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PROCESSES AND PREDICTABILITY IN RECENT WIDESPREAD HEAVY RAIN AND FLOOD EVENTS

Russ S. Schumacher* and Christopher A. Davis
*National Center for Atmospheric Research, Boulder, Colorado**

1. INTRODUCTION

In the United States in 2007 and 2008, several extended periods of heavy rainfall took place, resulting in destructive flooding and the establishment of new rainfall records in many locations. Major floods occurred in parts of the southern Plains and the Upper Midwest in 2007, the 2008 floods in Iowa and Wisconsin received national attention, and three tropical cyclones made landfall in 2008 that soaked large regions of the country. Considering the numerous impacts that heavy rainfall and flooding have on society, and the continuing challenges in predicting precipitation at all scales (e.g., Olson et al. 1995; Fritsch and Carbone 2004; Hamill et al. 2008), there is a need to understand the processes that lead to extreme precipitation events. Additionally, because numerical weather prediction (NWP) models provide much of the guidance for making precipitation forecasts, it is important to evaluate their performance in high-impact events so that forecasters and end users can have a better understanding of the skills and shortcomings of these forecasts.

This study will use global ensemble forecast data to test the determine the predictive skill and the limits of predictability for large-scale, extended periods of heavy rain in NWP ensembles, and to identify how these limits change for events forced by different atmospheric processes. Precipitation systems, particularly those involving deep moist convection, can be especially difficult to predict because of the small-scale, chaotic nature of the development and organization of deep convection. As a result, warm-season precipitation, which often occurs with weak synoptic-scale forcing, presents a very difficult forecast challenge (e.g., Carbone et al. 2002). Past studies (e.g., Mullen and Buizza 2001; Hamill et al. 2008) have investigated the performance of quantitative precipitation forecasts in global ensembles and confirmed that they provide skillful forecasts at low precipitation thresholds and that they perform better in the winter season; they generally perform much worse in the warm season and for heavy precipitation. The predictability of extreme rainfall in the United States has been examined for some cases by Mullen and Buizza (2001) and Zhang et al. (2006); however, these investigators focused primarily on rainfall on 24–36-hr temporal scales. This study will examine multiple-day, widespread rain events, which occur on spatial and temporal scales that should be well-resolved by global NWP models, which pose flooding threats over large areas, and which also have implications for seasonal climate predictions.

The atmospheric processes associated with heavy rainfall at various scales in the central and eastern United States have been established in numerous past studies (e.g., Maddox et al. 1979; Giordano and Fritsch 1991; Mo et al. 1997; Konrad 2001; Schumacher and Johnson 2005, among many others). In the cool season, US heavy rainfall is typically produced by strongly-forced synoptic-scale weather systems, such as extratropical cyclones. In the warm season, the processes leading to heavy rainfall are more varied: extratropical cyclones, mesoscale convective systems (MCSs; Houze 2004), and tropical cyclones are all important heavy rain producers (e.g., Schumacher and Johnson 2006). It is common for MCSs to occur within latitude "corridors" (Tuttle and Davis 2006), and in rare circumstances, the synoptic-scale flow pattern is so persistent that the corridor includes extended periods of MCS development over the same area. This type of situation led to the historic 1993 floods in the Midwest (e.g., Junker et al. 1999), as well as the 2008 Midwest floods, which will be discussed further later in this article.

2. DATA AND METHODS

The primary precipitation dataset used in this study is the "US daily precipitation analysis"

*The National Center for Atmospheric Research is sponsored by the National Science Foundation.
Corresponding author address: Russ Schumacher, NCAR, Boulder, CO 80307-3000; rschumac@ucar.edu

from the National Oceanographic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC), obtained online from `ftp://ftp.cpc.ncep.noaa.gov/precip/wd52ws/us_daily/`. This dataset is created from approximately 6000 rain gauge observations, gridded to a 0.25° latitude × 0.25° longitude grid. This dataset has relatively coarse resolution, so that it does not faithfully represent local precipitation maxima, but it is adequate for analyzing the large-scale, multiple-day rainfall events that will be discussed below.

The model datasets were obtained from the TIGGE archive at `http://tigge-portal.ecmwf.int`. The primary model that will be used is the European Centre for Medium-Range Weather Forecasts ensemble (ECMWF; Buizza et al. 2007), which has 51 members with a spectral truncation of T399 (corresponding to approximately 50 km horizontal grid spacing) and 62 vertical levels through 240 forecast hours. The ECMWF ensemble was chosen because of its large number of members and because of its superior performance based on several verification methods (e.g., Park et al. 2008). The 51 members of the ensemble comprise a control run and 50 members that are initially perturbed by singular vectors in pairs (i.e., a positive and negative perturbation.) The horizontal resolution of the singular vector perturbations is T42 with 62 vertical levels. Quantitative precipitation forecasts (QPFs) for all 51 members were obtained at 12-hr initialization intervals, on a 0.5° latitude × 0.5° longitude grid, for the events of interest. Other details about the ECMWF ensemble prediction system can be found in Buizza et al. (2007) and references therein.

