Global Ensemble Forecast Tracks for Tropical Storm Debby

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ABSTRACT

Operational-model track forecasts for Tropical Storm Debby (June 2012) diverged as much as 180°, making the National Hurricane Center forecast particularly challenging. Forecast tracks from the members of the National Centers for Environmental Prediction Global Ensemble Forecast System (GEFS) were similarly divergent; some forecast Debby to turn westward, some forecast Debby to go northward, and others forecast Debby to go eastward. Part of the divergence in the operational models can be from differences in model code, but the divergence in the GEFS is due only to differences in initial conditions. To understand the meteorological reasons for this model divergence, GEFS forecasts for Debby were examined in detail. Debby formed in the south-central Gulf of Mexico and then became a tropical storm by 1200 UTC 23 June 2012. Careful examination of the GEFS tracks showed that those storms turning east were stronger and deeper than those turning west. The storm strength was measured by the mean sea level pressure at the center of the storms and the maximum 10-m wind speed. The correlation coefficients between these two quantities and the longitude 12 and 24 h later were between 0.60 and 0.90, for all GEFS model runs initialized between 0000 UTC 24 June and 1200 UTC 26 June 2012. Further investigation showed that the initial midlevel moisture (specific humidity at 850 and 700 hPa) determined the subsequent strength and depth of the member storms. This variation in depth changed the effective layer for steering currents, which determined the direction to which the storms moved.

1. Introduction

Tropical Storm Debby formed in the south-central Gulf of Mexico in June 2012 as a weak surface low pressure area merged with a tropical wave (Kimberlain 2013). The resulting low pressure trough strengthened into a tropical storm by 1200 UTC 23 June 2012. Debby drifted slowly northward for the next 24 h and then slowly northeastward for the following 24 h, before moving more quickly off to the east after 1200 UTC 25 June. Debby made landfall in Florida at 2100 UTC 26 June 2012.

Operational model forecasts for the movement of Debby from 1200 UTC 23 June through 0000 UTC 25 June were not in agreement about whether Debby would turn west and head for the Texas Gulf Coast, would turn east and head for northern Florida, or would just drift slowly north. Discussions with National Hurricane Center (NHC) forecasters indicated that this model disagreement made the forecast difficult. The forecast tracks from a selection of operational model forecasts initialized at 0000 UTC 24 June 2012 appear in Fig. 1, showing an unusually large disparity among the various models. The official NHC forecast at this time, shown in Fig. 1 as the line with filled diamonds, took a westerly track. Instead, Debby turned to the east, resulting in forecast errors that were as large as 2 times the average over the last five years. Official forecasts made at 0600, 1200, and 1800 UTC 24 June and 0000 UTC 25 June all showed similar biases.

This paper examines the forecasts for Debby by using the National Centers for Environmental Prediction Global Ensemble Forecast System (GEFS) forecasts for this event. The GEFS, run once every 6 h, is an ensemble of 21 members in which each member is a coarser-resolution version of the operational Global Forecast System (GFS). One member (the control run) is initialized with an unperturbed set of initial conditions, and the other 20 members have initial conditions that are slightly perturbed. At the time of writing, the details of this procedure could be found online (http://www.emc.ncep.noaa.gov/GEFS/php). The GEFS was upgraded in February 2012 and now runs at spectral truncation T254,
equivalent to approximately 55-km grid spacing. The GEFS forecasts are examined here for two reasons. First, the member forecast tracks show a pattern that is similar to that of the larger set of operational forecast model tracks, making them a potential proxy for understanding the reasons for the large disparity in the forecasts. Using a single model for this analysis removes the influences of differences in the models themselves, which can affect the forecast tracks. Second, given the recent model improvements, it is useful to examine the GEFS forecast tracks to look for new ways in which they can be used operationally.

