Demonstration of a Cycled High-Resolution Rapid Refresh Capability During a Cool-Season Tornado Outbreak (extracted from report by David Dowell and collaborators)

1. Ensemble System Development

We are developing the HRRRE as part of a nested system of ensemble data assimilation and forecasting from global to regional convective scales, using a common set of community tools. Specifically, the community tools are the Global Forecast System (GFS) model, the Weather Research and Forecasting (WRF-ARW) model, the Gridpoint Statistical Interpolation (GSI) observation processing and assimilation system, and the associated Ensemble Kalman Filter (EnKF) software (Skamarock et al. 2008; Wang et al. 2013; DTC 2015a, b, c). GSI pre-processes observations (quality control, error estimation) and also computes GFS/WRF model prior estimates of these observations. Taking information from GSI along with an ensemble of prior model states ("forecasts"), EnKF then produces an ensemble of posterior model states ("analyses") updated by the observations.

NOAA's operational GFS employs an 80-member ensemble plus a higher-resolution deterministic ("control") analysis and forecast. The control analysis, produced by the four-dimensional ensemble variational method (4DEnVAR) every 6 h, is used to the initialize the deterministic GFS forecast and also to update the mean of the lower-resolution GFS ensemble. The ensemble perturbations are updated every 6 h by the EnKF. This system became operational at NOAA's Earth Modeling Center (EMC) in 2013. Output are available in real time and are also archived.

Since part of our study requires testing for a case in 2011, we have run the GFS ensemble retrospectively for the entire month April 2011. We ran the retrospective GFS experiment at dual resolution t254t670 with 64 vertical levels, somewhat coarser than the operational resolution but sufficient for our study. All of the observations used in the NCEP GDAS are assimilated every 6 hours using the GSI. The four-dimensional incremental analysis update (4DIAU) is used for both the control and the ensembles, while the digital filter (DFI) and tangent linear normal mode constrain (TLNMC) are turned off. The localization uses the same table as the operational forecast model. Multiplicative covariance inflation that acts to relax the posterior ensemble spread back to prior ensemble spread ("relaxation-to-prior spread") is used with a relaxation coefficient of 0.85. Stochastic physics methods are applied to represent model uncertainty within the ensemble forecast step while no additive inflation is applied. The simulation begins 01 April 2011 and produces 3-hourly output for the control and the ensemble prognostic and diagnostic variables. For the analysis times during the period April 25 and 28, 36-hour forecasts are produced from each analysis and the 3-hourly outputs are used to provide boundary conditions for 3-km WRF simulation. The appropriate gridded-binary (GRIB) files for WRF are produced directly from the GFS spectral and surface analysis files using the NCEP post-processor.

Cycling an ensemble of full-domain (5400 km × 3180 km) HRRR forecasts would be very expensive computationally. To provide the quick turnaround time needed for development experiments, we are using a 1800 km × 1500 km domain instead. With this approach for limiting the computational requirements, we can still demonstrate the potential capabilities of a full HRRR ensemble system.

A 6- to 36-h GFS ensemble forecast provides initial and boundary conditions for limited-domain HRRRE tests with 40 WRF members (corresponding to members 1-40 of the GFS ensemble). The HRRRE is then cycled hourly through this 30-h period employing GSI and EnKF to assimilate conventional observations. These observations, the same ones assimilated into the operational HRRR, are pressure, humidity, temperature, and wind from rawinsondes, surface and marine stations, ACARS, AIREP/PIREP, NEXRAD VAD, and profilers.

2. Demonstration for Warm-Season Tornado Outbreak: 27 April 2011

Initial HRRRE experiments are for the devastating outbreak of severe weather in the southeast US on 27 April 2011 (NOAA 2012; Knupp et al. 2014). We selected this case as a starting point owing to its high impact and also to the availability of reference research experiments (Yussouf et al. 2015). Comparisons to these reference experiments will be beneficial for optimizing the system.

