region on the 7th.

Figure 3 shows the NCEP NAM 00-hour forecasts of the 850 hPa heights from 07/1200 UTC through 08/1200 UTC. Two waves evolved with the system, leading to the elongated 850 hPa low at 08/0000 and 08/0600 UTC. Areas to the north and west of the 850 hPa cyclone observed snow an old rule of winter storms demonstrated by Goree and Younkin (1966) and in general, rain was observed on the warmer, east side of the 850 hPa cyclone. If the EPS can predict the track of the 850 hPa cyclone in a winter storm, this can provide guidance on the regions susceptible for heavy snowfall.

The GFS 00-hour forecasts of 850 hPa winds, precipitable water (PW), and mean-sea level pressure are shown in Figure 4. These data show the surge of high PW area with 2-3SD above normal anomalies in the southeast associated with the initial surface cyclone. On the cold side of the system, an anomalous 850 hPa easterly jet with -3 to -4.5 SD anomalies was present over the central Mississippi Valley and extended northeastward up the Ohio Valley. Snow was falling over many parts of this region including Louisville at this time. Stuart and Grumm (2006) demonstrated the association of the 850 hPa easterly jet with heavy snowfall in East Coast Winter storms. This works will and compliments the rule established by Goree and Younkin (1966). If the EPS can predict the low-level easterly jet, the area of heavy snow may be more readily defined, given a thermal profile cold enough to support snowfall.

By 07/1800 UTC the 850 hPa southerly wind anomalies focused along the coastal plain and the easterly wind anomaly moved over the Ohio Valley (Fig. 5). The PW surge was pushing up the East Coast with the surface cyclone over northwestern Florida. An emergent heavy rain signal was developing over the East Coast with strong v-wind anomalies and high PW anomalies.

By 08/0000 UTC (Fig. 6) the easterly wind anomalies increased over the Ohio valley as the second and stronger surface cyclone began to move northward. The 850 hPa u-winds were -3 to -4 SDs below normal over the Ohio Valley. By 08/0300 UTC thundersnow⁴ was observed in portions of

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Figure 2 National snow analyses of snowfall (inches) on 8 March 2008.
the Ohio Valley. Along the coastal plain, strong v-winds and high PW anomalies were contributing to the rainfall over the region. The surface cyclone was over Georgia with -2SD MSLP anomalies.

By 08/0600 UTC the cyclone had moved over South Carolina (Fig. 7d). The strong north-northeast winds persisted over the Ohio Valley (Fig. 7b). The v-winds and moisture had moved off the coast of New England (Figs. 7a & 7c) with the first sheared out wave and a second surge was developing along the southeastern United States.

By 08/1800 UTC (Fig. 8) the surface cyclone was deepening and located over Virginia. The strong easterly wind anomalies had shifted into central Ohio, where a new record snowfall would be set (Table 2) crushing a 98 year old record, demonstrating the potential value of u-wind anomalies in having confidence in record to near record events. Along the coast, a second and stronger v-wind anomaly had developed along with the surge of moisture associated with the second and stronger cyclone. The v-winds and high PW are good signals for both heavy rains and severe convection.

By 08/1800 UTC (Fig. 9) the v-wind anomalies exceeded 5SDs above normal along the East Coast in close proximity to PW anomalies over +4SDs above normal. Not surprisingly between approximately 08/1500 UTC to 09/2100 UTC heavy rain and severe weather would develop from Virginia and into New York. Though not shown, radar imagery showed on northward

Figure 3 NAM 00-hour forecasts of 850 hPa heights (dm) from forecasts initialized at a) 1200 UTC 7 March, b) 0000 UTC 08 March, c) 0600 UTC 8 March and d) 1200 UTC 8 March 2008. Contours event 3dm.
propagating enhanced convective band in close proximity the strong low-level southerly jet around 08/1800 UTC. The 850 hPa easterly wind anomalies were pulling northeastward but still focusing over northeastern Ohio, where 12 inches of snow fell in the Cleveland area.

By 09/0000 UTC (Fig. 10) the cyclone was over southeastern New York State. The strong easterly wind anomaly had moved into Quebec, Canada. The v-winds and PW anomalies associated with heavy rainfall were aimed at southern Maine. Behind the cyclone, strong +u wind winds developed and u-wind anomalies of 3 to 4SDs above normal brought high winds to central Pennsylvania.

**ii. Forecasts**

Early forecasts, 5 days out (03/0000 UTC) show the surface cyclone weak and along the coast. The trends was for a stronger coastal cyclone on 8 March from forecasts initialized at 03/1200 UTC (Fig 11-left). Note the large area of 8 hPa and greater spread suggesting high uncertainty with the surface cyclone forecast.

By 4 March the GEFS began showing a stronger cyclone and showed a cyclone crossing the Delmarva at 08/0600 UTC from forecasts initialized at 04/1200 UTC (Fig. 11-center). The forecasts showed considerable uncertainty with the timing,
track and intensity of the surface cyclone. Not the large area covered by the 4 to 8 hPa pressure differences. The screaming message was uncertainty with the track and depth of the cyclone.