2. Background

A tropical storm moves through the atmosphere as a rotating vortex, interacting with the surrounding environmental flow. Early research by George and Gray (1976) and Brand et al. (1981) compared the tracks of tropical cyclones with the wind field surrounding them by compositing soundings and tracks in the Pacific Ocean. Fiorino and Elsberry (1989), working with an ideal tropical cyclone, showed that advection of Earth’s vorticity creates an asymmetric component of the flow around the cyclone, and this flow controls the net advection of the vortex. They found that the tropical cyclone tended to move more to the west as the tangential flow 300km from the vortex center increased. Franklin et al. (1996) used detailed dropwindsondes, aircraft observations, satellite data, and available conventional observations to create detailed three-dimensional datasets for 16 storms that occurred in the Atlantic Ocean basin between 1982 and 1992. Their analysis showed that the storm motion was most closely correlated with the mean flow between the surface and 100 hPa within 3° of latitude of the storm center. This was the closest to the center that their data could reliably resolve the flow, and it updated the concept of a steering current as a deep-layer environmental flow close to the tropical-cyclone center.

Many factors, including initial conditions, boundary conditions (for regional models), model resolution, model errors, and choice of model parameterizations, can affect the forecast track from a hurricane model. Much research has focused on data assimilation to determine how to best use all available data, which can include special observations from aircraft platforms. Xiao et al. (2009) discussed the assimilation of airborne Doppler radar data into the Advanced Research Hurricane version of the Weather Research and Forecasting Model (known as AHW). The intent of their research was to have an impact on the
intensity forecasts, but the track improved slightly as well, reflecting the understanding that if the environmental conditions near the vortex are more accurate then the forecast track will improve. In particular, as shown by Pu et al. (2009) for Hurricane Dennis (2005), the track responds to the assimilation of wind data whereas the intensity appears to be sensitive to the assimilation of radar reflectivity. Brennan and Majumdar (2011) showed that small errors in the initial upper-level flow had a large influence on the track of Hurricane Ike in 2008. The method of initialization can affect the tracks as well. Hamill et al. (2011) showed that using an ensemble Kalman filter with the updated GFS model code reduced track errors for both the 2009 and 2010 hurricane seasons.

The method of handling the microphysics in a model can affect the intensity and depth of the circulation in a tropical cyclone and thus change the track, as shown by Fovell and Su (2007). Different ways of computing the radiation from cloud tops can also affect the cyclone intensity and the resulting track, as discussed by Fovell et al. (2010). Xue et al. (2013) showed that, for weaker tropical cyclones, increased model resolution had a larger impact on forecast track errors than did improved initial conditions.

Zhang and Krishnamurti (1997) and Krishnamurti et al. (1997) showed how an ensemble of models could be used to improve track forecasts for tropical cyclones. Goerss (2000) showed how a multimodel ensemble mean could improve track forecast errors by 16%–23% for a single season of Atlantic tropical cyclones. Goerss (2007) went on to develop predicted consensus errors, using multiple linear regression from previous seasons. The predicted error (Goerss predicted consensus error, or GPCE), shown as a circle around the consensus forecast position, quantifies the likely uncertainty in the current forecast position. Hansen et al. (2011) modified the GPCE circles to allow cross-track and along-track errors to be analyzed separately, thus producing GPCE ellipses. The NHC uses multimodel ensembles as well as single-model ensembles for operational forecasting of tropical storm tracks, including the GEFS and the European Centre for Medium-Range Weather Forecasts (ECMWF) 51-member ensemble. Given the previous research results that show how much the environment around a tropical cyclone affects the track, and given how tropical cyclones, forming over open water, are often in a data-sparse location, it is reasonable to use ensembles to provide insight into the range of possible hurricane tracks from a variety of possible initial conditions.

The “ensemble transform with rescaling” method for producing the range of initial conditions in the GEFS is discussed by Wei et al. (2008). Once the NHC identifies a system as a tropical storm, a message [Tropical Storm Vitals; Trahan and Sparling (2012)] that contains their best estimate of the location and intensity of the storm is sent to the National Centers for Environmental Prediction (NCEP). At NCEP (Liu et al. 2006; R. Wobus 2014, personal communication), this information is incorporated into the initialization process for the GFS. For the GEFS, the higher-resolution GFS initial analysis is interpolated to the lower resolution of the GEFS, producing the control analysis. To allow some variation in the initial vortex, the 6-h GEFS forecasts from the previous model cycle are separated into a background field and a storm file. Perturbations are created from the member 6-h forecast background fields, and these perturbations are added to the control analysis. This allows perturbations from the previous cycle to be carried into the current cycle. Last, the intensity of the storms in each member is modified using the perturbation storm files that were previously separated. This forces the initial location of the storm to be the same in each ensemble member, but with a spread in the initial intensities. The present investigation of the behavior of the GEFS for Tropical Storm Debby includes the examination of the initial conditions, both storm and background fields, and the influence of the steering currents.

