11.1 CONVECTION FORECASTS FROM THE HOURLY UPDATED, 3-KM HIGH RESOLUTION RAPID REFRESH (HRRR) MODEL

Tracy Lorraine Smith[1], Stanley G. Benjamin, John M. Brown,
Stephen Weygandt and Tanya Smirnova[2] , Barry Schwartz
NOAA Research – Earth System Research Laboratory, Global Systems Division
Boulder, Colorado, USA
[1]In collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA)
Colorado State University, Fort Collins, Colorado
[2]In collaboration with the Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado, Boulder, Colorado

1. INTRODUCTION

The next generation of the 1h Rapid Update Cycle (RUC) is being readied for operational use at the 13 km scale. The Rapid Refresh (RR) system is a WRF-ARW and GSI based forecast system that is planned to replace the operational RUC by early 2010. As described in a companion paper (Weygandt et al. 2008c), an effective technique for assimilating 3-d radar reflectivity data has been developed for the 13km RUC (Benjamin et al. 2008) and upcoming 13km RR model.

Here, we describe a new, hourly updated, high-resolution (3 km) nested model, the HRRR (High-Resolution Rapid Refresh) initialized from the radar reflectivity-enhanced 13km RUC. The HRRR has considerable promise for short-range severe weather prediction, and is a first for hourly updated, storm-scale model forecasts including hourly radar reflectivity assimilation.

The HRRR is currently nested over the northeastern US inside the 13km backup RUC run at NOAA/ESRL/GSD, run on a 1h cycle, and uses the same version of the WRF model applied to the Rapid Refresh except that it does not include the Grell-Devenyi (or any) convective parameterization. It relies on the RUC13 data assimilation, which includes radar reflectivity assimilation based on a digital filter initialization (DFI) technique. Using the forward (diabatic) DFI inside the RUC (and in the future 13km RR) dramatically improves reflectivity forecasts from the HRRR.

We will detail the configuration and environment of the HRRR runs and how the DFI-radar technique in the 13km RUC is applied to the 3km HRRR.   Verification of the HRRR forecasts highlighting the effects of this technique, especially in the all-important first few hours of the HRRR forecasts is included. Integrating radar information is critical in the location and intensity of the forecast precipitation and reflectivity fields.

Case studies from real-time 12-hour forecasts run hourly during summer 2008 chosen for efficacy in improving guidance for air-traffic management over the busy northeast US air traffic corridor will also be shown.

2. RUC-13 RADAR ASSIMILATION

The HRRR is currently nested within the RUC13 domain. (Fig. 1) The backup RUC13 is run in house at the ESRL/GSD as a fall back for the NCEP RUC13, and is meant to be as similar to the operational RUC as possible, while running on a different platform with different data access.
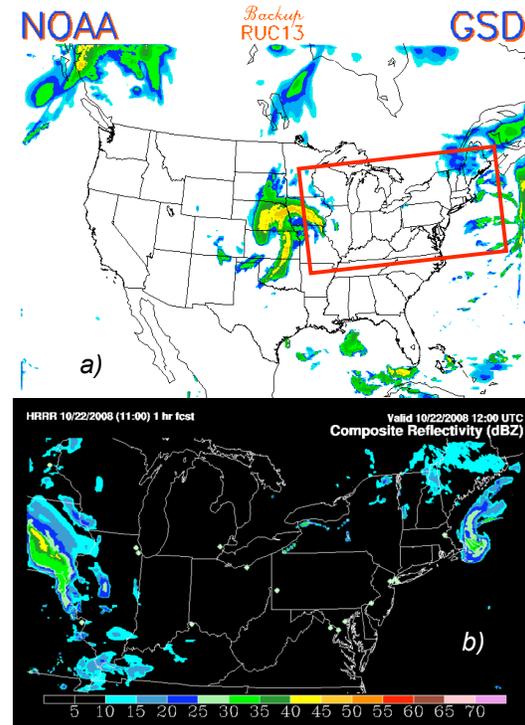

Figure 1. *a) RUC domain (backup RUC) showing HRRR nest. Reflectivity image a) from the backup RUC for 1200 UTC 22 Oct 08 (top), and b) HRRR domain showing 1-h forecast HRRR reflectivity image for same time (bottom).*

Corresponding author address: Ms. Tracy Lorraine Smith, NOAA/ESRL/GSD R/GSD1, 325 Broadway, Boulder, CO 80305-3328.   email :tracy.l.smith@noaa.gov; Rapid Refresh info, http://rapidrefresh.noaa.gov

The 3-D radar reflectivity data brought into the RUC is derived from the NSSL radar reflectivity mosaic product. This data is brought into the RUC via the diabatic digital filter initialization (DDFI, Benjamin et al. 2004a, section 2a) through a radar-based 3-d grid of latent heating. Radar reflectivity (in concert with lightning data acting as a proxy for reflectivity data) is also used to modify the background 1-h RUC 3-d hydrometeor/water vapor forecast (Benjamin et al. 2008). The radar/lightning-based reflectivity is also used in the overall RUC cloud/hydrometeor analysis in the following ways:

