Prediction and uncertainty of Hurricane Sandy (2012) explored through a real-time cloud-permitting ensemble analysis and forecast system assimilating airborne Doppler radar observations

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Received 16 December 2013; accepted 23 December 2013.

[1] Utilizing the Pennsylvania State University (PSU) real-time convection-permitting hurricane analysis and forecasting system (WRF-EnKF) that assimilates airborne Doppler radar observations, the sensitivity and uncertainty of forecasts initialized several days prior to landfall of Hurricane Sandy (2012) are assessed. The performance of the track and intensity forecasts of both the deterministic and ensemble forecasts by the PSU WRF-EnKF system show significant skill and are comparable to or better than forecasts produced by operational dynamical models, even at lead times of 4–5 days prior to landfall. Many of the ensemble members correctly capture the interaction of Sandy with an approaching midlatitude trough, which precedes Sandy's forecasted landfall in the Mid-Atlantic region of the United States. However, the ensemble reveals considerable forecast uncertainties in the prediction of Sandy. For example, in the ensemble forecast initialized at 0000 UTC 26 October 2012, 10 of the 60 members do not predict a United States landfall. Using ensemble composite and sensitivity analyses, the essential dynamics and initial condition uncertainties that lead to forecast divergence among the members in tracks and precipitation are examined. It is observed that uncertainties in the environmental steering flow are the most impactful factor on the divergence of Sandy's track forecasts, and its subsequent interaction with the approaching midlatitude trough. Though the midlatitude system does not strongly influence the final position of Sandy, differences in the timing and location of its interactions with Sandy lead to considerable differences in rainfall forecasts, especially with respect to heavy precipitation over land.

Citation: Munsell, E. B., and F. Zhang (2014), Prediction and uncertainty of Hurricane Sandy (2012) explored through a real-time cloud-permitting ensemble analysis and forecast system assimilating airborne Doppler radar observations, *J. Adv. Model. Earth Syst.*, *6*, 10.1002/2013MS000297.

1. Introduction

[2] When Hurricane Sandy made landfall on the New Jersey coastline during the evening of 29 October 2012, the damage was extensive and very costly. The tropical cyclone (TC) impacted high-density areas throughout the Mid-Atlantic including New York City, which is a metropolitan area not accustomed to landfalling TCs and their impacts. Preliminary reports have estimated that Sandy caused approximately $50 billion dollars in damages in the United States, including 72 deaths [*Blake et al.*, 2013]. This ranks Sandy as the second-costliest (not adjusted for inflation) TC to impact the United States since 1900.

[3] The initial disturbance that became Hurricane Sandy moved off the African coast on 11 October 2012 [*Blake et al.*, 2013]. Environmental conditions were mostly unfavorable for development as the disturbance tracked westward across the tropical Atlantic. The wave entered and crossed the Caribbean Sea before turning toward the southwest on 21 October 2012 and into a more favorable environment with reduced westerly shear. This allowed the circulation to become more defined and by 1200 UTC 22 October 2012 a tropical depression had formed in the southwestern Caribbean Sea, approximately 550 km south of Kingston, Jamaica. Convection continued to increase near the center and Tropical Storm Sandy was designated 6 h later at 1800 UTC 22 October 2012. Sandy was upgraded to a hurricane at 1200 UTC 24 October 2012 before making its first landfall near the

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1942-2466/14/10.1002/2013MS000297

community of Bull Bay, Jamaica. Sandy continued to rapidly intensify and became a major hurricane with maximum sustained winds of 100 kt just prior to making its second landfall in Cuba around 0600 UTC 25 October 2012.

[4] Sandy passed over Cuba and into the Bahamas, where it encountered a region of increased southwesterly shear that weakened the storm back down to tropical storm strength. As Sandy began to turn toward the northeast due to interactions with an upper-level trough, the storm regained hurricane strength, increased in size and evolved in structure with the strongest winds now located in the western portion of the storm. By 28 October 2012, as Sandy passed to the east of the North Carolina coastline, the cyclone regained some tropical characteristics, including the appearance of a developing eye. The cyclone reached a secondary peak in intensity on 29 October 2012 due to baroclinic forcing supplied by the trough located over the United States and higher sea surface temperatures (SSTs) associated with the Gulf Stream. Also at this time, Sandy began to take a more northward heading due to an anomalous blocking pattern in the North Atlantic that prevented Sandy from heading out to sea. This unusual synoptic setup allowed for the core of Hurricane Sandy to evolve into a warm seclusion and the cyclonic potential vorticity developed over the Gulf Stream was able to be easily axisymmetrized into Sandy's closed circulation, further intensifying the storm [*Galarneau et al.*, 2013]. The aforementioned trough, now digging across the southeastern United States, accelerated Sandy to the northwest and toward colder waters and a cooler air mass located over the Mid-Atlantic region. This caused Sandy to quickly undergo and complete an extratropical transition prior to making landfall at 2330 UTC 29 October 2012 near Brigantine, New Jersey with maximum sustained winds of 70 kt and a minimum sea level pressure (SLP) of 945 hPa.

[5] Although the track and evolution of Sandy was somewhat uncommon, as Atlantic Basin TCs typically do not curve toward the northwest and into the Mid-Atlantic and New England regions of the United States, the performance of the track forecasts of the operational models was very good [*Blake et al.*, 2013; *Knabb*, 2013]. However, some models failed to forecast a Mid-Atlantic region landfall particularly at longer lead times. It is therefore worth investigating the sensitivity and uncertainty of the track forecasts associated with Sandy in an attempt to identify the fields that have the largest influence on determining the success of a forecast. This study utilizes a 60-member ensemble forecast from the PSU WRF-EnKF real-time system of Hurricane Sandy initialized at 0000 UTC 26 October 2012, approximately 4 days prior to landfall, to detect the differences among the ensemble that lead to the divergence in the track forecasts. The impacts of this track divergence are then evaluated through an analysis of the rainfall forecasts and the midlatitude trough interaction that Sandy undergoes just prior to landfall.

[6] Section 2 describes the model setup and data sources. Section 3 presents the composite and sensitivity analyses of Sandy's track and precipitation forecasts. Section 4 highlights the main conclusions of this study.

2. Methodology and Data

2.1. PSU WRF-EnKF Real-Time System

[7] The PSU WRF-EnKF real-time forecast system has been producing experimental forecasts for Atlantic basin hurricanes since the 2008 season. This system takes advantage of airborne Doppler observations that have been available for over 20 years [*Gamache et al.*, 1995] but have not been utilized in operational models due to the lack of resolution and efficient data assimilation methods. *Weng and Zhang* [2012] describes a super-observation procedure in which the airborne Doppler observations are thinned to a spatial resolution that is appropriate for both the assimilation and the forecasting system before being transmitted to the ground in real time to be assimilated into the model. This procedure is now operational for all P-3 and G-IV reconnaissance missions. Between 2008 and 2012, 102 airborne Doppler missions spanning 22 Atlantic tropical cyclones have been utilized to generate forecasts in this manner and more details about the overall performance of the system can be found in *Zhang and Weng* [2014].

[8] The deterministic and 60-member ensemble forecasts for Hurricane Sandy are generated using version 3.4.1 of the Advanced Research Weather and Research Forecasting (AHW-WRF) model [*Skamarock et al.*, 2008] in addition to an EnKF data assimilation algorithm. Three two-way nested domains are used at horizontal grid spacings of 27, 9, and 3 km, which contain areas of 10,200 $\times$ 6600 km (378 $\times$ 243 grid points), 2700 $\times$ 2700 km (303 $\times$ 303 grid points), and 900 $\times$ 900 km (303 $\times$ 303 grid points). The grid spacing of the innermost domain is an upgrade to the prototype system in *Weng and Zhang* [2012] and *Zhang et al.* [2011]. The outermost domain is fixed and contains the majority of the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, as well as most of North America. The inner two domains are not fixed and instead are "vortex-following," with the center of the domain always coinciding with the center of the tropical cyclone. All domains have 44 vertical levels with the top level at 10 hPa. The Grell-Devenyi cumulus parameterization scheme [*Grell and Devenyi*, 2002] is used in the outermost domain only. Additional parameterization schemes include the WRF single-moment six-class with graupel scheme [*Hong et al.*, 2004] for microphysics, the Yonsei State University (YSU) scheme [*Noh et al.*, 2003] for the planetary boundary layer, the Monin-Obukhov scheme for the surface layer, and the thermal diffusion scheme for the land-surface processes. The ensemble is initialized using the NOAA Global Forecast System (GFS) operational analysis from approximately 6–12 h prior to the expected collection of the Doppler observations and perturbations are derived from this analysis by using the background error covariance option of the WRF data assimilation system [*Barker et al.*, 2004]. Boundary conditions are taken to

be the GFS operational forecast that is closest to the time at which the airborne Doppler radar observations are acquired.

2.2. Operational Model Data

[9] Throughout this study, comparisons are made between the PSU WRF-EnKF ensemble and operational model data. This additional model data is obtained from the THORPEX Interactive Grand Global Ensemble [*Bougeault et al*., 2010] and includes forecasts and analyses of Sandy from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the GFS. Tracks of the tropical cyclone for the operational ensembles (51 members for the ECMWF and 21 members for the GFS) are calculated by obtaining the location of the minimum sea level pressure (SLP) associated with Sandy. Wind profiles and steering flow vectors are calculated using wind fields obtained at 8 standard pressure levels.

3. Results and Discussion

3.1. Overview of the PSU WRF-EnKF Performance in Comparison to Operational Models

[10] Despite having a somewhat atypical track, the operational forecast performance for the position of Hurricane Sandy was above average [*Blake et al*., 2013]. The PSU WRF-EnKF ensemble also performed quite well, including at long lead times prior to landfall. Figure 1 shows the deterministic and ensemble track forecasts for the PSU WRF-EnKF real-time system, the ECMWF model, and the GFS at various lead times. The simulations (earliest with airborne Doppler data assimilation for PSU WRF-EnKF) initialized at 0000 UTC 26 October 2012 correspond to forecasts with an approximately 96 h lead time prior to best track landfall. In general, as the lead time to landfall decreases, the performance of the ensembles increases. At the 96 h

