Moisture Transport into Midlatitudes ahead of Recurving Tropical Cyclones and Its Relevance in Two Predecessor Rain Events

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ABSTRACT

Global ensemble forecasts from The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) are used to quantify the magnitude of moisture transport into North America ahead of recurving tropical cyclones (TCs). Two cases in which a predecessor rain event (PRE) occurred ahead of the recurving TC—Erin (2007) and Ike (2008)—are analyzed, with ensemble members correctly predicting TC recurvature contrasted from those predicting the TC to weaken or turn southward. This analysis demonstrates that TC-related moisture transport can increase the total water vapor in the atmosphere over North America by 20 mm or more, and that the moisture transport takes place both in the boundary layer and aloft. The increased moisture does not always correspond to increased rainfall in the ensemble forecasts, however, as the location and strength of baroclinic zones and their attendant secondary circulations that can lift this moist air are also crucial to the development of heavy rains.

1. Introduction

Recent studies have analyzed regions of heavy rainfall that occur ahead of recurving tropical cyclones (TCs), in which tropical moisture transported ahead of the TC enhances the precipitation in midlatitude convective systems (Wang et al. 2009; Galarneau et al. 2010; Schumacher et al. 2011). These situations were termed predecessor rain events (PREs) by Galarneau et al. (2010). PREs occur when tropical moisture is transported poleward of the TC and is lifted along a low-level baroclinic zone. Most PREs occur within a region of quasigeostrophic (QG) forcing for ascent under the equatorward entrance region of an anticyclonically curved upper-tropospheric jet and within strong warm-air advection in the lower troposphere. This forcing for ascent, along with the tropical moisture, provide the ingredients necessary for heavy rainfall (e.g., Doswell et al. 1996).

Two recent PREs that had particularly destructive impacts were those that occurred ahead of TC Erin in 2007 and TC Ike in 2008 (Fig. 1). The Erin PRE (Fig. 1a) was analyzed in detail by Galarneau et al. (2010) and Schumacher et al. (2011), who found that, in numerical model experiments, moisture attributable to Erin was responsible for increasing the total precipitation output of a mesoscale convective system (MCS) in Minnesota and Wisconsin by approximately 33%. This precipitation enhancement contributed to setting the all-time record for 24-h rainfall accumulation in Minnesota (383.5 mm at Hokah; Minnesota State Climatology Office 2010) and resulted in deadly flash floods. Other aspects of TC Erin, including its reintensification over land in Oklahoma on 19 August, have been addressed in detail by Arndt et al. (2009), Brennan et al. (2009), Monteverdi and Edwards (2010), and Evans et al. (2011).

The PRE ahead of Hurricane Ike (Fig. 1b), which occurred across Missouri, Illinois, Indiana, and Michigan, was considerably more complex than the Erin case. Moisture was

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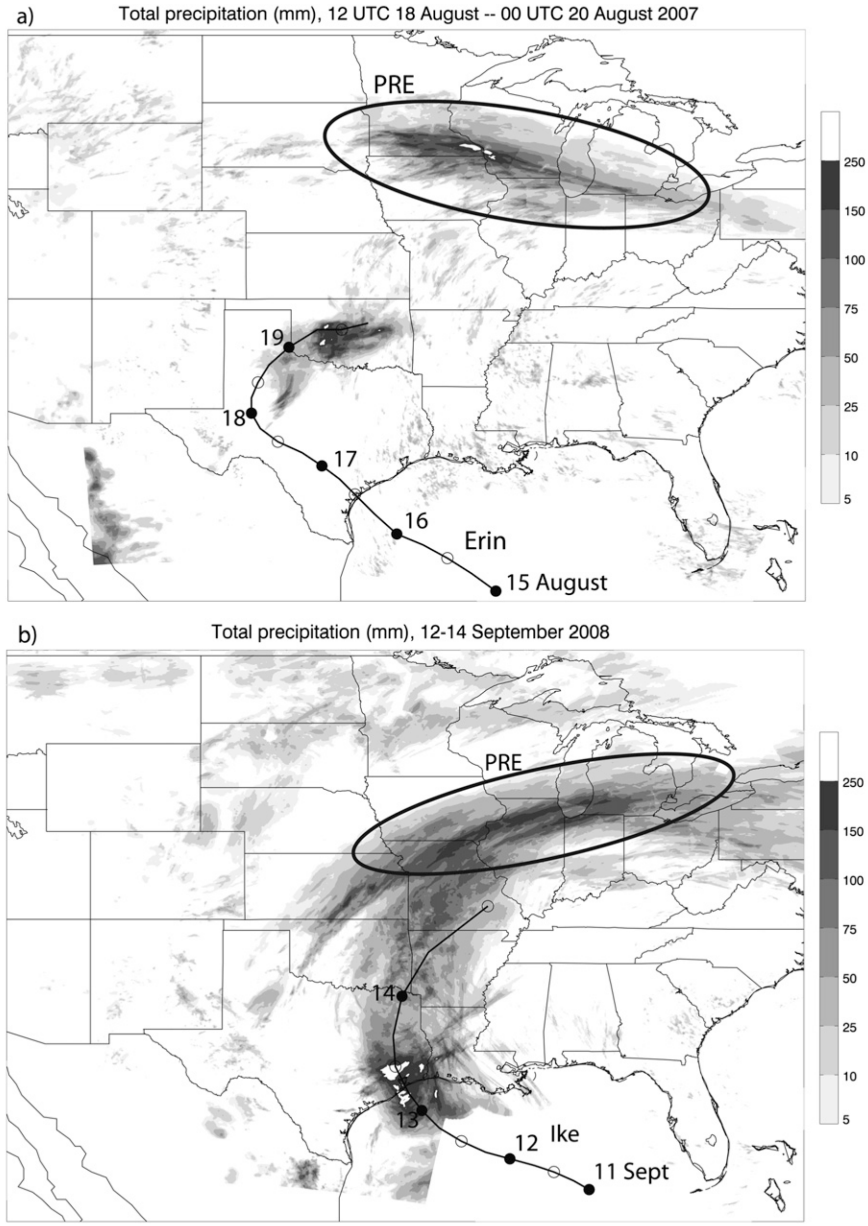

FIG. 1. NCEP stage IV gridded precipitation analysis (Lin and Mitchell 2005) for (a) the 36-h period 1200 UTC 18 Aug–0000 UTC 20 Aug 2007 and (b) the 48-h period 1200 UTC 12 Sep–1200 UTC 14 Sep 2008. Also shown are the National Hurricane Center's best track for (a) Erin and (b) Ike, with filled circles denoting positions at 0000 UTC and open circles denoting positions at 1200 UTC. The PRE is outlined in each. In (b), the track of Ike is only shown through 1200 UTC 14 Sep to correspond with the precipitation accumulation period, although the storm did continue beyond that time.

transported into the central United States not only by Ike, but also by eastern Pacific TC Lowell, whose remnants moved northeastward across the western United States (Berg 2010; Bosart et al. 2012). Heavy rains fell ahead of Ike along a southwest–northeast-oriented baroclinic zone through the central United States, and also along the track of Ike itself as it recurved and moved poleward. As part of this PRE, Chicago, Illinois, set its all-time record for 24-h rainfall [168.7 mm; (National Weather Service) NWS 2009],[1] and damaging flooding took place. These impacts from distant

[1] This record has since been broken, as 174.2 mm of rain was observed on 23 Jul 2011.

TABLE 1. Details of the three EPSs used in this study (obtained from http://tigge.ecmwf.int). Additional details are available at that site. GSI stands for gridpoint statistical interpolation, ETR stands for ensemble transform with rescaling, and ETKF stands for ensemble transform Kalman filter.

Center	Members	Horizontal resolution	Assimilation	Initial perturbations
NCEP	21	T126 (~90 km)	GSI	ETR
ECMWF	51	T399 (~50 km)	4D-Var	Singular vectors
UKMO	24	0.8333° lon × 0.5555° lat	4D-Var	ETKF

rainfall were in addition to the considerable impacts along the track of Ike itself (Berg 2010).

The studies cited above demonstrate that moisture transport ahead of TCs can substantially enhance rainfall in midlatitudes and intensify the impacts of the resulting flooding. However, the magnitude of the moisture transport attributable to the TC, and that attributable to other processes, remains unclear. In their numerical sensitivity experiment, Schumacher et al. (2011) reduced the atmospheric water vapor in the vicinity of TC Erin by limiting the relative humidity in the initial conditions. This brought the initial precipitable water to near-climatological levels, but this method did not necessarily represent the vertical structure of moisture that would have been in place had Erin not recurved at all. Quantification of this moisture transport, and its ultimate effect on precipitation, is important for both short-term and medium-range prediction of heavy rainfall and resultant flooding.

In this study, we will quantify the synoptic and mesoscale transport of moisture ahead of TCs by contrasting ensemble forecasts that correctly predicted the recurvature and moisture transport of these two TCs from those that predicted the TCs to weaken or take different tracks from those that were observed. section 2 will describe this method, and results for the Erin and Ike PREs will be presented in sections 3 and 4, respectively. Section 5 will provide conclusions and suggestions for future work.

2. Data and methods

a. *TIGGE*

The primary dataset used in this study is the collection of archived ensemble forecasts from The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE; Bougeault et al. 2010). In particular, forecasts from three national ensemble prediction systems (EPSs) that participate in TIGGE—the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Met Office (UKMO)—are analyzed. These three EPSs are used because they were the only ones with complete archives for the two cases of interest. These EPSs vary in their size, resolution, and configuration, and these differences are summarized in Table 1. All forecasts were obtained from the TIGGE archive (http://tigge-portal.ecmwf.int) on the same 0.5° latitude × 0.5° longitude grid covering most of North America. Although this is finer than the native grid for the NCEP and UKMO EPSs,

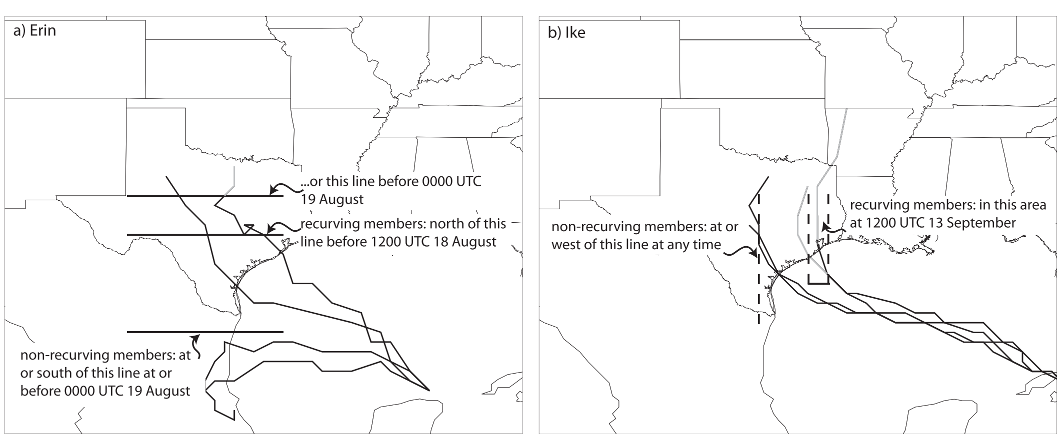

FIG. 2. Maps illustrating the grouping scheme for recurving and nonrecurving members as discussed in the text for (a) Erin and (b) Ike, along with examples of recurving and nonrecurving tracks from the EPSs. In (a), portions of the tracks after 0000 UTC 19 Aug 2007 are shown in gray. In (b), portions of the recurving tracks after 1200 UTC 13 Sep are shown in gray, and all tracks end at 1200 UTC 14 Sep.

