**FINAL REPORT**

**University:** Colorado State University

**Name of University Researcher Preparing Report:** Russ Schumacher (PI) and Charles Yost (Graduate research assistant)

**NWS Office:** Hydrometeorological Prediction Center

**Name of NWS Researcher Preparing Report:** David Novak and Wallace Hogsett

**Type of Project:** Partners

**Project Title:** Understanding the Causes of Displacement Biases in Numerical Forecasts of Convective Systems

**UCAR Award number:** Z12-93241

**Date:** 28 December 2012

## 1. Summary of Project Objectives

The primary purpose of this project was to build upon the findings established in our previous Partners project that operational numerical weather prediction models have a consistent bias in the predicted location of warm-season elevated convective systems. In particular, the models that use parameterized convection and relatively coarse resolution predicted the axis of heavy convective rainfall to be farther north than where it was observed. This investigation had two primary goals: to expand the study to include additional models, and to examine the causes for this bias.

## 2. Project accomplishments and findings

(note: figures, tables, and references are included at the end of this document)

### *2.1. Data and methods*

#### *2.1.a. Selection of cases*

Expanding upon the work described in the previous final report, the warm seasons of 2009—2011 were examined to identify elevated mesoscale convective systems (MCSs) located between the Rocky Mountains and the Appalachian Mountains. Using radar animations and stage IV precipitation analyses, 42 unique six-hour periods were identified in which an elevated MCS occurred (Fig. 1).

#### *2.1.b. Data*

To evaluate the forecasts, the National Stage IV Quantitative Precipitation Estimate (QPE) product (Lin and Mitchell 2005) for the corresponding 6-hour intervals was obtained from the National Center for Atmospheric Research Earth Observing

Laboratory. This data set is a multi-sensor (radar and rain gauge) regional precipitation analysis produced at the twelve River Forecast Centers (RFCs). This analysis includes a manual quality control performed at each of the RFCs and is then mosaicked into a national product.

Three operational models with parameterized deep convection and one convection-allowing model were evaluated against the Stage IV analysis to investigate possible displacement biases in their MCS forecast locations. The 0000 and 1200 UTC runs of the North American Mesoscale (NAM), Global Forecast System (GFS), and the European Centre for Medium-Range Weather Forecasts (ECMWF; hereinafter abbreviated ECM) models were all analyzed. The National Severe Storms Laboratory (NSSL) Weather Research and Forecast model, which is run at 4-km grid spacing with explicit convection, was also evaluated.

*2.1.c. Methods*

The Method for Object-Based Diagnostic Evaluation (MODE; Davis et al. 2006) was used to evaluate the location of precipitation features in both the model forecasts and the stage IV analyses. The MODE tool resolves any two fields into objects and computes statistics on these objects, both individually and paired. Example statistics computed are centroid location, object area, length, and width, axis angle, aspect ratio, curvature, and intensity. Here, the centroids of precipitation objects for forecasts and analyses are used to quantify displacement errors.

The output from the GFS and ECM models was regridded to the NCEP 212 grid, which is a regional Lambert Conformal grid with a 40-km grid increment, while the NAM and NSSL-WRF model forecasts remained at their native grids (12 km and 4 km, respectively). The Stage IV data was regridded to match the corresponding model's grid, and appropriate settings were chosen to define objects on each of these grids.

In order to see how each run of the models did over time, a temporal dimension associated with the verification of the models' forecasts was added. Named "first forecast," this is the most recent model forecast for a particular time period. The second and third forecasts are the second and third most recent forecasts of the same time period. For example, the corresponding model runs and forecast times for the 6Z to 12Z time frame would be:

| | **Model Run** | **Forecast time** |
|---|---|---|
| 1st Forecast | 0000 UTC | 6 to 12 hr |
| 2nd Forecast | 1200 UTC (previous day) | 18 to 24 hr |
| 3rd Forecast | 0000 UTC (previous day) | 30 to 36 hr |

Then, a case study of the 27-28 July 2011 MCS that produced heavy rainfall and flooding in the Dubuque, IA area was conducted to identify potential causes of displacement errors in that case.

