Ensemble-Based Analysis of the May 2010 Extreme Rainfall in Tennessee and Kentucky

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ABSTRACT

From 1 to 3 May 2010, persistent heavy rainfall occurred in the Ohio and Mississippi River valleys due to two successive quasi-stationary mesoscale convective systems (MCSs), with locations in central Tennessee accumulating more than 483 mm of rain, and the city of Nashville experiencing a historic flash flood. This study uses operational global ensemble forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) to diagnose atmospheric processes and assess forecast uncertainty in this event. Several ensemble analysis methods are used to examine the processes that led to the development and maintenance of this precipitation system. Differences between ensemble members that correctly predicted heavy precipitation and those that did not were determined, in order to pinpoint the processes that were favorable or detrimental to the system's development. Statistical analysis was used to determine how synoptic-scale flows were correlated to 5-day area-averaged precipitation. The precipitation throughout Nashville and the surrounding areas occurred ahead of an upper-level trough located over the central United States. The distribution of precipitation was found to be closely related to the strength of this trough and an associated surface cyclone. In particular, when the upper-level trough was elongated, the surface cyclone remained weaker with a narrower low-level jet from the south. This caused the plume of moisture from the Caribbean Sea to be concentrated over Tennessee and Kentucky, where, in conjunction with focused ascent, heavy rain fell. Relatively small differences in the wind and pressure fields led to important differences in the precipitation forecasts and highlighted some of the uncertainties associated with predicting this extreme rainfall event.

1. Introduction

a. Overview

Beginning 1 May and lasting until 3 May 2010, Tennessee and Kentucky experienced an extended period of heavy precipitation, resulting in destructive flooding and record rainfall in many locations. This rainfall was a result of two successive quasi-stationary mesoscale convective systems associated with an upper-level low pressure system that approached the eastern United States, along with a frontal boundary that stalled just west of Tennessee (Figs. 1a and 1b; Moore et al. 2012). There was persistent tropical moisture transport from the Caribbean Sea, the eastern tropical Pacific, and the Gulf of Mexico. Moore et al. (2012) used standardized anomalies as a tool to help explain and predict the high precipitation totals for the 1–3 May 2010 widespread rain event, finding integrated water vapor (IWV) anomalies of 1.5–2.5 standard deviations above the mean extended from the Yucatan Peninsula into the central Mississippi Valley at 1200 UTC 1 May 2010, as well as a large region of IWV anomalies ranging from 2.5 to well above 4 standard deviations above the mean, which coincided with the tropical IWV reservoir near Central America, feeding the heavy precipitation. The most rain fell in central Tennessee (Fig. 2), with the greatest impacts occurring in Nashville. Nashville International Airport (KBNA) recorded over 160 mm (6.3 in.) of rain on 1 May 2010 and over 183 mm (7.2 in.) on 2 May 2010. The 2-day rainfall total stood at 343.7 mm (13.53 in.). This more than doubled the previous 2-day record of 169.7 mm (6.68 in.) set on 13–14 September 1979 (NOAA/NWS 2012c). Benton County, just to the west of Nashville, recorded 493 mm (19.41 in.) of precipitation over this 2-day period (NOAA/NWS 2012a). The Cumberland River, which winds through downtown Nashville, crested at 51.86 ft (15.8 m) on 3 May 2010, spilling into the city and surrounding neighborhoods. It was the highest level recorded since the Cumberland

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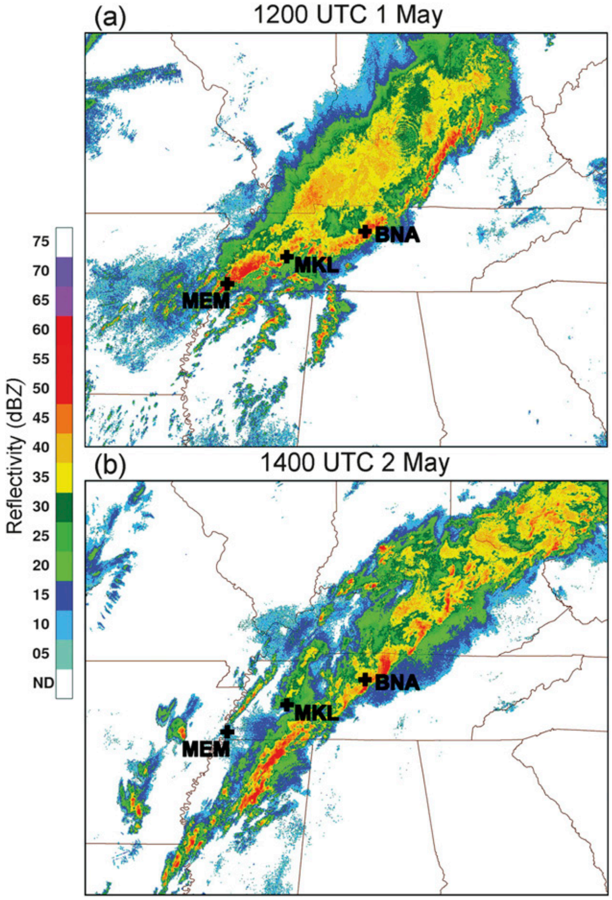

FIG. 1. National Mosaic and Multisensor Quantitative Precipitation Estimation (QPE) project composite reflectivity imagery (shaded in dBZ) depicting (a) the first MCS at 1200 UTC 1 May 2010 and (b) the second MCS at 1400 UTC 2 May 2010. For reference, the locations of Memphis (MEM), Jackson (MKL), and Nashville (BNA) in TN are denoted. [From Moore et al. (2012).]

River dam system was built in the early 1960s (NOAA/NWS 2012b). In Nashville alone, preliminary estimates of property damage were in excess of $2 billion (U.S. dollars) with 11 fatalities (NOAA/NWS 2011).

Boyd and Roberts (2010), Higgins et al. (2011), Moore et al. (2012), Durkee et al. (2012), and Lackmann (2013) examined the May 2010 flood event and found that the amount of moisture, combined with the duration of moisture transport, produced persistent, high rainfall rates and impressive rainfall totals over the Nashville area. In the present study, medium-range ensemble forecasts of the 1–3 May 2010 rain event will be examined to determine the reasons why some ensemble members produced a long-lived, slow-moving precipitation system, and others did not. The overlying question is, what were the key factors that were favorable for, or detrimental to, the development of widespread rainfall over multiple days?

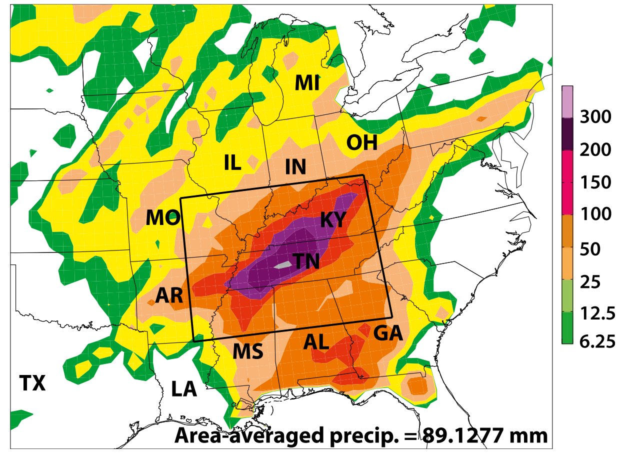

FIG. 2. The 5-day accumulated precipitation (color shading in mm) between 1200 UTC 29 Apr and 1200 UTC 4 May 2010. The black rectangle indicates the location for areal averaging of precipitation and other fields. Abbreviations are given for the states mentioned in the text.

b. *Use of ensembles for investigating weather systems*

Ensembles of numerical weather prediction models, composed of many individual deterministic forecasts, are now commonly used in weather forecasting. Additionally, researchers are beginning to use ensemble forecasts to gain more understanding of the dynamics of weather systems. Many studies have evaluated the performance of ensemble methods for precipitation forecasts (Hamill and Colucci 1997; Du et al. 1997; Petroliagis et al. 1997; Eckel and Walters 1998; Buizza et al. 1999; Mullen and Buizza 2001; Venugopal et al. 2005). Buizza et al. (1999) and Mullen and Buizza (2001) assessed the performance of the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) in predicting accumulated rainfall, proposing that precipitation is more predictable during the winter than the summer due to enhanced synoptic forcing and less prevalent convection. Buizza et al. (1999) and Mullen and Buizza (2001) also found that the accuracy in precipitation forecasts decreases as the rainfall threshold increases.

Hakim and Torn (2008) introduced the technique of ensemble synoptic analysis for an extratropical cyclone, finding the relationships between different synoptic features by computing statistical operators such as covariances and correlations within an ensemble of forecasts. Similarly, Torn (2010) used this method to examine the dynamical mechanisms that led to downstream ridging during extratropical transition. Hawblitzel et al. (2007) used similar techniques to examine the dynamics and predictability of a mesoscale convective vortex (MCV). Sippel and Zhang (2008) and Sippel and Zhang (2010)

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used short-range ensemble forecasts to study the dynamics and predictability of a nondeveloping tropical disturbance in the Gulf of Mexico as well as Hurricane Humberto, which made landfall along the Texas coast in 2007. Schumacher (2011) used the operational global ensemble forecasts from the ECMWF to study the predictability of a long-lived continental vortex that impacted the southern plains of the United States on 25–30 June 2007. The ECMWF EPS, which is one component of The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE; Bougeault et al. 2010), was used by Schumacher and Davis (2010) to investigate the atmospheric processes associated with a set of diverse heavy rainfall events. Schumacher (2011) made use of operational global ensemble forecasts from the ECMWF to examine the factors contributing to, or inhibiting, the development of a long-lived continental vortex and its associated rainfall. The methods of Schumacher (2011) will be applied to TIGGE output in this study; the details of TIGGE will be described later in the paper.

Considering the countless impacts that heavy rainfall and flooding have on society, there is a need to further research and understand the processes that lead to extreme precipitation events. Ensemble prediction systems provide information on the probability of the event occurring and allow an objective risk assessment (Böttger et al. 2011). This would include evaluating model performance and determining how far in advance an event such as the 1–3 May 2010 widespread rain event could have been predicted. As pointed out by Lorenz (1963), slightly differing initial states of the atmosphere can evolve into considerably different states of the atmosphere, allowing the use of an ensemble system to be very beneficial by providing multiple outcomes for the atmosphere based on the number of ensemble members.