- Use Yes/No/Unknown 3-d array that specifies at each 3-d grid volume whether the foregoing observations support clouds/no clouds/ are indeterminate (Benjamin et al. 2004b, Weygandt et al. 2006)
- Apply conditions for radar reflectivity usage based on 3-d temperatures, solar zenith angle, and reflectivity all designed to avoid susceptibility to ground clutter contamination.
- Add cloud water where reflectivity > 5 dBZ but only in temperature-indicated winter conditions where snow hydrometeors are likely.
- Add water vapor, moistening volume toward saturation, where reflectivity exceeds limits between 5 dBZ and 28 dBZ under previous conditions for usage (second bullet).
- Determine 3-d latent heating fields based on reflectivity, also subject to usage conditions, for subsequent use in RUC model diabatic initialization.
- Also determine horizontal "no echo" area at least ~100 km from any existing echo to be used in subsequent RUC model initialization, specifically for "convection suppression".

RUC / HRRR reflectivity assimilation
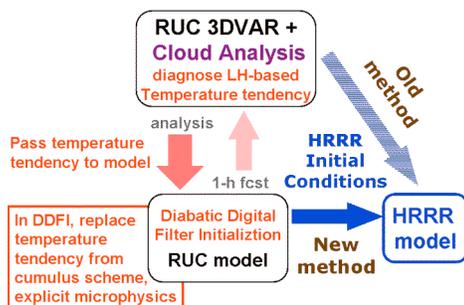
Figure 2. *Flow chart depicting the Diabatic Digital Filter Initialization (DDFI) - based radar assimilation within the RUC model and the specification of High Resolution Rapid Refresh (HRRR) fields from the RUC model, via two pathways (old and new). See text for details.*

More in depth description and discussion of the DFI based radar assimilation technique is found in Weygandt et al. (2008a,b,c) and Benjamin et al. (2008).

An advantage of the RUC radar-enhanced diabatic DFI is an enforcement of the balance between the wind (especially the divergent wind) and thermal response consistent with convection based latent heating. This ensures some response over an approximate time scale of 1-3h, often longer in RUC-based experiments.

Fig. 2 shows a schematic diagram illustrating how a latent heating-based temperature tendency field is diagnosed from the radar data in the RUC cloud analysis, and then applied within the RUC model DDFI. Also depicted is a key change in the pathway via which the HRRR is initialized from the RUC. In the original approach ("old method"), HRRR initial fields were obtained from the RUC 3DVAR analysis output. Because the DDFI radar assimilation was applied in the model (not the 3DVAR), this old method caused the radar-based storm information input into the HRRR to be an hour old (and propagated forward in time via the 13-km RUC with parameterized convection). A significant improvement was made in early June 2008 to output a RUC history file after the DDFI-based radar assimilation and use this to initialize the HRRR model run. This replaces the 1-h old storm information (propagated forward in time via the RUC model) with fresh storm information directly from the DDFI applied to the latest radar fields. This resulted in a significant further improvement to the HRRR performance. A sample comparison will be shown in Section 5.

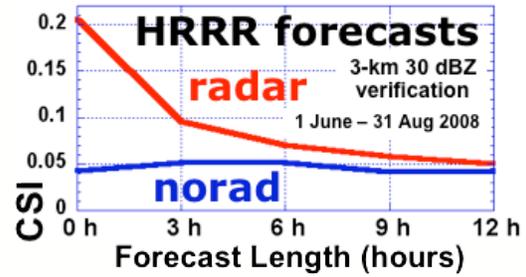## 3. HIGH RESOLUTION RAPID REFRESH (HRRR) MODEL

The HRRR is a WRF-ARW based model similar to the 13km Rapid Refresh (Benjamin et al. 2007) run at a 3km resolution. It is nested within the 13km backup RUC and run in house at ESRL/GSD. It is run hourly, based on the 13km RUC analysis. The grid is 745x383 in the horizontal, and 50 levels in the vertical, with the top level at 65 hPa. Physics include the RUC Land Surface Model, Mellor-Yamada-Janjic surface and planetary boundary layer, Thompson microphysics (no cumulus scheme, explicit), Dudia shortwave and Rapid Radiative Transfer Model longwave radiation. It should be noted that the HRRR reflectivity is qualitatively, but not precisely, consistent with the Thompson microphysics.
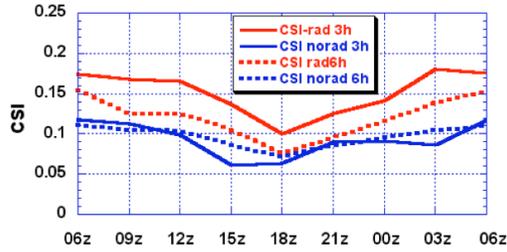
Figure 3. *CSI of HRRR 3 and 6h forecasts of 20 dBZ reflectivity valid every three hours over the 23 June – 25 August 2008 summer convective season. The solid lines represent the 3h forecasts and the dotted lines represent the 6h forecasts. Red lines denote the HRRR run with radar assimilation, and blue lines denote the run without radar assimilation.*

Figure 4. *Verification of HRRR forecasts of 30 dBZ reflectivity at 3km resolution by the forecast length over 1 June – 31 August 2008. The red line denotes the run with radar and the blue line denotes the no radar run.*

4. STATISTICAL VERIFICATION

Ongoing statistical verification of the HRRR forecast reflectivity fields (on the 3-km HRRR domain) was performed for summer 2008. NSSL reflectivity mosaic fields were used as truth and interpolated to the HRRR 3-km grid, allowing for the calculation of traditional categorical verification scores. This verification approach provided an extremely stringent test of the forecast skill, but yielded results that were consistent with our subjective impressions from qualitative plot comparisons.