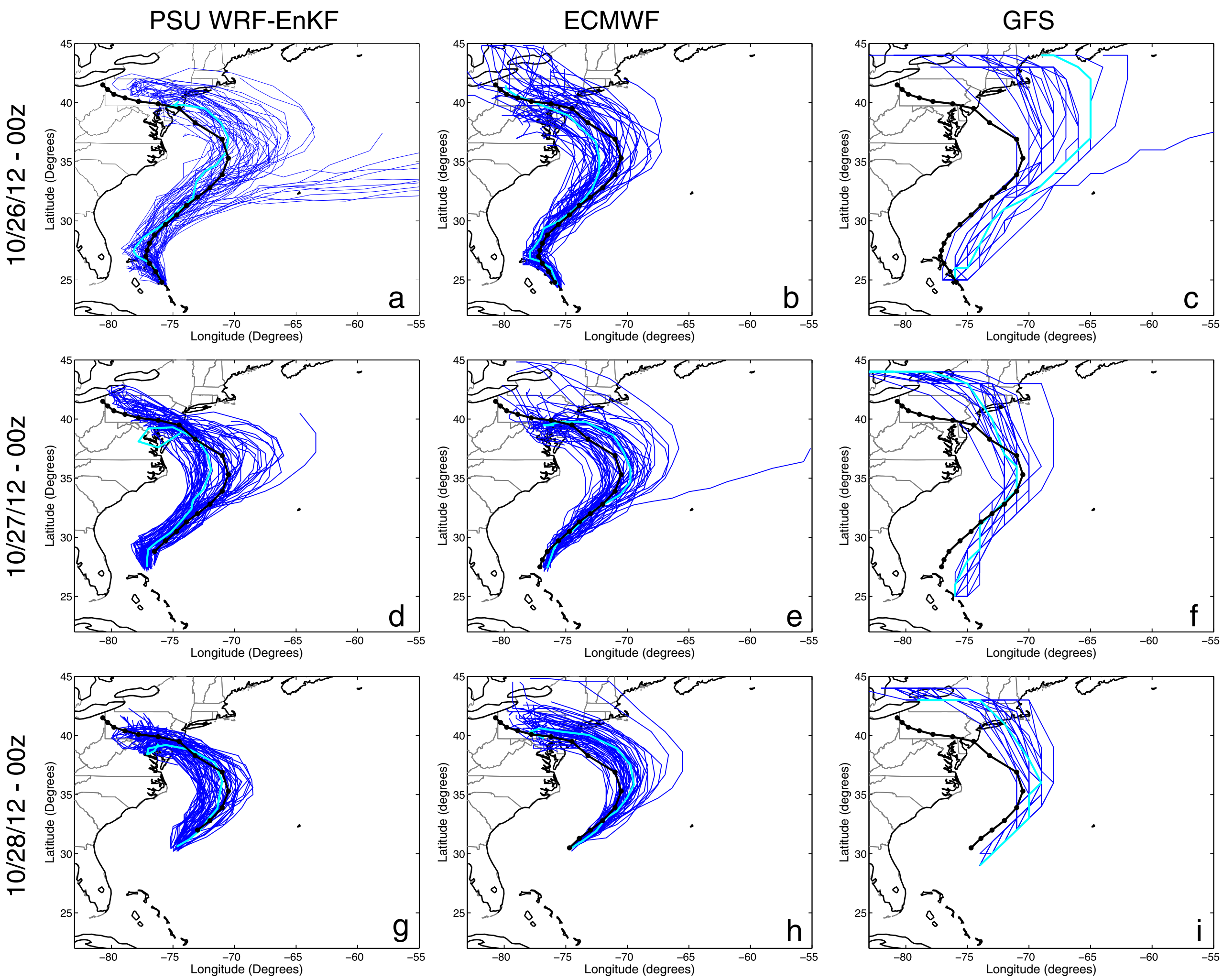

Figure 1. Ensemble tracks (blue lines) for the PSU WRF-EnKF (first column), ECMWF (second column), and GFS (third column) forecasting systems for Hurricane Sandy initialized at (a–c) 0000 UTC 26 October 2012, (d–f) 0000 UTC 27 October 2012, and (g–i) 0000 UTC 28 October 2012. The three forecasting systems utilize 60, 50, and 20 ensemble members, respectively. The NHC best track for Hurricane Sandy is overlaid in black, with positions marked every 6 h and the deterministic runs are plotted in cyan.

lead time (Figures 1a–1c), the ECMWF ensemble performs remarkably well, with the track of the deterministic run very close to the NHC official best track, while the spread of the 50 ensemble tracks encompasses the correct landfall location. The PSU WRF-EnKF forecast also performs well at the 96 h lead time, as the deterministic forecast is very close to the best track. The ensemble spread is a bit larger, with 50 of the 60 ensemble members correctly predicting a landfall with a slight northward bias, while the other 10 members forecast Sandy to move out to sea. The GFS ensemble is less successful as 19 of the 20 ensemble members correctly predict a landfall, but the landfall location is incorrect by about 650 km to the north. In addition, the forecast of the deterministic run is to the far right-hand side of the ensemble spread, or further away from the best track landfall location.

[11] At the 72 h lead time (Figures 1d–1f), the ensemble spread in the three operational models decreases, however, the track performance remains fairly consistent with the performance at the 96 h lead time. The ECMWF deterministic forecast is still accurate in predicting the landfall location of Sandy, although there are track errors associated with the shape of the forecast, as the position of the storm is north of the best track as Sandy approaches the United States coastline. The slight northward bias in the ECMWF forecast at this lead time is also reflected in the ensemble as a few more members landfall to the north of the best track landfall location than in the 96 h lead time forecast, and one member fails to landfall altogether. The PSU WRF-EnKF forecast improves at this lead time, as none of the 60 ensemble members head out to sea. In addition, the spread of the ensemble narrows, particularly focused around the landfall location of Sandy. The tracks of the ensemble members show the same general shape as the best track of Hurricane Sandy, and the performance of this ensemble is very comparable to the ECMWF ensemble performance at this lead time. The GFS forecast shows a marked improvement at this lead time, with the ensemble spread narrowing and the deterministic landfall location shifting westward toward the best track. However, the landfall location is still incorrect, with the majority of the members landfalling in the New York City or Connecticut coastline, rather than the southern New Jersey coastline.

[12] Finally, at the 48 h lead time the performance of the models is fairly comparable, however the PSU WRF-EnKF forecast performs the best (Figures 1g–1i). The deterministic forecast is very similar to the best track at this initialization time and is located in the center of the small spread of ensemble tracks. The ECMWF forecast is also successful, although a more noticeable northward track bias develops as the lead time decreases. The GFS forecasts at this lead time are similar to the 72 h forecasts with the landfall location of all the ensemble members located too far to the north, highlighting the inability of this model to capture the final northwestward turn that Sandy made toward the New Jersey coast. Overall, the track performance of the PSU WRF-EnKF, ECMWF, and GFS ensembles are above average and mostly successful, especially considering the unusual track of Hurricane Sandy. However, the overall structure of the track is better captured by the PSU WRF-EnKF and ECMWF systems, particularly the landfall location even at long lead times

3.2. Uncertainty in Track and Intensity Forecasts by the PSU WRF-EnKF Ensemble

[13] Not only does the PSU WRF-EnKF forecast initialized at 0000 UTC 26 October provide a sufficient deterministic forecast of the track and intensity of the cyclone, the diversity of the ensemble provides an opportunity to explore in detail what factors led to the divergence in track forecasts and therefore highlight the most influential fields in the model that determine the final position of Hurricane Sandy. Figure 2a shows the NHC best track and the tracks of the 60 ensemble members of the PSU WRF-EnKF simulation at the 96 h lead time. The ensemble has been divided into composite groups according to the performance of the track forecasts. The composite group GOOD (POOR) consists of the 10 ensemble members with the lowest (highest) cumulative root-mean-square error (RMSE) in track compared to the best track. All of the remaining members make landfall and 10 of these whose cumulative RMSE's fall between that of GOOD and POOR became the composite group FAIR. Figure 2b shows the mean tracks of each composite group and clearly highlights the success of the track of GOOD compared to the best track, the northward and somewhat incorrect landfall location of FAIR, and the failure to predict a United States landfall in POOR.

[14] In addition to the ensemble track forecasts, the mean intensity evolution of the composite groups also compare favorably with the best track intensity. Figures 2c and 2e show the minimum SLP and maximum 10 m wind speed evolution for each ensemble member and the best track intensity until Forecast Hour 90, while Figures 2d and 2f show the means in intensity for the composite groups. The steady intensification of Sandy as landfall approaches is forecasted in all composite groups. Both GOOD and FAIR predict a slight over-intensification, although this is most likely due to an intensity bias that is present in the PSU WRF-EnKF system. The intensity of POOR is the closest to the best track intensity, particularly in the latter half of the simulation, although this is a coincidence as POOR follows a completely different track than the best track and weakens in intensity due to the cooler SSTs that the members encounter. The maximum wind speeds are perhaps more representative of the intensity performance of this simulation, as the secondary intensification period of Sandy before landfall is somewhat captured in GOOD and FAIR, although not at the magnitude that is observed in the best track.

3.3. Comparisons of the Synoptic Environments of the Composite Groups

[15] In order to further explore what differences among the ensemble led to the divergence in tracks, an analysis of the overall synoptic environments is performed. Figure 3 shows composite plots for GOOD, FAIR, and POOR of