In the present study, differences between ensemble members that correctly predicted heavy precipitation and those that did not are determined, in order to pinpoint the processes that were favorable or detrimental to the development of the two quasi-stationary MCSs (Moore et al. 2012). Section 2 will provide an overview of the event and section 3 will describe the data and methods used in the study. In section 4, results of the ensemble-based analysis will be presented, section 5 will contain a discussion, and section 6 will conclude the manuscript.

2. Event overview

The precipitation in this event primarily came from two successive quasi-stationary MCSs on 1 and 2 May 2010 (Moore et al. 2012). In composite reflectivity imagery from 1200 UTC 1 May 2010, the first MCS was seen passing through western central Tennessee, extending from southwestern Tennessee to northern Kentucky (Fig. 1a). Following the initial MCS, at 1400 UTC 2 May 2010, the second MCS was passing through west-central Tennessee. This line of heavy precipitation was oriented from southwest to northeast, extending from northeastern Louisiana to southern Ohio (Fig. 1b).

Analyzing the synoptic-scale conditions at the time of the event reveals some of the factors that contributed to heavy precipitation across the central Mississippi Valley region. At both 0000 UTC 2 May and 0000 UTC 3 May 2010 at the 500-hPa level, there is a pronounced upper-level trough over the central United States. This trough exhibits a slight positive tilt with a tight height gradient over the Mississippi Valley (Figs. 3a and 3b). At the 850-hPa level, slight warm-air advection is present in the Tennessee area contributing to ascent, with an associated baroclinic zone. Additionally, Moore et al. (2012) suggested that lifting associated with the development of convection occurred along mesoscale surface outflow boundaries. There is an indication of a low-level jet positioned over the southeastern United States, with the strongest winds over Alabama, Georgia, and Tennessee. Strong southerly winds are transporting moisture into the Tennessee area, providing support for rainfall (Figs. 3c and 3d). The presence of a southerly low-level jet becomes a crucial component in the moisture transport into the Mississippi Valley, promoting strong, persistent convection (Doswell 1994; Moore et al. 2012). The evolution of the total column water field (Fig. 4) shows multiple sources of moisture for the heavy rainfall region, including both the eastern tropical Pacific and the Caribbean Sea. On 2 May 2010, a large reservoir of tropical moisture resides in the eastern Pacific just south of Central America, with values greater than 60 mm (Fig. 4a). Over the course of 2 days, high values of total column water moved from the eastern Pacific into the Gulf of Mexico. This moisture then became concentrated in a narrow corridor and moved poleward into the Mississippi Valley (Figs. 4b–d). By 0000 UTC 3 May, the total column water in central Tennessee was 50–55 mm (Fig. 4c). Moore et al. (2012) noted that this persistent corridor of strong water vapor transport helped to support the successive development of the two quasi-stationary MCSs that impacted Tennessee and surrounding areas. After 0000 UTC 3 May 2010, the moisture moved off to the east, ahead of the advancing trough (Fig. 4d). The Nashville sounding from 1200 UTC 2 May 2010 exhibits a near-saturated atmosphere from the surface to about 800 hPa. The atmosphere has a moderate amount of directional shear at low levels, as well as speed shear, with the wind speed increasing from 5 m s^{-1} at the surface to 50 m s^{-1} at the 400-hPa level (Fig. 5).

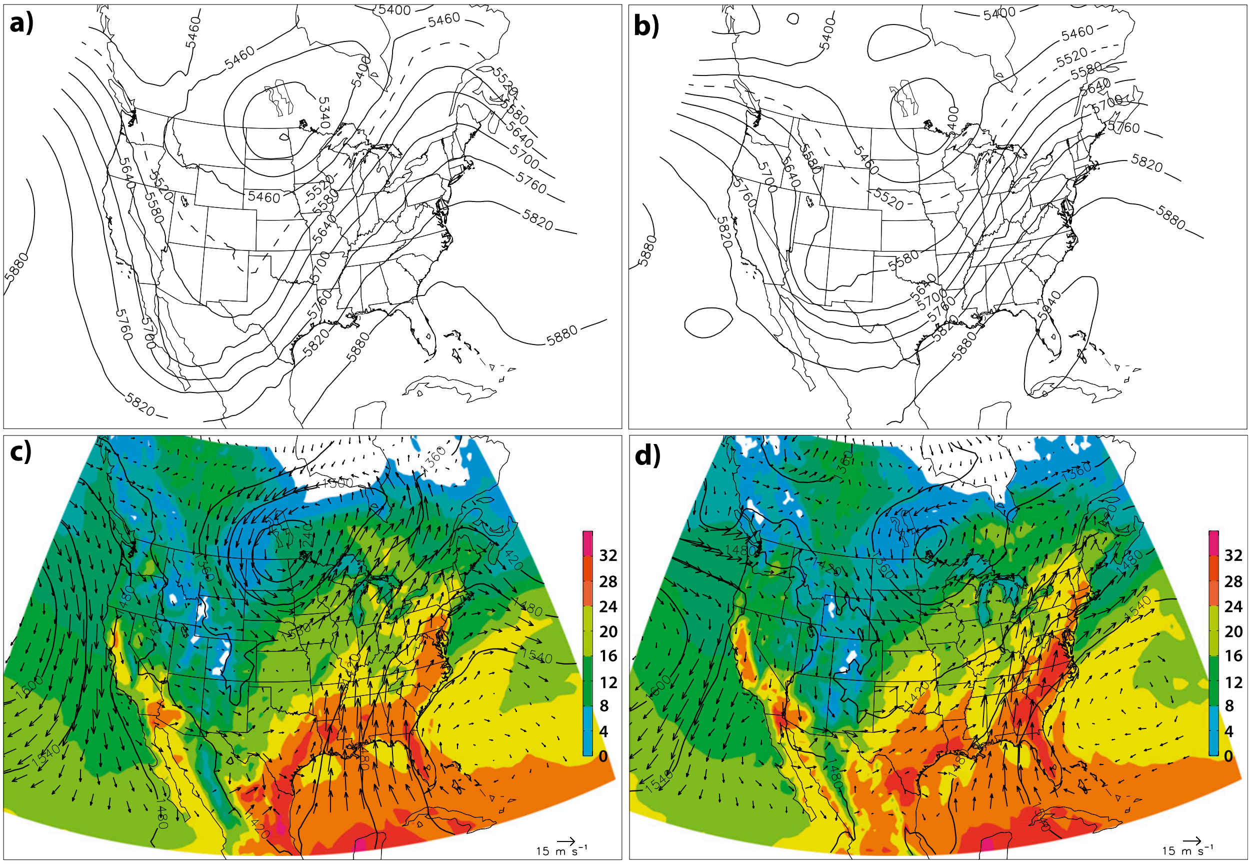

FIG. 3. ECMWF analysis of 500-hPa height (contoured in black every 60 m) at (a) 0000 UTC 2 May and (b) 0000 UTC 3 May 2010. ECMWF analysis of 850-hPa temperature (color shading in °C), height (contoured in black every 60 m), and wind (vectors overlaid, vector scale is shown at bottom right) at (c) 0000 UTC 2 May and (d) 0000 UTC 3 May 2010.

With both moisture and lift being present, the other ingredient needed for deep convection is instability. The Nashville sounding also has 1784 J kg^{-1} of most unstable and surface-based convective available potential energy (CAPE), and therefore the necessary ingredients for deep convection of moisture, instability, and lift are all present.

Maddox et al. (1979) identified three primary types of synoptic and mesoscale patterns as often producing excessive rain in the central and eastern United States. Both the mesohigh and frontal types are primarily mesoscale phenomena, while synoptic forcing drives the synoptic-type events. Consistent with the Maddox et al. (1979) depiction of a synoptic flash flood, a well-defined 500-hPa trough plunged into the central plains and then began to weaken and move off to the east (Figs. 3a and 3b). A surface cold front approaching Tennessee from the west stalled as it became parallel to the upper-level flow (Fig. 6). The front stalled, oriented from southwest to northeast (Fig. 6). Surface dewpoints exceeded 70°F (21°C) and strong 850-hPa winds transported additional moisture into the region. These features are remarkably similar to those shown in schematic diagrams of synoptic flash floods in Maddox et al. (1979, their Fig. 7), and we therefore conclude that the 1–3 May 2010 event was a classic synoptic-type flash flood. In the following analysis, we examine the synoptic and mesoscale processes that were favorable for, and those that were detrimental to, the development of this event.

3. Data and methods

The primary precipitation dataset used in this study is the U.S. Daily Precipitation Analysis (Chen et al. 2008), obtained from the National Oceanic and Atmospheric Administration/Climate Prediction Center (NOAA/CPC; information online at http://www.cpc.ncep.noaa.gov/products/precip/realtime/GIS/retro.shtml). This dataset consists of roughly 16 000 rain gauge observations, gridded to a 0.25° latitude × 0.25° longitude grid. Because this dataset has relatively coarse resolution, it does not accurately represent local precipitation maxima. However, it is well suited for comparison with global model forecasts at relatively coarse resolution.