As is common in precipitation verification studies, several verification metrics will be used. Because of the relatively large spatial and temporal extents of the events to be considered here, and the relatively coarse resolution of both the observational and the forecast data, "traditional" verification metrics can be employed. These include the Brier skill score (BSS) and the relative operating characteristic (ROC) curve (e.g., Wilks 2005). The BSS is calculated using the method described in Hamill and Juras (2006), which accounts for the varying climatological probability of events by calculating the score for subsets of climatological probability. The BSS for each event is calculated at points within the US and relative to the climatological probability of the event for that season. The calculation of the area under the ROC curve does not account for spatially varying climatology, but is compared with a random reference forecast with area 0.5.

In addition to the precipitation analyses and forecasts, atmospheric data will be presented where applicable. The primary source for upper-level atmospheric information is the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996). Daily analyses of pressure-level geopotential height are used to describe some of the large-scale atmospheric processes at work in the heavy rain events. Additionally, locations of other important weather phenomena (such as tropical cyclone tracks, fronts, etc.) were obtained from NOAA surface analyses archived at the National Climatic Data Center.

3. SELECTION OF EVENTS

To select the cases that will be discussed in this study, the gridded precipitation data described above were analyzed to find instances of widespread, multi-day heavy rainfall. All five-day periods in which the 100-mm contour covered over 350 grid points in the precipitation analysis were identified. Because the data are on a latitude/longitude grid, the physical area covered by 350 grid points varies somewhat depending on the orientation of the rainfall contours, though the approximate area covered by the 100-mm contour in these events is 800 000 km^2.

Such events occurring in 2007 and 2008 will be the primary focus of this study. To avoid including duplicate events that were associated with the same weather system, when there were overlapping five-day periods that exceeded the threshold, the period in which the 100-mm contour had the largest areal coverage was selected. After removing these overlapping periods, there were nine events in this two-year period; they are listed in Table 1 and precipitation totals from each event are shown in Fig. 1. In addition to widespread coverage of the 100-mm rainfall contour, each of these events had point accumulations exceeding 200 mm and was responsible for destructive (and in many cases deadly) flooding. The nine events happen to divide cleanly into three categories: three were associated with warm-season organized convective systems; three with cool-season, synoptic-scale weather systems; and three were landfalling tropical cyclones. All nine events occurred east of the Rockies; long-lived rain events are also relatively common along the Pacific coast, but they generally cover less overall area. The processes occurring during each of the nine events will be discussed where appropriate, and more detailed analyses of these events are underway and will be presented in future manuscripts.

Table 1: Listing of the nine widespread five-day rain events in 2007 and 2008, selected as described in the text. Each event is considered to have started at 1200 UTC on the first date given and ended at 1200 UTC on the second date given. The events have been classified as either cool season (CS), warm season (WS), or tropical cyclone (TC).

Dates	Location	Type	Process(es)
25-30 June 2007	Southern Plains	WS	Midlevel vortex
18-23 August 2007	Upper Midwest	WS	Stationary front; remnants of TS Erin
22-27 October 2007	Southeast	CS	Cutoff synoptic cyclone
15-20 March 2008	Mississippi Valley	CS	Synoptic-scale front
4-9 June 2008	Upper Midwest	WS	Stationary front
22-27 August 2008	Southeast	TC	Tropical Storm Fay
1-6 September 2008	South	TC	Hurricane Gustav
10-15 September 2008	South; Midwest	TC	Hurricane Ike and its predecessor rain event
8-13 December 2008	Southeast	CS	Synoptic cyclone