TABLE 2. Number of recurving/nonrecurving members for the initialization times used in the time-lagged, multimodel ensemble for TC Erin. Those entries for the individual models shown in bold were used in the analysis; those not set bold were not used owing to insufficient numbers in one or both groups.

Center	0000 UTC 14 Aug	1200 UTC 14 Aug	0000 UTC 15 Aug	Tot
NCEP	0/5	0/3	0/4	0/12
ECMWF	**9/12**	**7/6**	**14/15**	**30/33**
UKMO	**3/6**	**1/4**	**6/4**	**10/14**
Tot included	**12/18**	**8/10**	**20/19**	**40/47**

tests using the same data on a coarser grid show essentially the same results.

b. Vortex tracking

Many of the results in this study are based on differences in the predicted tracks of TCs among ensemble members, a method similar to the ''ensemble synoptic analysis'' discussed by Hakim and Torn (2008). As such, the results are sensitive to the method for identifying and tracking the TC vortices. Although the TIGGE archive includes forecast TC tracks from each of the EPSs, these tracks are only created once a disturbance becomes a tropical depression. Because some of the forecasts we desired to use were initialized prior to Erin becoming a tropical depression, TIGGE-defined tracks were unavailable. Therefore, we used a slightly modified

TABLE 3. As in Table 2, but for TC Ike.

Center	1200 UTC 9 Sep	0000 UTC 10 Sep	1200 UTC 10 Sep	Tot
NCEP	**5/6**	**3/8**	**2/14**	**10/28**
ECMWF	**13/8**	**10/20**	**12/10**	**35/38**
UKMO	8/0	14/0	5/0	27/0
Tot included	**18/14**	**13/28**	**14/24**	**45/66**

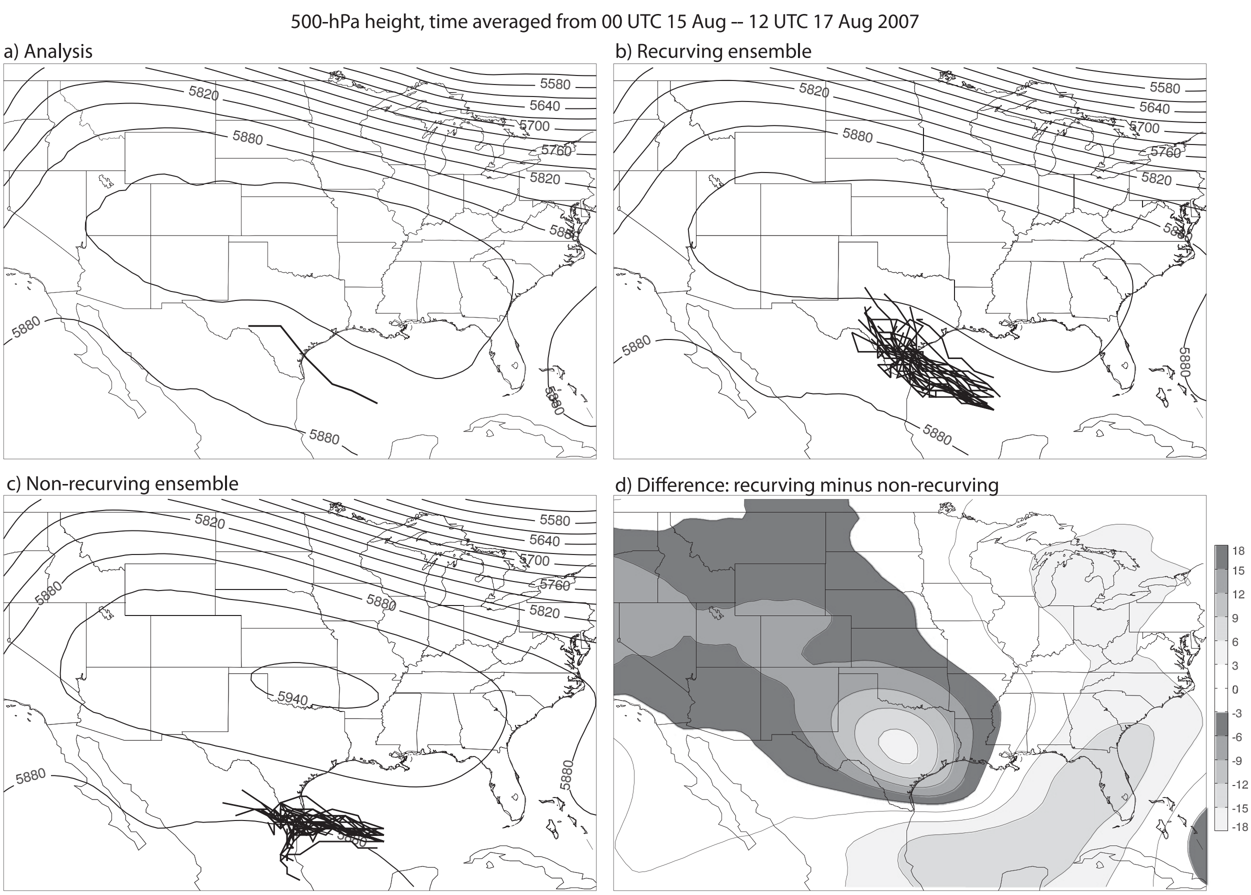

FIG. 3. The time-mean 500-hPa geopotential height (contoured every 30 m) from 0000 UTC 15 Aug to 1200 UTC 17 Aug 2007 from (a) the ECMWF analysis, (b) the recurving ensemble, and (c) the nonrecurving ensemble. (d) The 500-hPa height difference (recurving minus nonrecurving; shaded in m). The track of the Erin vortex from the analysis through 1200 UTC 17 Aug 2007 is shown in (a), and the forecast tracks from the recurving and nonrecurving ensembles are shown in (b) and (c), respectively. The forecasts used in the time-lagged ensembles were initialized between 0000 UTC 14 Aug and 0000 UTC 15 Aug 2007.

version of the ECMWF vortex-tracking algorithm (van der Grijn 2002). This algorithm uses the past movement of a vorticity maximum, along with the midtropospheric steering flow, to make a first guess at the location of the disturbance. Then, the maximum relative vorticity at 850 hPa within a box around this first guess is found, and this is defined as the center of the disturbance. In the ECMWF's operational vortex tracking, a sea level pressure minimum is then found within a radius around the 850-hPa vorticity maximum, but that step is not used here because a disturbance such as Erin in its predepression stage does not have a strong pressure minimum at the surface. In other words, the method used in this study tracks 850-hPa vortices rather than surface lows. If the maximum 850-hPa vorticity dropped below 6.5×10^{-5} s^{-1} at any time, the vortex was deemed to have dissipated. This value is slightly smaller than the 7×10^{-5} s^{-1} threshold used operationally by ECMWF, but it allowed for better tracking of the relatively weak Erin vortex. The tracks of these vortices were then grouped into categories as outlined in section 2c.

c. Grouping of recurving and nonrecurving tracks

The primary scientific objective of this study is to quantify the moisture transport ahead of recurving TCs by differentiating ensemble members where the TC recurved from those where it did not. This requires a definition of "recurvature" for the purposes of this analysis. For TCs Erin and Ike, the tracks of 850-hPa vortices in each EPS were first subjectively examined to identify the most commonly predicted tracks in each EPS. Then, an objective definition was created for each TC, and each ensemble member was classified as a "recurving member" (which corresponded closely to the observed track), a "nonrecurving member" (which was quite different from the observed track), or "in between," which are generally not used in the analysis. We define recurvature below as it will be used in the remainder of this study, recognizing that these definitions may differ slightly from how it is typically defined in the literature.

For TC Erin, a forecast track was classified as recurving if it either (i) was located at or north of 31.5°N latitude, and between 95° and 103°W longitude prior to 1200 UTC 18 August 2007, or (ii) was located at or north of 32°N latitude and between these same longitudes prior to 0000 UTC 19 August 2007 (Fig. 2a). It was classified as nonrecurving if it was located at or south of 25°N latitude and between these same longitudes prior to 0000 UTC 19 August 2007. All other forecast tracks were classified as in between. The recurving vortices are those that made it into approximately the northern half of Texas by 1200 UTC 18 August 2007, but remained east of the New Mexico border. These tracks are those most likely to have substantial poleward

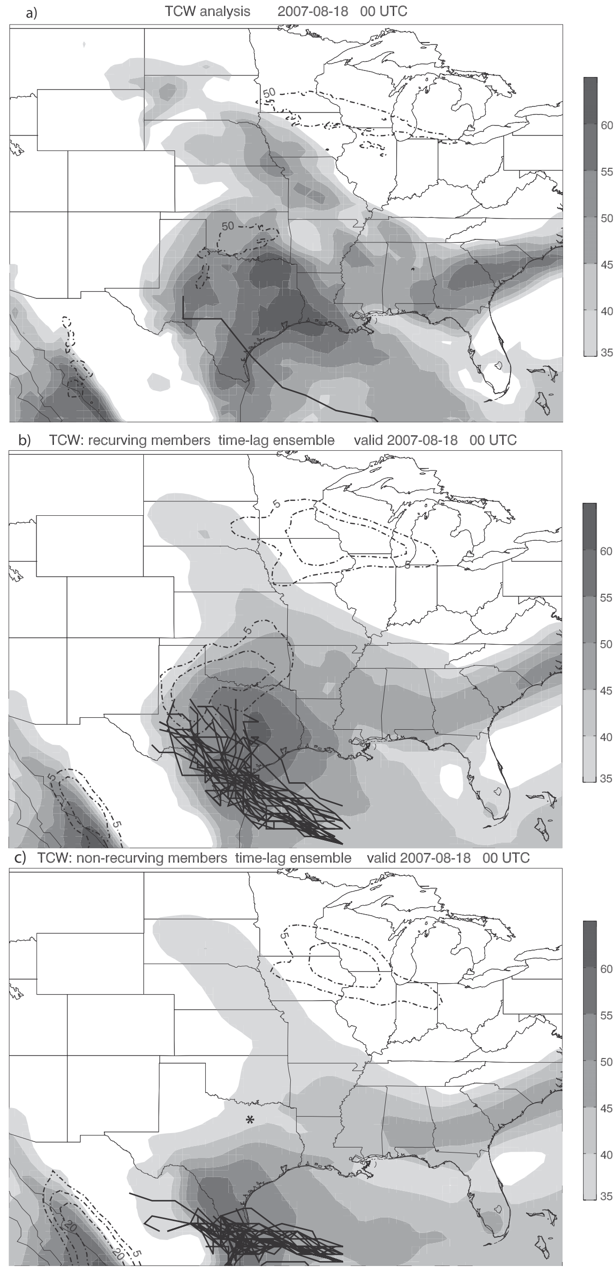

FIG. 4. Total column water (mm, shaded) in (a) the ECMWF analysis, (b) the recurving ensemble mean, and (c) the nonrecurving ensemble mean at 0000 UTC 18 Aug 2007. The tracks of the Erin vortex through this time in each member included in the ensemble are shown in (b) and (c), with (a) showing the track in the analysis using the same vortex-tracking method. Also shown is the 50-mm observed precipitation contour for the period 1200 UTC 18 Aug–0000 UTC 20 Aug in (a), and the probability of 50 mm in the same period in (b) the recurving ensemble and (c) the nonrecurving ensemble. The location of the Fort Worth, Texas, sounding shown in Fig. 5 is denoted with an asterisk in (c). In the TIGGE dataset, TCW is defined as the vertical integral of (water vapor + cloud water + cloud ice; ECMWF 2010).