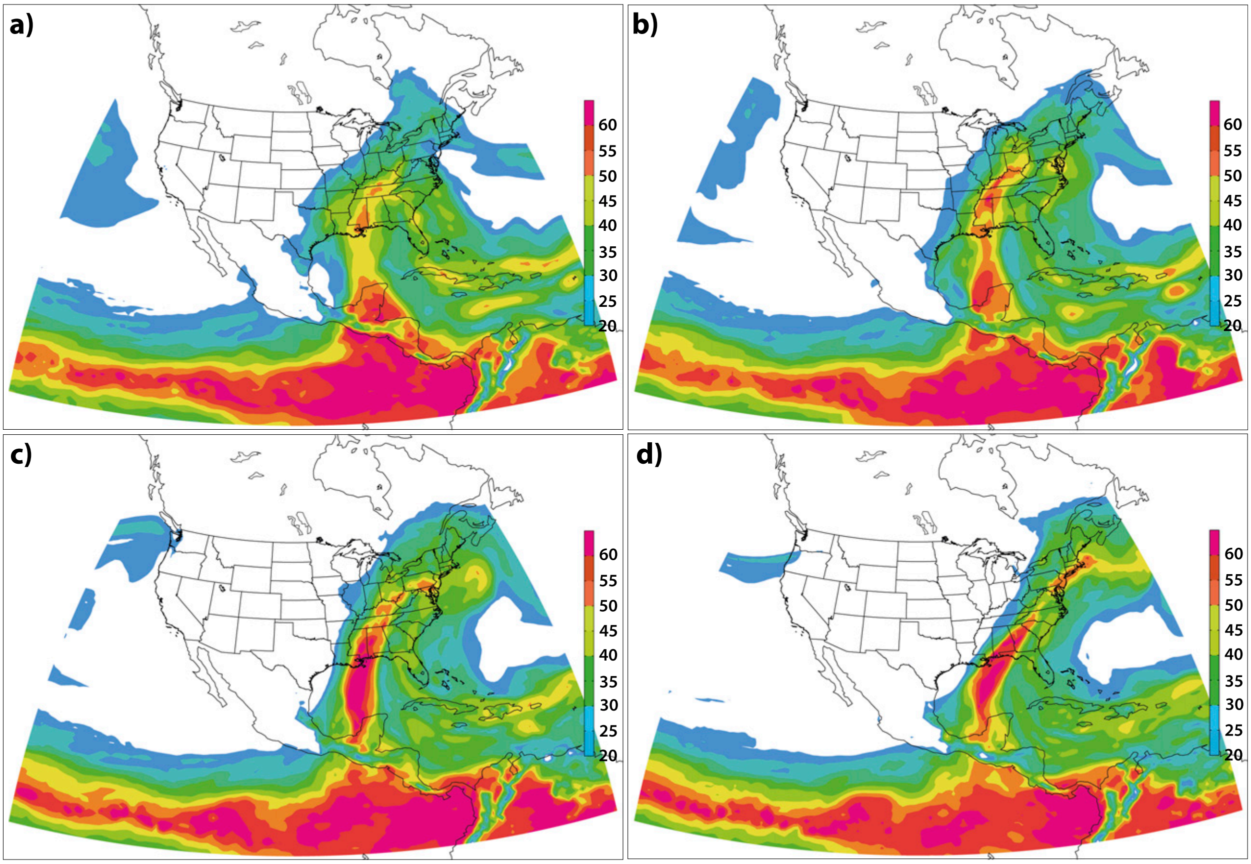

FIG. 4. ECMWF analysis of total column water (color shading in mm) at (a) 0000 UTC 2 May, (b) 1200 UTC 2 May, (c) 0000 UTC 3 May, and (d) 1200 UTC 3 May 2010.

Following the work of Schumacher (2011), the remainder of this study will use ensemble forecasts in order to analyze the synoptic- and mesoscale factors that led to the development of the two quasi-stationary MCSs (Moore et al. 2012). The ECMWF EPS is the primary ensemble forecast that will be used. The ECMWF EPS is a 51-member ensemble with a spectral truncation of T639 (corresponding to approximately 32-km horizontal grid spacing) and 62 vertical levels through 240 forecast hours (ECMWF 2010). The ECMWF EPS contains a control run and 50 members that are initially perturbed by singular vectors in pairs (i.e., a positive and negative perturbation) and by stochastic physics (ECMWF 2012). Singular vectors have been studied considerably in weather prediction models (Buizza and Palmer 1995; Palmer 2000). The singular vector perturbations within the ECMWF EPS have a horizontal scale of T42 with 62 vertical levels and are designed so that their impact is maximized over Europe at 48 h into the forecast. Forecasts for all 51 members were obtained on a 0.5° latitude × 0.5° longitude grid from the TIGGE archive (information online at http://tigge-portal.ecmwf.int). Additional information about the ECMWF EPS can be found in Molteni et al. (1996) and Buizza et al. (2007) and references therein. Ensemble forecasts from other centers were considered, notably the National Centers for Environmental Prediction (NCEP). However, the ECMWF EPS was chosen because of its large number of ensemble members, because it has a well-tuned ensemble spread (Park et al. 2008), and because the NCEP ensemble was found to have insufficient spread in its precipitation forecasts for this case, with no members correctly predicting at the medium range the amount of precipitation that was observed.

To identify relationships within the ECMWF ensemble members, linear correlation plots were created and analyzed. The correlation coefficient measures the strength of the linear relationship between 5-day area-averaged precipitation and the variable of interest at each grid point and forecast time, on a scale from −1 to 1. Correlations with magnitudes greater than approximately 0.36 are statistically different from zero at the 99% confidence level using a two-tailed significance test, assuming that beyond forecast hour 36 the 51 ensemble members of the ECMWF are equally likely. The correlation and covariance between variables shows the

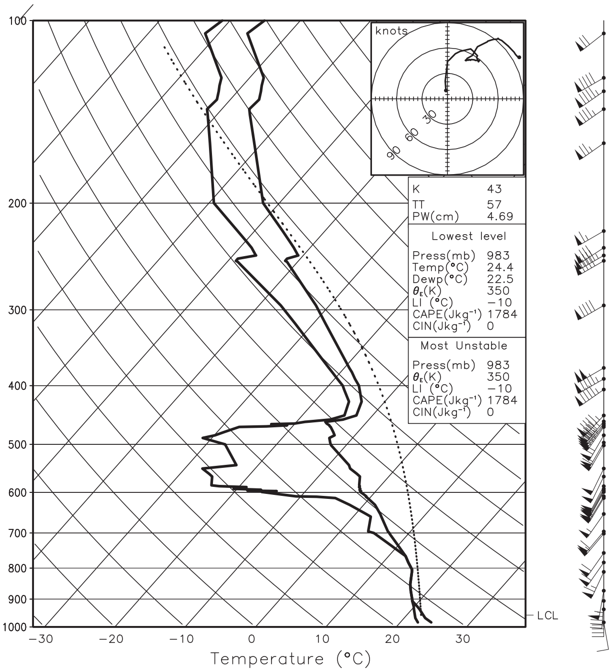

FIG. 5. Skew T–log$p$ diagram and wind hodograph of sounding from KBNA at 1200 UTC 2 May 2010. Parcel path for a parcel lifted from the surface is shown by the dotted line. The hodograph shows the winds in the lowest 600 hPa of the atmosphere. The wind barbs show the wind speed and direction at various levels of the atmosphere.

presence of linear relationships that can be used along with physical interpretation to understand the behavior of the ensemble forecasts. The equitable threat score (ETS) measures the fraction of observed and/or forecast events that were correctly predicted over a given threshold, and is adjusted for hits associated with random chance. A value of 1 is a perfect forecast and a value of 0 is a forecast with no skill relative to chance. When computing the ETS, the CPC analysis was upscaled to a 0.5° resolution.

4. Results

a. Selection of "wet" and "dry" ensemble members

Rather than presenting the forecasts of all 51 ECMWF ensemble members, subsets of the most accurate and the least accurate ensemble members from each forecast are focused on in this manuscript. To determine which ensemble members were most and least accurate, a combination of subjective and objective methods was used. The forecasted precipitation of each ensemble member was subjectively compared to the CPC precipitation, focusing on the spatial distribution of the 5-day accumulated precipitation as well as the maximum observed precipitation. Additionally, the observed 5-day precipitation from 1200 UTC 29 April to 1200 UTC 4 May 2010 was averaged over a region encompassing part of the eastern United States (shown in Fig. 2) and then compared to the 5-day area-averaged precipitation of the ensemble members. The ETS at a threshold of 100 mm was the final method used to determine the most accurate and least accurate ensemble members.

For the analysis in the remainder of this manuscript, the ECMWF ensemble forecast initialized at 1200 UTC 29 April 2010 will be used. This initialization time was chosen because each of the ensemble members predicted the general location of this event, in particular the placement of the 100-mm rainfall contour (Fig. 7), yet there was relatively large spread in the distribution of heavier precipitation and the maximum precipitation amounts, with some members correctly predicting heavy precipitation and others that did not. For the ensemble synoptic analysis, the 84-h (0000 UTC 3 May 2010) forecast was found to be the most useful. At 0000 UTC 3 May, the second MCS had just ceased training over Nashville and began to move eastward, impacting North and South Carolina by 1200 UTC 3 May.

Although the observed event began to taper off in Nashville shortly after 0000 UTC 3 May (forecast hour 84), choosing to analyze forecast hours 48–72 would provide very little insight into the factors that were favorable or detrimental to the development of the two quasi-stationary MCSs. This is because all of the ensemble members underpredicted the amount of precipitation Nashville would receive from the first MCS, leaving little to no spread in the individual ensemble members (Fig. 8). This underprediction is the result of all the individual ensemble members predicting the first quasi-stationary mesoscale convective system to be located west of where it was observed (shown later). For the ensemble analysis to be insightful, it is essential to choose a forecast hour with both accurate and inaccurate forecasts, allowing for an examination of the reasons for large differences in forecasted precipitation. Therefore, the 84-h forecast (0000 UTC 3 May) is used as the primary time for the ensemble analysis, which corresponds most closely to the time of the second observed MCS.