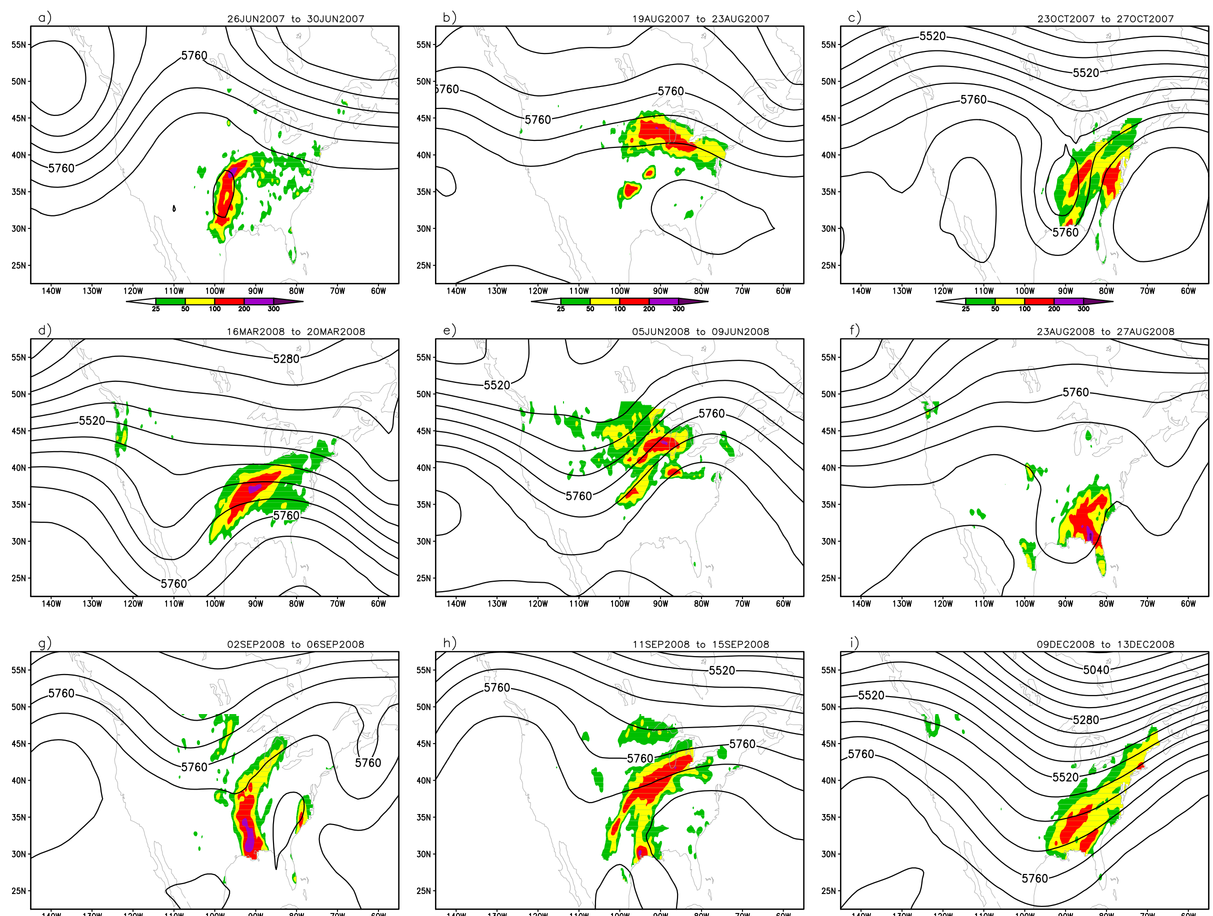

Figure 1: Five-day accumulated precipitation (color shading) and five-day average 500-hPa geopotential height (solid contours every 60 m) for each of the nine widespread rain events during 2007–2008 (see also Table 1). (a) 25–30 June 2007; (b) 18–23 August 2007; (c) 22–27 October 2007; (d) 15–20 March 2008; (e) 4–9 June 2008; (f) 22–27 August 2008; (g) 1–6 September 2008; (h) 10–15 September 2008; (i) 8–13 December 2008.

4. PREDICTIVE SKILL AND PREDICTABILITY

4.1 *Overview*

Now that the nine heavy rain events—three caused by strong synoptic-scale systems, three by tropical cyclones, and three by warm-season convection—have been introduced, the ECMWF ensemble forecasts will be used to assess the predictive skill and predictability for the rain events associated with these various processes. Since these events have impacts on local and regional scales, and on temporal scales ranging from subdaily to seasonal, an understanding of how well a current state-of-the-art ensemble predicts them may be useful to a variet y of users. This analysis can also potentially provide useful information about where predictability is weakest, which can pinpoint the most imp ortant topics for future research. In this subsection, the basic verification statistics and some of their notable aspects will be presented, an d the following subsection will delve deeper into the reasons for the results presented here.

We begin the verification of the ECMWF ensemble at a relatively low precipitation threshold for these events: 50 mm in 5 days, which covers a very large area in all of the events (Fig. 1). The predictions at this threshold provide a baseline of sorts for whether the ensemble correctly identifies that a particular large-scale region will receive a moderate amount of rain, without considering the details of the heaviest precipitation. For almost all of the events, both the BSS and ROC area metrics indicate very skillful predictions at this threshold, especially for forecasts initialized at the start of the rainy five-day period (Fig. 2a and Fig. 3a). In most of the events, the skill then gradually decreases with increasing lead time, with the ensemble still showing considerable skill in 96–216-hr precipitation forecasts. This suggests that, in general, the ECMWF ensemble QPFs provide high-quality guidance many days in advance as to the locations of widespread rainfall. However, two of the events are noticeable outliers at the 50-mm threshold: the June 2008 event (the purple line in Figs. 2a and Fig. 3a), and the June 2007 event (blue line). There is minimal skill in predicting the June 2008 event at short lead times; the skill is actually somewhat higher at longer lead times. In the June 2007 event, the ensemble forecasts are comparable to the ot her events at short lead times, but skill drops off sharply at longer lead times, such that the BSS is negative at lead times longer than 84–204 hr (Fig. 2a) and the area under the ROC curve is substantially smaller than for any of the other events at the longest lead times considered here (Fig. 3b).

At the 100-mm threshold, the skill is generally lower than at 50 mm, and the forecasts for several of the events have considerable forecast-to-forecast variability in skill (Fig. 2b and Fig. 3b). For forecasts initialized at the starting times of the events, the ensemble shows skill in almost all of the cases. Two of the tropical cyclone cases—Fay and Gustav—have the best forecasts, whereas there is essentially zero skill for the June 2008 event. At long lead times, the June 2007 and October 2007 events have the least skillful forecasts. Th e December 2008 case, which had some of the best forecasts at the 50-mm threshold, is among the worst at the 100-mm level.