*2.2. Results*

*2.2.a. MCS forecast displacement errors*

The locations of forecast MCS heavy-precipitation centroids compared with the observed centroids are summarized for the NAM, GFS, and ECM in Fig. 2 and Table 1.

Based on these figures and other analysis not described in detail here, the NAM and GFS were both found to have a northward displacement bias for elevated, heavy-rain-producing MCSs. In the NAM, 68% of forecast MCS centroids were displaced to the north, and 74% were displaced to the north in the GFS. The ECM had 65% of its MCSs displaced northward as well, although the average displacement distance was smaller. The mean distance displacement was 266 km for the GFS, 249 km for the NAM, and 179 km for the ECMWF. The GFS also frequently displaced the MCS centroids to the east, with 65% of the cases having an eastward displacement. The NAM and ECMWF did not exhibit a significant bias in the east or west direction. All three of these models underwent upgrades during the period of study and the effects of the upgrades on this bias were examined, but the sample sizes were relatively small and thus no definitive conclusions could be reached.

To investigate whether the primary cause of the displacement bias lies in the parameterization of deep convection, the NSSL WRF, which explicitly predicts convection, was also evaluated. However, the results are not entirely conclusive, as the NSSL WRF is only run once per day out to 36 h, and only forecasts from 2009-2010 were available, so the sample size is limited in comparison to the other models. However, in the cases for which data were available, the NSSL WRF did not exhibit a northward displacement bias; rather it had a very slight southward bias, consistent with the results of Marsh et al. (2012; Fig. 3). This suggests that the explicit prediction of convection, in conjunction with the better resolution of other atmospheric processes at smaller grid spacing, may help to alleviate the northward bias found in the models with parameterized convection. However, further study of this behavior in additional cases and high-resolution models is warranted.

*2.2.b. 27-28 July 2011 case study*

On 27-28 July 2011, an extreme-rain-producing MCS occurred along the borders of Iowa, Illinois, and Wisconsin. The greatest impacts were in the city of Dubuque, IA, which received 261 mm (10.31 inches) of rainfall and saw the Mississippi River rise 4 feet in 12 hours. Two NAM forecasts were compared – one with the heavy rainfall displaced well to the north of the observed location, and one where the precipitation axis was approximately correct, although the rainfall amounts were underpredicted.

One hypothesized cause for the displacement bias for MCSs is a displacement of the front or boundary responsible for initiating and organizing the MCS. This was found to be the primary reason for a northward displacement in the simulations of Schumacher et al. (2010). Frontal positions were objectively analyzed for the NAM analysis at 0600 UTC 28 July 2011, and also for the NAM forecasts initialized at 0000 UTC 27 July and 0000 UTC 28 July and valid at 0600 UTC 28 July. For these forecasts, the primary cause of the precipitation displacement appears to be a displacement of the stationary front that served to initiate and organize the heavy-rain-producing convection. The analyzed stationary front at 925 hPa was oriented from southwest to northeast across Iowa, and the heavy precipitation fell just on the cool side of this boundary (Fig. 4a). However, in the 30-h NAM forecast this front was located well to the north near the Iowa/Minnesota border (Fig. 4b). As a result, an axis of heavy precipitation developed, but it was displaced northward. In the 6-h NAM forecast valid at the same time, the frontal position was very similar to the analyzed position, and the heavy precipitation axis was located closer to the observed axis (Fig. 4c).

To further investigate this issue, ongoing work is aimed at comparing the 12-km NAM forecast with the forecast from the 4-km NAM nest: these models use the same analysis for initial conditions, and use the same physics parameterizations, except that convection is explicitly predicted on the 4-km grid. This will shed light on whether higher-resolution forecasts may reduce or eliminate the displacement bias. Preliminary analysis shows that the heavy-precipitation axis was indeed shifted southward in the 4-km NAM nest compared to the operational and experimental 12-km NAM forecasts (Fig. 5), but the axis was still displaced north of the observed location. Brad Ferrier (NCEP/EMC) has provided the full gridded forecast fields for these runs, which are currently being examined.