Of the 51 individual ensemble members, a few realistically reflected the spatial distribution of precipitation and the evolution of the precipitation event. Members 29 and 31 had spatial distributions that were very similar to the observed event, while members 36 and 5 had little to no resemblance (Fig. 10). Member 29 had a 5-day area-averaged precipitation total of 98 mm and member 31 had 5-day area-averaged precipitation of 95 mm, compared to the observed value of 89 mm (Fig. 9). Member 36 had a 5-day area-averaged precipitation

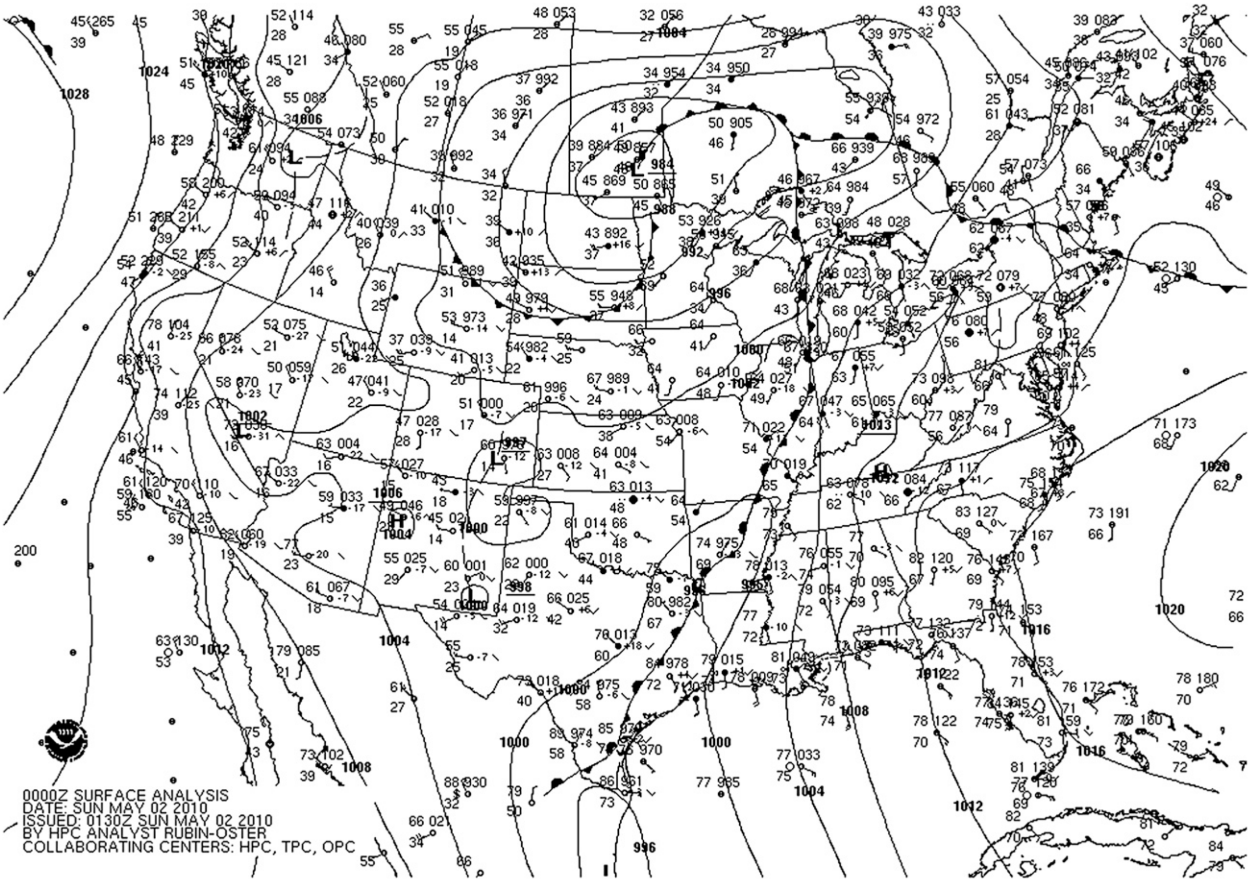

FIG. 6. Hydrometeorological Prediction Center (HPC) surface analysis for 0000 UTC 2 May 2010. Sea level pressure contoured in thin black every 4 hPa. Surface fronts are shown in standard frontal notation. Station observations are shown at various locations across the map, providing temperature, dewpoint, wind speed and direction, pressure, cloud cover, etc.

amount of 48 mm and member 5's 5-day area-averaged precipitation was 49 mm (Fig. 9). The 5-day area-averaged precipitation versus equitable threat score scatterplot reflects the positive correlation between precipitation amount and ETS. Figure 9 also shows that most ensemble members underpredicted the total precipitation at the medium range in the 1–3 May 2010 event.

Although analyzing the spatial distribution of precipitation and ETS to determine the most accurate and least accurate ensemble members is beneficial, it is not sufficient. As pointed out by Roulston and Smith (2003), identification of the best ensemble member should be done using multivariate forecasts, even if only univariate forecasts are required. This requires one to analyze all weather variables that are relevant to identifying the best ensemble members. After reviewing the precipitation forecasts as well as multiple weather variables including geopotential height and wind at various levels, total column water, moisture flux, and temperature for all 51 members, it was determined that the most accurate forecasts were from members 29 and 31 (hereafter referred to as the wet ensemble members), while the least accurate forecasts were from members 36 and 5 (hereafter referred to as the dry ensemble members). A spectrum of other forecast solutions existed between these two sets of members, with several other members that skillfully predicted the precipitation amount but were less consistent with the observations in other ways.

Members 29 and 31 (the wet ensemble members) forecasted a heavy, linear precipitation area that was oriented from southwest to northeast and extended from northern Mississippi to northern Kentucky (Figs. 10a and 10c). Although members 36 and 5 (the dry ensemble members) forecasted a linear precipitation distribution, the rainfall amounts were much smaller with the heavier precipitation displaced slightly to the west (Figs. 10b and 10d). Member 36 overpredicted precipitation in other locations such as Florida and Georgia (Fig. 10b). When comparing the forecasted and observed precipitation amounts, it is easily seen that members 29 and 31 (the wet ensemble members) were quite accurate (cf. Fig. 2 and Figs. 10a and 10c). However, in member 29, the maximum

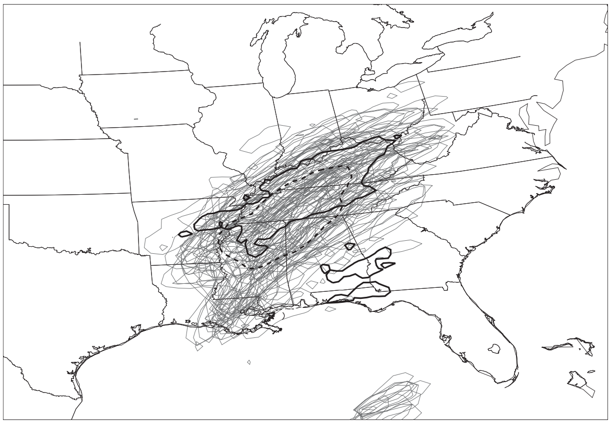

FIG. 7. Spaghetti plot showing the predicted 100-mm rainfall contour from 1200 UTC 29 Apr to 1200 UTC 4 May 2010 from each ECMWF ensemble member in gray. The observed 100-mm contour from 1200 UTC 29 Apr to 1200 UTC 4 May 2010 is shown in thick black. The ensemble mean 100-mm contour is shown in thick dashed black. Initialization time is 1200 UTC 29 Apr 2010.

forecasted precipitation is displaced a bit to the southeast of the observed maximum (Fig. 10a). The precipitation accumulation compared between the wet ensemble members and the dry ensemble members is very different.

The previous discussion has focused on the 5-day total precipitation, but additional insight can be obtained from looking at shorter accumulation periods. In the period from 1200 UTC 1 May to 1200 UTC 2 May 2010, rainfall totals exceeding 150 mm were observed in west-central Tennessee, western Kentucky, and northern Mississippi (Fig. 11a). Ensemble members 29 and 31 (the wet ensemble members) forecasted high rainfall totals in western Tennessee, northern Mississippi, and southeast Arkansas during this time period, a result of the first quasi-stationary MCS (Figs. 12a and 12c). Each of the wet ensemble members underpredicted the spatial extent of these higher precipitation amounts. Although members 5 and 36 (the dry ensemble members) forecasted high rainfall totals, they were displaced to the west, explaining the underprediction of rain at Nashville shown in Fig. 8. The dry ensemble members forecasted the initial MCS to push off to the east much too slowly (Figs. 12e and 12g). At 1200 UTC 2 May 2010, the second quasi-stationary MCS was impacting Nashville and surrounding areas. The accumulated 24-h precipitation from 1200 UTC 2 May to 1200 UTC 3 May 2010 exceeded 100 mm throughout central Tennessee and Kentucky, in the form of a linear feature due to the consistent training/backbuilding of the second MCS. Training refers to convective cells repeatedly passing over the same geographic region in a relatively short period of time. Alabama also received high rainfall totals, exceeding 75 mm (Fig. 11b). Members 29 and 31 (the wet ensemble members) forecasted high rainfall totals in central Tennessee, also in the form of a linear feature (Figs. 12b and 12d). Members 5 and 36 (the dry

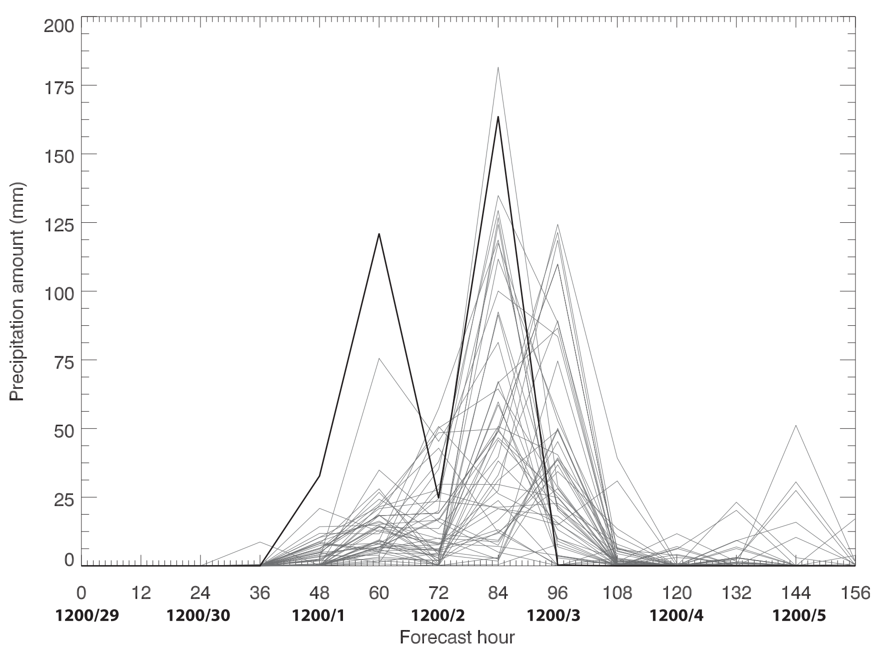

FIG. 8. Time series plot for Nashville (36°N, 87°W) showing the predicted 12-h accumulated precipitation from each ensemble member in gray. Initialization time is 1200 UTC 29 Apr 2010. The observed 12-h accumulated precipitation contour is shown in thick black.