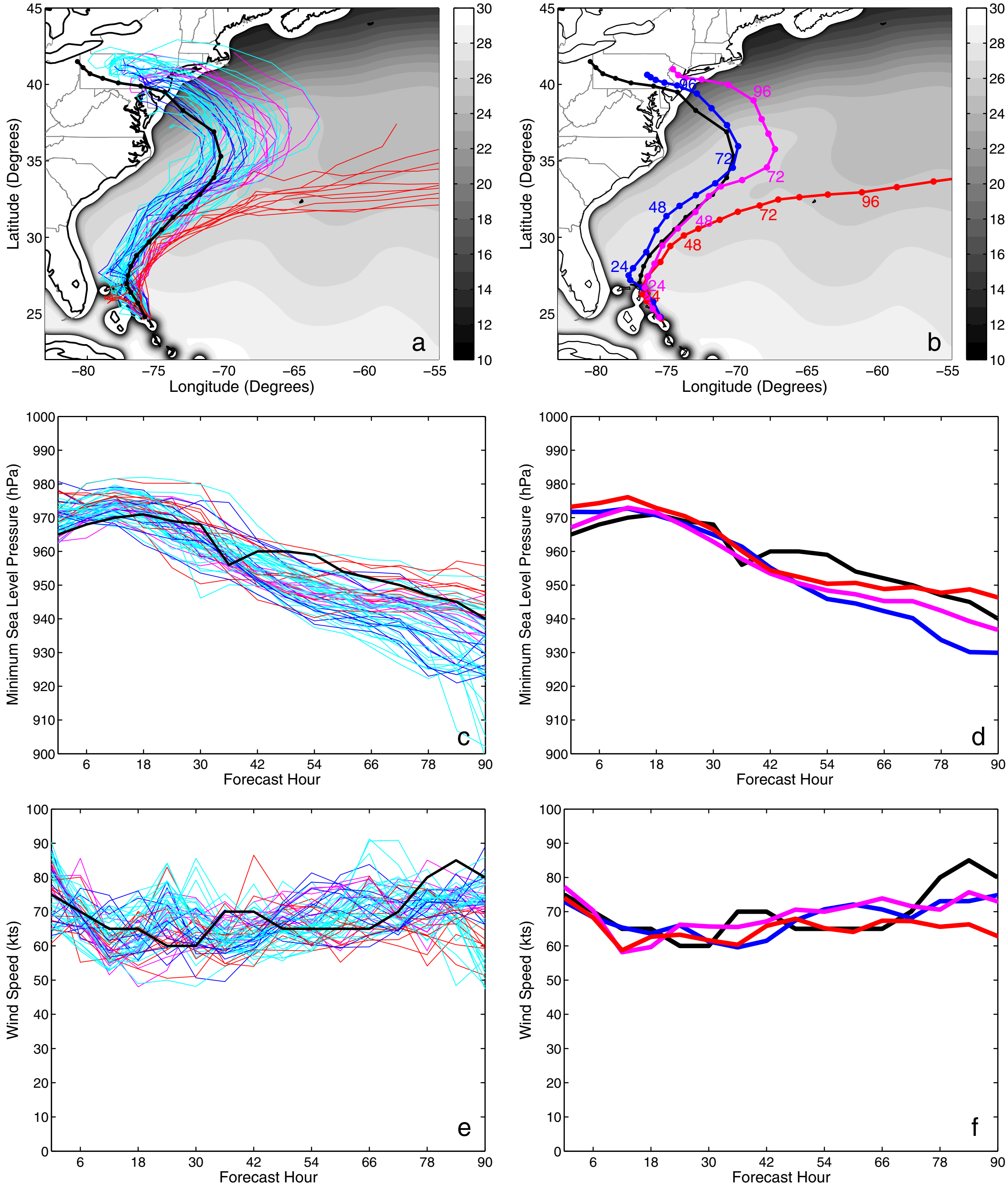

Figure 2. Evolution of (a) the tracks (composite means in (b)), (c) the minimum SLP (hPa) (composite means in (d)), and (e) the maximum 10 m wind speeds (kt) (composite means in (f)) of the best track of Hurricane Sandy (black line with position marked every 6 h in Figure 2a) and the 60 ensemble members of the PSU WRF-EnKF forecast initialized at 0000 UTC 26 October 2012 grouped by track performance; GOOD—the 10 members with the smallest cumulative track RMSE between the member and the best track (blue), FAIR—the 10 members whose cumulative track RMSE fall between that of GOOD and POOR (magenta), and POOR—the 10 members that do not landfall (red). A portion of the outermost domain in the WRF simulation is plotted in Figures 2a and 2b with sea surface temperature contours every 1°C. Numbers in Figure 2b indicate mean positions of each composite group at indicated forecast hour.

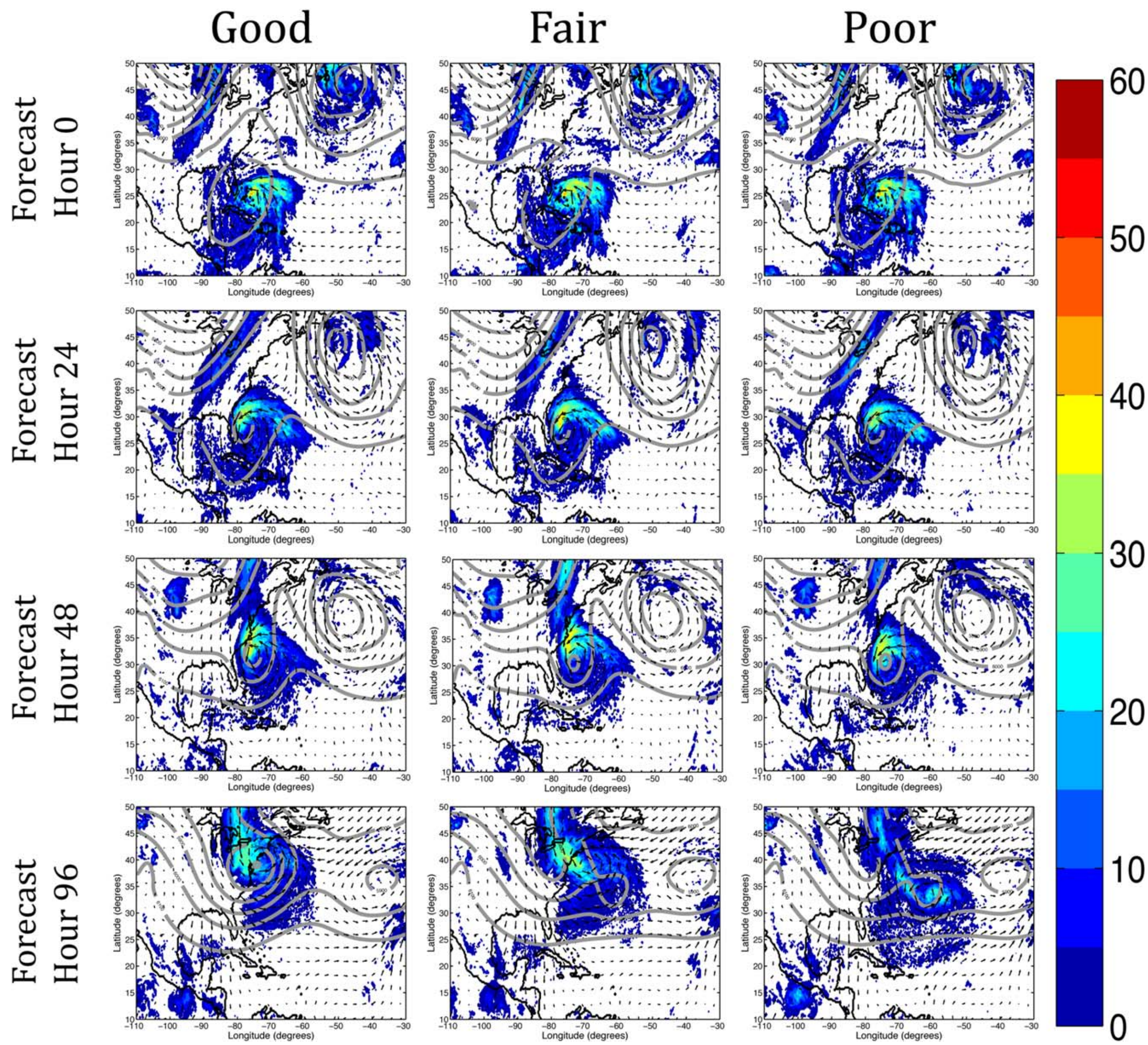

Figure 3. Surface maps of composite 2 km simulated radar reflectivity (filled contours every 5 dBZ), 500 hPa geopotential heights (gray contour lines every 100 m), and 10 m winds (vectors) for the GOOD, FAIR, and POOR composite groups at Forecast Hour 0, 24, 48, and 96 for a portion of the outermost domain in the forecast system. The geopotential height contours and the surface wind vectors have been smoothed (using a 1:2:1 smoother in both the *x* and *y* directions) 10 times for clearer visualization.

2 km radar reflectivity, 500 hPa geopotential heights, and surface wind vectors for a portion of the outermost domain at Forecast Hour 0, 24, 48, and 96. At Forecast Hour 0 (Figure 3, top), these "surface maps" reveal that there are no obvious differences among the initial conditions of the composite groups. Hurricane Sandy is located north of Cuba and just to the east of the coast of Florida, with the majority of the strongest convection located to the northeast of the circulation centers. In addition, a midtropospheric trough and frontal system of similar intensity is located across the Midwestern and Great Lakes regions of the United States in the three composites. Finally, a weaker low-pressure system is also located in the Northern Atlantic with once again no noticeable differences among the composite plots.

[16] At Forecast Hour 24 (Figure 3, second row), Sandy has continued to move toward the northwest in GOOD, FAIR, and POOR, and the structure of Sandy has evolved into a more asymmetric storm with the majority of the convection now located to the north of the center. In all the composites, the frontal system has also continued eastward and has begun to impact the Mid-Atlantic region of the United States. Discernible distinctions between these composites are again difficult to identify, so plots of the differences between the composites are created to aid in the visualization (Figure 4).

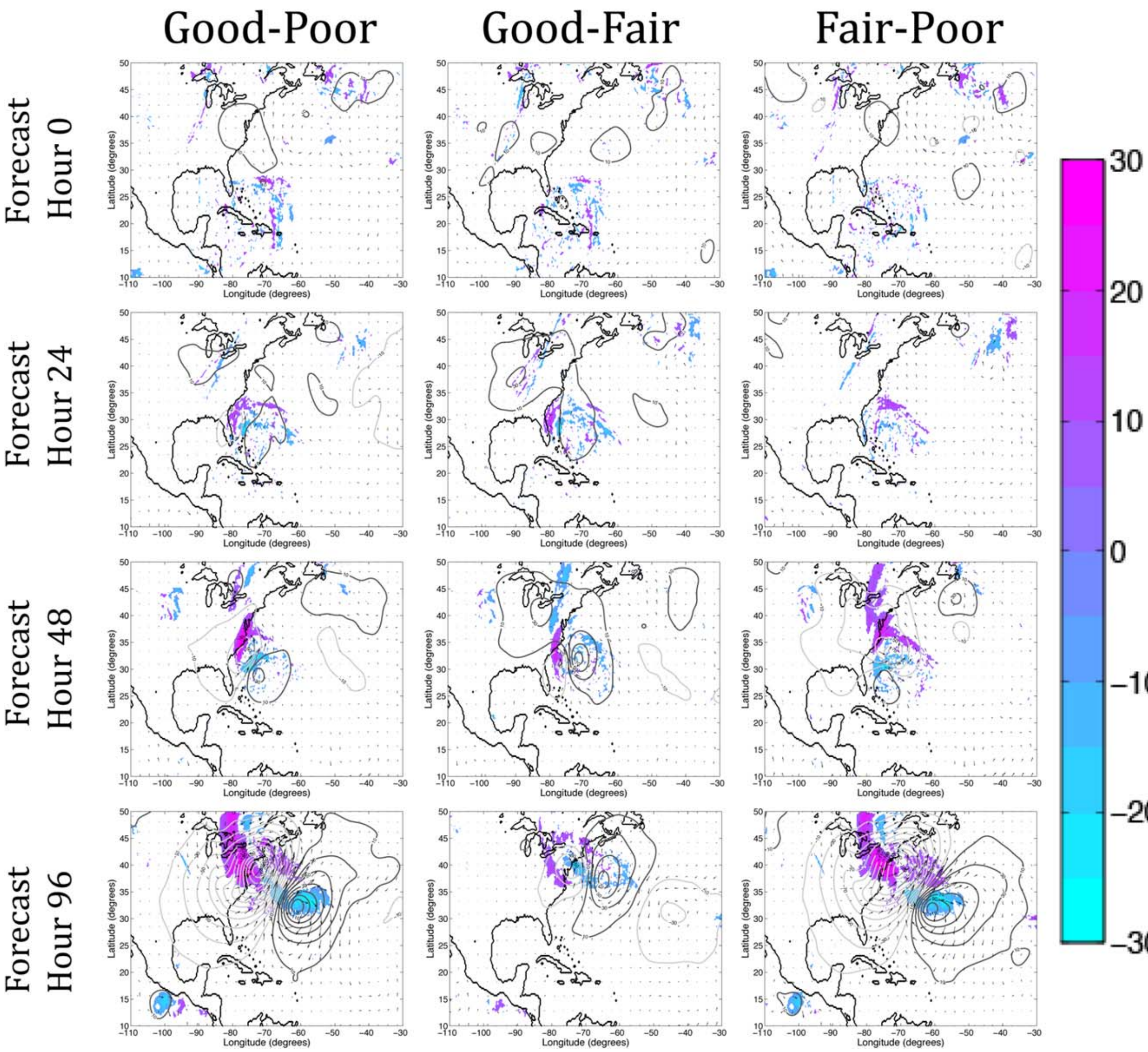

Figure 4. Differences between 2 km radar reflectivity (filled contours every 5 dBZ), 500 hPa geopotential height (contour lines every 100 m; light gray positive and dark gray negative), and surface winds (vectors) for the composite surface maps shown in Figure 3—GOOD-POOR (first column), GOOD-FAIR (second column), and FAIR-POOR (third column) for Forecast Hour 0, 24, 48, and 96.