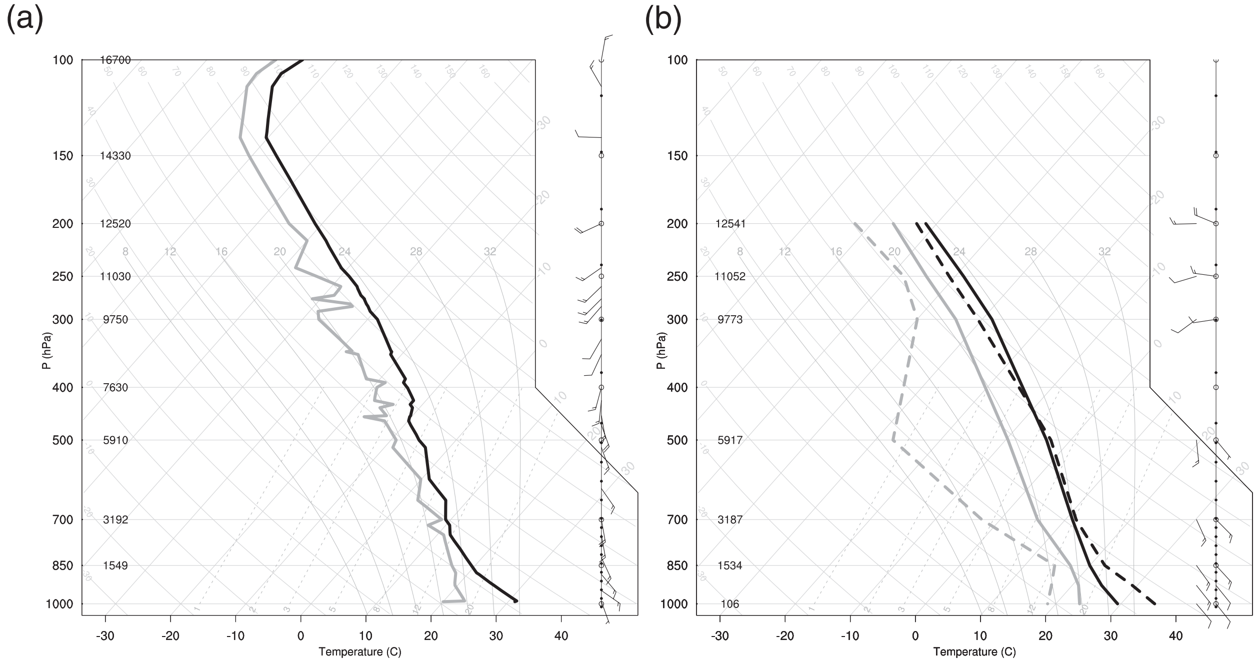

FIG. 5. (a) Skew T–log$p$ diagram from Fort Worth, TX (FWD), at 0000 UTC 18 Aug 2007. (b) As in (a), but for the recurving ensemble (solid) and the nonrecurving ensemble (dashed), averaged over the four grid points nearest FWD. The location of FWD is shown in Fig. 4c. The wind profile on the left in (b) corresponds to the recurving ensemble, the one on the right to the nonrecurving ensemble. Data in (b) are only plotted at 1000, 925, 850, 700, 500, 300, 250, and 200 hPa, as these are the only vertical levels available in the TIGGE archive.

moisture transport. The nonrecurving tracks, on the other hand, provide a contrasting set of circumstances, where no (or very little) TC-related moisture is transported poleward but the large-scale conditions are otherwise similar.

For TC Ike, a forecast track was classified as recurving if it was located north of 27.5°N latitude and between 94.5° and 95.5°W longitude at 1200 UTC 12 September 2008, but never west of 97°W at any point along its track (Fig. 2b). Essentially, these are vortices that made landfall along the eastern Texas coast and turned northward (but not westward), similar to the observed track of Ike. However, a few members that underwent extratropical transition much more quickly than Ike actually did—reaching 40.5°N by 1200 UTC 14 September 2008—were removed from this group since they would potentially produce *along-track* rainfall in the area where the PRE actually occurred. Tracks were classified as nonrecurving if they took a more westward track, moving to or westward of 98°W longitude at 1200 UTC 12 September 2008 or after. All other tracks were classified as in between. Although many of even the "nonrecurving" tracks eventually ended up turning toward the north, they did not do so in time to transport moisture poleward to be lifted along the baroclinic zone in the Midwest. Therefore, they provide a contrast to those predicted tracks that recurved at approximately the same time as Ike. The forecast initialization times used, and the number of members classified into each category, will be presented in section 2d.

d. Creation of multimodel, time-lagged ensemble

To obtain a robust estimate of the moisture transport ahead of recurving TCs that is not dependent on one particular model or one specific initialization time, we use the TIGGE output to create a multimodel, time-lagged ensemble. For each case, three consecutive initialization times were chosen that were far enough in advance of the PRE to have large spread in the forecast TC tracks and a reasonable number of both recurving and nonrecurving tracks, but not so far in advance that the spread has grown so much as to be uninterpretable. For Erin, the model initializations were 84–108 h prior to the beginning of the PRE (Table 2) and for Ike they were 48–72 h prior (Table 3). It was necessary to use forecasts with longer lead times for the Erin case compared to the Ike case so that the forecasts were initialized when Erin (and its associated moisture plume) was still over the Gulf of Mexico, rather than when it was inland.

In each case, one of the modeling systems consistently failed to provide a spread between recurving and nonrecurving forecast tracks among its members. For Erin, this was the NCEP EPS, which did not have any ensemble members predict a recurvature of the Erin vortex at these initialization times. From manual inspection of these forecasts, it appears that the vortex weakened before reaching land in nearly all ensemble members, which is perhaps a limitation of its coarse resolution. Thus, only the ECMWF and UKMO EPSs were used in the analysis of this case, and these had a nearly equal split between recurving and nonrecurving tracks (Table 2). For Ike, the UKMO EPS had no members with nonrecurving tracks, and generally had little spread in its ensemble forecasts of Ike (not shown). Because there were no nonrecurving members to compare against, the UKMO members were excluded from the analysis.

These results in themselves reveal some interesting information about the different EPSs. A "clustering" of TC tracks in the UKMO and NCEP EPSs was identified by Keller et al. (2011), whereas they found that the ECMWF EPS generally spreads its forecast tracks into different scenarios. The results found here are broadly consistent with their findings, although this is perhaps not surprising because one of the cases analyzed (Ike) in Keller et al. (2011) and the present study is the same. Similarly, Yamaguchi and Majumdar (2010) found that the initial perturbations in the ECMWF EPS grew via baroclinic and barotropic energy conversion within the vortex, and baroclinic energy conversion in the environmental flow, leading to relatively large spread 3 days into the forecast, whereas the NCEP EPS did not show these perturbation growth characteristics. The UKMO EPS's lack of any nonrecurving members for Ike represented a very skillful forecast in this case, as most of its members had tracks very similar to the observed track of Ike. Majumdar and Finocchio (2010) found that, during the 2008 season, the UKMO EPS was not strictly underdispersive for TCs, but that averaged over several cases, the observed track often fell outside defined "probability circles" because there were several cases where the ensemble mean had an inferior track forecast, and the probability circles were centered on the mean. Also of note for Ike is that the NCEP EPS, and to a lesser extent the ECMWF EPS, had better ratios of (correct) recurving members to (incorrect) nonrecurving members at *earlier* lead times; in other words, the envelope of predicted tracks had more error at shorter lead times. Some of the reasons for the forecast errors for Ike have been addressed by Brennan and Majumdar (2011).

With large samples of both recurving and nonrecurving forecast tracks for both cases (at least 40 of each; Tables 2 and 3) using multiple models, we can now examine how the poleward moisture transport, and resultant rainfall, differs between these sets of model forecasts. The results of this analysis will be presented in the next two sections.

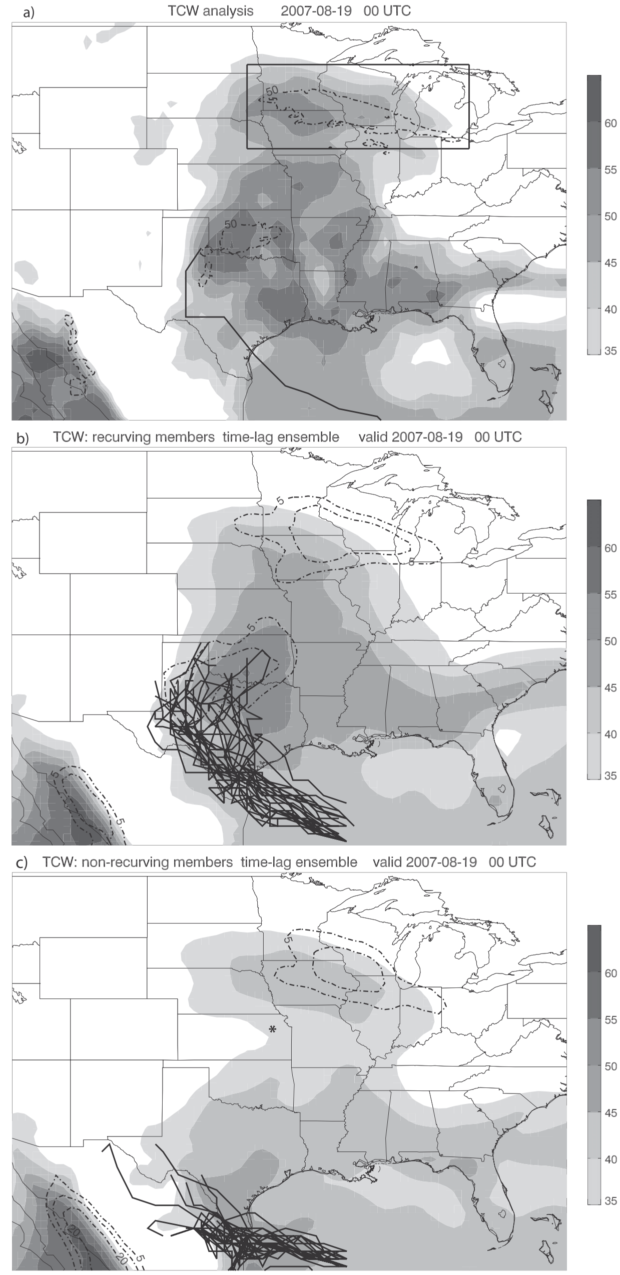

FIG. 6. As in Fig. 4, but the TCW is shaded at 0000 UTC 19 Aug 2007 and the Erin vortex tracks are shown through that time. (a) The rectangle is the area used for averaging of precipitation in Fig. 9. (c) The location of the Topeka, KS (TOP), sounding shown in Fig. 7 is denoted with an asterisk.