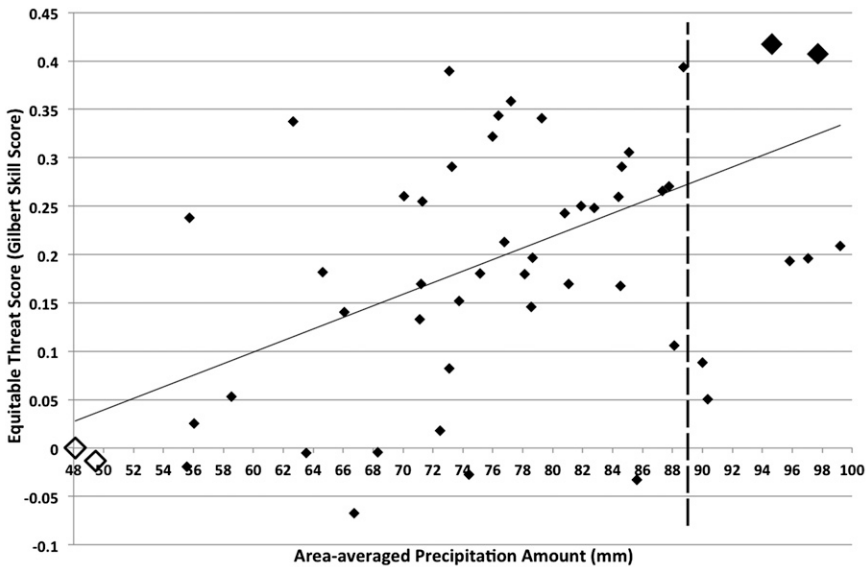

FIG. 9. Area-averaged precipitation vs ETS scatterplot at a threshold of 100 mm between 1200 UTC 29 Apr and 1200 UTC 4 May 2010. The ETS was calculated within the area-averaged box shown in Fig. 2. The wet ensemble members (members 29 and 31) are plotted in large, filled black diamonds and the dry ensemble members (members 36 and 5) are plotted in large, unfilled black diamonds. The dashed black line represents the observed area-averaged precipitation. The thin black line represents the best-fit line.

ensemble members) also forecasted high rainfall totals, but the highest precipitation amounts were displaced too far north, missing Nashville (Figs. 12f and 12h).

b. Correlations and covariance

The correlation of the 84-h forecast 500-hPa height field (valid 0000 UTC 3 May 2010) to the 5-day area-averaged precipitation reveals a region of positive correlation ($r \approx 0.5$) to the west-northwest of Tennessee, in the central plains region (Fig. 13a). This suggests that higher heights in the central plains were associated with more precipitation over the area of interest. A large core of positive correlation also resides over the Pacific Ocean and western United Sates, suggesting the possibility of the wet ensemble members having a higher-amplitude upper-level ridge off the coast of the western United States than the dry ensemble members (Fig. 13a). It is not clear what importance this has on the amount of precipitation Nashville received; therefore, more investigation would be required to determine its relevance. A negative correlation ($r \approx -0.4$) resides along the Texas–Mexico border. This denotes that a deeper, more elongated upper-level trough is correlated with more precipitation in the area of interest (Fig. 13a). The 500-hPa height covariance map shows signals in similar places, with magnitudes exceeding ± 12 m (Fig. 13c).

At 850 hPa, there is also a region of positive correlation ($r \approx 0.5$) to the northwest of Tennessee (Fig. 13b). In this region of positive correlation, as heights increase, the 5-day area-averaged precipitation increases. As will be shown in the next section, the dry ensemble members predicted a strong cyclone in this region that was not present in the wet ensemble members or the observations. Another region of positive correlation ($r \approx 0.5$) exists in the western United States and just off the coast into the Pacific Ocean (Fig. 13b). A statistically significant negative correlation ($r \approx -0.5$) lies just east of Mexico (Fig. 13b). This negative correlation could denote the presence of a lee trough from the Sierra Madre Oriental in Mexico, with lower heights linked to more precipitation. Moore et al. (2012) suggest the 850-hPa lee trough positioned along the eastern Mexico coast was likely linked to downslope flow along the Sierra Madre Oriental of eastern Mexico and a stronger height gradient across the Gulf of Mexico. Lackmann (2013) conducted sensitivity tests revealing the Sierra Madre Oriental played an important role in the strength of the low-level jet over the Gulf of Mexico and the precipitation amount in Nashville. Again, the 850-hPa height covariance map shows signals in similar places, with magnitudes exceeding ± 12 m (Fig. 13d). The correlations and covariance observed at both the 500- and 850-hPa levels are strikingly similar.

The 850-hPa meridional wind at forecast hour 84 is negatively correlated ($r \approx -0.4$) with precipitation to the west of Tennessee, encompassing Arkansas, Missouri,

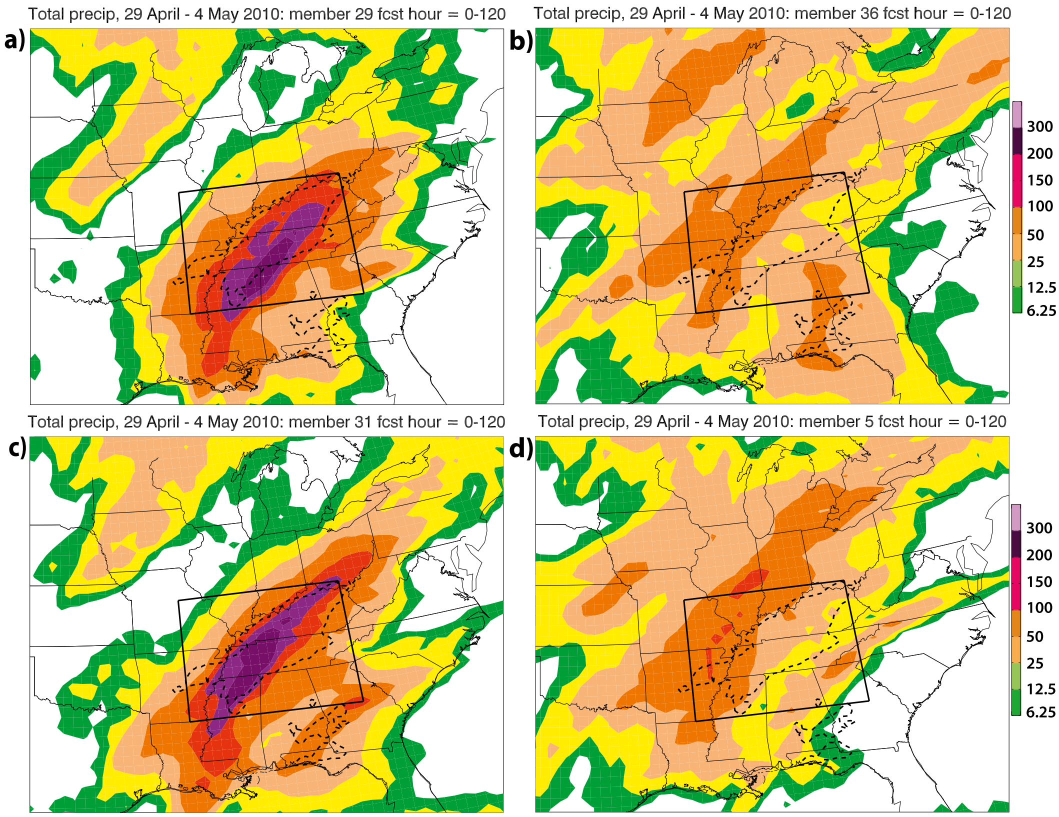

FIG. 10. The 5-day accumulated precipitation (color shading in mm) between 1200 UTC 29 Apr and 1200 UTC 4 May 2010: (a) member 29 (wet), (b) member 36 (dry), (c) member 31 (wet), and (d) member 5 (dry). The observed 100-mm contour from 1200 UTC 29 Apr to 1200 UTC 4 May 2010 is shown in thick dashed black. The black rectangle indicates the location for areal averaging of precipitation and other fields.

Illinois, and Indiana (Fig. 13e). In this region of negative correlation, decreased winds are associated with a precipitation increase in the area of interest. This reinforces that the dry ensemble members have forecasted a much stronger cyclone in the Midwest, hindering the amount of precipitation received in Nashville. This also reflects differences in the width of the low-level jet. More specifically, for heavy precipitation to occur in the area of interest, this analysis shows that the low-level jet should be slightly narrower, and not extend westward of west Tennessee. The ensemble-mean low-level jet has peak winds around 20 m s^{-1}, and very little correlation exists

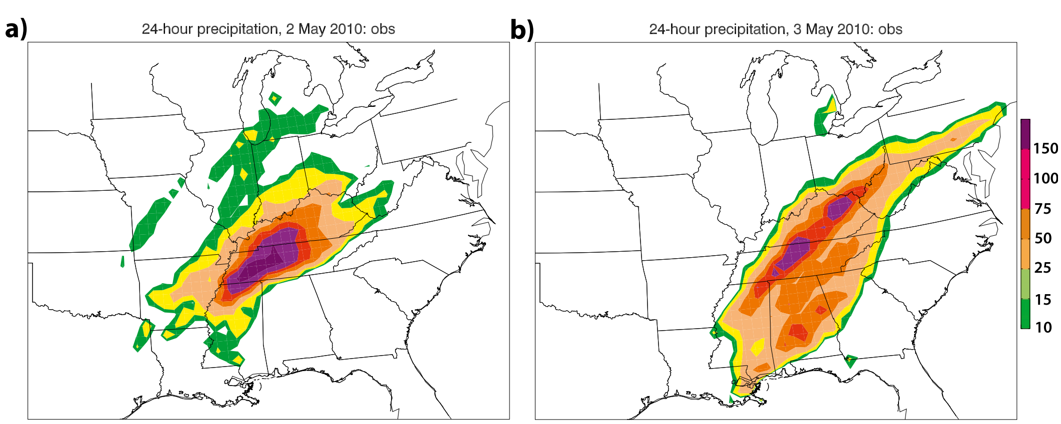

FIG. 11. Observed 24-h accumulated precipitation (color shading in mm) (a) from 1200 UTC 1 May to 1200 UTC 2 May 2010 and (b) from 1200 UTC 2 May to 1200 UTC 3 May 2010.