The verification statistics using a precipitation threshold of 150 mm appear to depend in part on the areal coverage of the 150-mm contour in each event. The ensemble has considerable skill for the events with widespread 150-mm accumulations, such as tropical cyclones Fay and Gustav (Fig. 2c and Fig. 3c), whereas it has no skill for several of the events with smaller 150-mm areas. There is again large run-to-run variability in the forecast quality for some of the events, particularly the March 2008 and Hurricane Ike cases, and especially when considering the area under the ROC curve (Fig. 3c). Somewhat surprisingly, the June 2007 event, which had relatively poor forecasts at lower thresholds, performs better at moderate lead times compared with many of the other events. At the longest lead times, the forecasts for the rainfall from Fay have by far the highest skill, with there being near-zero BSS and small ROC areas for 96–216-hr forecasts for all of the other events.

4.2 *Discussion*

As with all single-number forecast verification statistics, the results discussed above and shown in Figs. 2–3 do not paint a complete picture of the quality and usefulness of the ensemble forecasts for these cases. This subsection will delve deeper into *why* the spread and skill vary among the nine cases, and how the processes responsible for producing the heavy rainfall determine the predictability of each event.

One of the most striking features of both the BSS (Fig. 2) and the ROC area (Fig. 3) verification statistics is the poor performance at short lead times for the June 2008 event (shown by the dark purple lines in the figures) in the Midwestern US. Given

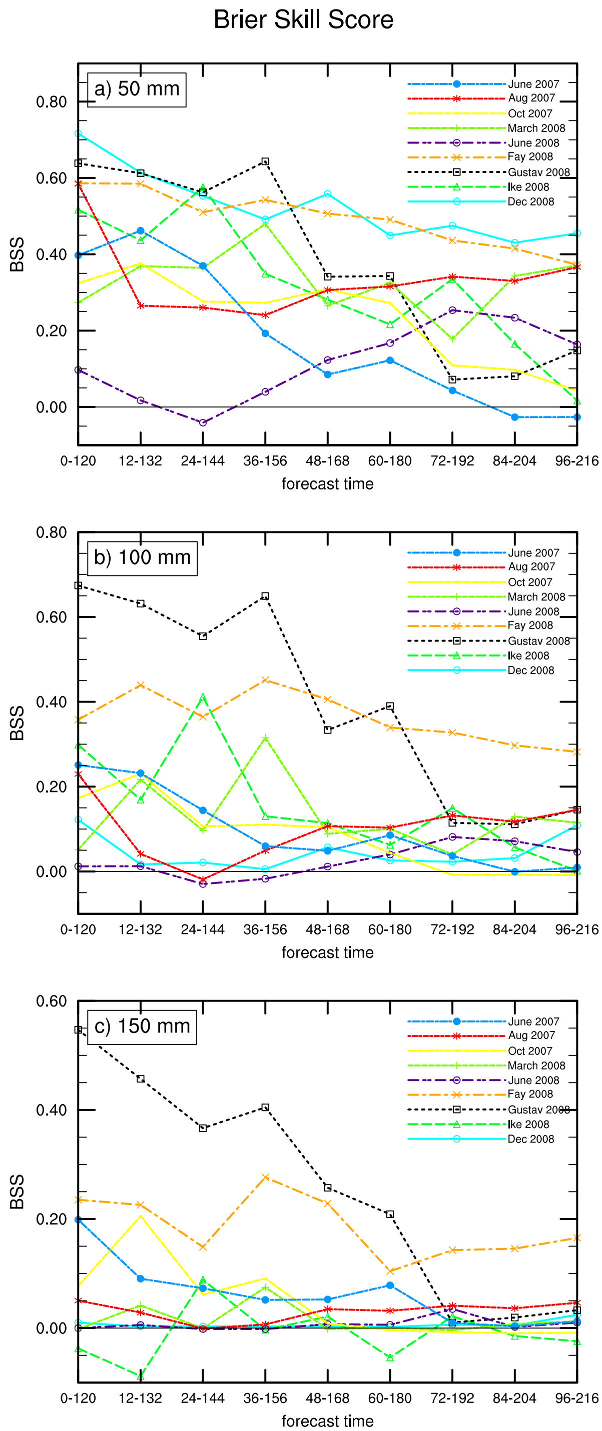

Figure 2: Brier skill score of the ECMWF ensemble for the nine widespread five-day rain events. Shown are 120-h precipitation accumulation thresholds of (a) 50 mm; (b) 100 mm; and (c) 150 mm. Skill scores are calculated relative to the seasonal climatology, as described in the appendix. A BSS of 1 is a perfect forecast; zero indicates no skill. Note that the values shown on the ordinate are scaled differently in each panel.