Forecasts initialized at 05/1200 UTC tracked the cyclone farther west (Fig. 11-right) and though about 12 hours too fast, represented a good forecast track on the apparent cyclone. Again there was considerable uncertainty with but the 8 hPa contour was no longer present. The spread was decreasing as was the uncertainty suggesting a convergence of solutions. Some of the westward tracking members in the 04/1200 UTC forecast (Fig. 11-center) clearly were on to something and the large spread was a screaming message out uncertainty.

Figure 12 shows the 850 hPa winds and the probability of snow in the band of 0.60 inches of QPF over Ohio. The high probability of 1 inch or more QPF was confined to coastal regions. Only a few members produced an inch contour over Ohio.

The 850 hPa winds (Fig. 12-left) showed the anomalous easterly jet north of the 850 hPa cyclone. In the ensemble mean wind field, though fast, the 850 hPa cyclone tracked close to the proper location. The large spread between members (not shown) likely contributed to the relatively weak anomalies over Ohio. Clearly, there was still considerable uncertainty as indicated by these forecasts.

Forecasts initialized at 06/0000 UTC were still to fast but began to show the stronger low-level winds along the coastal plain and the increased threat for heavy rainfall. The low-level anomalous easterly jet persisted and the 850 hPa low in the ensemble mean...
appeared to track well compared to the analysis. Though not shown, forecasts showed -2 to -3 SD u-wind anomalies as the 850 hPa low tracked from Texas to into eastern Tennessee.

The plume diagram for Louisville from the 06/1200 UTC GEFS (Fig. 14) showed that the potential for heavy snow in Louisville was a serious forecast issue. Snow was the dominant precipitation type the ensemble mean was 0.76 inches and one member forecast near 1.0 inches of snowfall. The potential for a 8-10 inch snowfall event, using a 10:1 ratio as a first guess was potential forecast issue for this portion of Kentucky.

Figure 15 shows the 06/1200 UTC GEFS 850 hPa winds and precipitation. These data show the strong u-wind anomaly forecast at 08/0000 UTC in the Ohio Valley. The -u wind anomalies were -2 to -3SDs below normal and the 850 hPa circulation was over southwestern Tennessee. The GEFS QPF showed the heaviest rainfall along the coastal plain and generally about 0.60 inches of liquid equivalent in the Ohio Valley. A comparison with Figure 1b suggests the pattern of the precipitation was well forecast but the mesoscale details on the local maximums in Ohio and Kentucky were under forecast.

Forecasts initialized at 07/1200 UTC are shown in Figure 16. These data show the same general trends as previous forecasts. As the forecast range decreased and the ensembles converged on a solution, the -u wind anomalies over the Ohio Valley increased in magnitude. There was also an increased in the v-wind anomaly along the coastal plain. The precipitation increased, showing a 1 inch contour in many GEFS members over Ohio for the 24 hours ending at 08/1800 UTC and over 2 inches of precipitation along the East Coast by 09/1200 UTC.

SREF QPFs from the 07/0900 UTC run are shown in Figure 17. These data show the potential for 1 inch of QPF in the Ohio Valley with the snow event and the potential for heavy rain along the coast. The SREF 850 hPa winds are shown in Figure 18. These data show the strong northeasterly jet over the Ohio Valley at 08/0000 UTC, this jet then slowly lifted to the northeast and weakened with time. The large v-wind anomalies with the surge of warm air were visible in the 850 hPa v-wind anomalies. They showed 2 surges of strong southerlies supporting the 2 wave concept.

4. CONCLUSIONS

A complex winter storm affected much of the eastern United States from 7 to 8 March 2008. The storm produced severe weather over the southeast on the 7th including tornadoes in Georgia and Florida and severe thunderstorms from Virginia to New on the 8th. Severe storm reports are summarized in Table 1. On the cold side of the storm, mainly north and west of the 850 hPa low track, the storm produced heavy snow. The heaviest snow was observed in the Ohio Valley from northern Alabama to northern Ohio. A records snowfall of 20.5 inches was observed in Columbus, OH, breaking a record that had stood for 98 years (Table 1). As much as 14 inches of snow was observed in the suburbs of Louisville, KY. On the warm side of the storm, heavy rainfall was observed from central Pennsylvania eastward into New Jersey and New York. Rainfall ranged from 1 to 3 inches across the region.

In this event, the large departure from normal in the u-wind and v-wind fields as forecast by the GEFS and SREF show the
practical use of standardized anomalies (Hart and Grumm 2001 Grumm and Hart 2001) in diagnosing and gaining confidence in the potential for a significant weather event. The u-wind anomalies are consistent with the findings of Stuart and Grumm (2007) demonstrating the use of standardized anomalies in predicting significant East Coast Winter storms. It appears this technique has validity over a large segment of the eastern United States. This case clearly demonstrates the value of using of standardized anomalies as a method by which forecasters can objectively analyze the departures from normal for specific variables and relate them to the forecast issues at hand.