An initial comparison is between a free 3-km ensemble forecast initialized from the GFS ensemble and a HRRRE initialized with 3-km ensemble DA (Fig. 1), to confirm that observations are indeed affecting the analyses and forecasts in plausible ways. The comparison in Fig. 1 is for a single ensemble member, representing trends seen in many other ensemble members (not shown). The forecast initialized without 3-km DA indicates a long convective line from Kentucky to northern Mississippi (Fig. 1, left). In contrast, the forecast initialized with 3-km DA (Fig. 1, right) indicates scattered small convective systems over this region. Farther south, the 3-km DA shifted the region of developing supercells from north-central Mississippi (left) to a longer swath from northern Alabama to southern Mississippi (right). All of these forecast differences resulting from the 3-km DA compare favorably with observations (Fig. 2). These differences in reflectivity forecasts are associated with substantial changes in the storm environment resulting from the 3-km DA (Fig. 3). In this case, the 3-km DA generally reduces the surface-based convective available potential energy (CAPE) over Mississippi and Alabama, but analyzed and forecasted values are still quite high, exceeding 3000 J kg^{-1} over a large region.

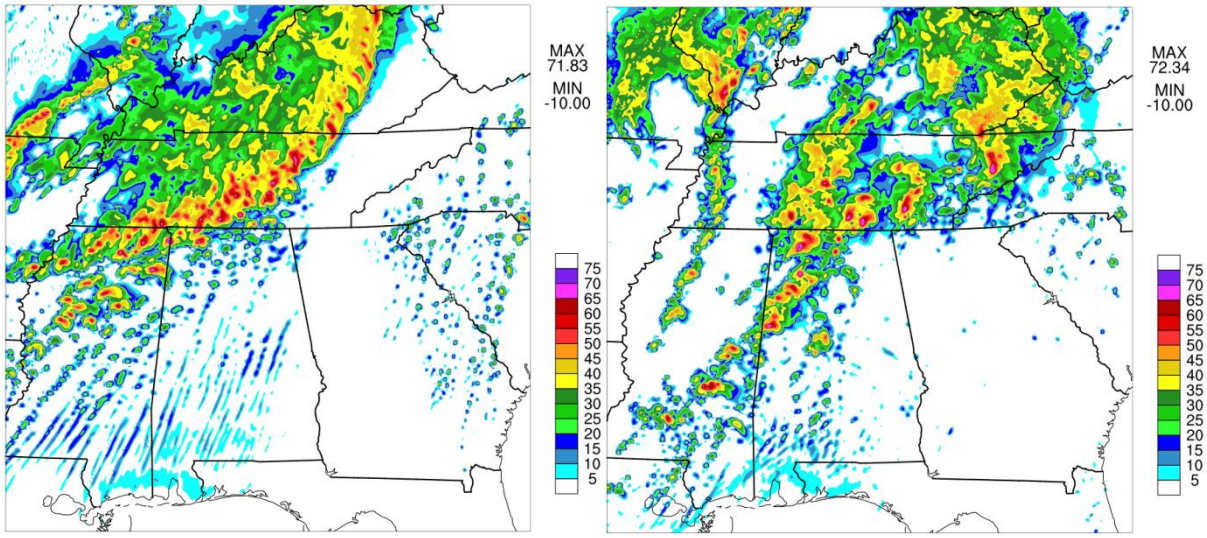

Figure 1. Composite reflectivity for ensemble member 2 at 2100 UTC 27 April 2011.
(left) 15-h forecast initialized directly from GFS ensemble without additional data assimilation
(right) 1-h forecast from HRRRE, following hourly cycling for 14 h

The actual initial development of supercells in Alabama and Mississippi (Fig. 2) was more widespread than indicated in most of the ensemble members (e.g., Fig. 1). As we continue to test possible refinements to the ensemble system's design in coming months, one desired but not guaranteed result is that the ensemble forecasts would show more robust development of supercells during the early portion of the afternoon tornado outbreak.