Fig. 3 shows the CSI for the 20dBZ reflectivity threshold for 3h and 6h forecasts over 23 June – 25 August. The Critical Success Index (CSI) values for HRRR runs utilizing the radar reflectivity show a higher value than corresponding runs that did not include the radar assimilation. In fact, the HRRR 6h forecasts with the radar outperform the HRRR 3h forecasts without the radar. This is true for every hour during the day. The technique shows the least impact during the afternoon hours when smaller scale, more random convection occurs.

We also stratified verification scores as a function of forecast length as shown in Fig. 4. Here again the version of the HRRR with radar verifies better, with improvement from the radar assimilation extending all the way out to the 12h forecast.
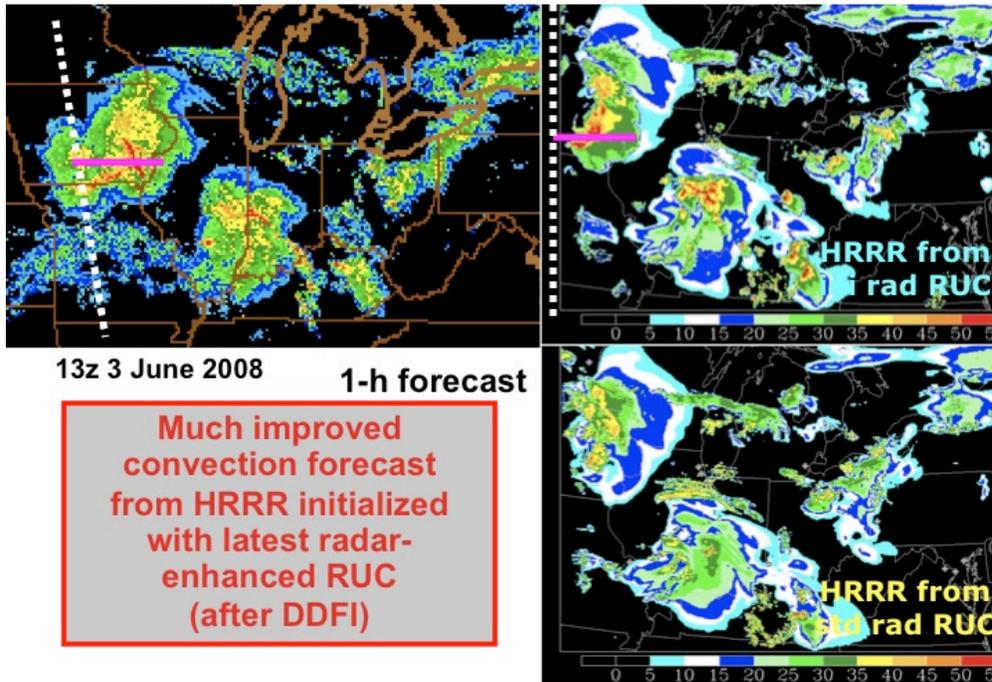
Figure 5. *HRRR case study plots from 3 June 2008. Upper left panel shows verification reflectivity at 13z. Upper right shows 1-h forecast from HRRR with RUC radar assimilation and initialization directly from the DDFI (the "new" method). The Lower right panel shows the 1-h forecast from the HRRR with the RUC radar assimilation, but using fields from the RUC 3DVAR (the "old" method). The white dashed line indicates the edge of the HRRR domain and the pink line indicates the southern extent of the lweading edge of the MCS at the initial time.*

5. CASE STUDIES

Examples of individual cases comparing observed reflectivity to forecast reflectivity show the type of impact the radar assimilation can have on the HRRR.

5.1 3 June 2008

The first example shows two very important aspects of HRRR forecasts initialized from the RUC with the DDFI-based radar assimilation: 1) the improvement due to the switch from the "old" to the "new" initialization pathway (HRRR fields extracted from the RUC directly after the DDFI, not after the 3DVAR), and 2) the significant impact of the lateral boundary conditions (especially for convective systems straddling the lateral boundary). Fig. 5 shows a comparison of two HRRR forecasts that both used the radar assimilation, but the upper panel used the new pathway and the lower panel used the old pathway. While both due significantly better than HRRR run without any RUC radar assimilation (not shown), the one with the new pathway is significantly stronger with the convective systems. This more vigorous convection is able to maintain itself much longer in the HRRR

forecast, and the forecast improvement is even greater at later forecast times (not shown).