*2.3. Summary of results*

Evaluation of additional cases and additional models confirmed the northward bias for forecasts of elevated MCSs in the NAM and GFS models, and found that it also exists but to a lesser magnitude in the ECMWF model. In the convection-permitting NSSL WRF model, this bias was not present, and there was actually a slight southward bias. However, the sample size of cases for the NSSL WRF was much smaller than for the other models, so this result requires further investigation. In a case study of the 27-28 July 2011 extreme rainfall in Dubuque, Iowa, it was found that the primary cause of the northward precipitation displacement was the northward displacement of the stationary front that served to initiate and organized the MCS. Ongoing work is aimed at further understanding the underlying causes for the model biases.

## 3. Benefits and lessons learned: operational partner perspective

Improving warm season rainfall forecast skill is the primary challenge for the QPF Desk at HPC. This project has accomplished the stated goal by objectively confirming forecaster's subjective impression that there is a northward displacement bias of elevated convective systems in the NAM and GFS. This knowledge and the finding that the ECMWF and NSSL-WRF exhibit less bias are directly applicable to the forecast process, during which forecasters often blend several model solutions. These results give forecasters greater confidence in adjusting the biased model solutions farther south in such convective situations, and ultimately improve QPF forecasts.

The project has also sparked forecaster interest in understanding why this bias may be present. This interest was sustained by several interactions. For example, PI Schumacher and student Charles Yost visited HPC in October 2012. During the visit, Charles Yost provided a seminar that was recorded and attended by HPC forecasters and EMC model developers. Interaction with the HPC-HMT regarding MODE was fruitful, as HPC considers different configurations for objective verification.

The NCEP Environmental Modeling Center (EMC) has been engaged through these interactions. During their 2012 visit, PI Schumacher and student Yost met with EMC to discuss the results of this project and future EMC guidance, including upcoming changes to the SREF and NAM. EMC subsequently provided PI Schumacher with NAM data to investigate the source of the bias in various versions of the model. The synergy between the researchers, model developers, and forecasters was a strength of this project.

Given the desirable bias characteristics of the NSSL-WRF identified during this project, HPC forecasters are increasingly looking to the convection-allowing models to assist with the displacement bias. Additionally, the recent finding that the location of frontal boundaries may contribute to the bias provides forecasters with additional information to diagnose the models.

HPC looks forward to working with Schumacher and Yost to publish the project results. HPC encourages continued research to identify the underlying source of the displacement bias. Future collaborations may include idealized experiments and continued analysis of the Dubuque case study.

## 4. Benefits and lessons learned: university partner perspective

This Partners project was beneficial to the university partners for several reasons.

First, the university PI (Schumacher) is early in his career as a faculty member, and has strong interests in both high-impact weather and in conducting research that is operationally relevant. Having a formalized collaboration with an operational center (HPC) provides insights into the sorts of issues that operational forecasters face that can potentially be addressed with scientific research. This collaboration over the course of more than two years has been very fruitful, and future opportunities to continue this collaboration will be sought out. The visit to the new NOAA Center for Weather and Climate Prediction also initiated contacts between the university participants and model developers at NCEP/EMC, and the exchange of ideas between academic researchers, operational forecasters, and model developers has identified several potential areas for future research that could potentially have a direct benefit to both the models and their operational users.

Second, this project offered an opportunity for MS Student Charles Yost to continue his research on displacement biases in model forecasts of MCSs. The project funded a visit for Schumacher and Yost to spend three days in residence at HPC in September 2012, which was Schumacher's third visit to HPC and Yost's second. This visit provided opportunities to shadow HPC forecasters (day 1 and 2 quantitative precipitation forecasting; surface analysis; medium-range forecasting, etc.). Furthermore, Yost gave a presentation of his updated and expanded results to a wide audience including forecasters, researchers, and model developers. Yost has consistently noted that he appreciates the operational relevance of his thesis research project. He successfully defended his MS thesis in the fall of 2012 under the support of this project.

## 5. Publications and presentations

Presentations:

Yost, C.M. and R.S. Schumacher, 2012: Do the Global Forecast System (GFS) and the North American Mesoscale (NAM) Models Have Displacement Biases in Their Mesoscale Convective System Forecasts? 26th Conference on Hydrology, Amer. Meteor. Soc., New Orleans, LA, January 2012. (poster presentation)

Yost, C.M. and R.S. Schumacher, 2012: Investigation into a Displacement Bias in Operational Models' Mesoscale Convective System Forecasts, Hydrometeorological Prediction Center Seminar, College Park, MD, October 2012

Yost, C.M., 2012: Investigation into a displacement bias in numerical weather prediction models' forecasts of mesoscale convective systems. M.S. thesis, Colorado State University.