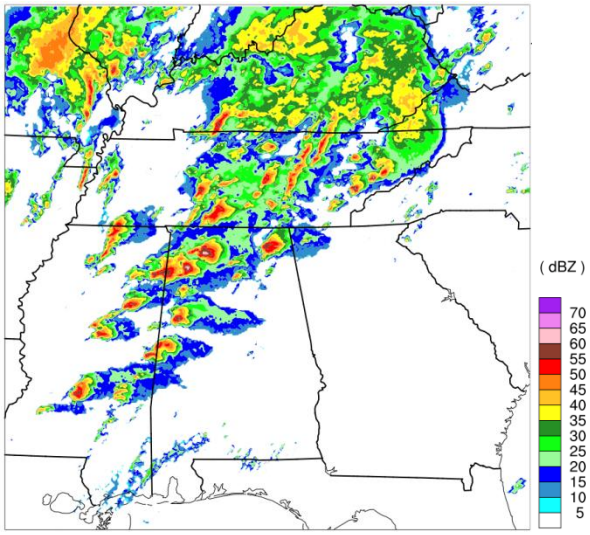

Figure 2. Observed (MRMS) composite reflectivity at 2100 UTC 27 April 2011.

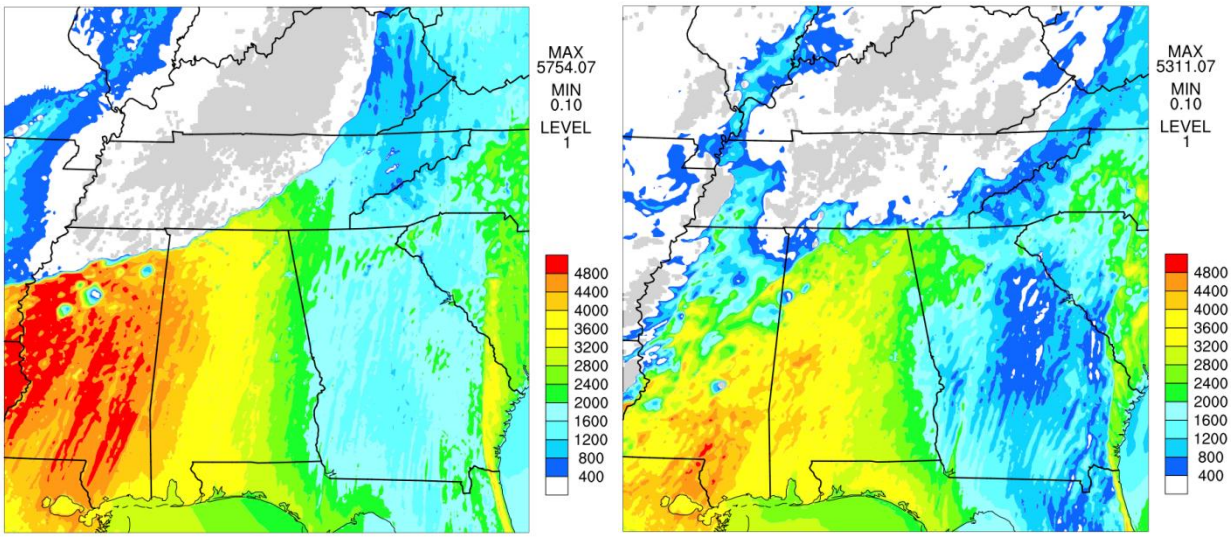

Figure 3. Surface-based CAPE for ensemble member 2 at 2100 UTC 27 April 2011. (left) 15-h forecast initialized directly from GFS ensemble without additional data assimilation (right) 1-h forecast from HRRRE, following hourly cycling for 14 h

To provide more insight into how 3-km DA affects the ensemble overall, we consider ensemble-based probabilities of where composite reflectivity exceeds 35 dBZ. This criterion serves as a proxy for where deep, moist convection is occurring. We again compare a forecast initialized directly from the GFS ensemble without DA to the HRRE (Fig. 4). As expected, the hourly assimilation of conventional observations in the HRRRE has altered the ensemble forecast significantly, producing sharper probability distributions (higher probabilities, narrower swaths) and also shifting some of the swaths of higher probabilities. The corridor of most severe observed storms at the time shown (dashed oval in Fig. 5) is brought into focus in the HRRRE (right panel in Fig. 4). Elsewhere in the domain, a qualitative comparison of forecast probabilities to observations hints at both forecast successes and also a tendency for too little spread in the ensemble forecasts. A quantitative assessment of forecast probabilities will require a full set of cases rather than one.