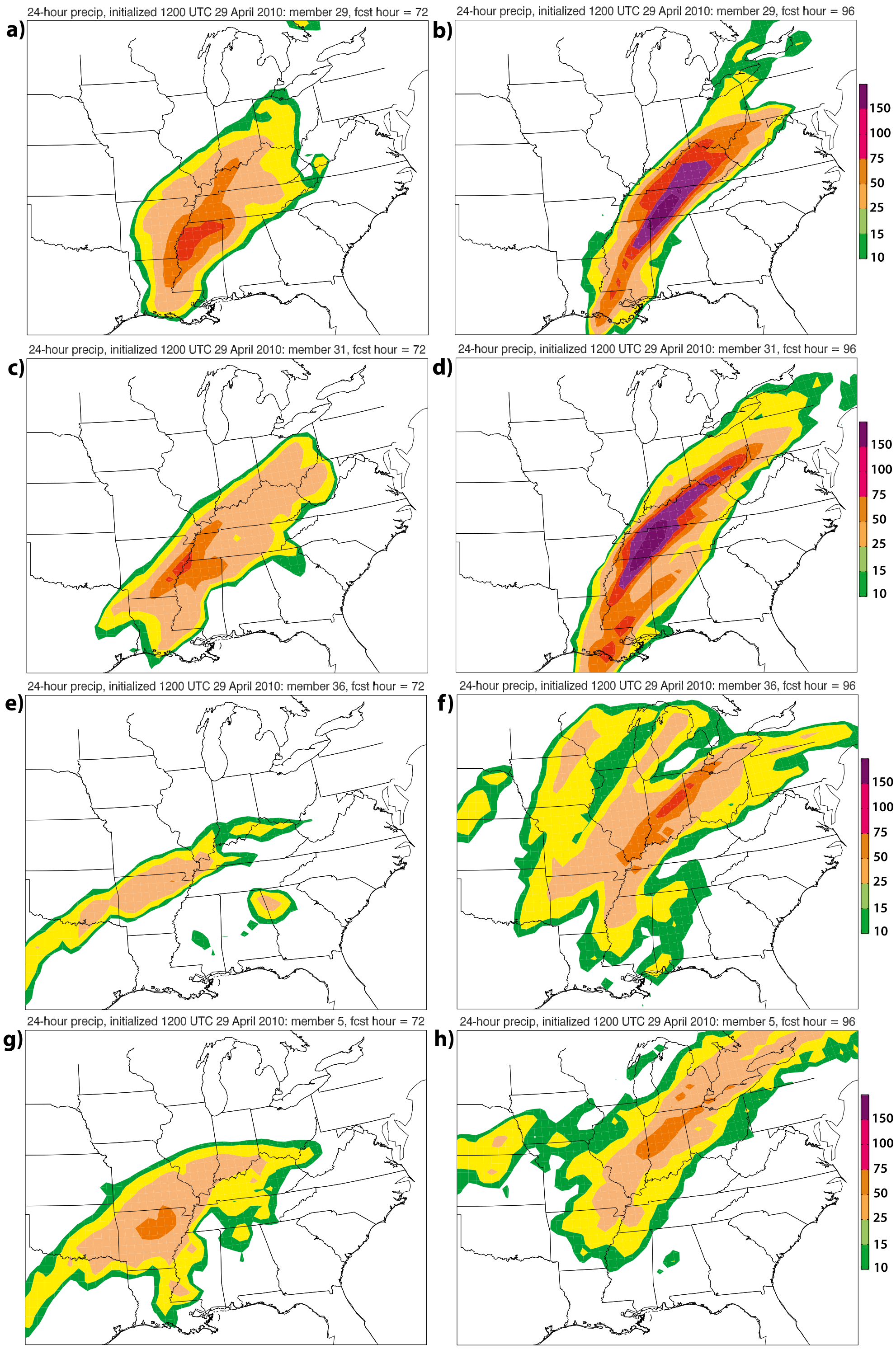

FIG. 12. Forecasted 24-h accumulated precipitation (color shading in mm) at 1200 UTC 2 May 2010, corresponding to forecast hours 48–72, for (a) member 29 (wet), (c) member 31 (wet), (e) member 36 (dry), and (g) member 5 (dry), and at 1200 UTC 3 May 2010, corresponding to forecast hours 72–96, for (b) member 29 (wet), (d) member 31 (wet), (f) member 36 (dry), and (h) member 5 (dry).

Fig(s). 12 live 4/C

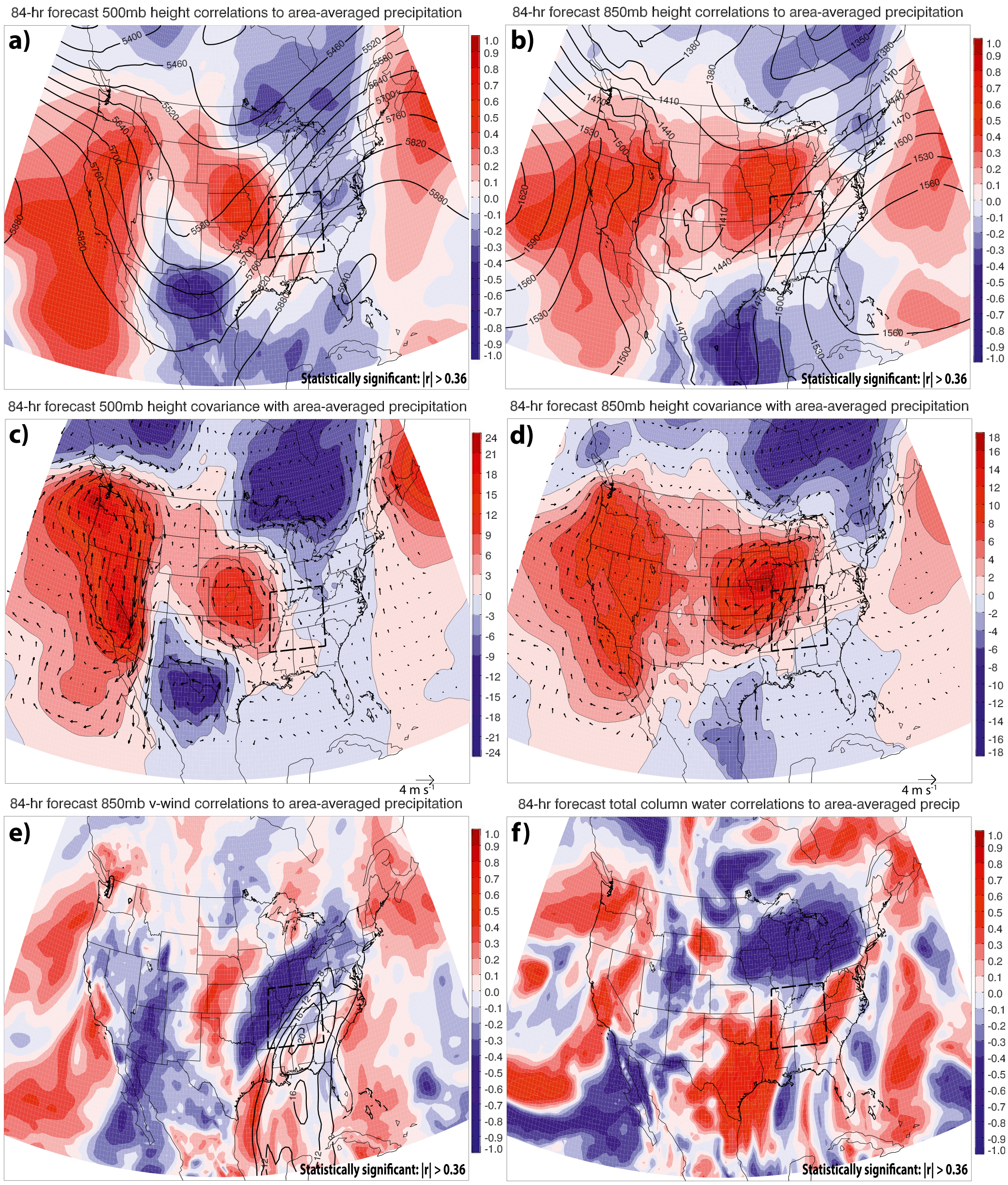

FIG. 13. Correlation of area-averaged precipitation between 1200 UTC 29 Apr and 1200 UTC 4 May 2010 with (a) 500-hPa height at 0000 UTC 3 May 2010, corresponding to forecast hour 84. The ensemble mean 500-hPa height is contoured in thick black every 60 m. (b) The 850-hPa height at 0000 UTC 3 May 2010, corresponding to forecast hour 84. The ensemble mean 850-hPa height is contoured in thick black every 30 m. Covariance of area-averaged precipitation between 1200 UTC 29 Apr and 1200 UTC 4 May 2010 with (c) 500-hPa height at 0000 UTC 3 May 2010, corresponding to forecast hour 84; and (d) the 850-hPa height at 0000 UTC 3 May 2010, corresponding to forecast hour 84. Correlation of area-averaged precipitation between 1200 UTC 29 Apr and 1200 UTC 4 May 2010 with (e) 850-hPa v wind at 0000 UTC 3 May 2010, corresponding to forecast hour 84. The ensemble mean 850-hPa v wind ($m\,s^{-1}$) is contoured in thick black every $4\,m\,s^{-1}$. (f) Total column water at 0000 UTC 3 May 2010, corresponding to forecast hour 84. Warm colors represent a positive correlation, while cool colors represent a negative correlation. The dashed black rectangle indicates the location for areal averaging of precipitation and other fields.