The difference plots at Forecast Hour 0 (Figure 4, top) confirm what was observed in the surface maps; there is virtually no difference between the locations of the frontal system, the low-pressure system in the North Atlantic and Hurricane Sandy. However, at Forecast Hour 24, both the GOOD-POOR and GOOD-FAIR difference plots reveal a displacement in the position of Hurricane Sandy that was not easily observable in the surface maps alone (Figure 4, second row). This shift in location is indicated by the displacement in the radar reflectivity fields and the differences in the geopotential height contours. This difference in the center position of Hurricane Sandy is not observed in the FAIR-POOR plot, indicating that at this time the FAIR and POOR ensemble members have not begun to separate from each other, and only the GOOD members have traveled further to the northwest and are therefore the closest to the United States coastline. This is consistent with the mean track of GOOD (Figure 2b), which first indicated this difference in position. It is interesting to note that at this forecast hour there are very few differences among the composites in the position of the front and the low-pressure system in the North Atlantic, indicating that the differences in tropical cyclone track between GOOD and FAIR at this time are dictated by the position of Hurricane Sandy itself.

[17] By Forecast Hour 48 (Figure 3, third row), Sandy has made a turn toward the northeast in all three composites, with the areas of strongest convection now located to the north and northwest of the center. The

frontal system has also progressed eastward and is nearing its interaction with Hurricane Sandy, particularly in GOOD and FAIR. The difference plots in Figure 4 for this forecast hour (third row) reveal a clear separation in the location of Hurricane Sandy in all three composites. The FAIR-POOR plot demonstrates that the previously overlapping centers are now also displaced from each other. The geopotential height contours in particular indicate that the center of FAIR is now located to the north of the center of POOR. Therefore, in the time between Forecast Hour 24 and 48, the members of FAIR have traveled to the northeast more quickly than the members of POOR. The GOOD-FAIR differences reveal that the centers of these composite groups are still displaced longitudinally, with the center of GOOD located to the west of the center of FAIR. If one combines the latitudinal displacement between FAIR and POOR with the longitudinal displacement between GOOD and FAIR, the difference between GOOD and POOR should be in both directions. This is consistent with what is seen in Figure 4, as the vortex of GOOD is located to the northwest of the vortex of POOR. Once again, at this forecast hour the differences between the positions of Sandy are far greater than any differences between the front and the low-pressure system in the composites, indicating that the location of Sandy is the dominant factor that leads to the deviation in tracks.

[18] The surface maps for Forecast Hour 96 (Figure 3, bottom) clearly show the divergence in track for this ensemble. In the GOOD and FAIR composites, Sandy has turned back toward the northwest and landfall at the United States coastline is imminent in GOOD and is being approached in FAIR. The frontal system and Sandy have interacted and merged into one, with the strongest areas of convection located where this merge has taken place. Meanwhile, it is clear from the POOR composite that Sandy has continued its northeast trajectory and is turning even more toward the east as it begins to head out to sea. Given these noticeable differences in the surface plots, the GOOD-POOR and FAIR-POOR difference plots at this forecast hour (Figure 4, bottom) noticeably show a very large separation between the centers of the cyclones. The GOOD-FAIR composite confirms that the longitudinal displacement between the centers of the GOOD and FAIR composite persists throughout the simulation, which leads to a difference in location and timing of the landfall of Sandy. It is clear from this analysis that differences in the location of Hurricane Sandy that develop throughout the first 48 h of the simulation determine whether a given ensemble member will make landfall or not, in addition to controlling the accuracy of the landfall location and timing. Given this information, it is important to next identify and understand what causes the differences in the position of Hurricane Sandy in order to determine the most influential factors on the tracks of this ensemble.

3.4. Causes of Ensemble Track Divergence: Differences in the Environmental Steering Flow

[19] The surface maps and difference plots analyzed above revealed a connection between the location of Hurricane Sandy during the first 48 h of the simulation and the final location of Sandy. Since these differences in position are related to differences in translational speed among the ensemble (members of GOOD travel a greater distance to the northwest in the first 24 h of the simulation than FAIR or POOR), it is useful to examine the differences in the environmental steering flow among the ensemble. Steering flow theory is often used in forecasting to predict both direction and speed of the movement of a tropical cyclone. Typically, midtropospheric flow (700 hPa–500 hPa) averaged over an area of 5–7 degrees of latitude from the center of the TC is highly correlated with tropical cyclone movement [*Chan and Gray*, 1982]. Figures 5a–5c show the height profiles of the mean zonal component of wind averaged between 200 and 500 km from the TC center for the composite groups GOOD, FAIR, and POOR at Forecast Hours 12, 18, and 24. The profiles of the ECMWF and GFS analysis are also shown and are for the most part comparable to the wind profiles for the PSU WRF-EnKF ensemble. Profiles calculated by averaging the winds between a 300 km and 600 km radius and a 500 km to 800 km radius from the TC center reveal slightly different wind magnitudes but the differences amongst the composite profiles are consistent with Figure 5 (not shown). At Forecast Hour 12, the GOOD profile is located to the left of the profiles for both FAIR and POOR. In the midtropospheric region (particularly between heights of 4–8 km), the average zonal winds in GOOD are more negative than those in FAIR and POOR. This difference in zonal wind persists at Forecast Hour 18 and 24, although the magnitude of the winds in all profiles begin to decrease over time as the forward motion of Sandy slows in preparation for its turn toward the northeast. This stronger negative zonal wind corresponds to Sandy being embedded in stronger easterly winds in GOOD that increase the zonal motion of Sandy over the first 24 h of the simulation. This difference in zonal motion leads to the displacement in the position of the vortices that influences the eventual landfall position of Sandy for a given member.

[20] Although the vertical profiles of zonal wind provide evidence toward differences in the steering flow of the composite groups contributing to the track divergence among the ensemble, it is difficult to visualize the precise direction of the steering flow vector by analyzing only one component of the wind at a time. In an ensemble sensitivity study on Super Typhoon Megi, *Qian et al.* [2013] demonstrated that plotting the mean steering flow vector for subsets of an ensemble helped to explain the divergence in track. Therefore, Figure 6 shows the evolution over the first 48 h of the simulation of the mean steering flow vector for the 700 hPa to 500 hPa layer averaged between 200 km and 500 km from the TC center for the various composite groups.

[21] Also calculated are the steering flow vectors for both the ECMWF and GFS forecasts. Initial differences in the magnitude and direction of the steering flow vector among the composites are difficult to identify, however, by Forecast Hour 6 and 12 the magnitude of

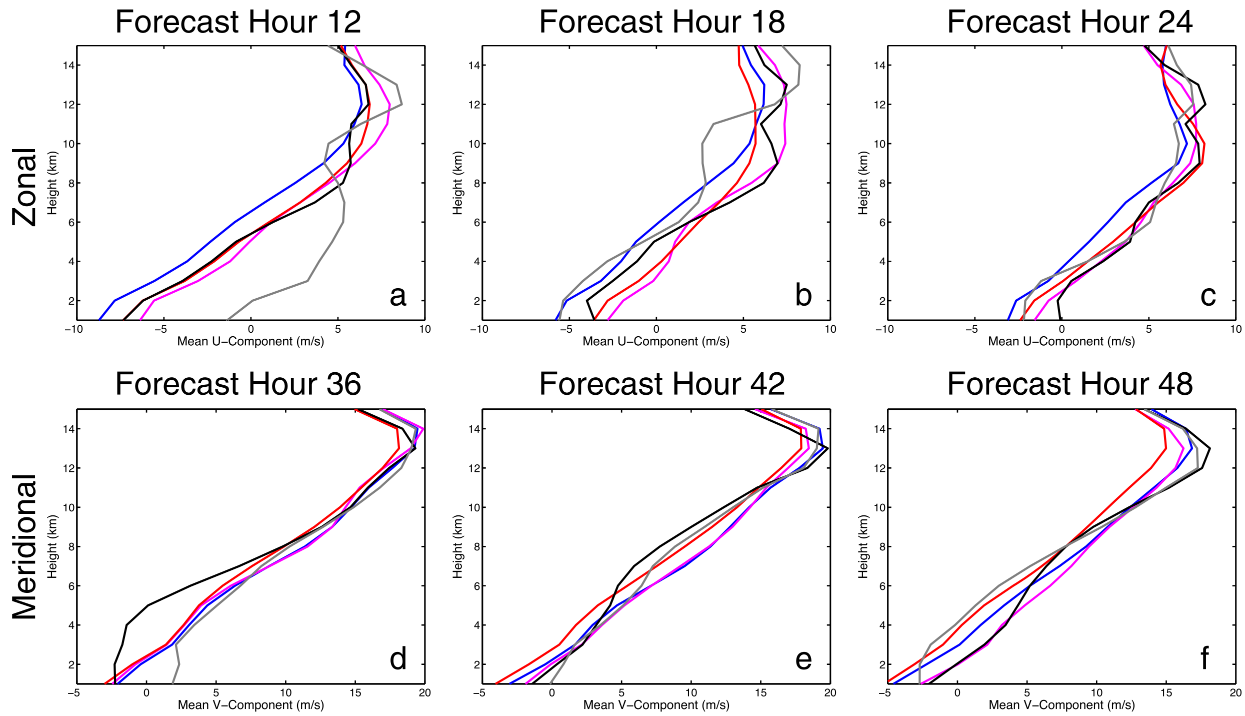

Figure 5. Vertical profiles of mean zonal (top row) and meridional (bottom row) winds (averaged over radii between 200 km and 500 km from the surface center for each ensemble member) for the composite groups GOOD (blue), FAIR (magenta), and POOR (red), as well as the analysis of the ECMWF (black) and GFS (gray) at Forecast Hour (a) 12, (b) 18, (c) 24, (d) 36, (e) 42, and (f) 48.

the GOOD steering flow vector is larger and the vector is oriented in a direction further west than the FAIR and POOR steering flow vectors. At Forecast Hour 18, the steering flow vectors of the composite groups have similar magnitudes, however, the direction of the GOOD vector is still oriented to the northwest, while the directions of both the FAIR and the POOR vector is oriented toward the northeast. This reveals that in the members composing both FAIR and POOR, Sandy has already turned toward the northeast and has begun to move away from the United States coastline. This difference in both the magnitude and direction of the steering flow vector is consistent with the GOOD composite members traveling a further distance over the first 24 h of the simulation, leading to a displacement in the location of the vortices from FAIR and POOR, which influences the final landfall location of Sandy.

[22] It is interesting to note that the evolution of the steering flow vectors and the subsequent differences in the performance of the track forecasts of Sandy for the operational models are also consistent with the PSU WRF-EnKF ensemble. Although initial differences in the operational steering flow vectors are not apparent, at Forecast Hour 12 the steering flow vector for the ECMWF forecast is stronger in magnitude and oriented further to the west than the vector associated with the GFS forecast. By Forecast Hour 18, the ECMWF steering flow vector is still directed toward the northwest, while the GFS steering flow has already turned toward the north. This difference in the magnitude and direction of the steering flow vectors is in agreement with the PSU WRF-EnKF ensemble, where the subsequent performance of the ECMWF forecasts is more aligned with the GOOD composite group and the GFS track forecasts are more consistent with the FAIR and POOR composites. This is an indication that differences between the steering flow in the ECMWF and GFS forecast runs may have contributed to the differences in track forecasts produced by these models.