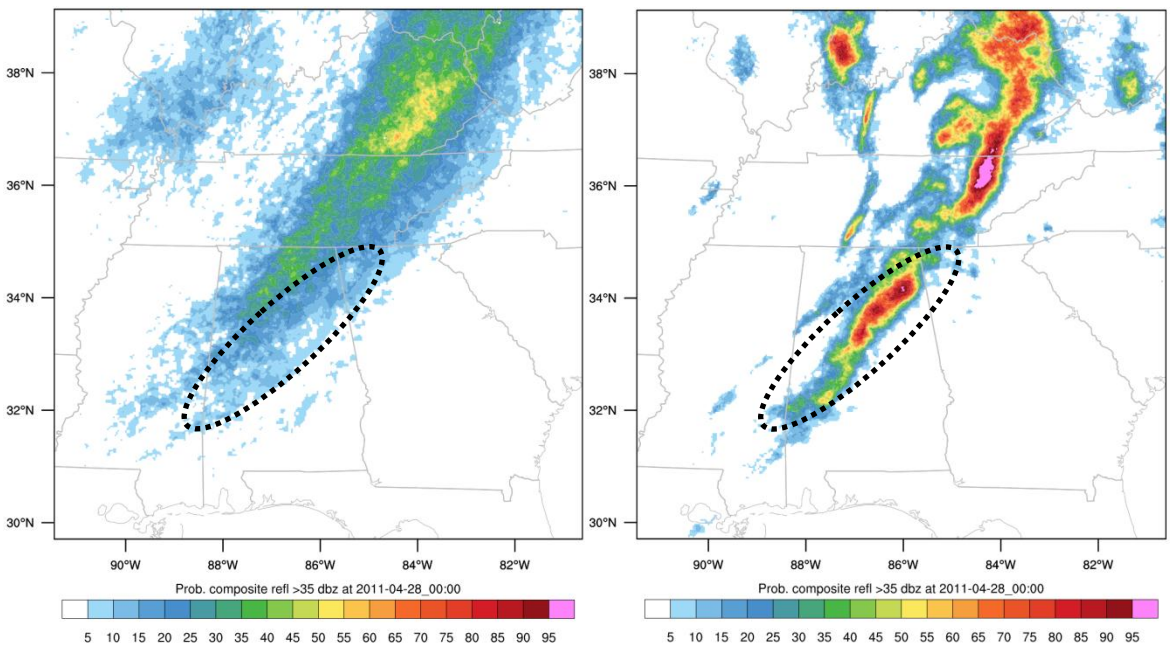

Figure 4. Probability of composite reflectivity exceeding 35 dBZ at 0000 UTC 28 April 2011, computed from WRF 3-km ensembles of 40 members.
(left) 18-h forecast initialized from the GFS ensemble without data assimilation
(right) 1-h forecast initialized from hourly-cycled HRRRE

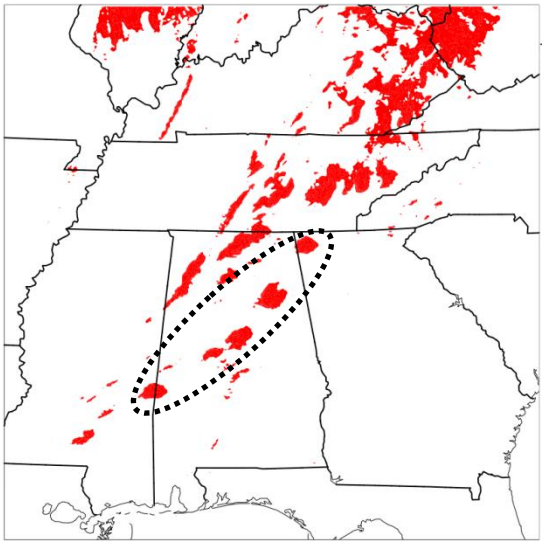

Figure 5. Observed (MRMS) composite reflectivity exceeding 35 dBZ (red shading) at 0000 UTC 28 April 2011. The region of most destructive supercell storms at this time is indicated by the dashed oval.