Charles Yost's MS thesis research is currently in preparation for submission to a peer-reviewed journal

## 6. Summary of University/Operational Partner Interactions and Roles

- Prof. Russ Schumacher, university PI: co-designed the research project; identified possible cases for examination; assisted in the collection of data and in preparation of software for analysis; mentored the supported graduate student; visited HPC with graduate student, which included shadowing forecasters and discussing the research with HPC and EMC staff.

- Charles Yost, graduate research assistant: collected necessary data; conducted the analysis; prepared the research results for this report and for presentation at HPC; made presentation at HPC seminar; shadowed forecasters; discussed research results with HPC and EMC staff

- Dr. David Novak, NOAA/NWS/NCEP/HPC PI: co-designed the research project; identified possible cases for examination; suggested methods for analyzing the data; hosted university partners at HPC; disseminated research results to HPC and EMC staff

- Dr. Wallace Hogsett, NOAA/NWS/NCEP/HPC co-PI: hosted university partners at HPC; disseminated research results to HPC and EMC staff

## Figures

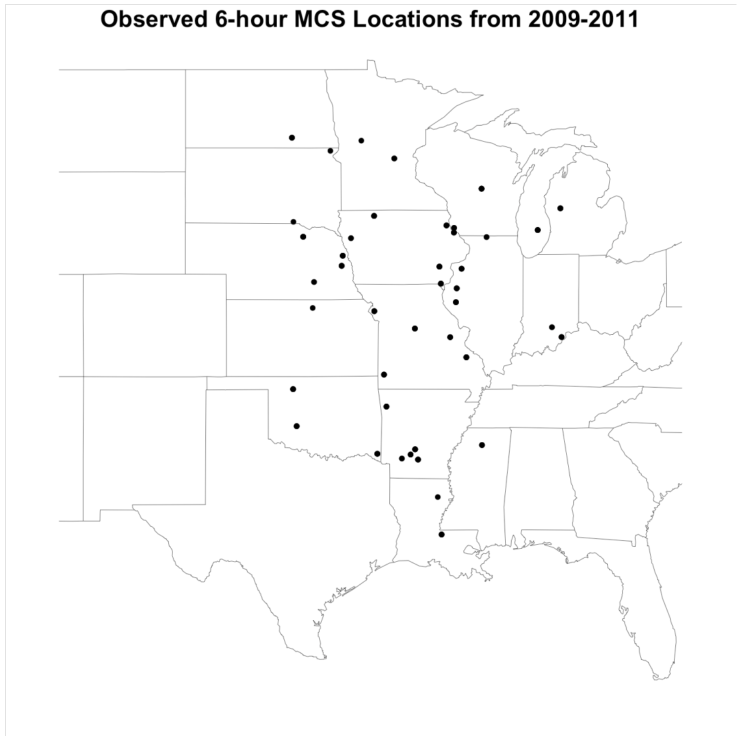


FIG. 1. Locations of observed elevated MCSs during 2009-2011 considered in this study.