3. Results: Erin PRE

The large-scale environment in which TC Erin made landfall and recurved consisted of a midtropospheric anticyclone over the southern United States, with the Erin vortex moving westward and then northwestward around the southern edge of that anticyclone (Fig. 3a). A ridge was located over the northwestern United States, with a trough over the Northeast. This pattern was replicated well by the recurving ensemble (Fig. 3b), with forecast errors in the time-mean 500-hPa field of less than

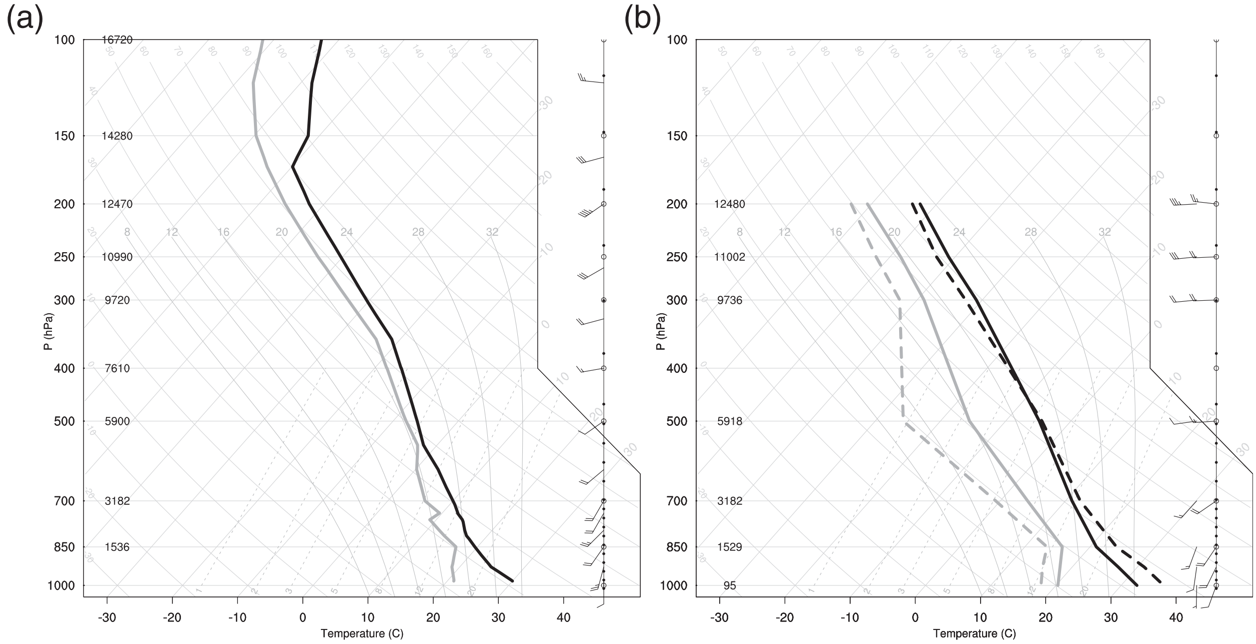

FIG. 7. As in Fig. 5, but soundings are at (a) Topeka, KS (TOP), and (b) the four grid points nearest TOP at 0000 UTC 19 Aug 2007. The location of TOP is shown in Fig. 6c.

5 m over most the United States. The nonrecurving ensemble had a stronger anticyclone over the southern plains of the United States (Figs. 3c,d), which was likely responsible in part for the southward track of the Erin vortex in these members. The 500-hPa height difference field (Fig. 3d) shows lower heights (in other words, a weaker anticyclone) in the recurving ensemble both near the vortex itself and throughout most of the western United States.

There are distinct differences in the amount of moisture over the southern United States between the recurving and nonrecurving ensembles by 0000 UTC 18 August, approximately 12 h prior to the initiation of the PRE (Fig. 4). The analyzed total column water (TCW) at this time shows a large region of values greater than 55 mm in eastern Texas and western Louisiana (Fig. 4a), and the recurving ensemble mean shows a similar area of high TCW in eastern Texas (Fig. 4b). The spatial extent of the high TCW in the ensemble mean is somewhat smaller than that in the analysis, but several individual members (not shown) have TCW values comparable to the analysis. The nonrecurving ensemble mean TCW is very different, with values over eastern Texas only in the 35–45-mm range (Fig. 4c). Both ensemble subsets show a tongue of TCW $>$ 35 mm extending from eastern Kansas northwestward into South Dakota, suggesting that they both represent the environment in that area similarly. This area of increased moisture is similar to the analysis, though the ensembles underestimated the amount of moisture somewhat (cf. Figs. 4a–c).

Temperature and moisture profiles in these two time-lagged ensembles show that the moisture transport ahead of Erin occurred both in the boundary layer and aloft (Fig. 5). The recurving ensemble's mean profile in an area near Fort Worth, Texas, is very similar in structure to the observed Fort Worth sounding at 0000 UTC 18 August (Fig. 5), with moist conditions through the depth of the troposphere. The nonrecurving ensemble mean has a very different profile at this same point, with much warmer (surface temperature approximately 5°C higher) and drier (surface dewpoint approximately 5°C lower) conditions in the boundary layer. There is also a very dry layer between 700 and 500 hPa in the nonrecurving ensemble profile. These analyses demonstrate that the turning of the Erin vortex and the moisture plume surrounding it into Texas led to a considerable change in the character of the airmass over much of the southern United States. The sounding from the nonrecurving ensemble is broadly similar to that used in the initial conditions of the ''NOPLUME'' experiment in Schumacher et al. (2011, see their Fig. 11c) in terms of the total moisture in the atmosphere, except that the NOPLUME simulation used a boundary layer that was somewhat too dry and upper levels that were too moist.

Twenty-four hours later, as Erin moved poleward in the Texas Panhandle, the high values of TCW were also transported poleward within the general southerly low-level flow (Fig. 6a; see also Galarneau et al. (2010) for a more detailed analysis of the observed moisture transport).

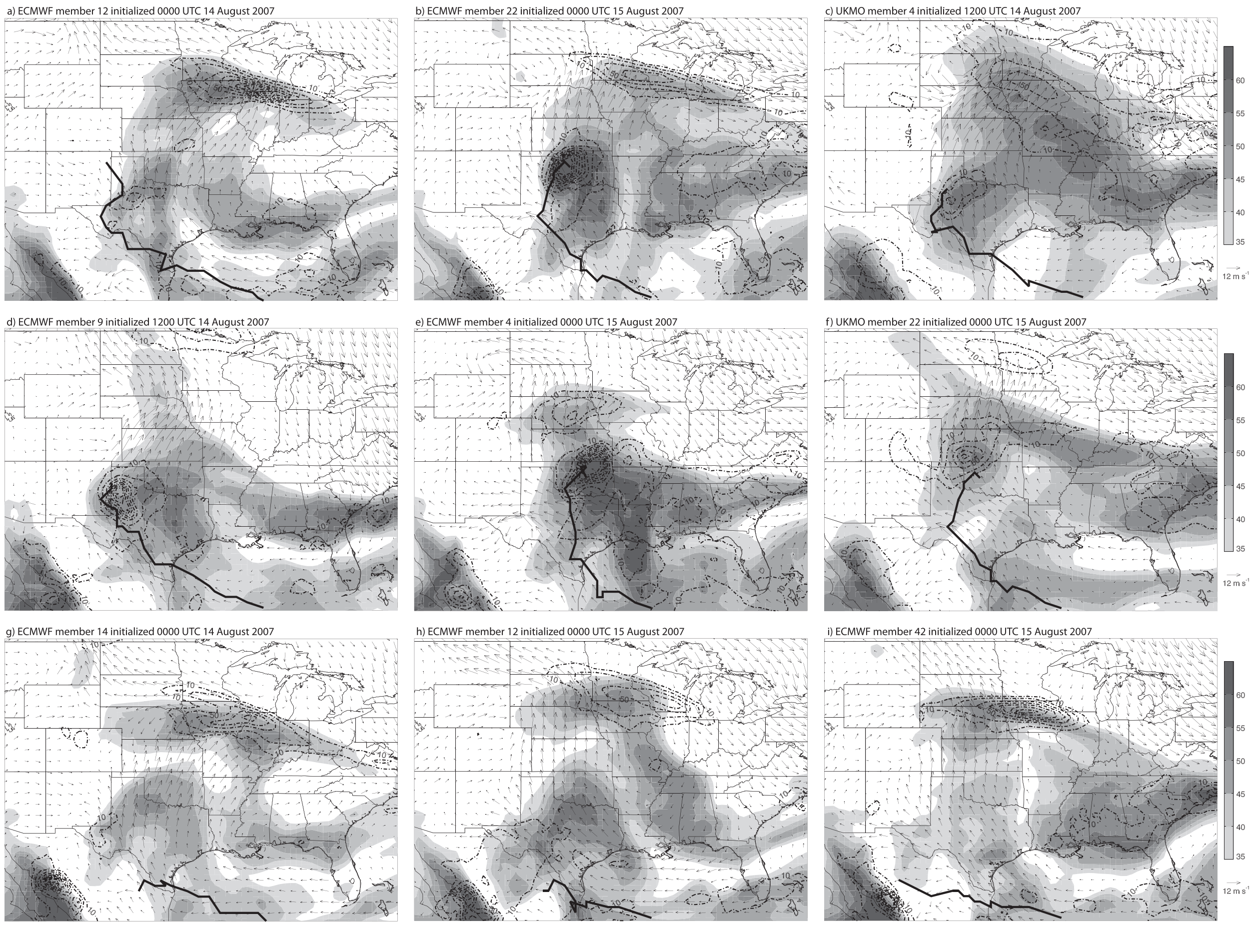

FIG. 8. Total column water (mm, shaded) and 850-hPa winds (vectors) at 0000 UTC 19 Aug 2007, and accumulated precipitation between 1200 UTC 18 Aug–0000 UTC 20 Aug 2007 (dashed contours at 10, 25, 50, 75, 100, 125, 150, and 175 mm) from members selected to demonstrate the variability in the ensemble. The track of the Erin vortex through 0000 UTC 20 Aug 2007 is shown with a thick curve for each member. Members shown are (a) ECMWF member 12 initialized at 0000 UTC 14 Aug, (b) ECMWF member 22 initialized at 0000 UTC 15 Aug, (c) UKMO member 4 initialized 1200 UTC 14 Aug, (d) ECMWF member 9 initialized 1200 UTC 14 Aug, (e) ECMWF member 4 initialized 0000 UTC 15 Aug, (f) UKMO member 22 initialized at 0000 UTC 15 Aug, (g) ECMWF member 14 initialized at 0000 UTC 14 Aug, (h) ECMWF member 12 initialized at 0000 UTC 15 Aug, and (i) ECMWF member 42 initialized at 0000 UTC 15 Aug. Members (a)–(f) are from the recurving ensemble; (g)–(i) are from the nonrecurving ensemble.