The rest of this paper is as follows. Section 3 provides details about the data that are used in this work. Section 4 describes the forecast tracks from the GEFS for 14 forecast initialization times, at 6-h intervals, beginning 1200 UTC 23 June. Section 5 describes the upper-level flow for each of these forecasts, and section 6 examines the vertical structure of the forecast cyclones. Section 7 analyzes the relationships between atmospheric variables and storm development in the GEFS members. Section 8 summarizes the findings and relates them to operational forecasting.

3. Data sources

The NHC best-track hurricane database (HURDAT2; Landsea et al. 2013) provided the actual track of Tropical Storm Debby. This dataset is tabulated in Kimberlain (2013) and is available online in digital form from the NHC (ftp://ftp.nhc.noaa.gov/atcf/archive/2012/). The GEFS member forecasts were obtained from the same online location. Both datasets provided initial and forecast latitude, longitude, mean sea level pressure (MSLP) of the circulation center, and highest 1-min-sustained wind speed (MaxWind) at a height of 10 m. Three-dimensional fields of geopotential height, temperature, humidity, and wind were obtained online from the ECMWF, under the auspices of The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble...
4. GEFS forecast tracks

The GEFS member forecast tracks, beginning with the 1200 UTC 23 June 2012 initialization time and continuing through the 1200 UTC 26 June 2012 initialization, showed three distinct patterns. The first available time in HURDAT2 for Debby was 1200 UTC 23 June 2012, and 1200 UTC 26 June 2012 was 24 h before the last time in HURDAT2. As Debby moved north toward land, the forecast tracks turned west, turned east, or drifted slowly north. The best-track data ended at 1200 UTC 27 June 2012. The due-north tracks (termed neutral here) were considered to be those tracks whose 1200 UTC 27 June 2012 forecast locations were no more than $2^\circ$ of longitude different from their initial positions. Two degrees of longitude was chosen to separate the tracks that had a definite direction from those in which the forecast storm appeared to drift. Using this criterion for categorizing the tracks, the results are shown in Table 1. The total number of tracks does not add up to 21 in Table 1 because some of the ensemble members failed to produce a storm that could be tracked and the control run was not included. In general, there were fewer westward tracks than neutral or eastward tracks, with two exceptions: 0600 UTC 24 June and 0000 UTC 25 June 2012. There was a clear tendency for the first five initializations to produce eastward tracks, and seven of the rest of the initializations produced more-neutral tracks. The mean maximum wind speeds and their standard deviation are shown for each category for each initialization time. Even though the maximum intensities, as measured by the maximum wind speed, can occur at any forecast lead time for each member, the means and standard deviations are all largest for the eastward-moving members and smallest for the westward-moving members.

Figure 2 shows plots of all of the ensemble-member forecast tracks for the 0600 UTC 24 June 2012 initialization time, grouped by track type. The differences between the groups are clearly shown, and these differences are typical of what is seen for most of the forecast initialization times. When all of the ensemble forecast tracks were plotted on one diagram, an apparent relationship between the MaxWind and the direction of the forecast track appeared. To verify this relationship, statistics were computed that relate the forecast track (west) longitude to both the MaxWind and the MSLP at the circulation center. While the MaxWind depends on the pressure gradient rather than the MSLP, one could expect that, for similar-sized storms with similar history, pressure gradients will be similar among the ensemble members. This would result in correlation coefficients between longitude and MSLP being close in magnitude to those between longitude and MaxWind, but with the opposite sign.

Beginning with forecasts initialized at 0000 UTC 24 June 2012, and continuing through forecasts initialized at 1200 UTC 26 June 2012, the correlation coefficients between the MaxWind and longitude range from $-0.68$ to $-0.97$ with only a very few exceptions. Similarly, the correlation coefficients between the MSLP and longitude range from 0.62 to 0.97, with the same few exceptions. Thus, the forecast storms that are located to the east had lower MSLPs and higher MaxWinds than did those that were located to the west. Table 2 shows some of these correlation coefficients. The full sample of GEFS forecasts for Debby has the same characteristics. The blanks in the table are for forecast times after Debby became extratropical; HURDAT2 only contains locations for tropical systems.