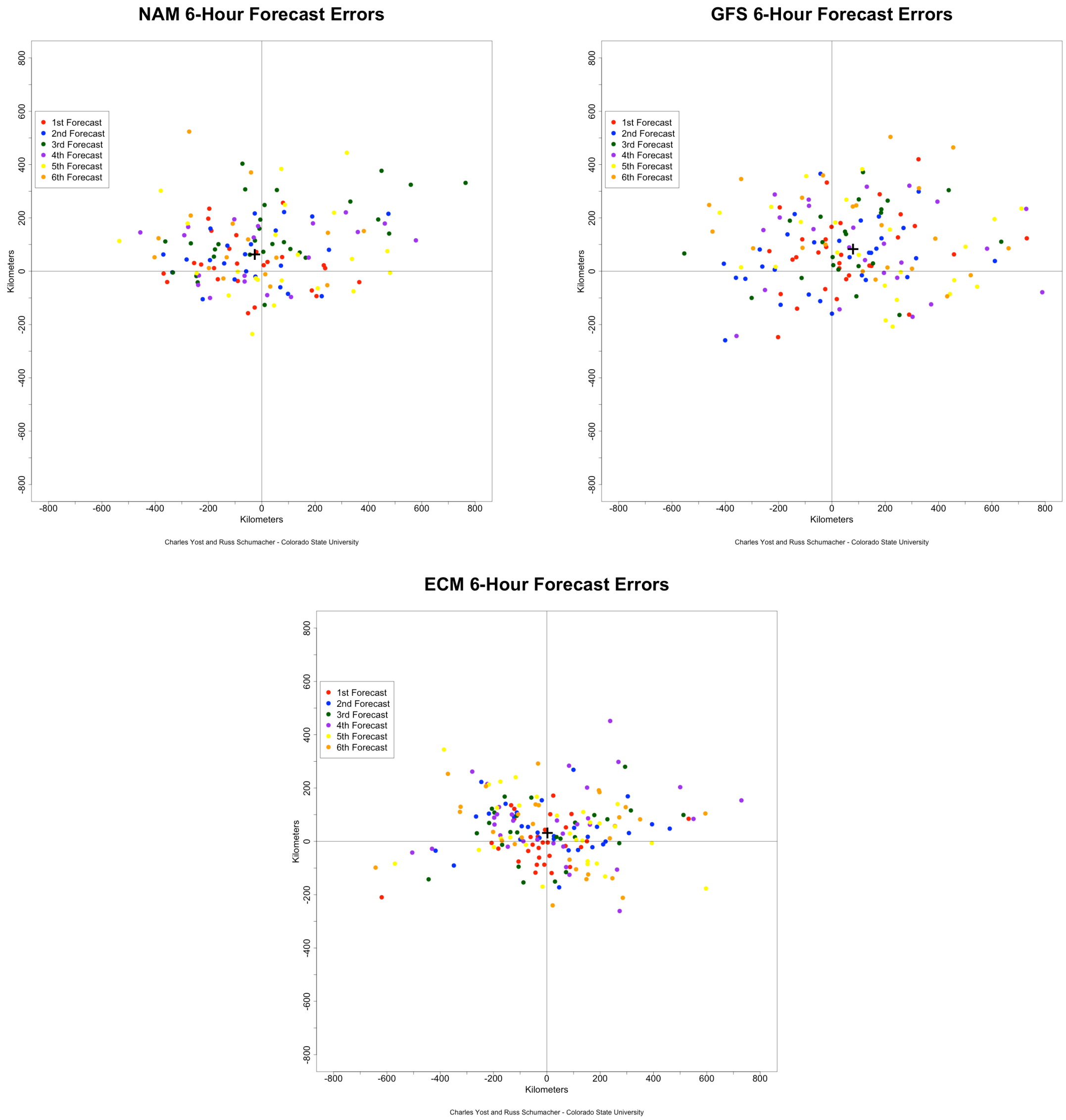


FIG. 2. Model forecast precipitation centroid locations relative to the observed centroids for the (a) NAM, (b) GFS, and (c) ECMWF, for all forecast lead times. The observed centroid is placed at the origin for each figure, with colored dots representing forecast MCS centroids. The dots are color-coded by forecast lead time, with the "1st forecast" representing the shortest lead time and the "6th forecast" representing the longest lead time. The "+" symbol is placed at the median displacements in the x- and y-directions.