The combination of forecast data from an EPS and the use of standardized anomalies based on mean fields from the EPS may offer additional insight during the forecast process. Toth et al (2001) demonstrated the value of using climatic data and spread to distinguish between forecasts of small and large uncertainty. They found that forecasts that converged toward a similar solution typically were more likely to verify and were therefore associated with lower uncertainty.

In this case, there was considerably larger spread in earlier forecasts, suggesting high uncertainty. This was shown with the surface cyclone. As the forecast length decreased the forecasts converged toward a similar solution. This produced both smaller spread in the forecasts and larger anomalies in such fields as the 850 hPa winds. The u-wind anomalies dramatically increased as forecast length decreased. This was due on large part due to the convergence of the forecasts. This relates back to the work of Toth et al. (2001) which showed that the convergence of forecasts decreases the spread and is likely to produce larger climatic anomalies.

Ultimately, there was considerable uncertainty with this event at 3-5 days in advance. Uncertainty is inherit in all weather forecasting activities. The uncertainty quickly decreased in the 1-2 day time frame. The convergence quickly indicated a potential for heavy snow fall in the Ohio Valley which was demonstrated here. Also shown, but not emphasized as much was the potential for heavy rainfall along the East Coast.

5. Acknowledgements

The NWS in State College for gathering data and reports and plotting maps and summaries of the event in real-time.

6. References


Du et al 2006 New Dimension of the NCEP Short-Range Ensemble Forecasting (SREF) System: Inclusion of WRF members.


Manikin, G., J. McQueen, B. Ferrier, and J. Du, 2004: Changes to the NCEP SREF System and Their Impact on Convection Forecasting, 22nd Conference on Severe Local Storms, paper 17.4, Hyannis, MA, Amer. Meteor. Soc. Click here to view it (PDF)


Figure 6. As in Figure 4 except valid at 0000 UTC 8 March 2008.


Toth, Z., Y. Zhu, and T. Marchok, 2001: On the ability of ensembles to distinguish between forecasts with small and large uncertainty. Weather and Forecasting, 16, 436-477.


Figure 7. As in Figure 4 except valid at 0600 UTC 8 March 2008.

of the American Meteorological Society, 83, 73-83.
Figure 8. As in Figure 4 except valid at 1200 UTC 8 March 2008.

Figure 9. As in Figure 4 except valid at 1800 UTC 8 March 2008.
Figure 10. As in Figure 4 except valid at 0000 UTC 9 March 2008.

Figure 14. GEFS plume diagram from forecasts initialized at 1200 UTC 6 March 2008 showing accumulated precipitation by type for the period from 1200 UTC 3 March through 1200 UTC 15 March 2008. Gray lines show the GEFS 6-hourly precipitation by member, the colored lines show the accumulated precipitation by type. The types and amounts are summarized to the left. The point is near Louisville, Kentucky.
Figure 11 GEFS forecasts of MSLP from forecasts initialized at (left) 1200 UTC 3 March, (center) 1200 UTC 4 March and (right) 1200 UTC 5 March 2008. Upper panels the spread about the mean (hPa) and each members 1020, 1008, and 996 hPa contours lower panels show the ensemble mean from which the spread was derived and the departure of this field in standard deviations form normal.
Figure 12 GEFS forecasts initialized at 1200 UTC 5 March 2008 showing (left) 850 hPa winds and a) u-wind anomalies and b) v-wind anomalies valid at 0600 UTC 8 March 2008 and (right) the a) probability of 1.00 inches of QPF and the 1.00 inch contour and b) the 24 hour total QPF and each members 1 inch contour.

Figure 13 As in Figure 12 except from forecasts initialized at 0000 UTC 6 March 2008.
Figure 15. As in Figure 13 except GEFS initialized at 1200 06 March 2008 showing 850 hPa winds valid at 0000 UTC 8 March and the 24 hour QPF valid at 1200 UTC 08 March 2008.

Figure 16. As in Figure 13 except GEFS forecasts initialized at 1200 UTC 7 March 2008 showing the 850 hPa winds valid at 0000 UTC 8 March 2008, and the 24 hour QPF ending at 1800 UTC 8 March and the 36 hour QPF ending at 1200 UTC 9 March 2008.
Figure 17. SREF precipitation forecasts initialized at 0900 UTC 7 March showing 24 hour accumulated precipitation and the probability of 1 inch in 24 hours ending (left) 1200 UTC 8 March and (right) 1200 UTC 9 March 2008.

Figure 18. SREF initialized at 0900 UTC 7 March 2008 showing 850 hPa winds and a) u-wind anomalies and b) v-wind anomalies valid at (left) 0000 UTC, (center) 0600 UTC, and (right) 1200 UTC 8 March 2008.