The relationship between storm strength and west longitude is very strong. For the 20-member ensembles, these correlations, with the exception of the 12-h forecasts from 1200 UTC 25 June 2012, are all significant at the 99.9% level. Correlation coefficients were also computed using the location 12 h later than the time for the MSLP or MaxWind. That is, the MSLP or MaxWind at a given time was compared with the location of that storm 12 h later. The correlation coefficients, shown in Table 3, are almost identical to those shown in Table 2. This result suggests that a strong storm will not only be found toward the east but that stronger storms will tend
to move to the east. This anticipates that there is directional shear in the vertical direction, thus allowing deeper storms to be influenced by flow over a deeper layer. The next section shows that this is the case for Debby. In addition to these correlations, track errors were compared with intensity errors for the GEFS member forecasts. These correlation coefficients appear in Table 6 (described in more detail below).

5. Upper-level flow patterns

With sheared flow, easterly at low levels and westerly at upper levels, stronger storms could track to the east whereas weaker storms would be unaffected by the upper-level eastward flow. Conversely, the beta effect (Franklin et al. 1996) will cause tropical cyclones to move to the northwest, and this effect will be more pronounced for more-intense storms. Steering flows, following the work of Franklin et al. (1996), were computed for each ensemble-forecast storm for all initialization times by using the three-dimensional TIGGE data. The location of the lowest 1000-hPa height was found for each storm center, and the mean horizontal $u$ and $v$ components of the wind at each level, at a radius of 3° of latitude distance from the center, were computed. Four different steering flows were then constructed. The shallowest used only data from 1000 to 700 hPa. A medium-deep steering flow used data from 1000 to 500 hPa. A deeper steering flow used data from 1000 to 300 hPa, and the deepest steering flow was found by using data from 1000 to 250 hPa. Thus, the relative influence of the uppermost flow was increased from the shallow flows to the deep-layer flows. For the GEFS forecasts, the shallow and medium-deep steering flows varied from westerly to easterly. The deeper-layer and deepest-layer steering flows for most of the storms at all forecast times were westerly. At the time of the initial turn to the west, the deeper and deepest steering flows were all westerly. Thus, both the storms that took an eastward track and those that went westward had deep-layer steering flows toward the east. Figure 3 (top panel) shows an example from ensemble number 19, initialized at 0600 UTC 24 Jun 2012, at the initial time, and Fig. 3 (bottom panel) shows the steering currents after 24 h of simulation. The initial steering flows are all toward the north, with the deeper ones being less to the west. After 24 h, the shallow and medium-deep-layer steering flows have easterly components, whereas the deeper flows are westerly. The cyclone center moved east. Figure 4 shows the steering currents for ensemble number 20 from the same model run, again at the initial time and after 24 h of simulation. Notice that the initial steering currents are essentially identical to those in Fig. 3 (top panel) but that...
after 24 h the storm center has drifted slightly west already. Despite the presence of the westerly deepest steering flow, the storm continues to the west, consistent with the shallow and medium-deep steering flows. Similar behavior was observed in all of the GEFS ensemble runs for Debby.

6. Cross sections

Zonal cross sections were plotted for each of the ensemble forecasts, at all initialization times, to examine the vertical storm structures. The results suggest that the westward-moving ensemble storms had shallower circulations. The cross sections were drawn at the location of the minimum 1000-hPa height and used all of the vertical levels available. The cross sections extended 3/8 of longitude to the west and east of the 1000-hPa minimum location. The vertical size of each storm’s circulation was estimated by looking at the relative vorticity patterns and, in particular, at the level of the 0 and 10 × 10⁻⁵ s⁻¹ contours. The initial vorticity patterns were almost identical for each ensemble member. Figure 5 shows two examples of cross sections for mean relative vorticity (specifically, the vertical component of the relative vorticity). The top panel of Fig. 5 is for the GEFS model run initialized at 0600 UTC 24 June, and the bottom panel of Fig. 5 is for the GEFS model run initialized at 0000 UTC 25 June, both at the time of initialization. These model runs were chosen because both contained more than five eastward- and five westward-tracking members. Figure 5 shows the initial mean relative vorticity for the ensemble members that had storms that tracked to the east, and the difference in initial mean relative vorticity between the eastward-tracking members and the westward-tracking members. The positive contours indicate that the eastward-tracking members had larger relative vorticities than did the westward-tracking members. These figures show that the initial flow fields for the cyclone centers and their near environments were nearly identical. The other model initialization times are similar with nearly identical initial flow fields.