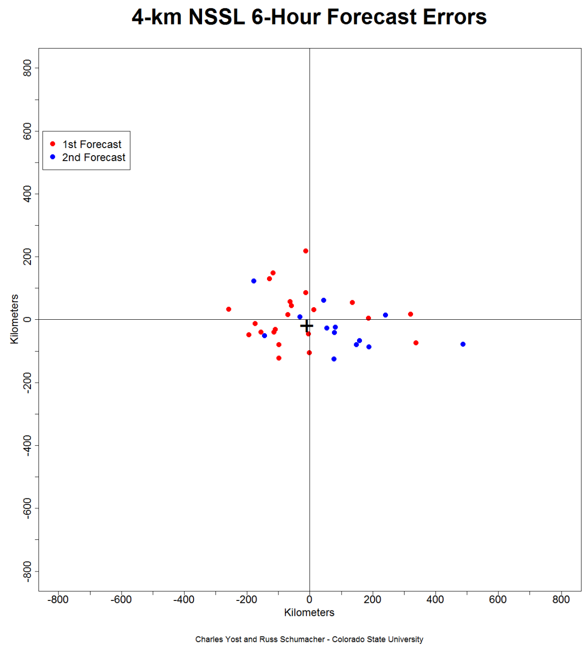


FIG. 3. As in Fig. 2, except for the NSSL WRF model. NSSL WRF forecasts were only available for 2009 and 2010, and this model is only run once per day (at 0000 UTC) out to 36 h.