[23] The differences in zonal wind and the steering flow vectors among the composite groups over the first 24 h of the simulation help to explain the eventual divergence in track of GOOD from FAIR and POOR, however at this time the tracks of FAIR and POOR have not yet separated. Between Forecast Hour 24 and 48 though, the divergence in track is sufficient to cause FAIR to make landfall and POOR to head out to sea. Differences in translational motion among the members as Sandy moves predominantly to the northeast also lead to this track divergence. Figures 5d–5f show the height profiles of the mean meridional component of wind averaged between 200 and 500 km from the TC center for the composite groups GOOD, FAIR, and POOR and the ECMWF and GFS analysis at Forecast Hours 36, 42, and 48. The wind profiles and steering flows are very similar at Forecast Hour 36, but by Forecast Hour 42 the POOR profile has begun to separate from the other composite groups. Throughout nearly the entire profile, the magnitude of the composite meridional wind is smaller in POOR. This difference

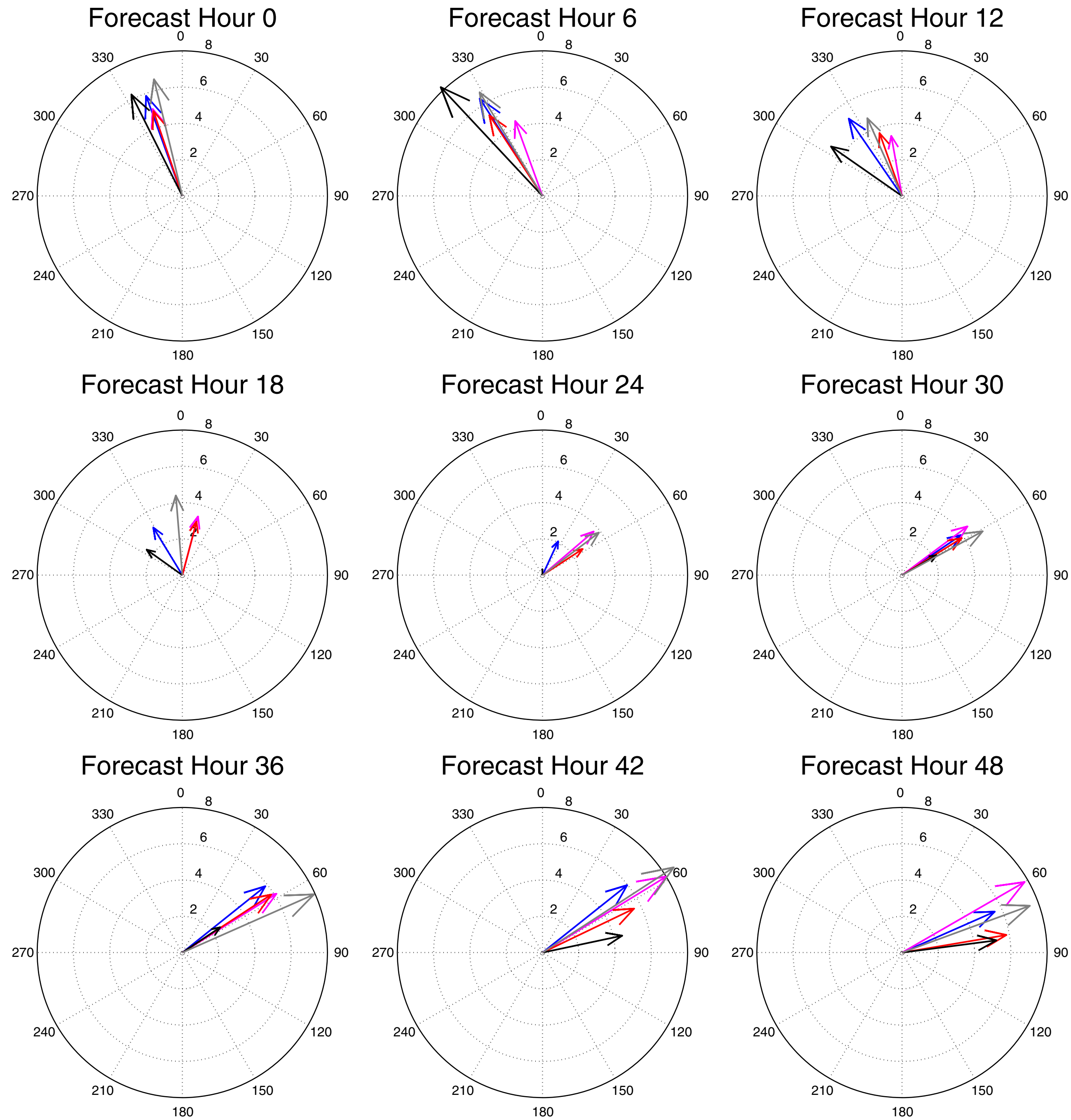

Figure 6. Evolution (every 6 h between Forecast Hour 0 and 48) of the environmental steering flow vectors (winds averaged over radii between 200 km and 500 km from the surface center and between the 700 hPa and 500 hPa vertical levels) for the composite groups GOOD (blue), FAIR (magenta), and POOR (red), as well as the ECMWF (black) and GFS (gray) forecasts initialized at 0000 UTC 26 October 2012. The steering flow vectors are oriented in the direction that the compass rose specifies and magnitudes are indicated by the length of the vectors (m/s).

indicates that these composite members are traveling to the northeast at a slower translational speed due to weaker winds in the steering-flow layer. The steering flow vectors for these Forecast Hours (Figure 6) confirm the conclusions drawn from the wind profiles. At Forecast Hours 30 and 36, there are no discernible differences between the steering flow vectors of the composite groups. However, by Forecast Hours 42 and 48 the magnitude of the FAIR steering flow vector has increased, allowing Sandy to be steered further to the northeast over this time than the weaker steering flow vector that is associated with POOR. There is also a subtle difference in the direction of the FAIR and POOR steering flow vectors at these times, as the FAIR vector is oriented further to the north than the POOR vector, which contributes to the difference in the latitudinal location of the composite vortices of FAIR and POOR over the first 48 h of the simulation. It is this difference in latitudinal position that leads to the track divergence between the composite groups FAIR and POOR.

3.5. Track Sensitivity and Uncertainty to the Initial Conditions: Tropical Versus Midlatitude

[24] Although the PSU WRF-EnKF simulation of Hurricane Sandy showed a clear divergence among the tracks of the ensemble that appeared to develop due to differences in the environmental steering flow over the first 48 h of the simulation, it is worth investigating how sensitive the evolution of these members were to their initial conditions. It has already been shown in this ensemble, as well as in other similar TC ensemble simulations [*Zhang and Sippel*, 2009; *Sippel and Zhang*, 2010; *Munsell et al.*, 2013] that small and usually unobservable differences in initial conditions can lead to large spread in both track and intensity forecasts of tropical cyclones. In addition, studies such as *Torn and Hakim* [2009] and *McTaggart-Cowan et al.* [2001] have utilized sensitivity techniques on other case studies of tropical cyclones to determine the dominant factors in the initial conditions that contribute to divergent forecasts.

[25] In order to search for possible relationships between the tracks of Sandy in this ensemble and the initial conditions a set of sensitivity experiments was performed. All fields of the initial conditions for the 10 members comprising the groups GOOD, FAIR, and POOR were averaged together and the resulting composite initial conditions were utilized in an otherwise identical simulation to the original ensemble. The resulting tracks and intensities from these three sensitivity experiments (GOODCOMP, FAIRCOMP, POORCOMP) as well as the composite tracks and intensities of GOOD, FAIR, and POOR that were used in the above analysis are shown in Figure 7. Other than the fact that the tracks and intensities have more variation in their evolution (due to hourly output being recorded rather than 6 hourly output), the tracks, minimum SLP and maximum wind evolutions of GOODCOMP, FAIRCOMP, and POORCOMP are very similar to the track and intensity evolution of GOOD, FAIR, and POOR. This provides evidence that although the initial conditions among the ensemble are very similar (Figure 4, first row), the initial conditions of a given ensemble member have a large influence on the final track and intensity of Sandy. The differences in steering flow that led to divergence in the location of the vortices of Sandy over the first 48 h of the simulation therefore are determined by and develop from the initial conditions. The similarity in the results of this sensitivity experiment also suggests that the track forecast error growth is fairly linear with respect to uncertainties in the initial conditions.

[26] Given the conclusion that the divergence of the tracks in this ensemble appears to have been produced by differences in the location of the vortices of Sandy caused by variance in the environmental steering flow

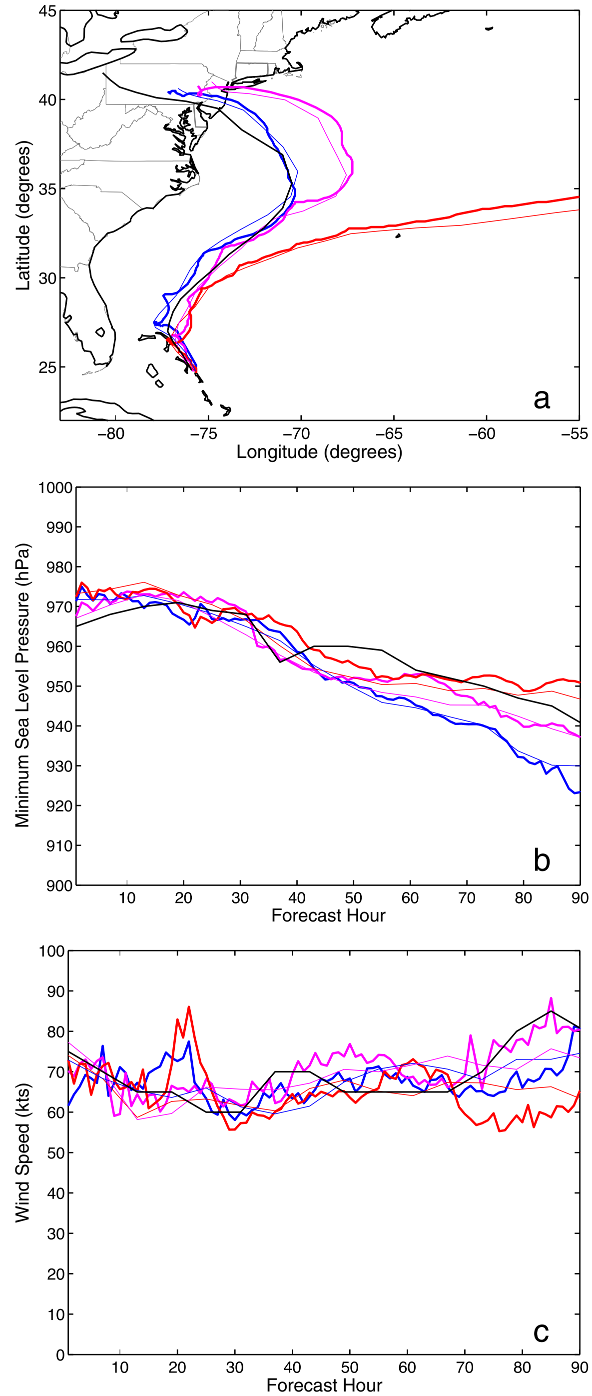

Figure 7. (a) Tracks, (b) minimum SLP (hPa), and (c) maximum 10 m wind speeds (kt) from the first sensitivity experiment (GOODCOMP—thick blue, FAIRCOMP—thick magenta, POORCOMP—thick red) and the original composites (GOOD—thin blue, FAIR—thin magenta, POOR—thin red). Best track information is also plotted in black. The sensitivity experiment results are plotted at hourly intervals while the original simulation is recorded at 6 h intervals.