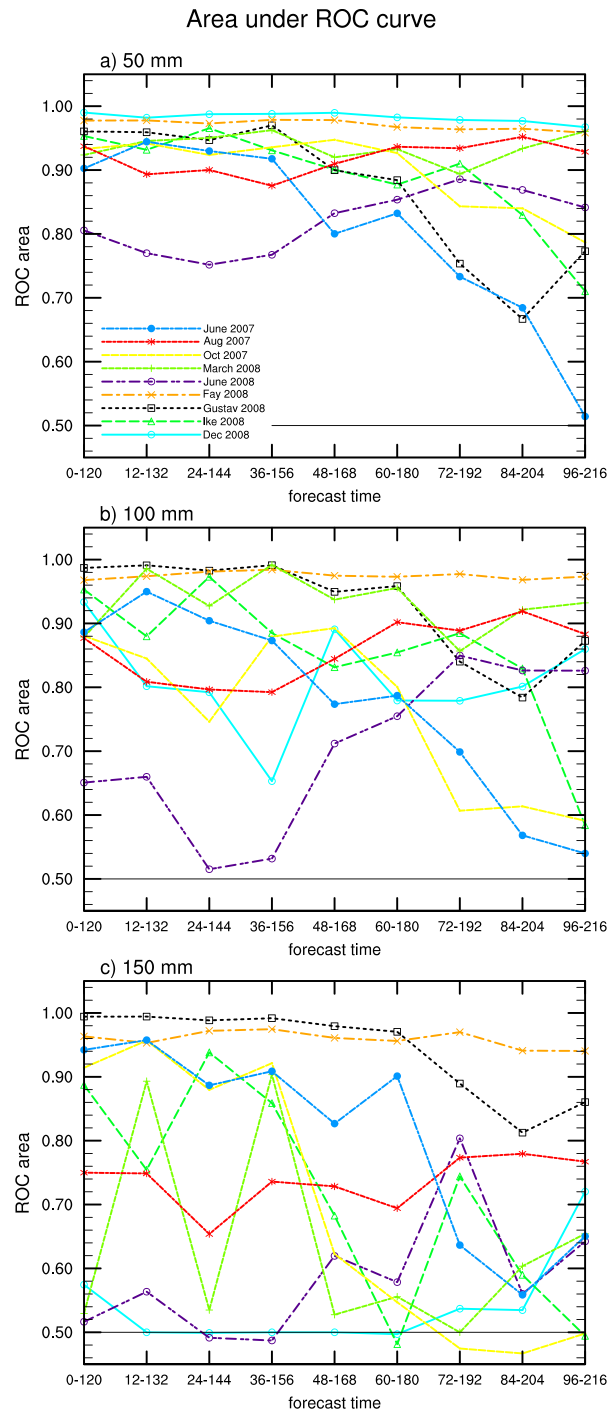

Figure 3: As in Fig. 2, except for the area under the ROC curve. A perfect forecast has ROC area of 1; a random reference forecast has area 0.5.

the severe impacts of the rainfall during that time period, the low skill scores for this event are concerning. A summary of the raw ensemble forecast probabilities (Fig. 4a) shows that there are several reasons for the low verification scores. At the shortest lead times considered here (Fig. 4a–b), probabilities of 50 mm are very high throughout the upper Midwest, particularly in the northern halves of Minnesota and Wisconsin, and also farther west in South Dakota. However, the observed heavy precipitation mainly occurred farther south, in a band extending through southern Wisconsin and Iowa, and southward into Kansas and Oklahoma. The ensemble did not provide any indication of heavy rainfall in Indiana—this was an extreme rain event caused by a quasi-stationary mesoscale convective system, and global models at coarse resolutions are generally unable to predict an event of this type. Finally, the band of observed precipitation in Missouri, Kansas, and Oklahoma was not well forecast. This precipitation occurred near the end of the 120-hr forecast period and was also associated with mesoscale convection. At longer lead times (Fig. 4c–e), however, probabilities were lower overall (which is to be expected, as model errors have had more time to grow), and they correctly identified the possibility for widespread rainfall in the general area where it would occur. As a result, verification skill scores are higher at longer lead times for this event. Despite the low skill scores at short lead times, this collection of forecasts could still provide valuable guidance to forecasters, as it suggested the possibility of widespread rain at long lead times, and at short lead times there are other sources of model guidance available that could be more useful, such as short-range ensemble forecasts and models with explicitly-predicted convection.

The other notable outlier at the 50-mm threshold in Figs. 2a and 3a is the lack of forecast skill at long lead times for the June 2007 event (shown by the blue lines in the figures) in the Southern Plains (see Goebbert et al. 2008 for an overview of this event). While forecasts for all of the other events are shown to be skillful relative to climatology even at the 96–216-hr forecast time, the June 2007 case shows a negative BSS for lead times beyond 84 hr (Fig. 2a) and has a ROC area considerably lower than that for the other events beyond 48 hr (Fig. 3a). The heavy rainfall in this case was associated with a long-lived, slow moving vortex that owed its existence to latent heat release from deep convection. At relatively short lead times, the ensemble forecasts of this event appear subjectively to be quite good (Fig. 5a–b), consistent with the objective metrics. With increasing lead time, however, the forecasts degrade substantially (Fig. 5c–d), such that in the 96–216-hr forecast, there was zero probability of 50 mm of rain in much of the region that received greater than that amount (Fig. 5e). Additionally, the highest probabilities of 50 mm at long lead times were in the northern Plains, which generally had no precipitation at all during this time period (Fig. 1a).