The second aspect, the lateral boundary condition difference, can be seen by considering the dashed white line, which represents the edge of the HRRR domain. At the initial time, the strong MCS across Eastern Iowa was straddling the HRRR boundary. The pink horizontal line indicates the southern extent of the leading edge of the mesoscale convective system (MCS) at the initial time (1200 UTC). As can be seen in the 1-h forecast, the southern extent of the MCS remains strongly anchored to this line.   This is because the only information available to the HRRR on the further extension of the line is from the lateral boundary conditions provided by the RUC forecast. While the RUC forecast of the MCS (not shown) is improved by the radar assimilation, the parameterized depiction of the storm in the RUC, leads to a weaker explicit convective signal in the portion of the HRRR domain impacted by the lateral boundary conditions. The behavior was fairly common along the western boundary of the HRRR domain and underscores the need for placing the upstream boundary sufficiently far from the region of interst.
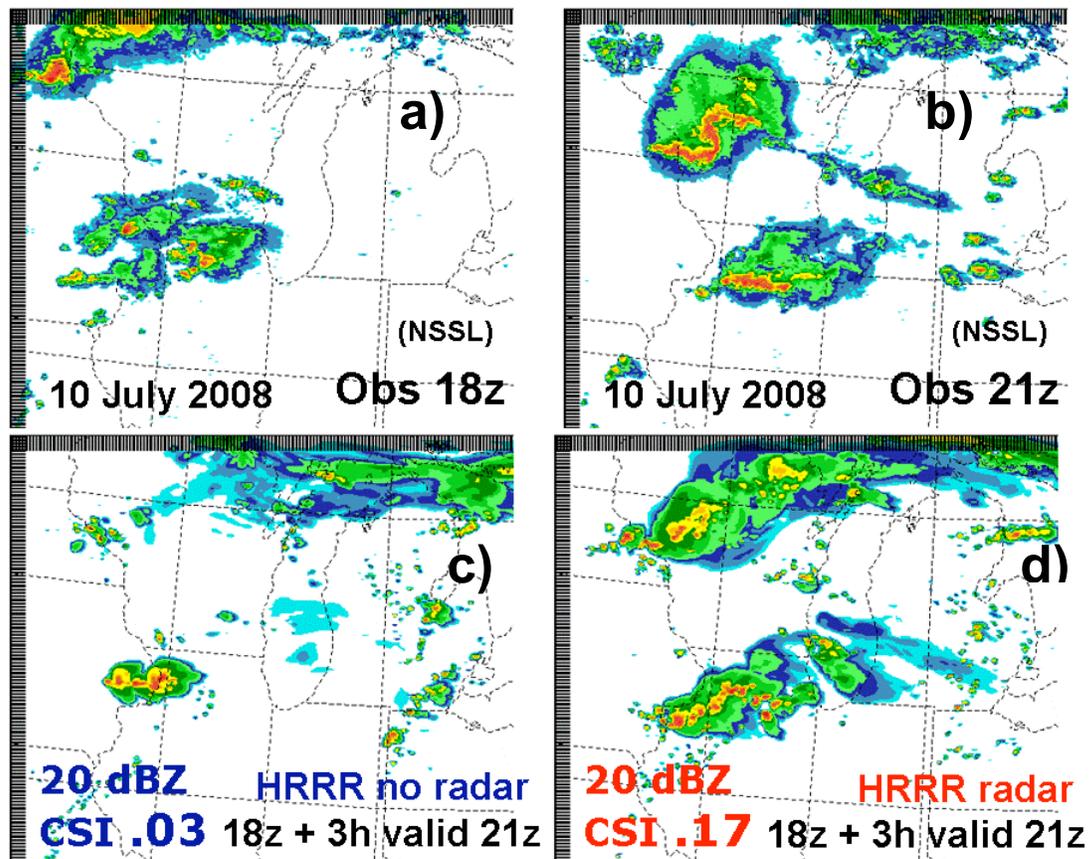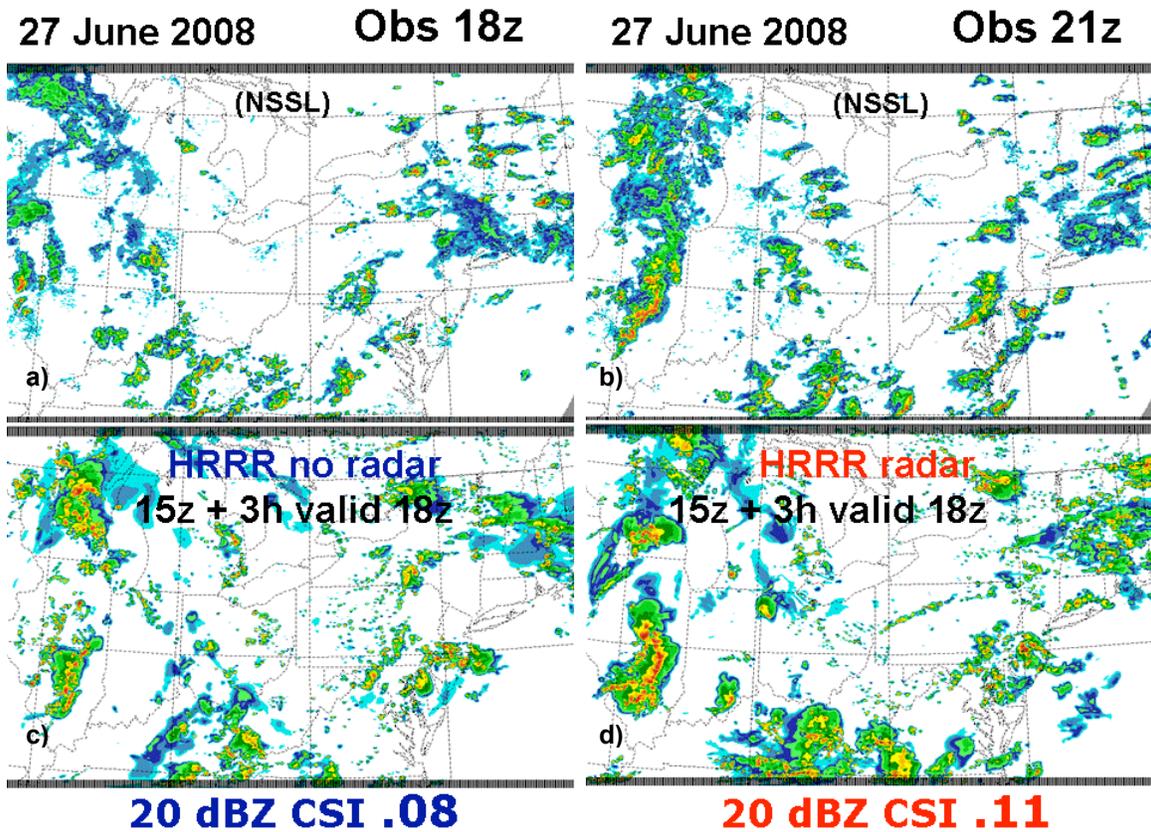
Figure 6. *a) Observed reflectivity from the NSSL mosaic for 1800 UTC 10 July 2008. b) Same as 6a , except for 2100 UTC. c) 3h forecast from the 1800 UTC 10 July 2008 no radar HRRR valid at 2100 UTC. d) Same as 6c except for the HRRR using radar assimilation.*