Figure 6 shows examples of cross sections for ensemble numbers 2 and 3 after 12 h of simulation. For the eastward-moving storm (Fig. 6, top panel), the 0 contour is between 250 and 200 hPa and the 10 × 10⁻⁵ s⁻¹ contour is almost entirely above 400 hPa. For the westward-moving storm (Fig. 6, bottom panel), the 0 contour runs along the 300-hPa level and the 10 × 10⁻⁵ s⁻¹ contour is entirely below 400 hPa. These patterns are typical for what is seen in all of the ensemble members.

7. Analysis

All of the data discussed here point to one conclusion. The ensemble-member forecast cyclones that headed west were weaker, shallower storms than those that moved eastward. The correlation coefficients show that this relationship held for all three patterns: eastward, neutral, and westward. The model initializations of 0000–1200 UTC 26 June 2012 show very high correlations between west longitude and storm strength, even though there are only neutral and eastward-moving storms.

There are a number of possible reasons for the storm strengths and vertical depths to be so variable. Tropical storms depend on the presence of strong surface latent heat fluxes, driven in part by high sea surface temperatures (SSTs; Dare and McBride 2011) and high ocean thermal heat content in the upper layer of the ocean. Halliwell et al.
used a coupled atmospheric–oceanic model to demonstrate the relationship between ocean heat content and intensity for an idealized tropical cyclone. For the GEFS, the only input from the ocean heat content to the atmosphere comes through the initial SSTs, since the GEFS is not a coupled model. Given the limitations of the GEFS code, ocean thermal heat content will be determined by SST. Since SSTs are not perturbed in the ensemble members, variations in SST cannot explain the variations in vortex development in the ensemble members.

Vertical wind shear can also have an effect on the development of tropical storms. Although tropical cyclones can form and thrive in environments characterized by a range of vertical wind shear magnitudes, shear magnitudes of less than 10 m s$^{-1}$ are usually considered not to be detrimental to storm development (Dunkerton et al. 2009). If certain ensemble members had more environmental vertical wind shear, then the storms in those members would again tend to be weaker and smaller in depth. Also, the presence or absence of moist air at midlevels in the atmosphere can affect the development of a tropical storm. If the air at 850 or 700 hPa is dry, it will be difficult for a tropical storm to continue to develop.

The mean vertical wind shear between 300 and 850 hPa was computed for each of the ensemble members within the same initialization-date range. The 300-hPa level was chosen as a representative upper level for the ensemble storms, since, as has already been shown, those storms that developed strongly had circulations that reached this level whereas those that did not had circulations that remained below 300 hPa. The mean shear magnitudes for all GEFS runs ranged from 1.5 to as much as 6.2 m s$^{-1}$ but never reached values that might be considered to be large enough to disrupt the tropical-cyclone circulation while the storms were in the Gulf of Mexico. Correlations between the mean vertical wind shear and the MSLP, surface maximum wind speed, and longitude were computed for each ensemble member. The correlations were calculated by comparing the initial shear values with the three variables at the initial time, the values after 12 h, and the values after 24 h (Table 4). Correlations were also computed that compared the mean vertical wind shear after 12 h with the MSLP, surface wind speed, and longitude at the same time (12 h of simulation), 12 h later, and 24 h later (not shown). The correlation coefficients were inconsistent. For the initial conditions, the correlation coefficients were all smaller in magnitude than 0.5, and were often close to zero. Of the 12 GEFS model runs with complete data, five showed positive correlations between the magnitude of the vertical wind shear and the MaxWind, six were close to zero, and only one was negative. For the 12-h forecasts, six showed negative correlations between the magnitude of the vertical wind shear and the MaxWind, four runs showed positive correlations, and two were close to zero. The vertical wind shear was not an important factor in determining whether a given member storm would strengthen or weaken.