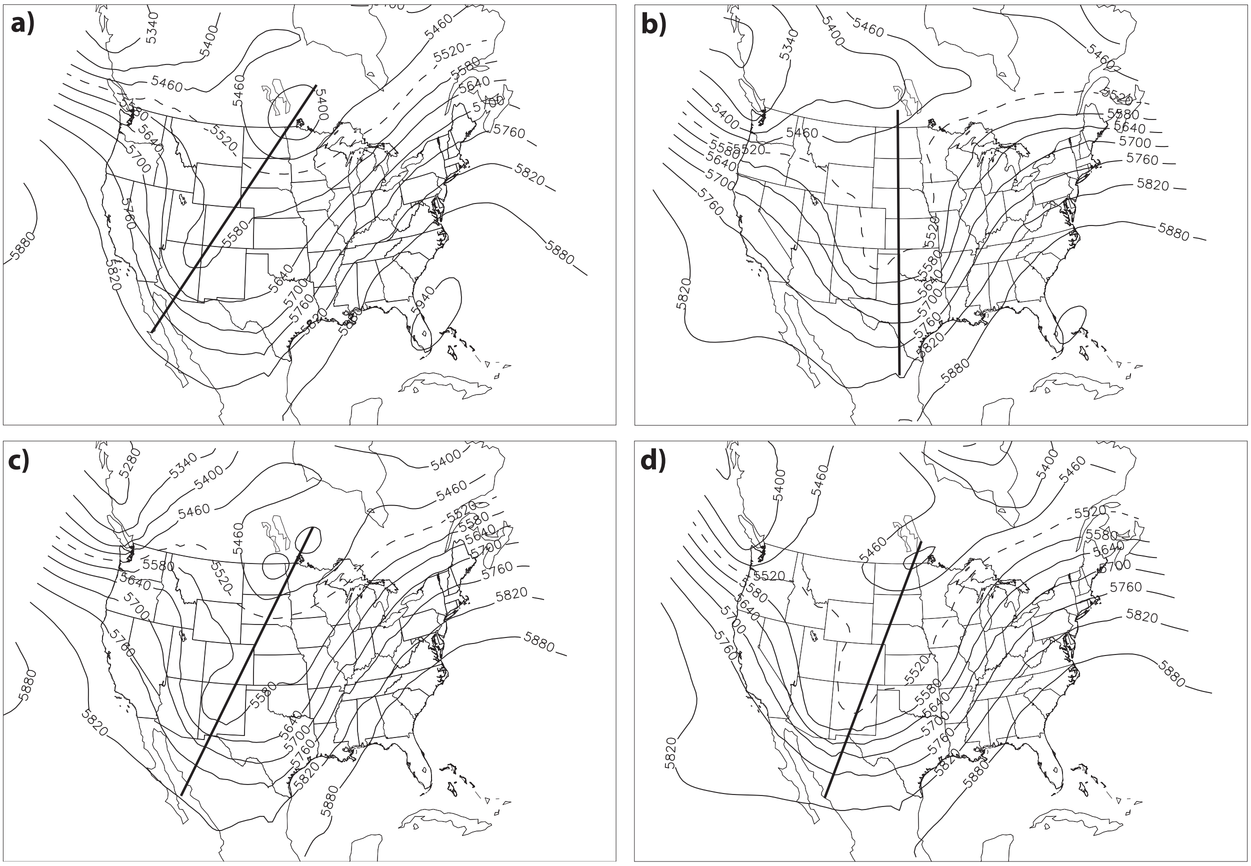

FIG. 14. Forecasted 500-hPa height (contoured in black every 60 m) at 0000 UTC 3 May 2010, corresponding to forecast hour 84: (a) member 29 (wet), (b) member 36 (dry), (c) member 31 (wet), and (d) member 5 (dry). The thick black line represents the trough axis. The dashed black line represents the 5520-m height contour.

along this jet axis because all ensemble members forecasted strong southerly winds in this area (Fig. 13e).

In both eastern Tennessee and the area to the southwest of Tennessee, the total column water and 5-day area-averaged precipitation have a statistically significant positive correlation ($r \approx 0.6$) oriented parallel to the surface front (Fig. 13f). There is also a large region of negative correlation in the Great Lakes region. The statistically significant positive correlation in eastern Tennessee and just to the southwest of Tennessee suggests the wet ensemble members have advected the moisture into Tennessee and nearby areas where it could have rained out. In contrast, the statistically significant negative correlation in the Great Lakes region is a result of the dry ensemble members advecting the moisture much farther poleward.

c. *Ensemble member comparison*

To put the previously presented results into physical perspective, plots of the two most accurate members and the two least accurate members were constructed. By analyzing the synoptic features within the ensemble, one can determine the synoptic-scale processes that were favorable or detrimental to the development of the two quasi-stationary MCSs (Moore et al. 2012). Beginning at the 500-hPa level at 0000 UTC 3 May 2010, ensemble members 29 and 31 (the wet ensemble members) forecasted a high-amplitude upper-level trough extending into southern New Mexico. Consistent with the analysis, the trough axis is positively tilted from southwest to northeast (Figs. 14a and 14c). Members 36 and 5 (the dry ensemble members), however, have a slightly deeper trough in the central United States (Figs. 14b and 14d). Ensemble member 36 forecasted a trough axis of neutral tilt (Fig. 14b).

At the 850-hPa level, both the wet and the dry ensemble members forecasted a low pressure system in the central United States. However, members 29 and 31 (the wet ensemble members) forecasted a weak 850-hPa cyclone along the U.S.–Canadian border near Minnesota. With the Bermuda high located over the western Atlantic, a narrow low-level jet was present entering the Mississippi Valley. The wet ensemble members

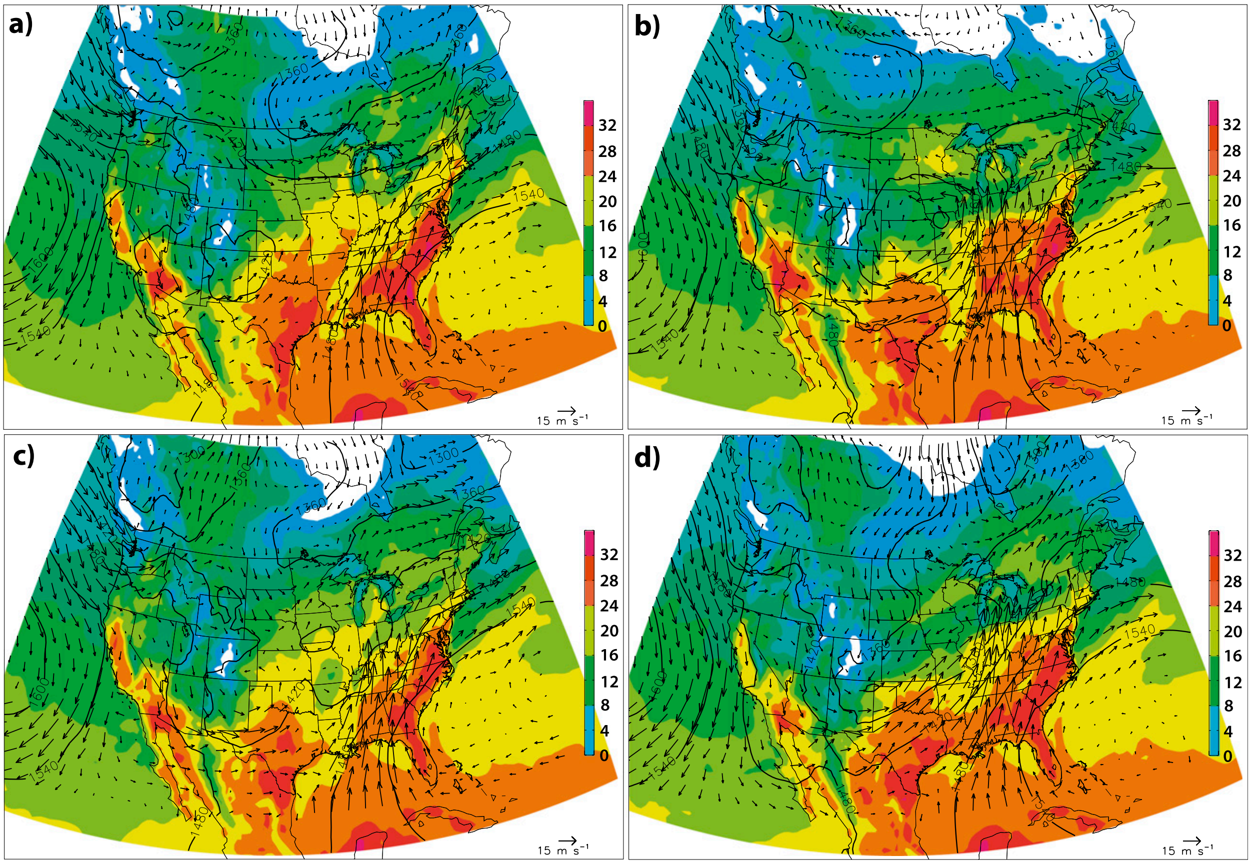

FIG. 15. Forecasted 850-hPa temperature (color shading in °C), height (contoured in black every 60 m), and wind (vectors overlaid, vector scale is shown at bottom right) at 0000 UTC 3 May 2010, corresponding to forecast hour 84: (a) member 29 (wet), (b) member 36 (dry), (c) member 31 (wet), and (d) member 5 (dry).

predicted slightly cooler temperatures in central Tennessee, with a defined frontal boundary extending from eastern Texas into the New England region (Figs. 15a and 15c). In contrast, members 36 and 5 (the dry ensemble members) forecasted 850-hPa geopotential heights that are much lower over the central plains region and similarly a deeper trough. This deep 850-hPa trough allowed for a tight pressure gradient over Tennessee, supporting the wide, strong low-level jet mentioned previously. Strong cyclonic rotation was present just to the west of Tennessee, possibly transporting drier air from the southwest into the Tennessee region, along with the southerly flow already present. Members 36 and 5 (the dry ensemble members) also forecasted slightly warmer temperatures throughout Tennessee, with a less defined frontal boundary. This is likely due to strong cyclonic rotation causing warm-air advection ahead of the closed cyclone in these members. Additionally, the dry ensemble members forecasted a strong warm front to develop across northern Kentucky (Figs. 15b and 15d). The 850-hPa height, wind, and temperature fields from members 29 and 31 (the wet ensemble members) resemble those of the observed. The trough and associated low pressure system are quite weak, with consistent southerly flow entering the southeastern United States (Fig. 3c).