5.2 *10 July 2008*

The afternoon of 10 July 2008 was active in the Great Lakes states of Wisconsin and Illinois. Large convective complexes were organizing in northern Wisconsin and Illinois. As shown in Fig. 6a, at 1800 UTC the Wisconsin storm was just coming into the HRRR domain, and the Illinois storm was still a large area of unorganized convection. By 2100 UTC (Fig. 6b), both storms are strong and well organized.

HRRR 3h forecasts from 1800 UTC valid at 2100 UTC show the importance of the radar data. In Fig. 6c, the forecast without radar data assimilation, the Wisconsin storm is not evident in the 3h forecast, while the Illinois storm is much smaller. Assimilation of the radar data into the HRRR 3h forecast (Fig. 6d) greatly improves this forecast, showing organized systems in both locations. The CSI for 20 dBZ also shows this, with a CSI of .17 for the radar HRRR compared to only .03 for the no radar HRRR.

Figure 7. *a) Observed reflectivity from the NSSL mosaic for 1800 UTC 27 June 2008. **b)** Same as 7a, except for 2100 UTC. **c)** 3h forecast from the 1800 UTC 27 June 2008 no radar HRRR valid at 2100 UTC. **d)** Same as for 7c, except for the HRRR using radar assimilation.*

5.3 *27 June 2008*

This example (Fig. 7) shows a case where the convection is less organized and most of the storms have a smaller horizontal scale. This represents a more difficult forecast challenge for the HRRR. As expected the overall skill is less, and the most significant improvement from the radar assimilation appears to be for the mopre organized system across southern Illinois. Despite the greater challenge for this type of convection (and likely reduced degree of predictability) the scores for the radar assimilation HRRR are better than the HRRR without the radar assimilation.