vectors, a new set of sensitivity experiments is performed where the initial conditions are altered to determine whether the main factors that determine the track of Sandy are associated with the region that Sandy is initially embedded in, or in the region containing the midlatitude frontal system. To show this, new initial conditions are created by combining portions of the initial conditions of GOODCOMP, FAIRCOMP, and POORCOMP together based on a latitudinal division between Sandy and the midlatitude system. Experiment MLPOOR_TCGOOD combines the southern portion of the GOODCOMP initial conditions, which contains Hurricane Sandy, with the northern portion of the POORCOMP initial conditions, which contains the midlatitude system. Two additional experiments that combine the initial conditions in the different regions are also performed; MLFAIR_TCGOOD uses the southern section of GOODCOMP and the northern section of FAIRCOMP, while MLGOOD_TCPOOR uses the southern section of POORCOMP with the northern section of GOODCOMP. In all three of these combinations of initial conditions, the tropical portion containing Sandy contains all points south of 32°N, the midlatitude portion consists of all points north of 35°N and between 32°N and 35°N a linear combination of the two original initial conditions is performed based on the distance away from these latitudinal boundaries. These initial conditions were then simulated under an otherwise identical set up to the original ensemble and the resulting tracks of Hurricane Sandy are given in Figure 8a.

[27] Over the first 24–36 h of the simulation, the MLGOOD_TCPOOR track turns toward the northeast without traveling as far of a distance as the other tracks and is therefore more similar to the POORCOMP track. The MLFAIR_TCGOOD and MLPOOR_TCGOOD simulations produce storms that do travel further to the northwest before turning to the northeast, much like the GOODCOMP track. As the simulation advances, the MLFAIR_TCGOOD and MLPOOR_TCGOOD tracks diverge slightly as Sandy moves toward the northeast before curving back toward the northwest to make landfall. It is worth noting that the landfall position of MLFAIR_TCGOOD is very near the landfall position of GOODCOMP and the landfall location of MLPOOR_TCGOOD is at the same location as FAIRCOMP. Meanwhile, MLGOOD_TCPOOR closely follows the track of POORCOMP and heads out to sea. These simulations provide strong evidence that the portion of the domain containing Hurricane Sandy that is south of 32°N is the most influential in determining the final position of Hurricane Sandy. The simulations run with the initial conditions of the tropical region from GOODCOMP make landfall, while the simulation run using the POORCOMP tropical initial conditions heads out to sea. The midlatitude region is not irrelevant as MLFAIR_TCGOOD and MLPOOR_TCGOOD make landfall in different locations, with the MLFAIR_TCGOOD landfall position ultimately closer to the best track than the MLPOOR_TCGOOD landfall position. However, these results clearly illustrate that the impact that the midlatitude region and frontal system has on the landfall location of Sandy is secondary to the position of Sandy itself, which is controlled by the environmental steering flow in the surrounding area. This is consistent with what was shown above in the steering flow analysis.

[28] Next, the areas of the initial conditions fields (over the tropical region south of 32°N) that have the largest effect on the tracks of the ensemble members are explored in more detail. To do this, two-dimensional correlation contour fields between the location of Hurricane Sandy at landfall (calculated as the distance from the best track position at landfall) and the 500 hPa

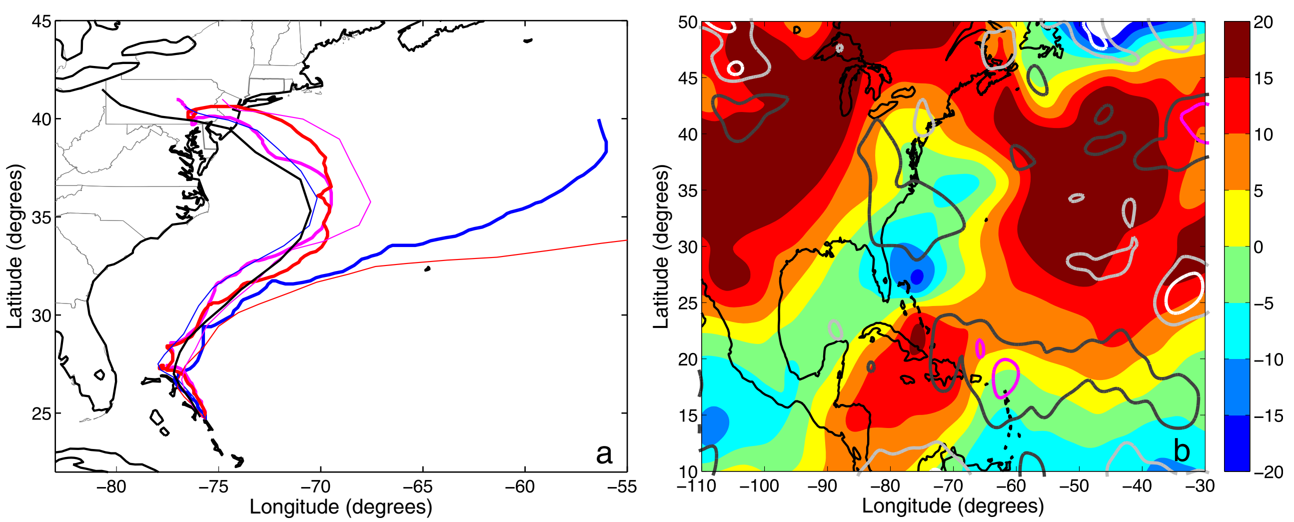

Figure 8. (a) Tracks from the second sensitivity experiment (MLGOOD_TCPOOR—thick blue, MLFAIR_TCGOOD—thick magenta, MLPOOR_TCGOOD—thick red) and the original composites (GOOD—thin blue, FAIR—thin magenta, POOR—thin red). The NHC Best Track (black) is also plotted. (b) Ensemble mean 500 hPa zonal wind (filled contours every 5 m/s) at Forecast Hour 0 for the PSU WRF-EnKF simulation initialized at 0000 UTC 26 October 2012. Correlation contours between the distance from the Best Track landfall position and the 500 hPa zonal winds are also overlaid (+0.3 in dark gray, +0.5 in magenta, −0.3 in light gray, −0.5 in white).

zonal winds are calculated and overlaid on the ensemble composite mean zonal winds at 500 hPa (Figure 8b). The mean zonal wind composite reveals a somewhat expected structure characterized by positive zonal winds to the south and negative zonal winds to the north of the center of Sandy, which is associated with the cyclonic circulation of a tropical cyclone. In addition, the midlevel zonal winds of the frontal system are positive and relatively strong as the system is moving toward the east, while the winds in the southern portion of the domain are weak easterlies associated with the trade winds.

[29] The correlation contours reveal a large swath of weak to moderate positive correlation between the final position of Sandy and the zonal winds, indicating that in this region there are stronger easterly winds in the ensemble members that make landfall in the locations closest to the best track. The stronger midlevel easterlies in the more successful ensemble members steer the vortex of Sandy further to the northwest over the first day of the simulation, in agreement with the steering flow analysis presented above. In addition, there is another area of significant correlation located to the north of the composite center of Sandy that provides further evidence that the easterly background environmental steering flow of the ensemble members that eventually make landfall is stronger than the flow of the members that head out to sea. In summary, the divergence of tracks in this ensemble simulation is predominantly caused by differences in the initial environmental midlevel steering flow that Sandy is embedded in, which leads to a separation in the location of the vortices amongst the members that determines the final position.

3.6. Impacts of Ensemble Track Divergence: Differences in Rainfall Distributions and Interactions With the Midlatitude System

[30] The divergence in track in the PSU WRF-EnKF ensemble simulation of Hurricane Sandy not only increases the difficulty in forecasting where the storm will make landfall, but the divergence also introduces additional uncertainty in other forecasts associated with a landfalling tropical cyclone such as cumulative rainfall and storm surge. It has been shown that predicting local maxima in rainfall distributions of tropical cyclones can be difficult due to how quickly the rainfall distribution can change during landfall, as contributions from the eyewall, inner and outer rain bands evolve [*Villarini et al.*, 2011]. These evolutions can develop from the presence of certain environmental conditions such as vertical wind shear, which can cause rainfall to organize in certain downshear quadrants of the storm and subsequently alter the rainfall distribution [*Corbosiero and Molinari*, 2002; *Rogers et al.*, 2003; *Chen et al.*, 2006; *Matyas*, 2010]. In addition, many landfalling tropical cyclones either have undergone or are in the process of an extratropical transition, which introduces more uncertainty in the distribution as rainfall typically aligns to the left of the center or right of the center as tropical cyclones interact with midlatitude troughs [*Atallah et al.*, 2007; *Chen*, 2011]. Given the dependence of landfalling tropical cyclone rainfall distributions on track, divergence and high sensitivity in the tracks of this ensemble combined with the uncertainty involved in tropical cyclone rainfall prediction in general, yields a challenging rainfall distribution forecast.

[31] Figure 9 shows the cumulative rainfall forecasts for the composite groups GOOD, FAIR, and POOR for the time period between 0000 UTC 26 October 2012 and 0600 UTC 31 October 2012. Also plotted are the National Weather Service's observed rainfall totals associated with Hurricane Sandy. An evident comparison can be made between the observed rainfall totals and the GOOD composite rainfall distribution, as the simulated rainfall totals are very similar in both location and magnitude to the observations. Even more remarkable is the ability of the PSU WRF-EnKF system to correctly forecast areas of localized heavy rainfall, such as the orographic intensification over the inland region in West Virginia and the maxima near the shores of Lake Erie and Lake Ontario. The rainfall associated with the FAIR composite is structured in a very similar way to the distribution of GOOD; however, the cumulative totals in the areas of significant rainfall are approximately 50% of the totals in GOOD. The rainfall totals in POOR are significantly lower and do not exceed 10–20 mm, as the only contribution to the rainfall distribution is from the midlatitude system as Sandy heads out to sea.