Similar poleward transport of moisture was apparent in the recurving ensemble mean (Fig. 6b), although the magnitude and northward extent were somewhat less than in observations, which is partially a result of averaging over many ensemble members. Nonetheless, TCW values >45 mm were present in a contiguous swath from the Gulf Coast into central Iowa in the recurving members. In contrast, the nonrecurving ensemble mean showed much drier conditions throughout the Great Plains, with TCW everywhere less than 45 mm (Fig. 6c). A region of TCW >40 mm was located in a west-northwest–east-southeast band across South Dakota, Nebraska, Iowa, and Illinois in the nonrecurving ensemble (Fig. 6c), showing that there was a relative moisture maximum in this region that was independent of Erin's track. The vertical structure of temperature and moisture at this time at Topeka, Kansas, shows that the moisture plume surrounding Erin is being transported poleward in both observations and the recurving members (Figs. 7a,b). The nonrecurving ensemble sounding at Topeka continues to be much warmer and drier than that in the recurving ensemble.

Although there are vast differences in the TCW and predicted precipitation in the central and southern United States between the ensemble members that predicted Erin to recurve and those that did not, Figs. 4 and 6 show that the probability of heavy rainfall occurring in Minnesota and Wisconsin is not very different between the two sets of forecasts. Both the recurving and nonrecurving ensembles have between 10% and 20% of their members

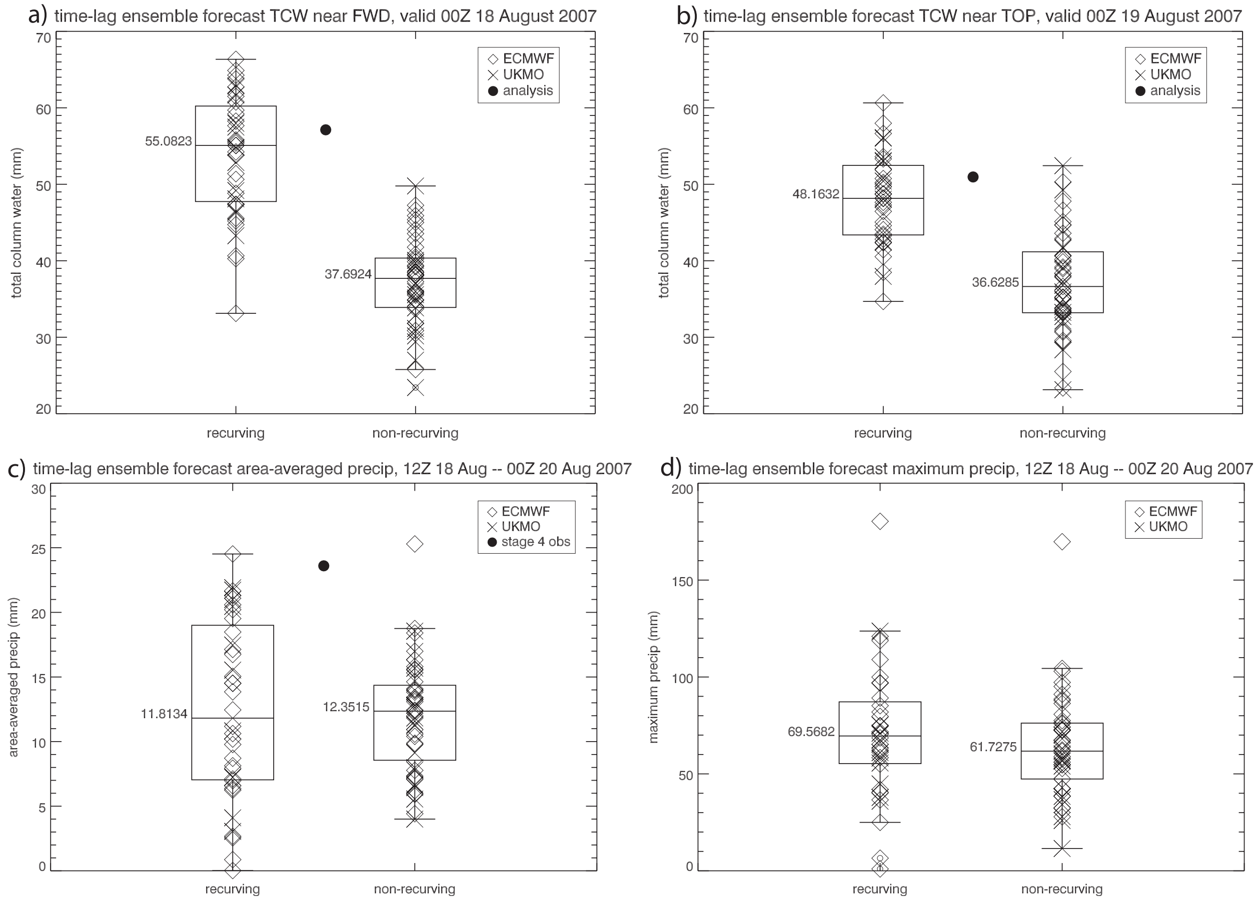

FIG. 9. Box-and-whisker diagrams of the recurving and nonrecurving ensembles for (a) TCW averaged over the four grid points nearest FWD at 0000 UTC 18 Aug 2007, (b) TCW averaged over the four grid points nearest TOP at 0000 UTC 19 Aug 2007, (c) precipitation averaged over the area shown in Fig. 6a, for the period 1200 UTC 18 Aug–0000 UTC 20 Aug 2007, and (d) the maximum predicted precipitation within that same area. The values for individual ensemble members are shown using diamonds for ECMWF members and crisscrosses for UKMO members. Observed/analyzed values are shown with filled circles. The observed maximum precipitation of 383 mm is not shown in (d). The median values are shown to the left of each box-and-whisker diagram. The boxes encompass the interquartile range (25th–75th percentile), with the whiskers representing either the minimum and maximum value, or 1.5 times the interquartile range if values exist outside that range.

predicting over 50 mm of rain in the approximate area where the PRE occurred. At first glance, this may suggest that, in contrast to the results of Schumacher et al. (2011), the moisture transported ahead of Erin was unimportant to the rainfall amounts in Minnesota and Wisconsin. However, the two sets of results are not necessarily in conflict. Inspection of the individual members making up each ensemble reveals that the predicted location and strength of the baroclinic zone in that area varied widely among the members. Because these are medium-range ensemble forecasts, such variation is to be expected.

Ensemble members illustrating some of this variability are shown in Fig. 8. Figures 8a–c show members in which, similar to observations, the Erin vortex recurved, moisture was transported poleward, and heavy rain was predicted along a boundary in the upper Midwest. Examples of members where the Erin vortex recurved but a PRE was not predicted are shown in Figs. 8d–f. In these members, the baroclinic zone was displaced to the north or south, and the low-level winds differed in speed and direction, such that there was no mechanism to lift the moist air transported ahead of Erin; in other words, the large-scale pattern was not favorable for a PRE. Finally, members in which Erin did not recurve, but heavy rainfall was still predicted in the Midwest, are shown in Figs. 8g–i. Here, there was little or no connection between the tropical moisture associated with Erin and the boundary in the Midwest, but the nontropical sources of moisture were sufficient to produce a swath of heavy precipitation along the boundary. Figures 8g–i also show that the large-scale environment was still

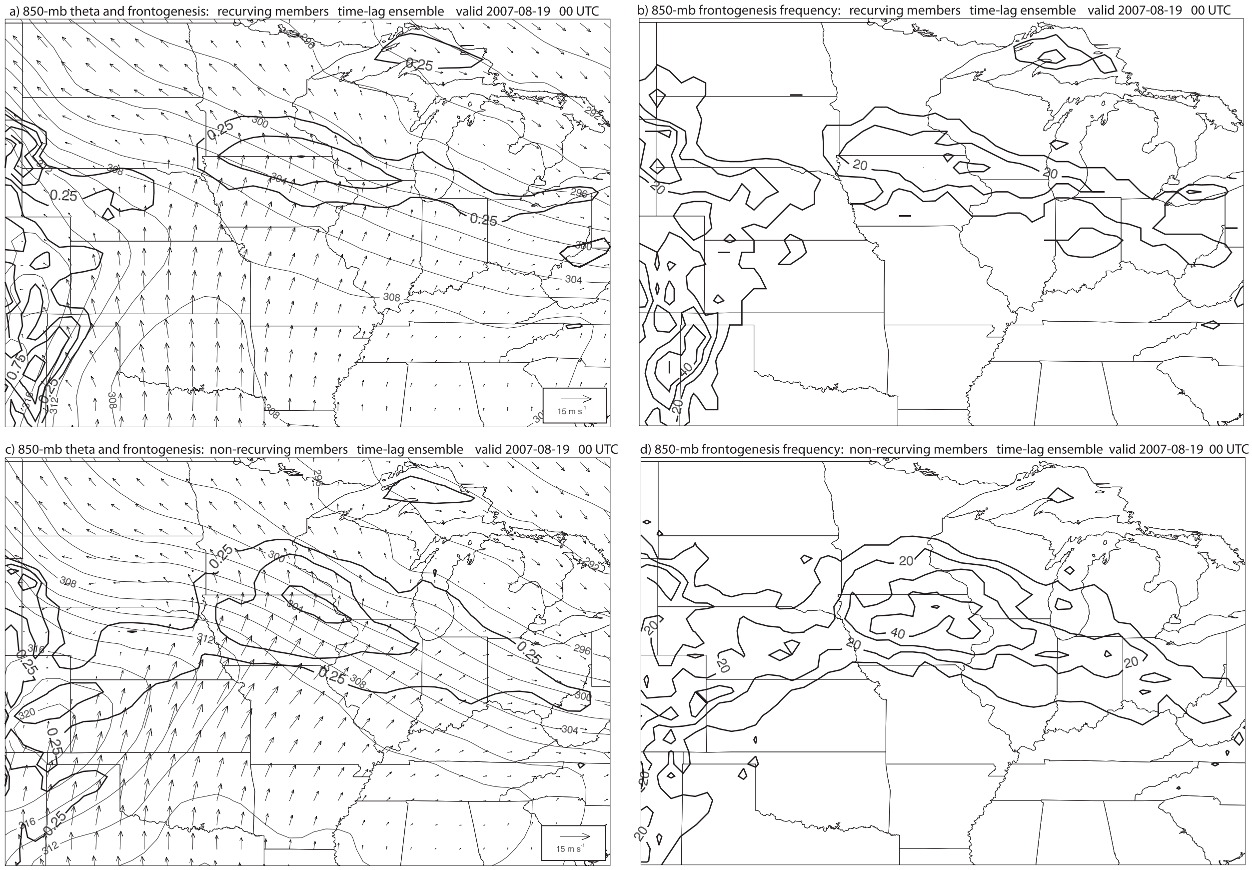

FIG. 10. Potential temperature (thin contours every 2 K), wind vectors, and frontogenesis [K (100 km 3 h)$^{-1}$, thick contours every 0.25 K (100 km 3 h)$^{-1}$ for positive values only] at 850 hPa for the (a) recurving ensemble and (c) nonrecurving ensemble at 0000 UTC 19 Aug 2007. Percentage of (b) recurving and (d) nonrecurving members with frontogenesis exceeding 0.75 K (100 km 3 h)$^{-1}$ at 0000 UTC 19 Aug 2007.

favorable for poleward transport of moisture into the south-central United States, but the values of TCW were not as great and did not reach as far poleward without the recurvature of Erin.