Correlation coefficients were computed between thermodynamic variables and the longitude, MSLP, and MaxWind for each member storm. The thermodynamic variables used were the temperature, specific humidity, and relative humidity at 850 and 700 hPa. These levels were chosen since the variations between ensemble members were the largest at these levels. The initial values of the variables were correlated with the position, MSLP, and MaxWind at the initial time, after 12 h of simulation, and after 24 h of simulation. For the two GEFS model runs initialized on 23 June 2012, there were no significant correlations between any of the thermodynamic variables and the longitude, MSLP, or MaxWind.

<table>
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<th>1200 UTC 24 Jun</th>
<th>0000 UTC 25 Jun</th>
<th>1200 UTC 25 Jun</th>
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FIG. 3. GEFS member 19, a westward-moving member, initialized at 0600 UTC 24 Jun 2012, at the (top) initial time and (bottom) the 24-h forecast time. The gray plus sign is the location of the lowest 1000-hPa height. Arrows emanating from that location are steering flows computed using four different layers: black is 1000–700 hPa, dark gray adds 500 hPa, medium gray adds 300 hPa, and light gray adds 250 hPa. The arrow in the bottom margin shows the size of a 2 m s⁻¹ arrow. Gray contours are 1000-hPa heights (m).
These are the same model runs that did not show strong correlations between longitude and storm strength. Beginning with the model runs initialized on 24 June 2012, and continuing through the model runs initialized at 1200 UTC 26 June 2012, the correlation coefficients between the initial specific humidity at 700 hPa and the MaxWind and MSLP 12 and 24 h later were consistently large in magnitude. Some model runs had significant

FIG. 4. As in Fig. 3, but for GEFS member 20.
FIG. 5. Mean relative vorticity (gray shades; color key $\times 10^5 \text{s}^{-1}$) at model initialization time of (top) 0600 UTC 24 Jun and (bottom) 0000 UTC 25 Jun 2012 for GEFS model members with eastward-tracking storms, and the difference between mean vorticity (black contours at $0.5 \times 10^5 \text{s}^{-1}$ intervals) for members with eastward-tracking storms and members with westward-tracking storms. The cross section was taken along the latitude of the minimum 1000-hPa location, and the vertical axis is in hectopascals.
correlations between the 850-hPa specific humidity, and the relative humidity at both levels, but these were not consistent throughout the model runs. Since the initialization process for the GEFS allows the temperature and specific humidity perturbations to be independent, having high correlations between specific humidity and storm strength/longitude will not guarantee that similarly high correlations between relative humidity and storm strength/longitude will also be found. The correlation coefficients for the temperatures at the two levels showed no consistent pattern but the range of variation in temperatures between ensemble members was very small. The range of variation in temperature at the two levels among the 20 ensemble members was at most 1 K, with a standard deviation as large as 0.3 K. The range of specific humidity at 700 hPa was as large as $1 \times 10^{-3}$ g g$^{-1}$.
and the standard deviation was as large as 0.4 × 10⁻³ g g⁻¹, showing much more variation relative to the mean values than did the variation in temperatures. Table 5 shows the correlation coefficients between 700-hPa specific humidity and MaxWind. The two variables are not correlated initially, but the correlation coefficients become significantly large for 12 and 24 h into the model run. Storms with higher 700-hPa specific humidity become storms with stronger winds 12 and 24 h later. Figure 7 shows two examples of cross sections for mean specific humidity: one for the GEFS model run initialized at 0600 UTC 24 June and one for the GEFS model run initialized at 0000 UTC 25 June, both at the time of initialization. These model runs are shown because both contained more than five eastward- and five westward-tracking members. Figure 7 shows the mean specific humidity for the ensemble members that had storms that tracked to the east, and the difference in mean specific humidity between the eastward-tracking members and the westward-tracking members. The positive contours indicate that the eastward-tracking members had larger specific humidities than did the westward-tracking members. Unlike the difference fields for vorticity, these fields show clear differences in mean specific humidity between the eastward-tracking members and the westward-tracking members. The positive contours indicate that the eastward-tracking members had larger specific humidities than did the westward-tracking members. Unlike the difference fields for vorticity, these fields show clear differences in mean specific humidity at initialization of the model runs, with the largest difference being between 700 and 800 hPa. Table 4 shows the correlation coefficients between the magnitude of the vertical wind shear from an annulus between 200 and 800 km from the lowest 1000-hPa height and the MaxWind. Table 4 shows that there is no clear correlation. As mentioned already, the shear magnitudes were all relatively small, and therefore the lack of correlation is not surprising.