[32] Given the similarity in the spatial structure but differences in magnitude between the rainfall distributions of GOOD and FAIR, it is worth investigating from where the differences in total rainfall arise. It has been shown that particularly in synoptic situations where a midlatitude system is interacting with a tropical system, a potential vorticity (PV) approach can be utilized to better understand the underlying dynamics that is governing the interaction [*Hoskins et al.*, 1985; *Morgan and Neilsen-Gammon*, 1998; *Atallah and Bosart*, 2003]. Because Hurricane Sandy is a warm-core system, a maximum in PV is observed in the lower levels (850 hPa–700 hPa) with little PV in the upper troposphere, while the cold-core midlatitude system must have a maximum in PV in the upper troposphere (300 hPa–200 hPa). Therefore, the upper-level and lower-level PV can be plotted together (Figure 10) with the areas of upper-level PV clearly attributed to the midlatitude trough and the areas of lower-level PV associated with Sandy. The PV composites for GOOD and FAIR at Forecast Hour 72 are very comparable. In both composites, the low-level PV maximum (greater than 2.2 PVU) associated with Sandy is nearing the negatively tilted midlatitude trough, although an interaction between the two systems has not yet commenced. Although difficult to distinguish in these plots, one has to remember that the center of Hurricane Sandy in GOOD is actually closer to the coast and the midlatitude trough than the center of Sandy in FAIR. This difference in the position of Sandy becomes evident in the PV plots at Forecast Hour 84, as the TC is clearly interacting with the midlatitude trough in GOOD while the interaction in FAIR is only just beginning. Due to this interaction, a strong

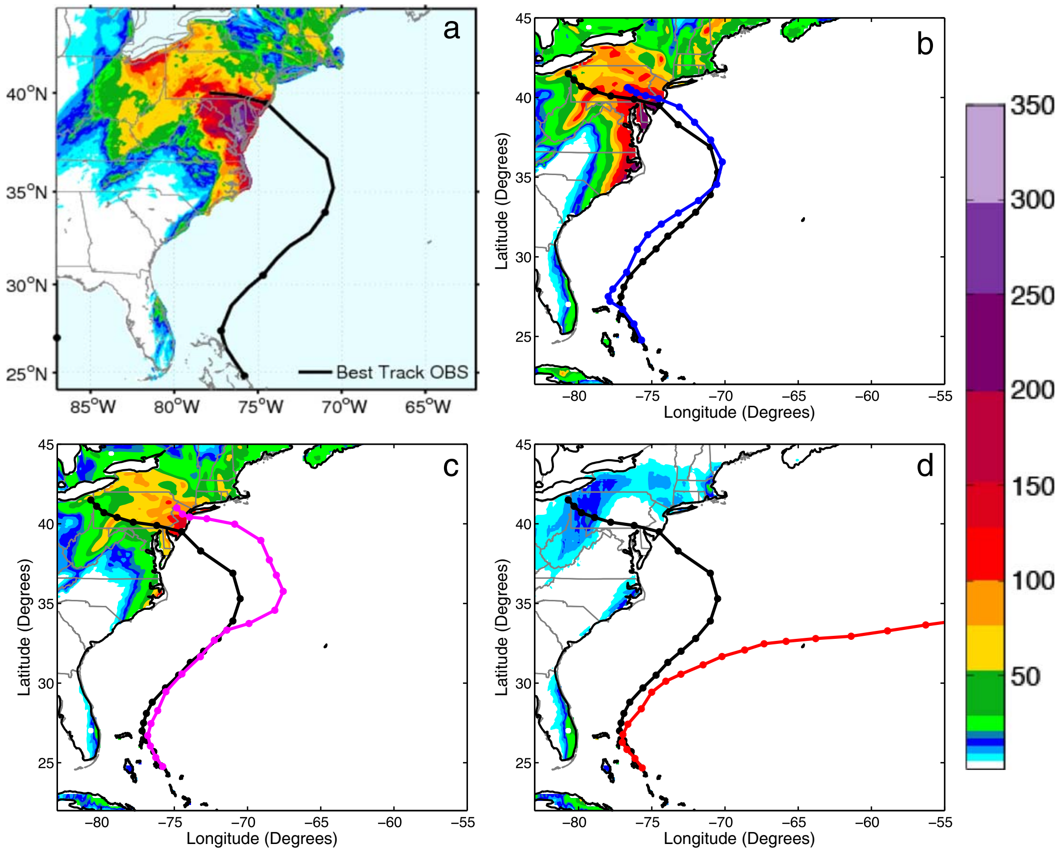

Figure 9. Cumulative precipitation over land (in mm) associated with Hurricane Sandy according to (a) the National Weather Service observational network and the PSU WRF-EnKF, (b) GOOD, (c) FAIR, and (d) POOR composite forecasts. The NHC Best Track (black; position marked every 24 h in Figure 9a and every 6 h in Figures 9b–9d) and the PSU WRF-EnKF composite tracks (blue in Figure 9b, magenta in Figure 9c, and red in Figure 9d with positions marked every 6 h) are also plotted.

baroclinic zone exists and the PV associated with Sandy in GOOD is increasing.

[33] By Forecast Hour 96, Sandy is making landfall in the GOOD composite exactly when the interaction between Sandy and the midlatitude trough is at its strongest. The PV field associated with Sandy has not only intensified but also has increased in size, as the PV field associated with the midlatitude trough is somewhat weakened. Meanwhile, at Forecast Hour 96 in the FAIR composite, Sandy is still located off shore and is therefore at a larger distance away from the midlatitude trough, which appears to cause a lack of intensification in the PV field of Hurricane Sandy. Given these differences in the PV interactions between Sandy and the midlatitude trough, it is worth investigating how these differences in the timing and strength of the interaction contribute to the rainfall distributions associated with the composites. Figure 11 shows the accumulated rainfall over the previous 6 h for the three forecast hours discussed above (72, 84, and 96) for the composite groups GOOD and FAIR. It is immediately apparent that in both composite groups the rainfall distribution of Sandy can be considered to be "left of center," as there is very little rainfall located on the eastern half of the tropical cyclone. Although there are isolated areas of rainfall with higher amounts in FAIR, the distribution of rainfall in GOOD is more spread out and extends further westward into the Mid-Atlantic region of the United States. Because Hurricane Sandy is closer to making landfall at this time, it follows that more of this rainfall occurs over land rather than over the Atlantic Ocean. This interaction again highlights the importance of the position of Sandy in determining the subsequent rainfall magnitudes and distribution.

[34] Since there is a shift in the timing of landfall among the composites, where GOOD makes landfall at Forecast Hour 96 or approximately 18 h prior to landfall of FAIR (Forecast Hour 114), it is useful to compare the midlatitude and tropical system interactions among the composites in terms of number of hours prior to and after landfall, rather than at a given Forecast Hour. This "Lagrangian" comparison more clearly demonstrates the importance of the timing of the midlatitude trough and Hurricane Sandy interaction on the composite rainfall distributions and in particular on the rainfall distributions over land. Figure 12 shows the upper-level and lower-level PV plots for GOOD and FAIR (as in Figure 10) for the forecast hours leading up to and immediately after landfall for the respective composite groups. At 24 h prior to landfall, the

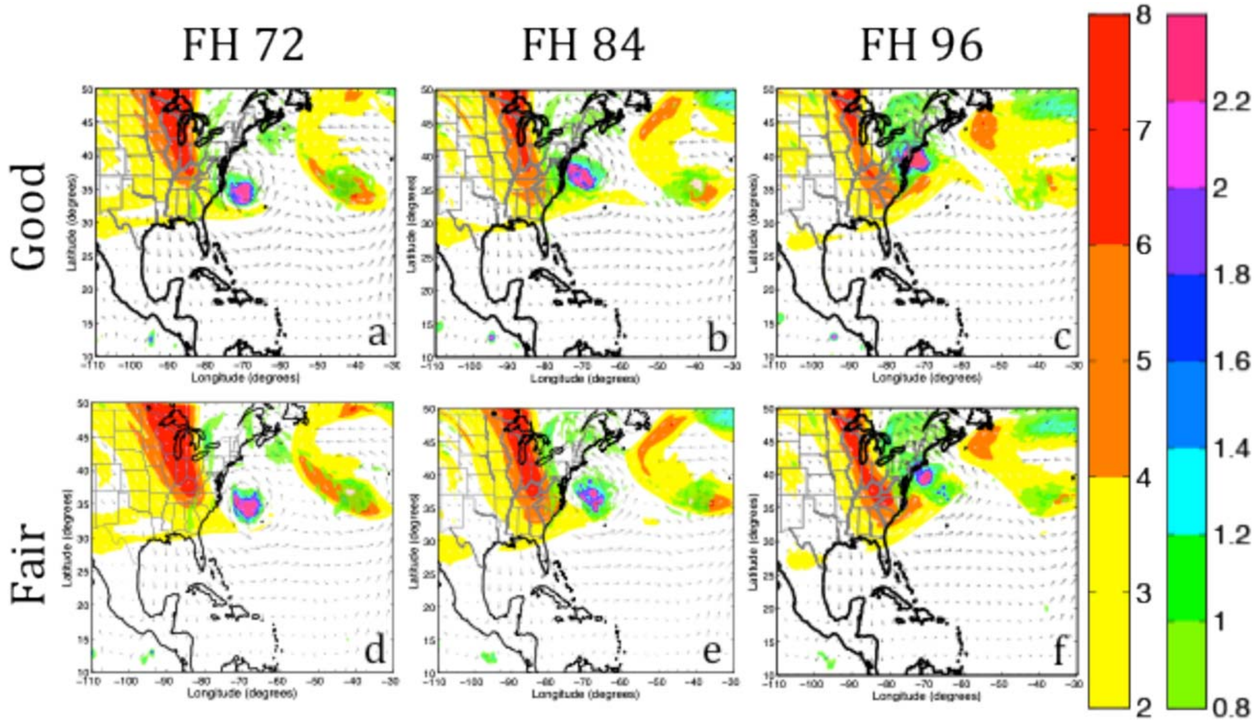

Figure 10. Upper-level (averaged over the 300 hPa to 200 hPa layer; filled warm contours every 2 PVU) and lower-level (averaged over the 850 hPa to 700 hPa layer; filled cool contours every 0.2 PVU) potential vorticity (PV) composites for (top) GOOD and (bottom) FAIR at Forecast Hour (FH) (a and d) 72, (b and e) 84, and (c and f) 96. Upper-level winds (white vectors) and lower-level winds (black vectors) are also plotted.