5.4 *28 August 2008*

On 28 August 2008 Tropical Storm Fay was weakening over the eastern US while a large mesoscale convective system is coming into the domain over Illinois. Figures 8 and 9 show the HRRR radar and noradar 6h forecasts from the 0600 UTC run valid at 1200 UTC. Figures 10 and 11 show the 3h forecasts from 0900 UTC also valid at 1200 UTC, and Figures 12 and 13 are NSSL national mosaic radar images at 1200 UTC zoomed in over the eastern (fig. 12) and the western (fig. 13) part of the domain. Note the MCS over Illinois and the heavy showers over Pennsylvania in the actual verifying radar images. In both the 3 and 6h forecasts valid at 1200 UTC these features were not forecast well by the run without radar assimilation, but the run with radar assimilation captures these events nicely.
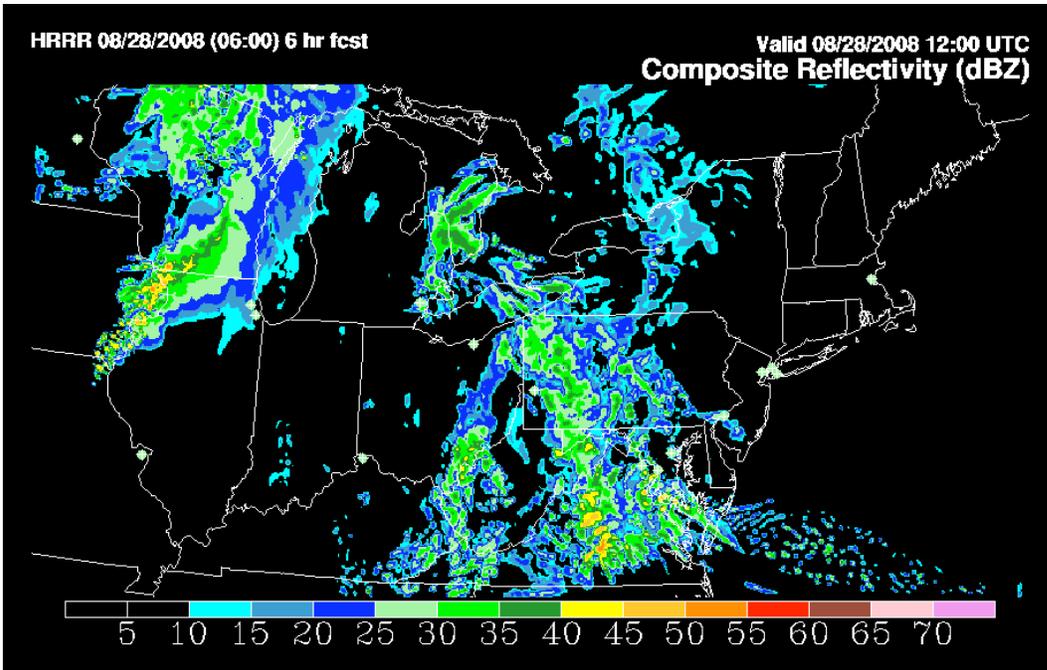
Figure 8. *Radar HRRR 6h forecast of reflectivity from 0600 UTC 28 August 2008, valid at 1200 UTC.*
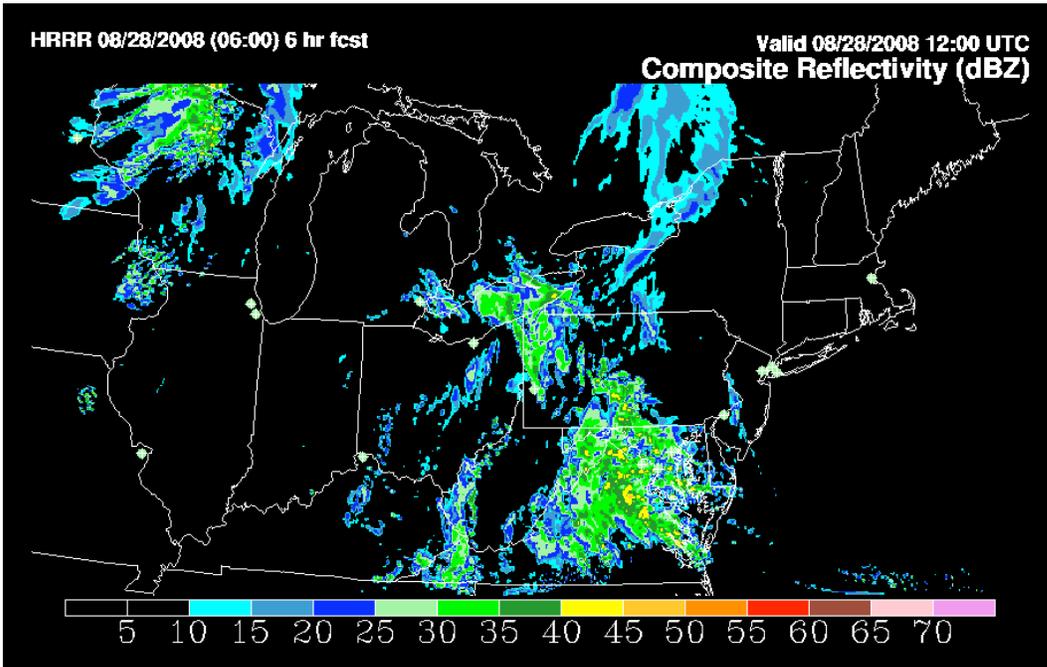