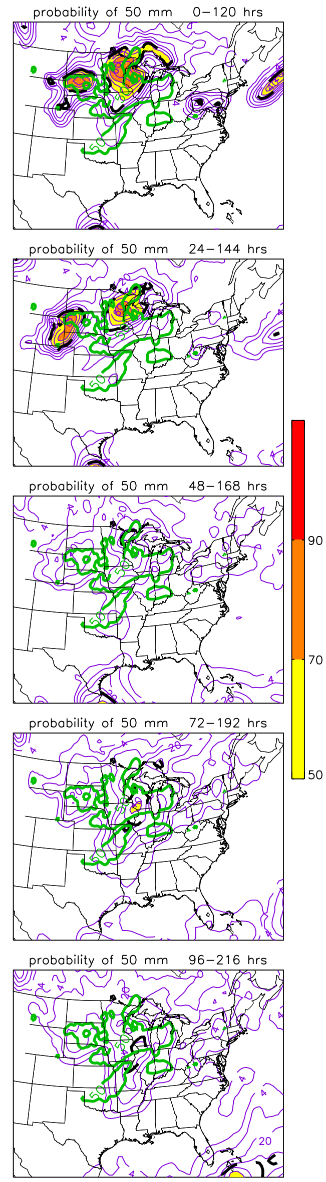

Figure 4: (Left column) Raw ensemble probabilities, at increasing lead times, of 50 mm of precipitation in the 120-hr period between 1200 UTC 4 June and 1200 UTC 9 June 2008. Probabilities are contoured in purple at 4% (i.e., two ensemble members), 10%, and every 10% above that. Probabilities above 50% are shaded in yellow; 70% in orange; and 90% in red. The ensemble mean is shown in the thick black dashed line. The observed 50-mm precipitation contour is shown in green. Model initialization times shown are 1200 UTC (a,f) 4 June, (b,g) 3 June, (c,h) 2 June, (d,i) 1 June, and (e,j) 31 May 2008.

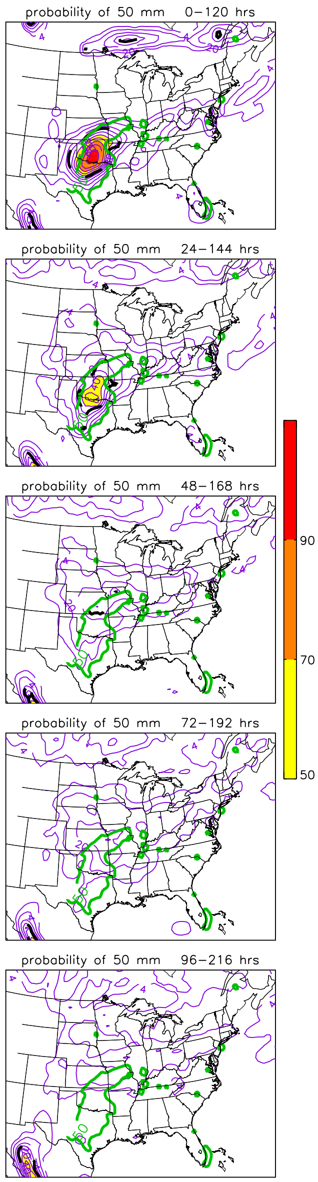

Figure 5: As in Fig. 5, except for the June 2007 event. Model initialization times shown are 1200 UTC (a,f) 25 June, (b,g) 24 June, (c,h) 23 June, (d,i) 22 June, and (e,j) 21 June 2007.

An initial understanding of the limited predictability of this event can be gained by examining the atmospheric processes responsible for the hea vy rains in this case. As mentioned above, a midlevel vortex developed over the southern Plains in late June and remained nearly stationary through the first week of July. Convective processes were primarily responsible for the spin-up of this vortex, and also for its development into a warm-core circulation. By 28 June (Fig. 6a), a low-level circulation was apparent, and the low-l evel vorticity center became better defined over the coming days (Fig. 6b–d). Ensemble forecasts of this vortex showed rapidly increasing spread and decreasing quality at increasing lead times (Fig. 7). At relatively shorter lead times (Fig. 7a–b), numerous ensemble members predicted low-level vorticity maxima in the southern Plains; the precipitation forecasts from these same ensemble initializations were also quite skillful (cf. Fig. 5). At longer lead times (Fig. 7c–e), there was much greater spread in the locations of the predicted vortices, and very few of these vortices were in the correct location over the southern Plains. For the longest lead time shown (Fig. 7e), the southern Plains region is devoid of predicted low-level vorticity maxima, and as a result, there is also essentially no suggestion of heavy rainfall in that area in the ensemble QPFs (Fig. 5e).