The differences between the ensembles are summarized in Fig. 9, which shows that there is variability within each ensemble, and some overlap between the two sets of members. In total, however, there is significantly more TCW in the recurving ensemble members near both Fort Worth, Texas (FWD), on 18 August (Fig. 9a) and Topeka, Kansas (TOP), on 19 August (Fig. 9b). Near FWD at 0000 UTC 18 August, the recurving ensemble median (55.1 mm) has more TCW than any member in the nonrecurving ensemble (Fig. 9a). These differences in TCW over the plains do not translate to a strong signal in the precipitation forecasts in the PRE region, though. Both sets of members have substantial variability in their precipitation forecasts, with members ranging from near zero to an area average of over 25 mm in both sets of members (Fig. 9c).

This wide range of outcomes reflects variability in the timing, location, and intensity of the synoptic-scale lifting mechanisms in the northern United States. In fact, the magnitude of the forcing for ascent in the Midwest was, on average, stronger in the nonrecurving ensemble than in the recurving ensemble (Fig. 10). Although both ensemble means show a northwest–southeast-oriented baroclinic zone at 850 hPa (Figs. 10a,c), the temperature gradient was tighter in the nonrecurving ensemble mean owing to an area of potentially warmer air over the Great Plains (Fig. 10c). This warm air is consistent with the Topeka soundings shown in Fig. 7, and is likely a result of greater insolation and deeper boundary layer mixing owing to the relatively dry air in the nonrecurving members. The 850-hPa winds were also stronger, and from a more southwesterly direction, in the nonrecurving composite (Figs. 10a,c). The combination of these factors led to greater and more widespread 850-hPa frontogenesis in the nonrecurving composite (cf. Figs. 10a,c), and to a higher percentage

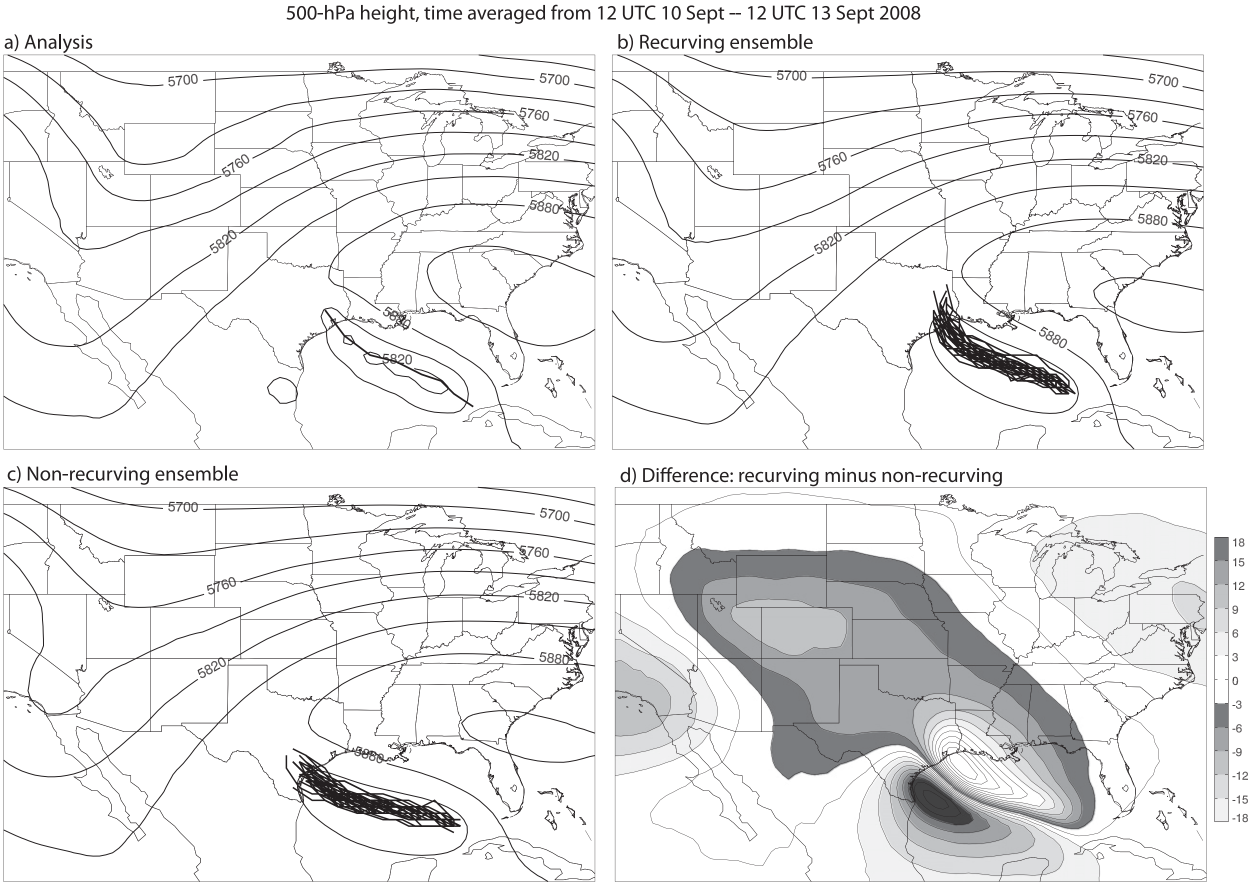

FIG. 11. As in Fig. 3, but the averaging is done from 1200 UTC 10 Sep–1200 UTC 13 Sep 2008. (a) The track of the Ike vortex from the analysis through 1200 UTC 13 Sep 2008 and the forecast tracks from the (b) recurving and (c) nonrecurving ensembles. The forecasts used in the time-lagged ensembles were initialized between 1200 UTC 9 Sep and 1200 UTC 10 Sep 2008.

of the nonrecurving members having strong frontogenesis in the Midwest (cf. Figs. 10b,d). Therefore, although there was no source of deep tropical moisture in the nonrecurving members, the stronger ascent may have made for more efficient processing of the moisture that was present into precipitation, explaining the small differences in precipitation between the two composites despite large differences in moisture.

Thus, the relatively controlled experiments of Schumacher et al. (2011), where only the moisture was modified but the effects of Erin could not be completely removed, and the ensemble-based analysis presented here, where the fully nonlinear forecasts reflect true atmospheric variability, but are more difficult to interpret, are complementary approaches to attacking the same scientific question. The increased moisture in the southern plains clearly increased the chances of a major rain event in the upper Midwest like the one that occurred—the results of Schumacher et al. (2011) show that, all else being equal, the poleward transport of tropical moisture was able to transform a heavy rain event into a record-breaking rain event. On the other hand, the results derived from the ensembles here show that increased poleward moisture transport ahead of Erin did not *necessarily* mean there would be a major rain event, and that changes in the timing, strength, and location of the baroclinic zone could have led to heavy rainfall even without the recurving TC. Perhaps the primary practical message that the ensemble-based results convey is that moisture transport ahead of a recurving TC can increase the precipitable water by 20 mm or more, making the environment much more favorable for a high-impact rain event far ahead of the TC, but not guaranteeing that such an event will occur.

4. Results: Ike PRE

Tropical Cyclone Ike approached the U.S. coast from the southeast as it moved around the western flank of an anticyclone that was centered over Georgia (Fig. 11a).

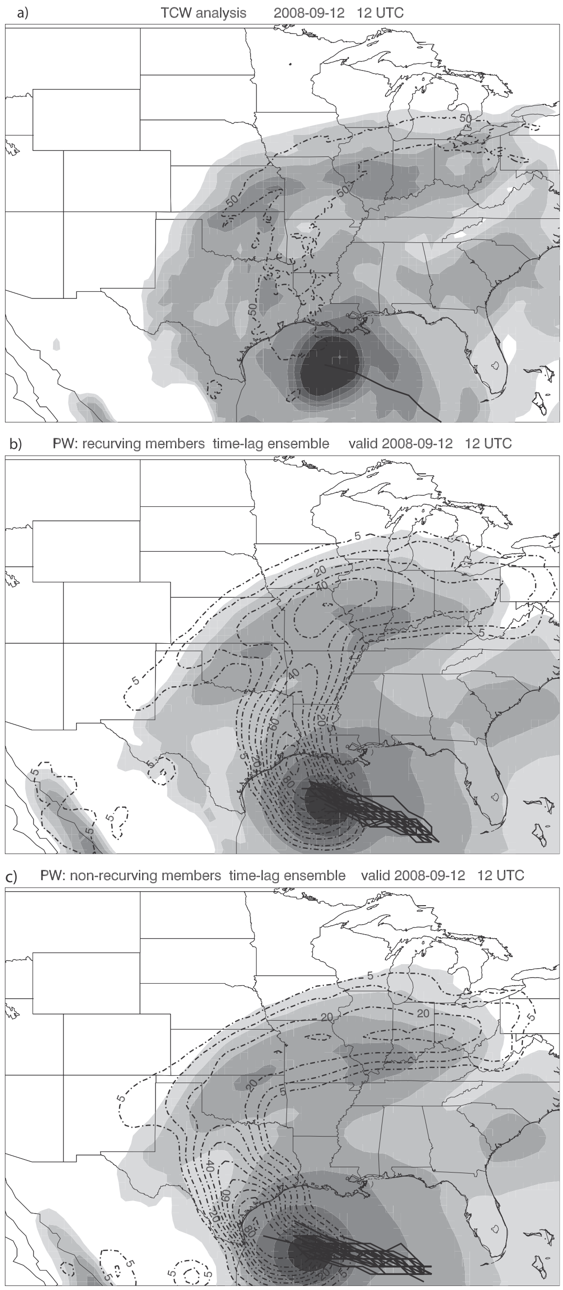

FIG. 12. Total column water (mm, shaded) in (a) the ECMWF analysis, (b) the recurving ensemble mean, and (c) the nonrecurving ensemble mean at 1200 UTC 12 Sep. The tracks of the Ike vortex through this time in each member included in the ensemble are shown in (b) and (c), with (a) showing the track in the analysis using the same vortex-tracking method. Also shown is the 50-mm observed precipitation contour for the period 1200 UTC 12 Sep–1200 UTC 14 Sep in (a), and the probability of 50 mm in the same period in (b) the recurving ensemble and (c) the nonrecurving ensemble.