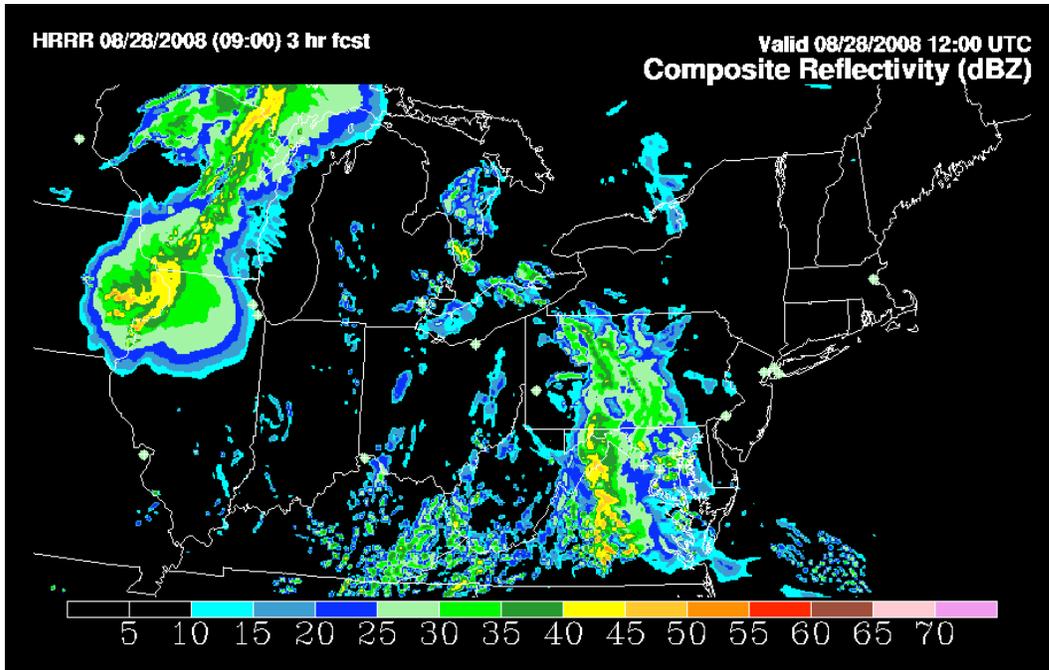**Figure 9.** *Same as figure 8, but for the no radar HRRR.*

Figure 10. *Radar HRRR 3h forecast of reflectivity from 0900 UTC 28 August 2008, valid at 1200 UTC.*
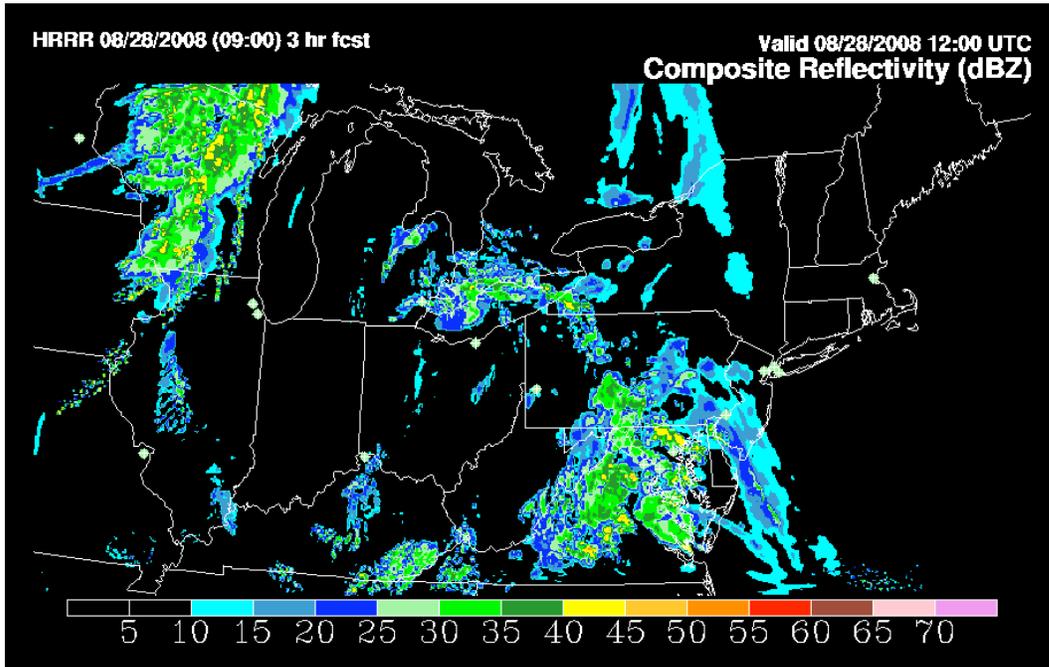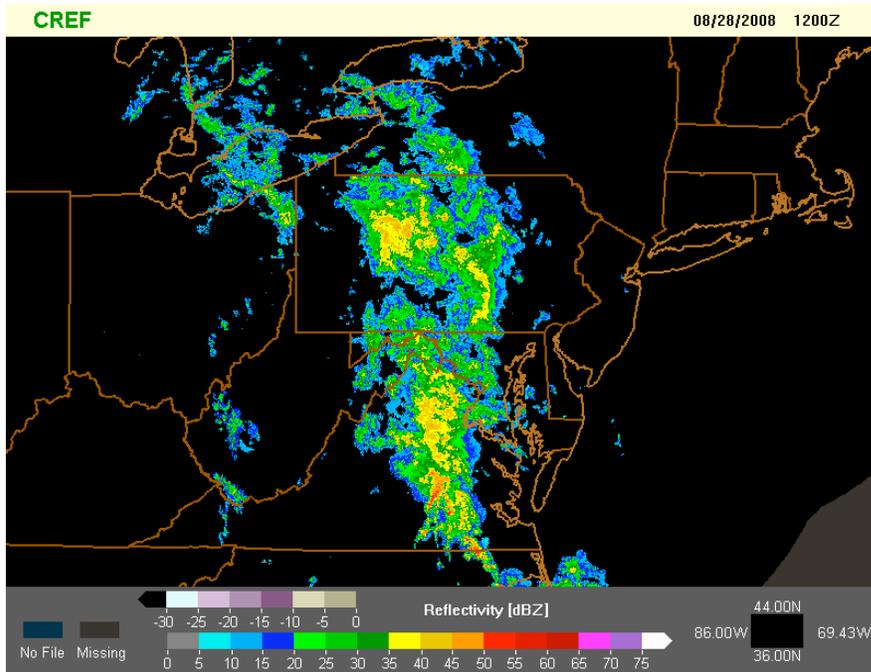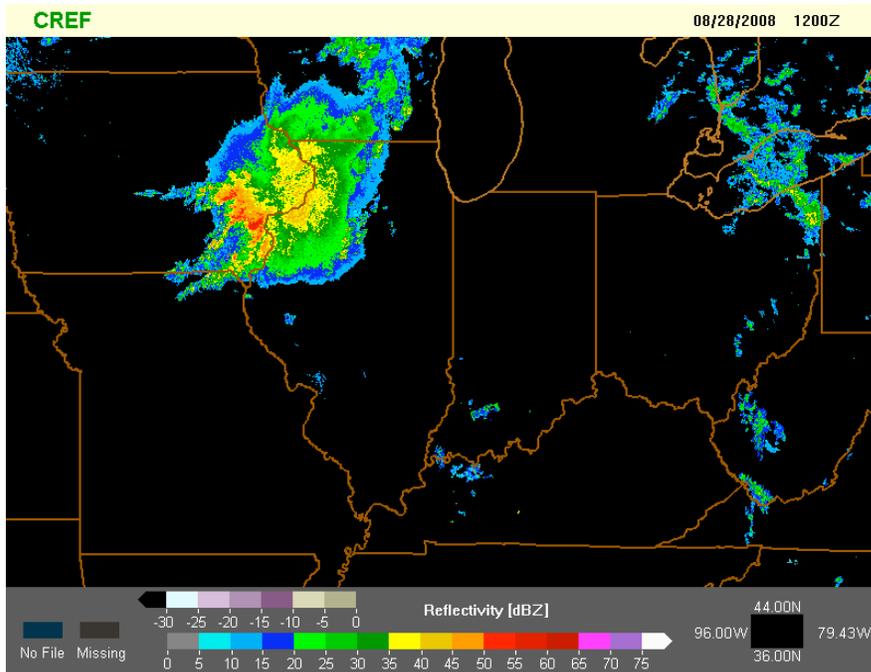