Table 4. Correlation coefficients between initial environmental wind shear magnitude and MaxWind 0, 12, and 24 h later in the GEFS forecast. Shear is calculated as the vector difference between the 200-hPa average wind and 850-hPa average wind. Averages are calculated as the mean in the annulus between 200 and 800 km from the lowest 1000-hPa height.

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<td>−0.07</td>
<td>−0.28</td>
</tr>
</tbody>
</table>

Table 6 contains the correlation coefficients between track errors and the magnitude of the wind speed errors. These coefficients show that the GEFS member storms with the smaller intensity errors were also those storms that had the smaller track errors. The coefficients are mostly small for the 1200 UTC 23 June forecasts, when there was not a strong correlation between the GEFS member storm intensities and the west longitude. Beginning with 0000 UTC 24 June and continuing through the last forecast shown (1200 UTC 26 June), there are significant positive correlations between the magnitude of the wind speed errors and the track errors. Smaller intensity errors are found with smaller track errors. Some of the correlations for the 12-h forecasts do not show this pattern, since it usually took time for the GEFS member storms to develop and differentiate themselves from one another. The GEFS forecast that was initialized at 1200 UTC 24 June is also unusual, since the correlation coefficients for the first 36 h are all negative. This model run was also one of the few with no member storms tracking to the west. Examination of the individual tracks for this model run shows that the first 36 h of the forecast were characterized by storms drifting slowly north or northeast, which delayed the period during which these coefficients would become strongly positive.

8. Summary and future work

Operational model forecasts for the track of Tropical Storm Debby were divergent: some forecast Debby to turn to the west toward Texas while others forecast Debby to turn to the east toward Florida. This made the NHC’s task of making an official forecast for Debby
Fig. 7. Mean specific humidity (gray shades; g kg⁻¹) at model initialization time of (top) 0600 UTC 24 Jun and (bottom) 0000 UTC 25 Jun 2012 for GEFS members with eastward-tracking storms, and the difference between mean specific humidity (black contours at 1 g kg⁻¹ intervals) for members with eastward-tracking storms and members with westward-tracking storms. The cross section was taken along the latitude of the minimum 1000-hPa location, and the vertical axis is in hectopascals.
especially difficult. Additionally, ensemble-model track forecasts were also divergent. The research discussed here shows that the track direction for the GEFS member forecasts was highly correlated with the strength of the storm: the strongest storms turned to the east and the weakest storms turned to the west. This behavior in the GEFS has not been previously documented.

NHC forecasters are well aware that tropical-cyclone tracks can vary with the vortex intensity. Among the GEFS member forecasts for Debby, the stronger storms had circulations that reached deeper into the atmosphere and were steered by deeper-layer steering currents that took them to the east. The weaker storms, with shallower circulations, turned west with shallower-layer steering currents. Further investigation now identifies variations in the initial specific humidity at midlevels, especially near 700 hPa, as the cause of the differences in the strength of the ensemble member storms. Environmental vertical wind shear was not strong for any of the member forecasts and was not correlated with the subsequent storm strength. There were no variations in SST. The average initial specific humidity at 700 hPa near the circulation centers varied by as much as 10%.

Establishing that the mean GEFS track forecast errors are generally smaller when the tracks are strongly correlated with the member storm intensities would allow NHC forecasters to rely more on the ensemble forecast. More research will be needed to determine whether this relationship exists in other storms and under what conditions it can be relied on. In this case, the forecasters were faced with operational model forecast tracks varying by as much as 180°. Observations showed that Debby was strengthening as the storm slowly drifted northward. Using the knowledge that the GEFS track forecasts that showed strengthening were all forecasting a turn to the east would have provided them some confidence in choosing the eastward tracks for this tropical cyclone.

Of the six longest-lived tropical storms of 2012, five had periods during which the GEFS member tracks were highly correlated with storm strength. Research is ongoing to determine the cause of these correlations, and to determine whether the correlations could have been useful in forecasting the tracks of these storms. There is potential for the development of a new way to use the GEFS to forecast the tracks of tropical storms.

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