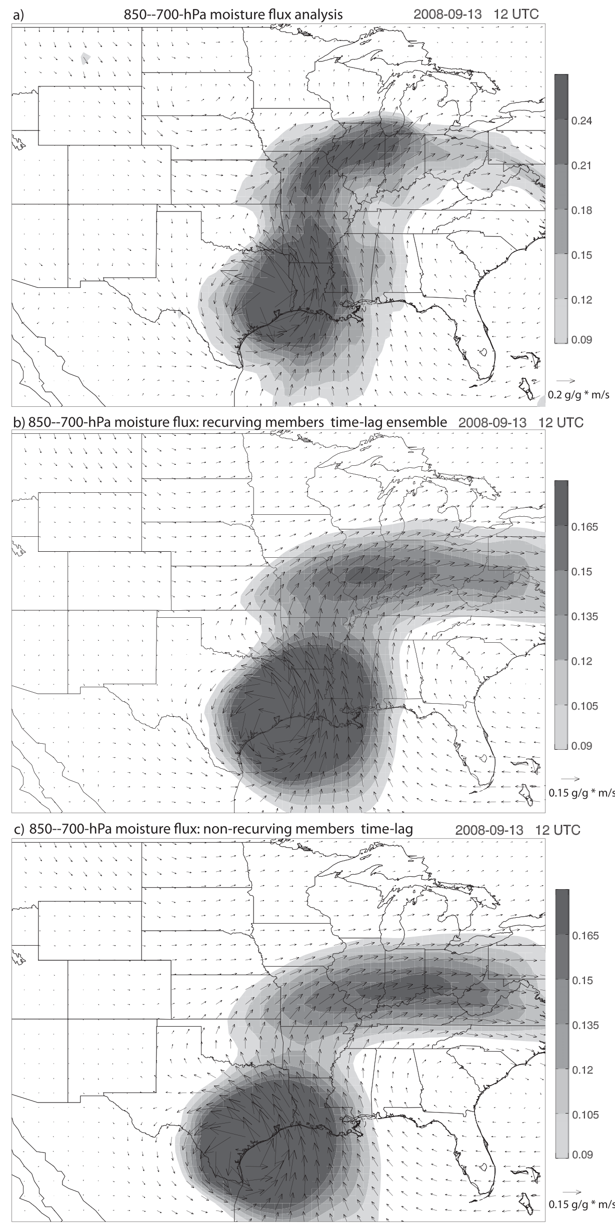

FIG. 13. Moisture flux (g g^{-1} m s^{-1}, shaded) and moisture flux vectors averaged over the 850–700-hPa layer in (a) the ECMWF analysis, (b) the recurving ensemble mean, and (c) the nonrecurving ensemble mean at 1200 UTC 13 Sep. The shading scale and the reference vector for the analysis in (a) are different from those for the ensembles in (b),(c).

A trough was present over the western United States, and as this trough moved eastward the attendant southerly flow began to steer Ike poleward. The primary difference in the upper-level height field between the recurving and nonrecurving ensembles was in the depth and location of the trough, with the recurving ensemble having lower heights through much of the western and central United States, and with these differences maximized in Utah, Colorado, and Wyoming (Fig. 11d). In contrast, the nonrecurving ensemble's trough had more of a positive tilt, with an area of lower heights in Southern

California and the adjacent Pacific Ocean. This suggests that the track of Ike was closely tied to the trough moving across the United States, with a deeper, more progressive trough in the western and central United States being favorable for Ike's recurvature. The magnitude of the height differences between the two ensemble subsets were relatively small within the anticyclone in the southeastern United States, but the anticyclone in the nonrecurving ensemble extended slightly farther to the west. Also, both subsets underestimated the analyzed maximum heights within the anticyclone by 12–15 m. These results suggest that the depth and orientation of the trough in the western United States, along with the strength of the anticyclone in the southeastern United States were factors in Ike's recurvature in the model forecasts used here. In forecasts initialized at 0000 UTC 9 September (somewhat earlier than those analyzed here), Brennan and Majumdar (2011) and Komaromi et al. (2011) found that the anticyclone to the north of Ike was the primary influence on Ike's track, but the results shown here suggest that the trough over the western United States may have become more important in later forecasts. This issue is a possible subject for a future investigation.

In contrast to the Erin case, the differences in moisture between the recurving and nonrecurving ensembles for the Ike PRE were subtle. Prior to Ike's landfall, there was considerable moisture already present over the central United States, with TCW values greater than 50 mm along an axis from western Texas through Ohio in the analysis (Fig. 12a) and the two ensemble means (Figs. 12b,c). This moisture was attributable to several sources, including the remnants of east Pacific TC Lowell (Berg 2010; Bosart et al. 2012). Surrounding Ike itself was another region of TCW exceeding 50 mm, with a maximum greater than 70 mm near the storm's center. Thus, even with Ike taking a track farther to the south and west than what was observed, conditions would have been favorable for heavy rainfall in the central United States ahead of the upper-tropospheric trough, as sufficient moisture and lift were present.

After Ike made landfall on 13 September, the plume of moisture surrounding the TC moved poleward (Fig. 13a) and merged with the existing regions of moisture, causing the TCW to increase to above 60 mm in a southwest–northeast axis from northeastern Oklahoma through southwestern Michigan (Fig. 14a). The recurving ensemble mean reflects this northward surge of moisture (Fig. 13b), with an area of TCW greater than 55 mm in central Missouri, Illinois, and Indiana (Fig. 14b). In the nonrecurving ensemble, axes of enhanced 850–700-hPa moisture flux and high TCW also exist across the central United States, but the orientation of these axes is more zonal than that in the analysis or the

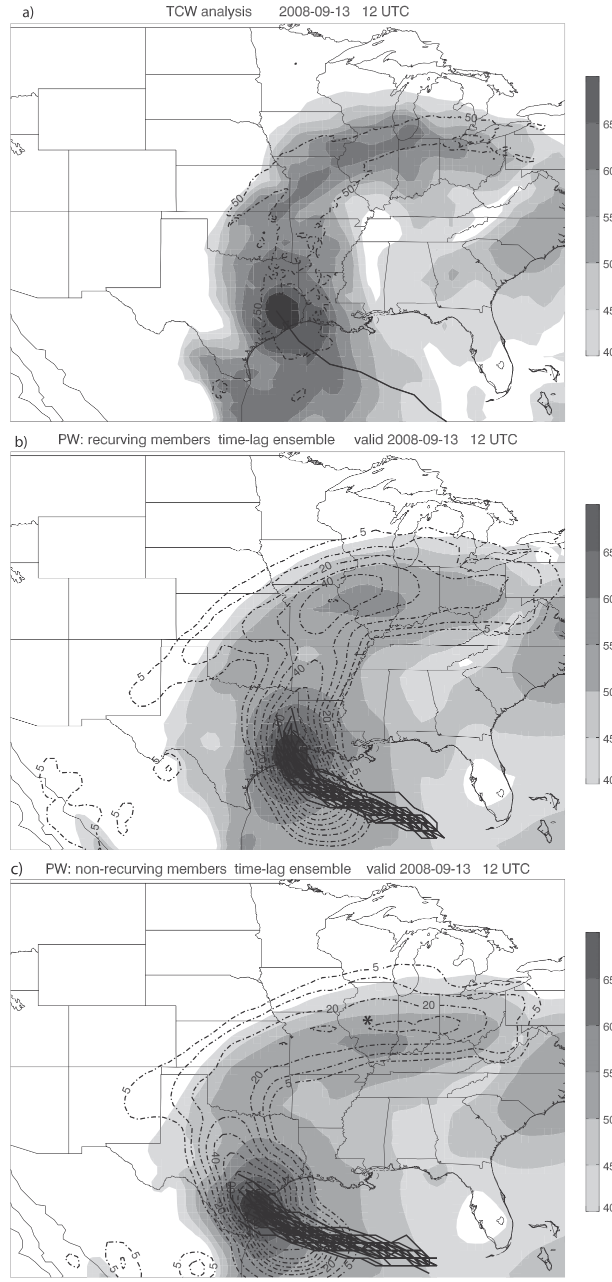

FIG. 14. As in Fig. 12, but the TCW is shaded at 1200 UTC 13 Sep and the Ike tracks are shown through that time. (c) The location of the Lincoln, IL, sounding shown in Fig. 5 is denoted with an asterisk.

recurving ensemble (Figs. 13c and 14c). Furthermore, the poleward transport of moisture ahead of Ike in the nonrecurving ensemble shows less of a connection to the west–east boundary in the Midwest than in the recurving ensemble mean (Figs. 13b,c), and the spatial extent encompassed by the 50-mm TCW contour is slightly less than that in the recurving ensemble (Figs. 14b,c).

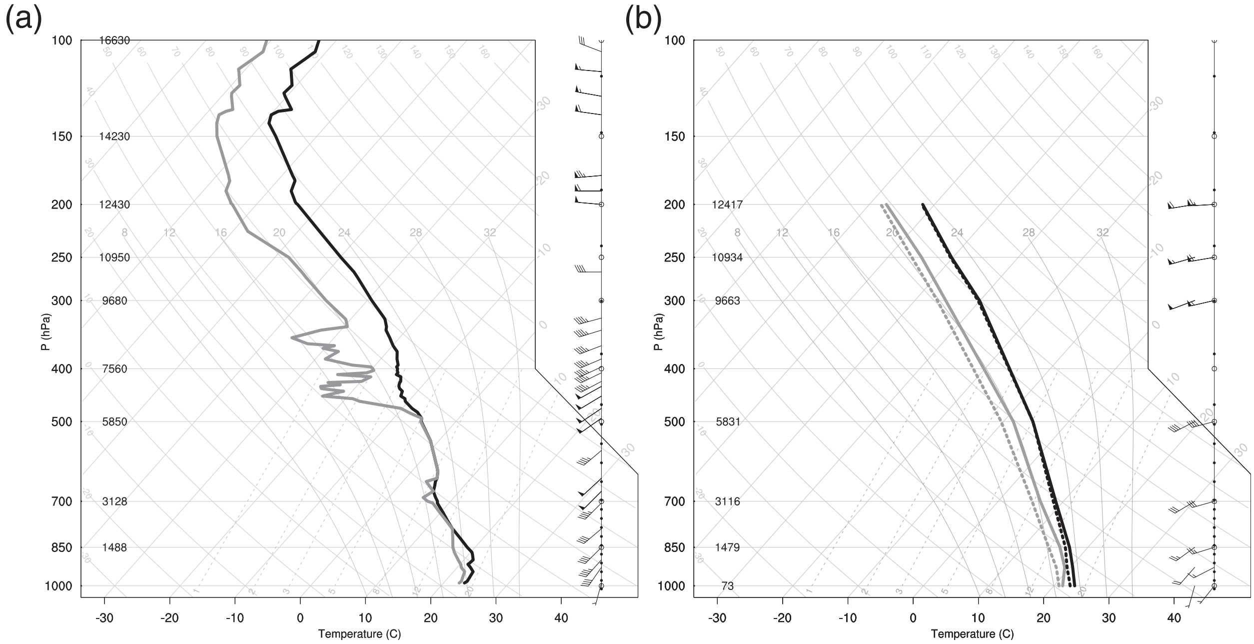

FIG. 15. (a) Skew T– log$p$ diagram from Lincoln, IL (ILX), at 1200 UTC 13 Sep 2008. (b) As in (a), but for the recurving ensemble (solid) and the nonrecurving ensemble (dashed), averaged over the four grid points nearest ILX. The location of ILX is shown in Fig. 14c. The wind profile on the left in (b) corresponds to the recurving ensemble, the one on the right to the nonrecurving ensemble. Data in (b) are only plotted at 1000, 925, 850, 700, 500, 300, 250, and 200 hPa, as these are the only vertical levels available in the TIGGE archive.