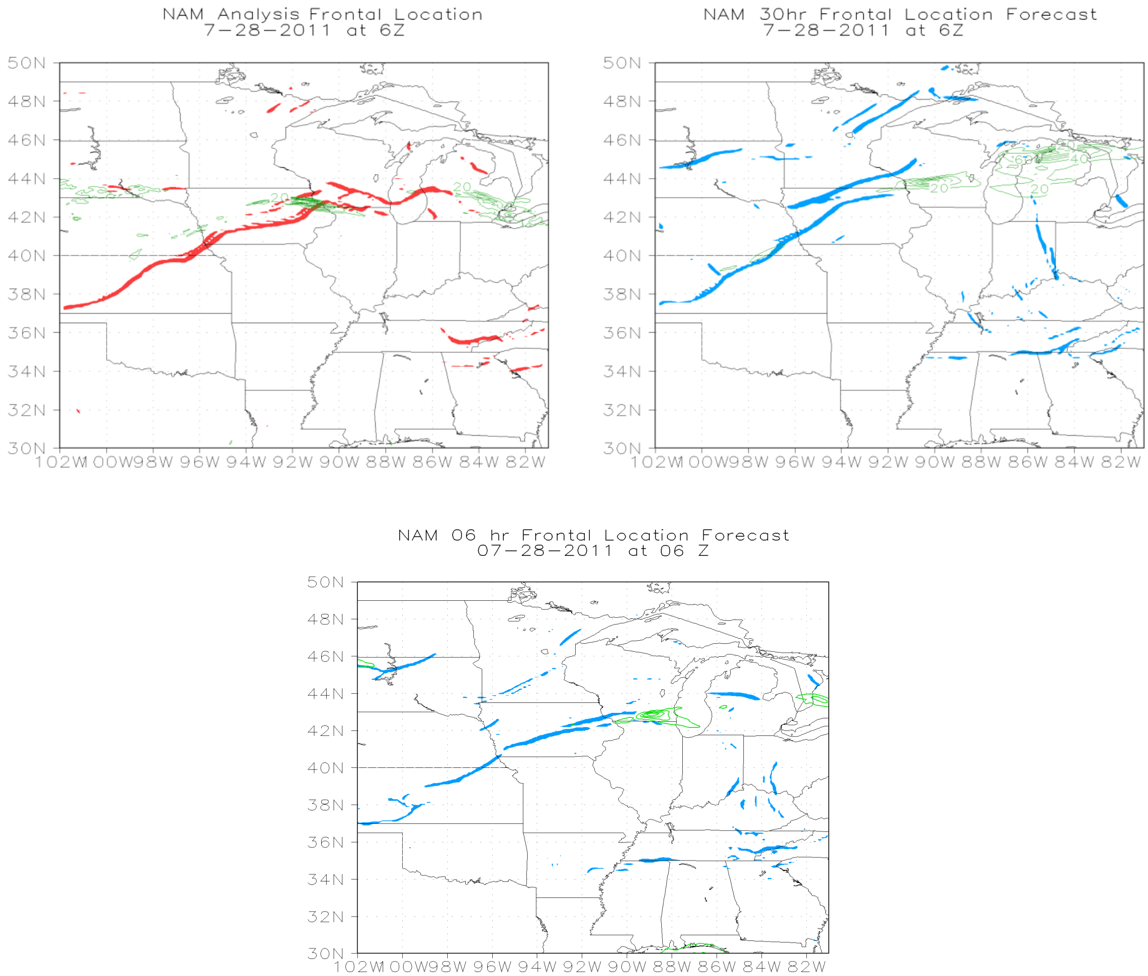


FIG. 4. Objectively analyzed position of the 925-hPa stationary front in (a) the NAM analysis valid 0600 UTC 28 July 2011; (b) the 30-h NAM forecast initialized 0000 UTC 27 July 2011 and valid at 0600 UTC 28 July; and (c) the 6-h NAM forecast initialized 0000 UTC 27 July 2011 and valid at 0600 UTC 28 July. The objectively analyzed fronts (using the method of Renard and Clarke 1965) are colored, and analyzed or forecast precipitation are contoured every 20 mm in green.

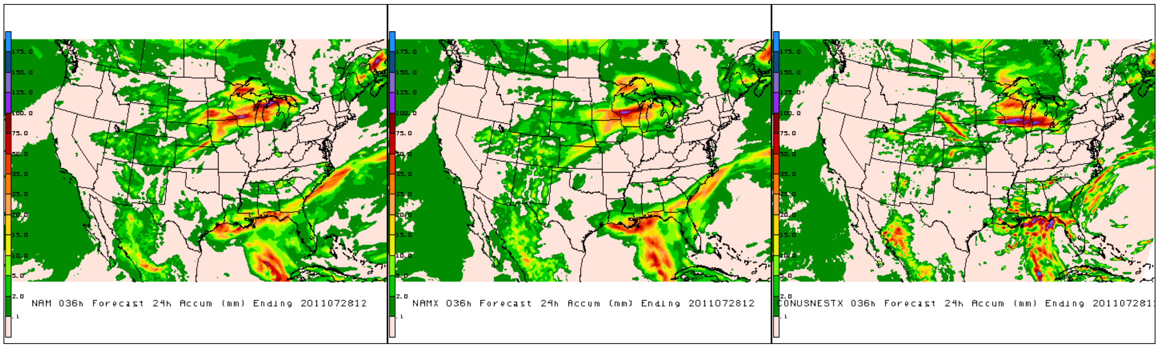


FIG. 5. 12—36-h precipitation forecasts (mm) for the period ending 1200 UTC 28 July 2011 for (a) the operational NAM (same forecast as shown in Fig. 4b); (b) the experimental NAM; and (c) the experimental NAM 4-km nest. All were initialized at 0000 UTC 27 July 2011. Obtained from http://www.emc.ncep.noaa.gov/mmb/ylin/pcpverif/daily/2011/20110728/#VERF36.

## Tables

Table 1: Mean, median of the centroid displacement errors for each of the operational models for forecasts 1-3 (corresponding to forecasts with lead times of 36 h or less), along with the standard deviation.

| | **Mean (km)** | **Median (km)** | **Stand. Dev. (km)** |
|---|---|---|---|
| **NAM** | 231.8 | 202.1 | 145.4 |
| **GFS** | 239.0 | 214.5 | 149.9 |
| **ECMWF** | 182.4 | 154.2 | 128.4 |

Table 2: Percentage of predicted MCS centroids in each quadrant relative to the observed location for all forecast times.

| | **NE** | **NW** | **SE** | **SW** |
|---|---|---|---|---|
| **NAM** | 43% | 49% | 13% | 19% |
| **GFS** | 44% | 30% | 21% | 9% |
| **ECMWF** | 31% | 34% | 19% | 16% |
| **NSSL WRF** | 19% | 28% | 25% | 28% |

## References


Davis, C., B. Brown, and R. Bullock, 2006: Object-based verification of precipitation forecasts. Part I: Methods and application to mesoscale rain areas. *Mon. Wea. Rev.,* **134,** 1772–1784.

Lin, Y., and K. E. Mitchell, 2005: The NCEP stage II/IV hourly precipitation analyses: Development and applications. Preprints, 19th Conf. on Hydrology, San Diego, CA, Amer. Meteor. Soc., CD-ROM, 1.2.

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Schumacher, R. S., T. J. Galarneau Jr., and L. F. Bosart, 2011: Distant effects of a recurving tropical cyclone on rainfall in a midlatitude convective system: A high-impact predecessor rain event. *Mon. Wea. Rev.,* **139**, 650–667.