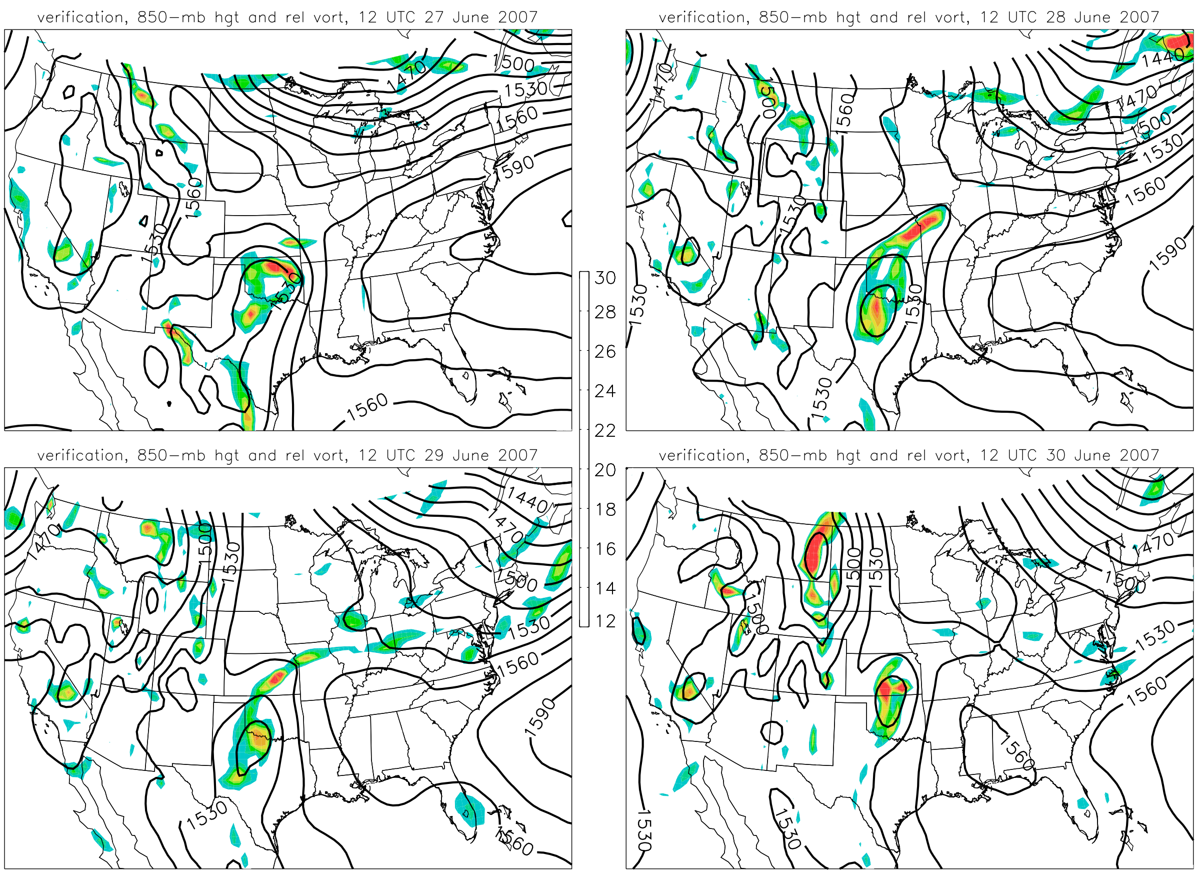

Figure 6: Analysis of 850-hPa geopotential height (m, solid contours) and relative vorticity ($\times 10^{-5}$ s^{-1}, color shading) from the ECMWF initial analysis at 1200 UTC (a) 27 June, (b) 28 June, (c) 29 June, and (d) 30 June 2007.

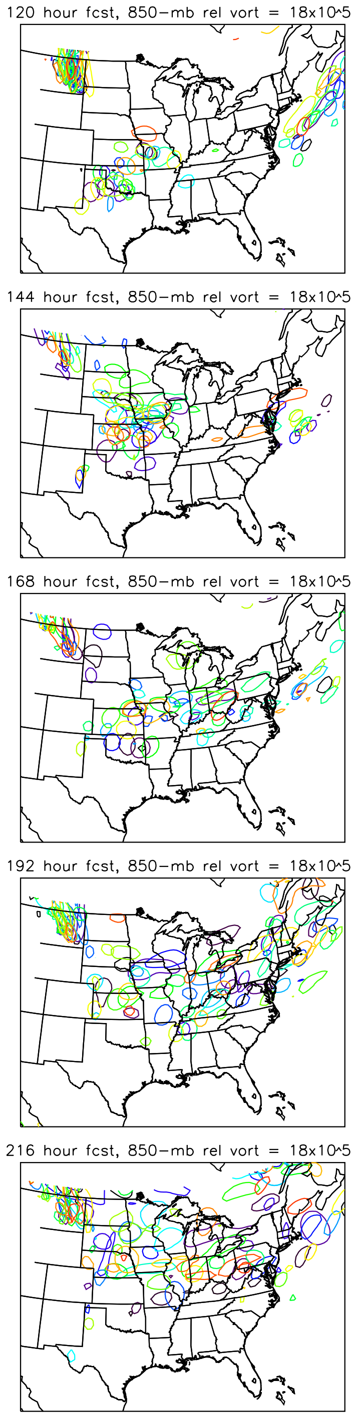

Figure 7: "Spaghetti" plot, showing the locations of the 18×10^{-5} s^{-1} 850-hPa relative vorticity contour for each of the ensemble members (for members that have vorticity values exceeding this threshold). All panels are forecasts valid at 1200 UTC 30 June 2007, for ensemble forecasts initialized at 1200 UTC (a) 25 June, (b) 24 June, (c) 23 June, (d) 22 June, and (e) 21 June 2007. The observed 850-hPa relative vorticity field at this time is shown in Fig. 6d.