Differences in the thermodynamic profile between the recurving and nonrecurving ensembles were small in comparison to the Erin case, but were apparent nonetheless. At Lincoln, Illinois (ILX), at 1200 UTC 13 September, the atmosphere was very moist, with conditions either saturated or nearly so from the surface through 500 hPa (Fig. 15a). Both the recurving and nonrecurving ensemble mean profiles are also moist, though neither is saturated (Fig. 15b). The recurving ensemble mean sounding is slightly more moist than the nonrecurving ensemble mean (Fig. 15b), reflecting the influence of the poleward moisture transport ahead of Ike. It is also slightly warmer, and has a wind profile with stronger veering in low levels, indicative of stronger warm advection. The differences in warm advection are illustrated in Fig. 16a,c, where the southerly winds at 850 hPa are stronger across Missouri and Illinois and have a greater cross-frontal component in the recurving ensemble mean than in the nonrecurving ensemble mean. This was associated with stronger average frontogenesis (cf. Figs. 16a,c) and more members with strong frontogenesis (cf. Figs. 16b,d) in the recurving composite, in addition to the changes in the location and orientation of the baroclinic zone mentioned above. The more-amplified 500-hPa trough in the western United States in the recurving composite (Fig. 11) may have also contributed to the stronger warm-advection pattern, regardless of the location of Ike. The variability of TCW within the nonrecurving ensemble is much greater than that in the recurving ensemble (Fig. 17), with all but three members (93%) of the recurving ensemble having TCW greater than 50 mm at ILX, but only 74% of the members in the nonrecurving ensemble having greater than 50 mm of TCW. Overall, these results suggest that the recurvature of Ike, and the large-scale flow that Ike was embedded in, was associated with a small enhancement in warm advection and moisture transport across the central United States.

The rainfall differences along the track of TC Ike itself are straightforward, as the recurving ensemble shows a swath of high probabilities of 50 mm through eastern Texas and western Louisiana, which is in close agreement with observations (cf. Figs. 14a,b). In the nonrecurving ensemble, on the other hand, there are high probabilities of heavy rainfall through central Texas and very low probabilities near the Texas–Louisiana border. But as in the Erin case, diagnosis of the effect of the TC-related moisture transport on the precipitation forecasts far from the TC is complicated. Because of the other moisture sources and the lifting ahead of the eastward-moving trough and along its associated baroclinic zone, both ensembles showed greater than 30% probabilities of 50 mm of rainfall in a west–east corridor across the central United States (Figs. 14b,c). The recurving ensemble

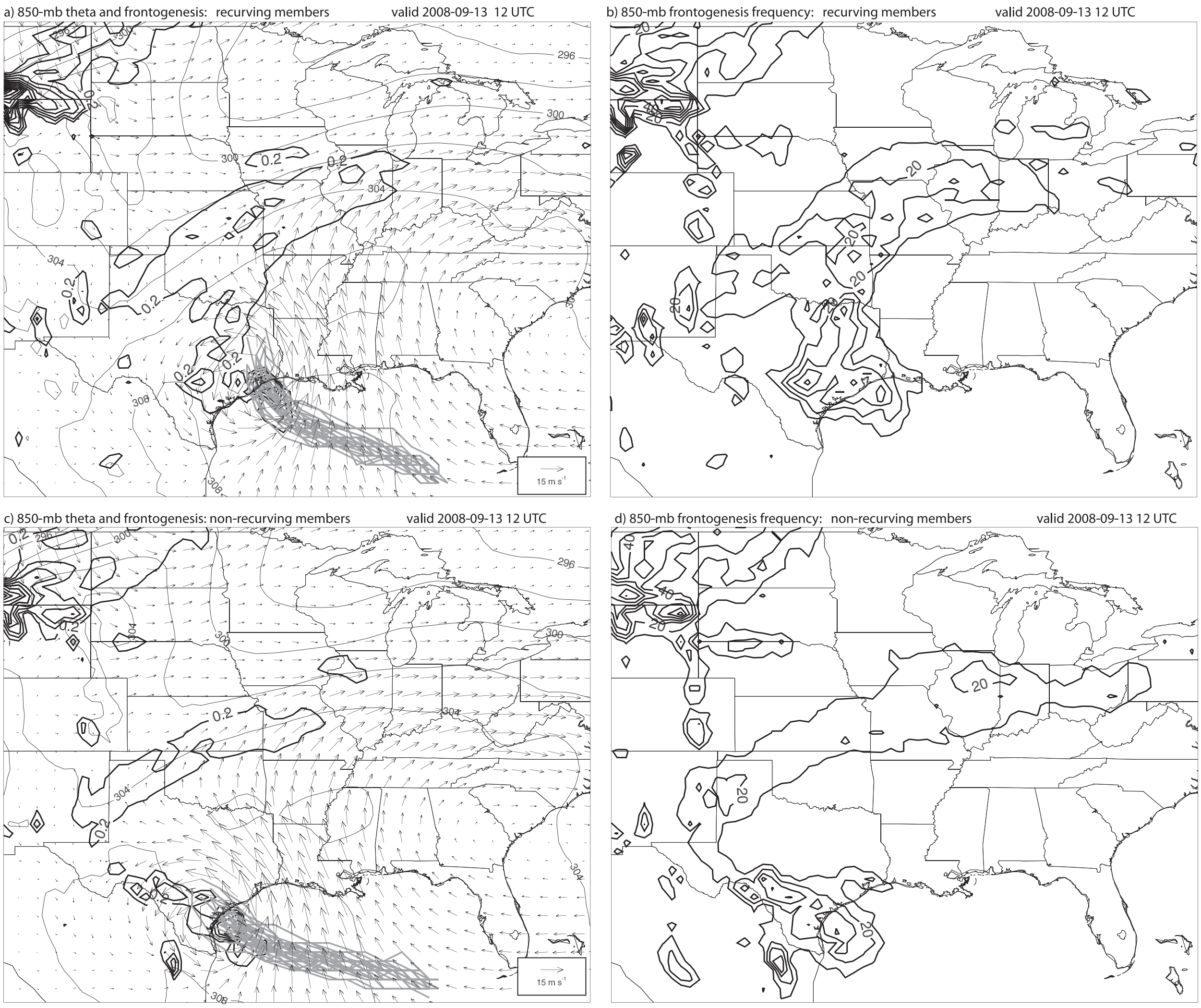

FIG. 16. As in Fig. 10, but for the Ike case at 1200 UTC 13 Sep 2008. For this case, the calculations of the average frontogenesis and the percentage of members exceeding the threshold were weighted to account for the relatively coarse native resolution of the NCEP ensemble, which showed consistently lower values of frontogenesis than the ECMWF ensemble. (b),(d) The threshold for "strong" frontogenesis in NCEP members was 0.2 K (100 km 3 h)$^{-1}$, whereas it remained at 0.75 K (100 km 3 h)$^{-1}$ for the ECMWF members. (a),(c) A similar weighting was applied when calculating the average. The tracks of the Ike vortex through 1200 UTC 13 Sep 2008 in each set of members are shown in gray in (a),(c).

better reflected the location of the heavy-rainfall axis, however, with its highest probabilities in the PRE region extending from central Missouri into north-central Illinois (Fig. 14b), which was similar in location to where the axis of heaviest rain actually occurred (Fig. 1). In the nonrecurving ensemble, the axis of highest probabilities was located farther south (Fig. 14c), and the probabilities of 50 mm of rain were lower than those in the recurving ensemble. In total, it appears that a more amplified large-scale trough–ridge pattern was favorable for the landfall and recurvature of Ike along the east Texas coast, and was also slightly more favorable for the poleward transport of moisture ahead of Ike and an associated PRE along a southwest–northeast axis in the central United States. Under the scenario where the synoptic-scale pattern was less amplified and Ike remained farther south and west, conditions were still favorable for heavy rainfall in the central United States, but a PRE of the magnitude that was observed was less likely.

5. Conclusions

This study used differences in tropical cyclone track forecasts to examine and quantify the transport of moisture ahead of recurving TCs and their effects on precipitation

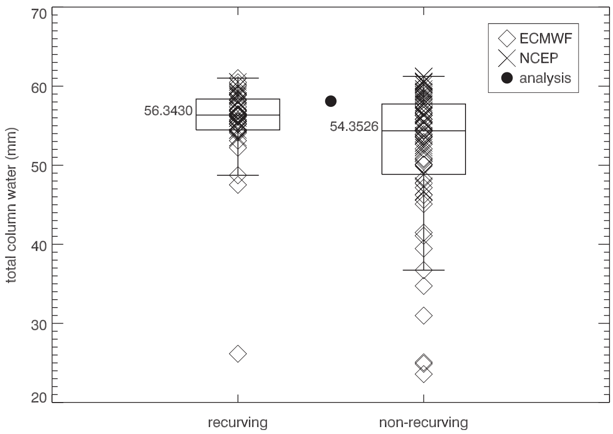

FIG. 17. Box-and-whisker diagrams of the recurving and nonrecurving ensembles for TCW averaged over the four grid points nearest ILX at 1200 UTC 13 Sep 2008. The values for individual ensemble members are shown using diamonds for ECMWF members and crisscrosses for NCEP members. The analyzed value is shown with a filled circle. The median values are shown to the left of each box-and-whisker diagram. The boxes encompass the interquartile range (25th–75th percentile), with the whiskers representing either the minimum and maximum value, or 1.5 times the interquartile range if values exist outside that range.

forecasts. Ensemble forecasts from multiple operational forecasting centers and multiple initialization times were analyzed for the predecessor rain events ahead of TCs Erin (2007) and Ike (2008). These forecasts were categorized into the members where the TC recurved in a similar location and at similar time as what was observed, and the members where the TC took a substantially different track. The differences between these ensemble subsets are then used to isolate the effects of the recurving TC from what might have happened had the TC not recurved.

In the Erin PRE, the poleward moisture transport resulted in increased water vapor at both low levels and upper levels, with a column-integrated increase of nearly 20 mm far ahead of the Erin vortex. In the Ike PRE, the effects of the TC-related moisture transport were not as obvious, as other sources of moisture were also responsible for the high values of TCW over the central United States. Nonetheless, the results demonstrated a general increase in moisture ahead of Ike as it recurved.

However, the ultimate influence of the moisture transport on precipitation is much less clear in these ensemble forecasts. In the Erin PRE, the distributions of accumulated precipitation in the Midwest among the recurving and nonrecurving ensembles are very similar, despite very different magnitudes of moisture transport between the two ensembles. In the Ike PRE, the effects of TC-related moisture transport and of a slightly different configuration of the large-scale flow pattern led to higher probabilities of heavy rain in the ensemble with a recurving Ike. However, the differences in probabilities between the recurving and nonrecurving ensembles were modest.

These results highlight some of the important challenges associated with predicting PRE rainfall at both the medium range and short range. Forecasts of TC tracks continue to become more accurate as observations and models improve, and this study shows that if the track is known, the moisture transport ahead of it may be fairly predictable. However, just because deep tropical moisture is transported into higher latitudes does not necessarily mean that more rain will fall. Although the increase in moisture makes the environment more favorable for heavy precipitation, it is only one of the necessary ingredients (Doswell et al. 1996). The timing, location, and magnitude of ascent associated with synoptic-scale features such as baroclinic zones and upper-level shortwaves are just as important in determining when and where heavy rain will occur. Thus, even with an accurate forecast of a TC's track after landfall and the associated enhancement of poleward moisture transport that this study has quantified, predicting whether an extreme-rain-producing PRE will occur will remain a challenging task. As further research is done for additional PREs, and the performance of numerical prediction systems in these events are better understood, perhaps this challenge will become slightly less daunting.

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