Figure 11. *Same as figure 10, but for the no radar HRRR.*

Figure 12. *NSSL national radar mosaic for 1200 UTC 28 August 2008 for the NE US, note the remnants of Tropical Storm Fay moving up over VA/WV/MD/PA.*

Figure 13. *Same as figure 12, but for the upper Midwest states. Note MCS moving into Illinois.*

6. CONCLUSIONS

We have described a high resolution (3km), hourly updated forecast system where real time radar reflectivity data is assimilated, along with many other types of data. This system is shown to outperform an identical system that lacks the radar assimilation in both ongoing statistical and case study verification.

The radar data assimilation is dependent on the storms being active at the initial time therefore we see less radar impact in forecasts initiated during the morning hours when there are fewer convective storms. This can be seen in fig. 3, where the difference in CSI between the radar and non-radar initialized HRRR runs is smallest for the 3 and 6h forecasts valid at 1800 and 2100 UTC. The tendency for upscale growth in convective systems from predominantly small individual storms during the afternoon initiation period toward mesoscale convective systems during the evening modulates the impact of the radar assimilation diurnally, as shown in the verification of fig. 3. Note that the greatest impacts of the radar assimilation on 3 and 6h forecasts of reflectivity as measured by the CSI are for forecasts initialized at 0000 UTC. We speculate that by this time there has been sufficient upscale growth from the afternoon initiation period that the RUC radar initialization, despite its 13km grid-point spacing, introduces qualitatively realistic mesoscale features into the initialization, such as mesoscale updrafts and cold pools, that allow the HRRR forecast to realistically describe the propagation and lifetime of initialized mesoscale convective systems.

The HRRR downscales radar information to storm-scale, giving us more realistic details, however the predictability is best for larger scale systems. As shown in the case studies, lateral boundary condition issues were significant aling the upstream edge and dramatic forecast improvements when storms were first depicted on the HRRR domain at the initial time

We need to further evaluate the predictability time scale for the smallest convective elements. Future work will also include applying the radar initialization directly on the 3 km HRRR domain. This will allow us to evaluate predictability of smaller initial convective elements and to test the hypothesis that this will further improve predictive skill in these short range forecasts.

ACKNOWLEDGEMENTS

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