Members 29 and 31 (the wet ensemble members) forecasted a very strong inflow of moisture across the Gulf of Mexico, similar to the analysis. This plume of moisture extended from the Caribbean Sea up to northern Kentucky (Figs. 17a and 17c). In contrast, member 36 (one of the dry ensemble members) forecasted a high total column water amount to be located in western Tennessee (Fig. 16b), and member 5 (the other dry member) forecasted a different scenario, with a similarly structured plume of moisture but decreased moisture values in the region of interest as compared to the wet ensemble members (Fig. 16d). Overall, both the wet and dry ensemble members accurately forecasted the transport of deep tropical moisture poleward into the Mississippi Valley. How that tropical moisture interacted with the synoptic-scale flow is what caused the

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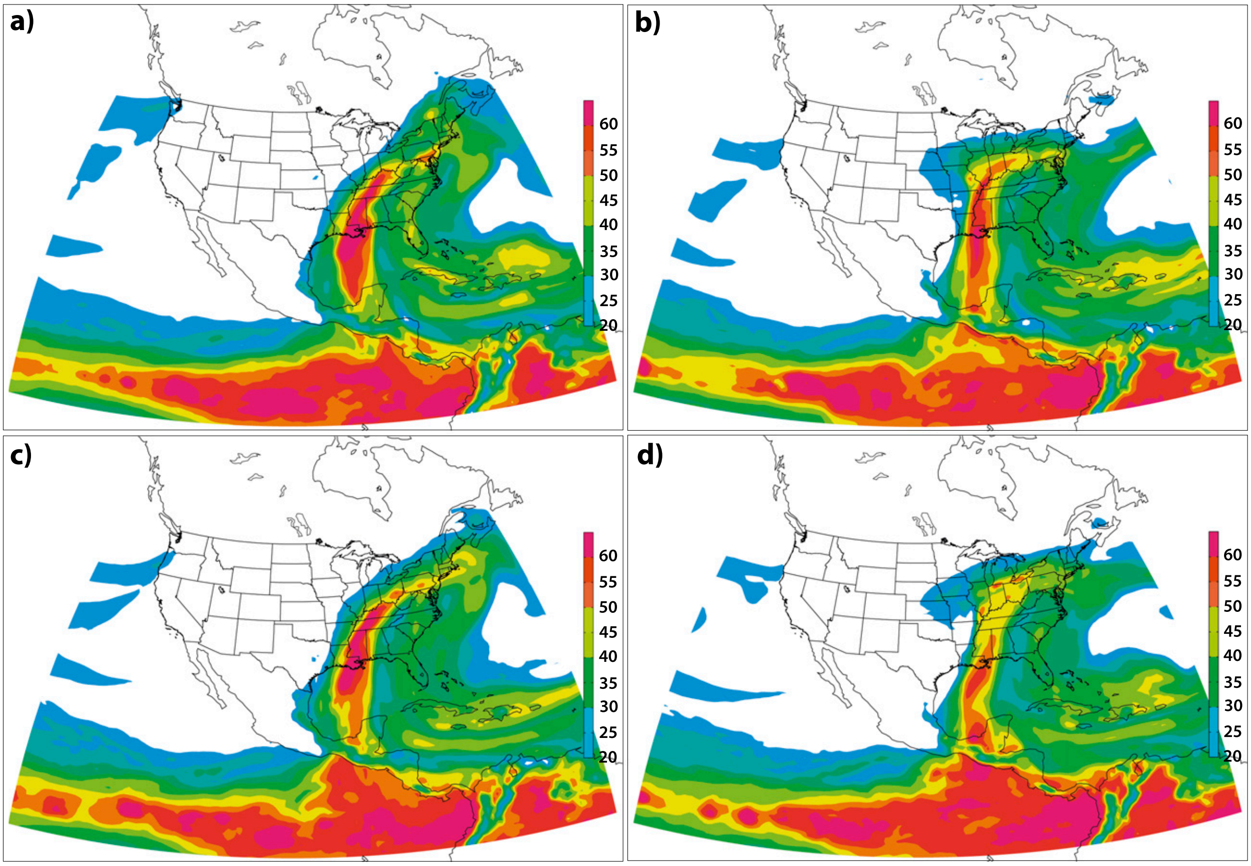

FIG. 16. Forecasted total column water (color shading in mm) at 0000 UTC 3 May 2010, corresponding to forecast hour 84: (a) member 29 (wet), (b) member 36 (dry), (c) member 31 (wet), and (d) member 5 (dry).

forecasts between the wet and dry ensemble members to differ. This is consistent with the 84-h forecast of the total column water correlations to 5-day area-averaged precipitation (Fig. 11f). The dry ensemble members were advecting the high values of total column water to the Great Lakes region due to a much broader low-level jet. On the other hand, the wet ensemble members were transporting this moisture only as far north as Tennessee and Kentucky, allowing for heavy localized precipitation in the region.

5. Discussion and conclusions

The 1–3 May 2010 case study used ECMWF ensemble forecasts to explore the processes responsible for the development and maintenance of a multiday precipitation event that occurred in early May 2010, due to two successive quasi-stationary mesoscale convective systems (Moore et al. 2012). Although the 1–3 May 2010 extreme precipitation event occurred ahead of a large-scale upper-level trough and cyclone over the central United States, our ensemble-based analysis reveals the counterintuitive result that a stronger low-level cyclone over the central United States would have been associated with *less* precipitation over Kentucky and Tennessee. Within the ensemble, a stronger cyclone was associated with a much broader corridor of southerly winds, which in turn led to the development of frontal structures and the transport of moisture into the Great Lakes (Fig. 17b). In these dry members, lighter precipitation was spread out over a large geographic area, with no extreme amounts. The wet members, which predicted a weaker low pressure system and a more elongated trough, proved to be accurate. The weaker low pressure system was associated with a narrower corridor of southerly flow, transporting moisture from the Caribbean Sea, eastern tropical Pacific, and Gulf of Mexico as far north as Tennessee, where a long-lived, slow-moving precipitation system developed (Fig. 17a). In these members, the heavy precipitation was focused over a small geographic area, resulting in extreme local rainfall amounts.

The analysis in this case study provides insight into the uncertainty in medium-range predictions of a

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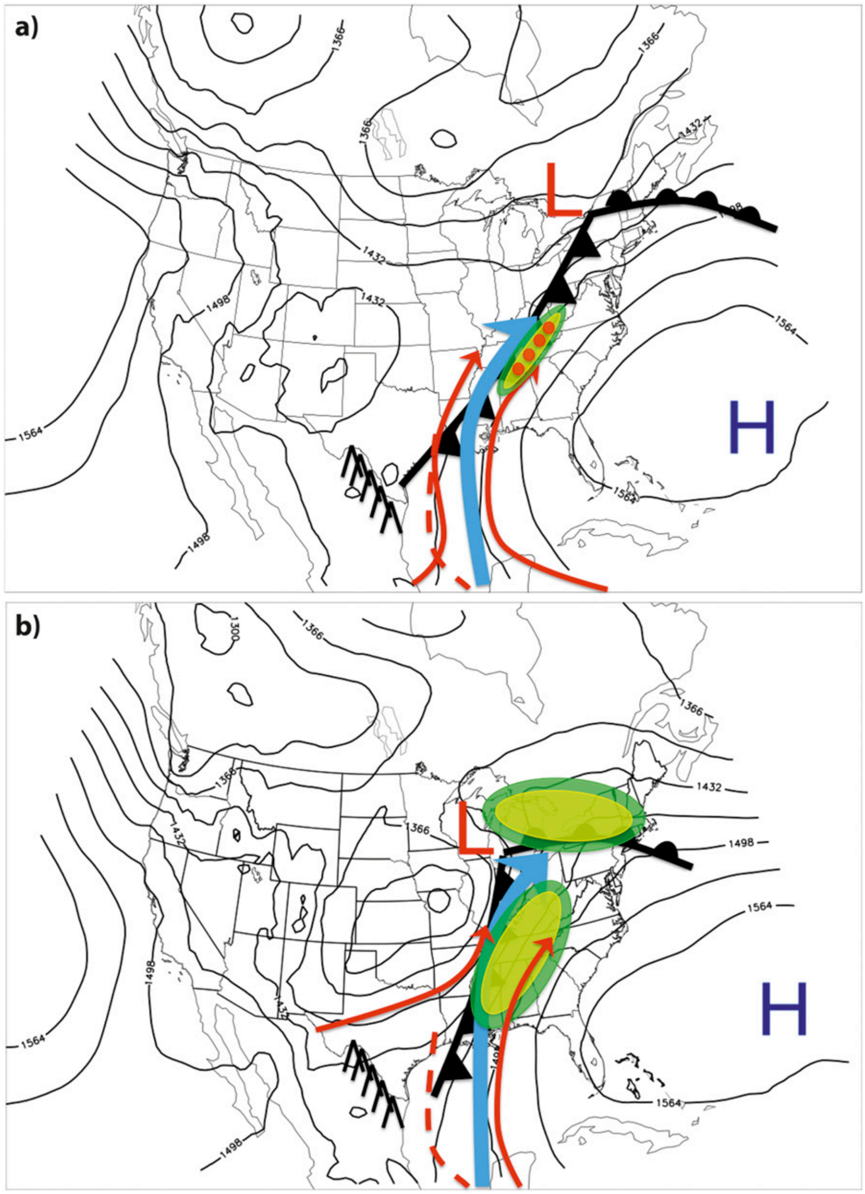

FIG. 17. Schematic illustration of the key features and processes for the (a) wet and (b) dry ensemble members. Black contours every 33 m show the 850-hPa geopotential height distribution at 0000 UTC 3 May 2010 (member 29 was used to demonstrate the wet ensemble members and member 36 was used to demonstrate the dry ensemble members); red arrows show the 850-hPa streamlines, with surface fronts shown in standard frontal notation; H and L symbols indicate the positions of the maxima and minima in sea level pressure, respectively; dashed red line shows the axis of the 850-hPa lee trough and the thick blue arrow shows the plume of moisture; carets (∧) indicate the Sierra Madre Oriental; and dark green, yellow, and red shaded regions represent the radar reflectivity.

widespread, heavy precipitation event. Relatively small differences in the height and wind fields were ultimately associated with vastly different forecasts of precipitation over Tennessee and surrounding areas. This strong sensitivity to small differences in the atmospheric state highlights the importance of using ensembles for predicting the development of precipitation systems over both land and ocean, especially for an event such as the 1–3 May 2010 precipitation event, which received national attention for having produced extensive flooding across Nashville and surrounding areas.

Fig(s). 17 live 4/C

Acknowledgments. The ECMWF ensemble forecast data were obtained from TIGGE archive online (http://tigge-portal.ecmwf.int). Precipitation data were obtained by the Climate Prediction Center (CPC) and 12-h precipitation accumulations were obtained from the National Climatic Data Center (NCDC). Archived surface analyses were obtained from the Hydrometeorological Prediction Center (HPC). Thanks also go to Richard Johnson and three anonymous reviewers for their constructive comments and valuable suggestions. This research was supported by National Science Foundation Grants AGS-0954908 and AGS-1157425.

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