Inspecting the evolution of the vortices in the ensemble forecasts also suggests a connection between the presence (and strength) of a midlevel vortex in the model initialization and the resulting forecasts of the vortex (not shown). For example, in the forecasts initialized at 0000 and 1200 UTC 25 June, the vortex was already present in its early stages and was captured in the initial analysis, as illustrated by the closed 500-hPa height contour and broad region of midlevel vorticit y in north Texas. In these runs, the predicted vortices follow similar paths: the spread in the locations of these vortices is rather small, and the resulting precipitation forecasts are relatively good (e.g., Fig. 7a and Fig. 5a). At earlier initialization times, a good precipitation forecast only results if the model is successful in capturing the timing and location of the deep convection that initially forms the vortex, then the intensification of the vortex, and then the resulting deep convection and the vortex's maintenance. Given the role of moist convection in limiting mesoscale predictability, accurate representation of the feedbacks between all of these processes is a very challenging proposition for a numerical model in a chaotic atmosphere. As a result, the medium-range predictability of this event is quite limited compared with other long-lived heavy rain events, which suggests that such an event could wreak havoc on medium-range and seasonal forecasts. On the other hand, the relatively accurate forecasts at short lead times suggest that such a system is predictable in the short term, on the time scale of weather forecasts. These forecasting challenges provide motivation for further study of this case; ongoing research is investigating the processes in this event using both observations and numerical simulations.

In contrast to the events with relatively poor predictability discussed above, there were other events that were notable for their very skillful forecasts at long lead times. Although the ensemble forecasts had nonzero skill for nearly all of the events at the 50-mm precipitation threshold and 96–216-hr lead time (Fig. 2 and 3), some stood out as having particularly high quality. One of these events was Tropical Storm Fay (Stewart and Beven 2009), which was an outlier in terms of its high skill, even at the 150-mm precipitation threshold and at long lead times (the orange lines in Figs. 2c and 3c). The ensemble forecasts correctly identified the high probability of 50-mm of precipitation in 5 days over a large swath of the southeastern US, as well as the smaller area exceeding 150 mm of rainfall (not shown). In fact, at the 150-mm threshold, the ensemble shows a positive BSS all the way out to the 180–320-h precipitation forecast (not shown).

The high predictability of the heavy rains in this case can also be related to the timing and evolution of atmospheric processes. Fay initially developed in the Caribbean Sea on 15 August, nearly a week before it would dump heavy rains in the southeastern US. The storm then moved slowly northward toward and later across Florida. In other words, the forcing for the heavy rains was present in the model's initial conditions long before the event took place, and the model succeeded in predicting the appr oximate track of the storm such that it would make landfall in the US, move slowly, and produce widespread heavy rains. The processes here can b e compared to those in the June 2007 event: in that case the "genesis" of the forcing mechanisim (a mesoscale vortex) took place only a day or two before the heavy rains fell, and the ensemble predictions of precipitation at lead times beyond a few days were poor. In the case of Fay, the genesis occurred long before the rain event in the US, and the resulting medium-range precipitation forecasts were quite skillful. The ensemble's success with Fay (and the other TC events discussed previously) should not be generalized too broadly, however. It is likely that medium-range forecasts for TCs that form near the US coast and quickly make landfall (such as Tropical Storm Allison in 2001; Sippel et al. 2006) would be much less skillful. In fact, the forecasts for Hurricane Gustav's rainfall, which were the best of all the events at short lead times and high rainfall thresholds, dropped off in skill rapidly with increasing lead time. At longer lead times, the storm was still in the Caribbean Sea, far from the US coast, but as the storm neared the coast the track of the storm became more certain and the corresponding rainfall forecast became much more accurate.

5. CONCLUSIONS

This study used ensembles of global numerical weather forecasts to analyze the skill of models in predicting widespread, multiple-day rain events in the United States, related the performance of the ensembles in the events to the relevant atmospheric processes in each event, and came to conclusions about the relative predictability of such events. Nine events in 2007–2008 were analyzed in which widespread accumulations of 100 mm in 120 h occurred, comprising three warm-season cases, three cool-season cases, and three tropical-cyclone cases. The ECMWF ensemble prediction system was used for most of the analysis. A summary of the primary findings is as follows:

- In general, the ECMWF ensemble provides skillful predictions of widespread heavy rain at relatively short lead times (for instance, 0–120-hr to 24–144-hr forecasts). This is particularly true for rainfall amounts exceeding 50 and 100 mm in 120 h; the results were varied at higher thresholds.
- In a few of the events, the ensemble showed considerable skill at longer lead times, out to the 96–216-h precipitation forecasts.
- The ensemble performed best overall for the tropical cyclone events; particularly the rainfall from Tropical Storm Fay and Hurricane Gustav. Two of the cool-season events associated with strong synoptic-scale forcing were also well predicted at longer lead times.
- Two of the warm-season events showed particularly limited predictability: the June 2008 event in the Upper Midwest had very low verification scores at short lead times, and the June 2007 event in the southern Plains had low predictability at long lead times. Both of these events were associated in part with organized mesoscale convection and interactions between mesoscale features.

The availability of the data in TIGGE archive provides a great resource for continued studies on the predictive skill and predictability of high-impact weather events across the globe, and for understanding the atmospheric processes that are important in these events. As more data are collected on a greater variety of weather systems, more will certainly be learned about how best to employ ensembles for predicting the weather at medium-range and seasonal time scales. Understanding the situations in which these ensembles perform well (and not so well) may be a way that human knowledge of synoptic meteorology and numerical weather prediction can be combined to make improved forecasts. Although the limitations to long-range weather prediction owing to chaos will remain, ensemble forecasts will continue to be an important tool in providing enhanced weather forecasts, and better information about forecast uncertainty, for the benefit of the wide variety of users of this information.

6. ACKNOWLEDGMENTS

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