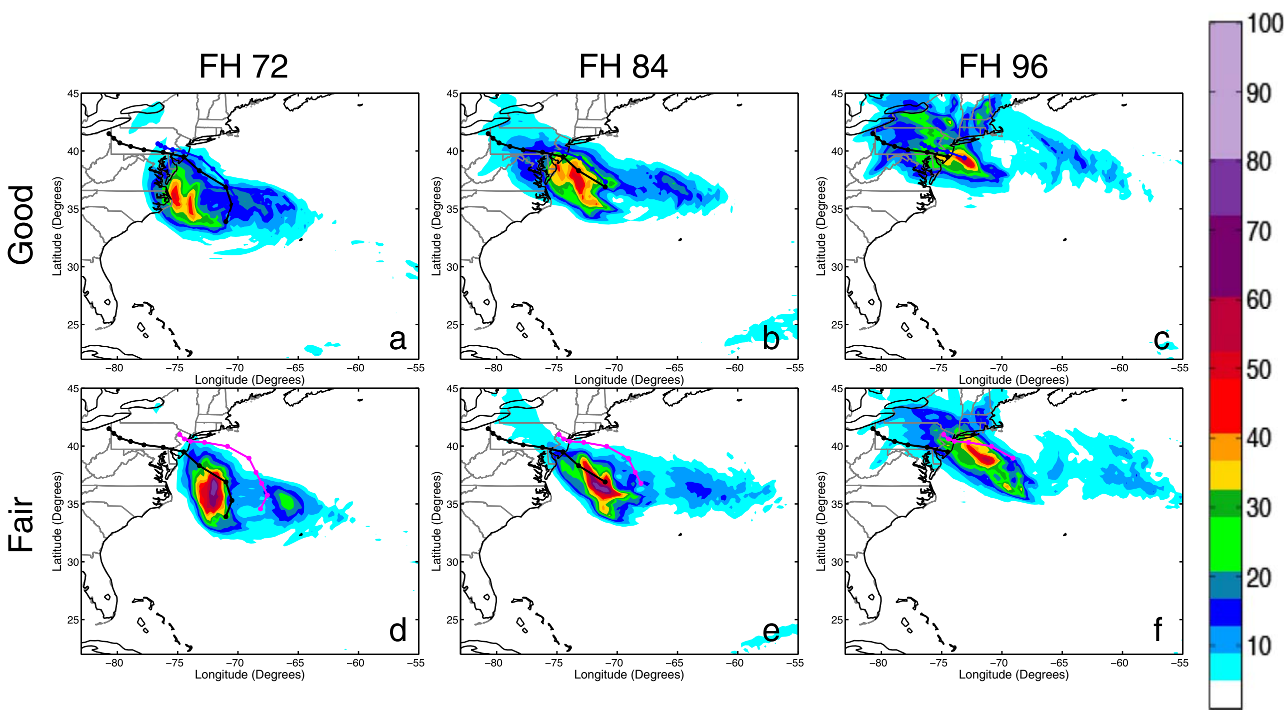

Figure 11. Accumulated precipitation (in mm) over the 6 h prior to Forecast Hour (FH) (a and d) 72, (b and e) 84, and (c and f) 96 for the composite groups (top) GOOD and (bottom)FAIR. The NHC Best Track (black with positions marked every 6 h) and composite tracks (blue—GOOD, magenta—FAIR with positions marked every 6 h) are also plotted from the analyzed Forecast Hour until Sandy's dissipation/the end of the simulation.

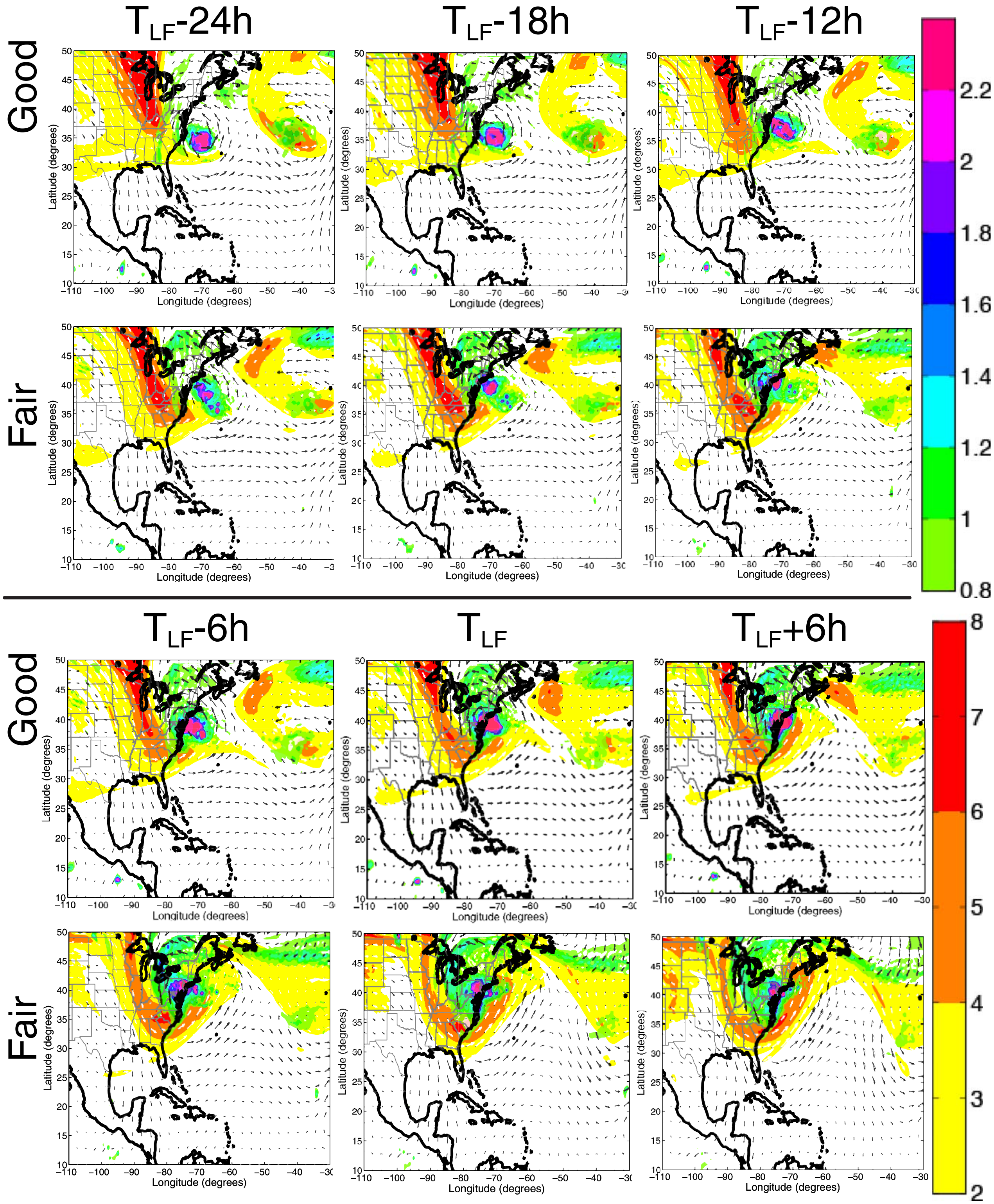

Figure 12. As in Figure 10, but for 24, 18, 12, and 6 h prior to landfall, at landfall, and 6 h after landfall.

difference in tracks is apparent as the PV maximum associated with Sandy is located both further to the east as a result of the track divergence and much further to the north due to the difference in the timing of landfall. Since there is no observable differences between the locations of the midlatitude trough in both composite groups, this stagger in landfall time allows Sandy to interact with the midlatitude trough in FAIR at least 24

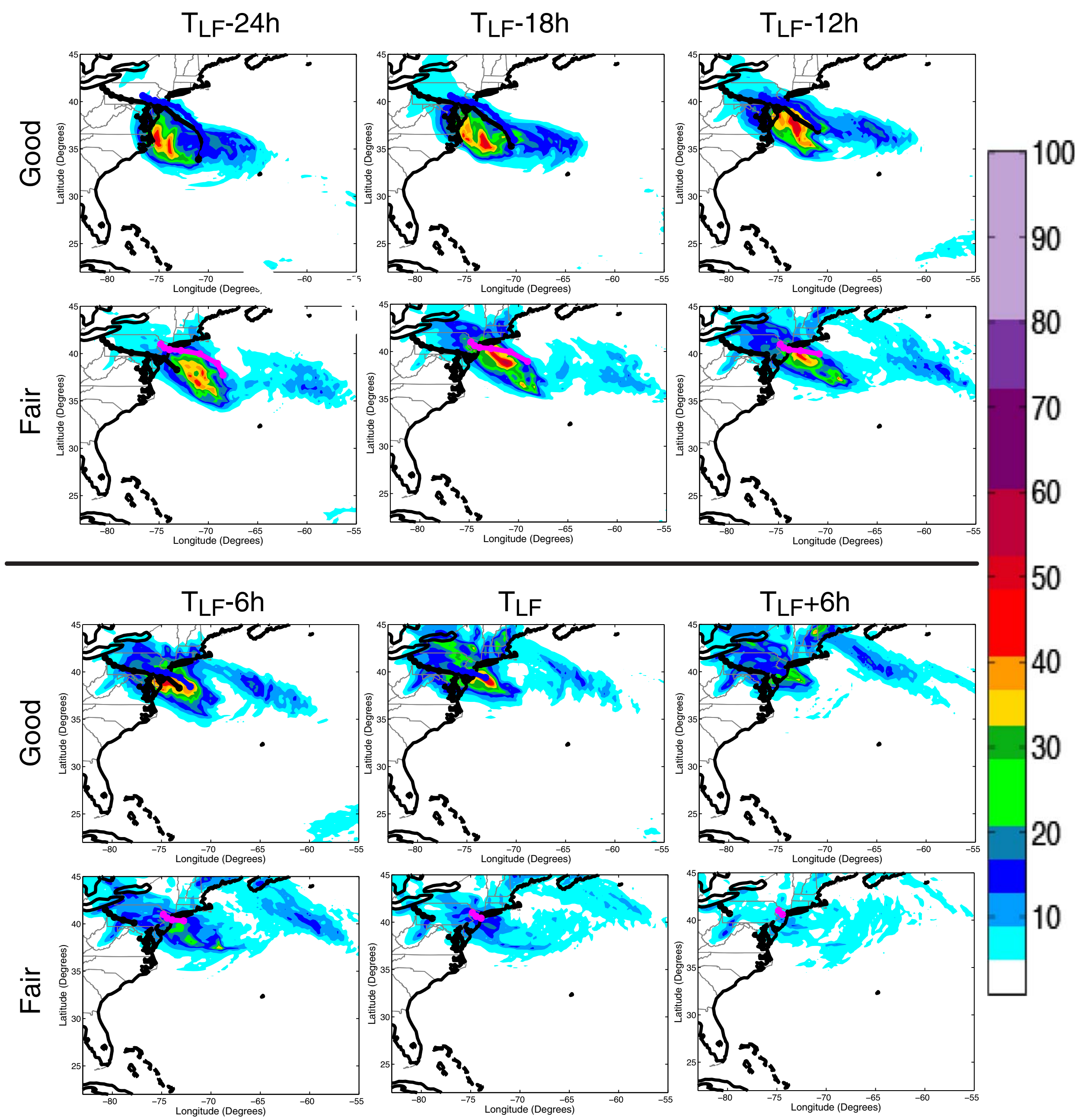

Figure 13. As in Figure 11, but for 24, 18, 12, and 6 h prior to landfall, at landfall, and 6 h after landfall.

h prior to landfall, while the interaction in GOOD does not begin until approximately 12 h before landfall. The rainfall distributions (Figure 13) reflect this difference in the timing of the midlatitude trough and tropical cyclone interaction, particularly when the total rainfall over land is considered. At 24, 18, and 12 h before landfall, the GOOD composite rainfall is concentrated to the left of the center of Sandy, with heavier amounts of rainfall occurring over the coastal regions of the United States than in the FAIR composites, primarily due to the proximity to the coast of Sandy in GOOD compared to FAIR. In addition, the rainfall distributions in FAIR have a more elongated, rather than circular shape, as the additional distance between the midlatitude trough and Sandy creates this structure in the rainfall distribution.

[35] By 6 h prior to landfall, the members of Sandy in GOOD are strongly interacting with the midlatitude trough and are therefore continuing the production of heavy rainfall that is located very near or over the Mid-Atlantic region of the United States. Meanwhile, the FAIR composite has already completed the interaction between the midlatitude trough and Sandy and the majority of the precipitation has already fallen. These rainfall structures continue to be observed throughout landfall and in the 6 h after landfall, although at these times the members of Sandy have begun to weaken as well due to

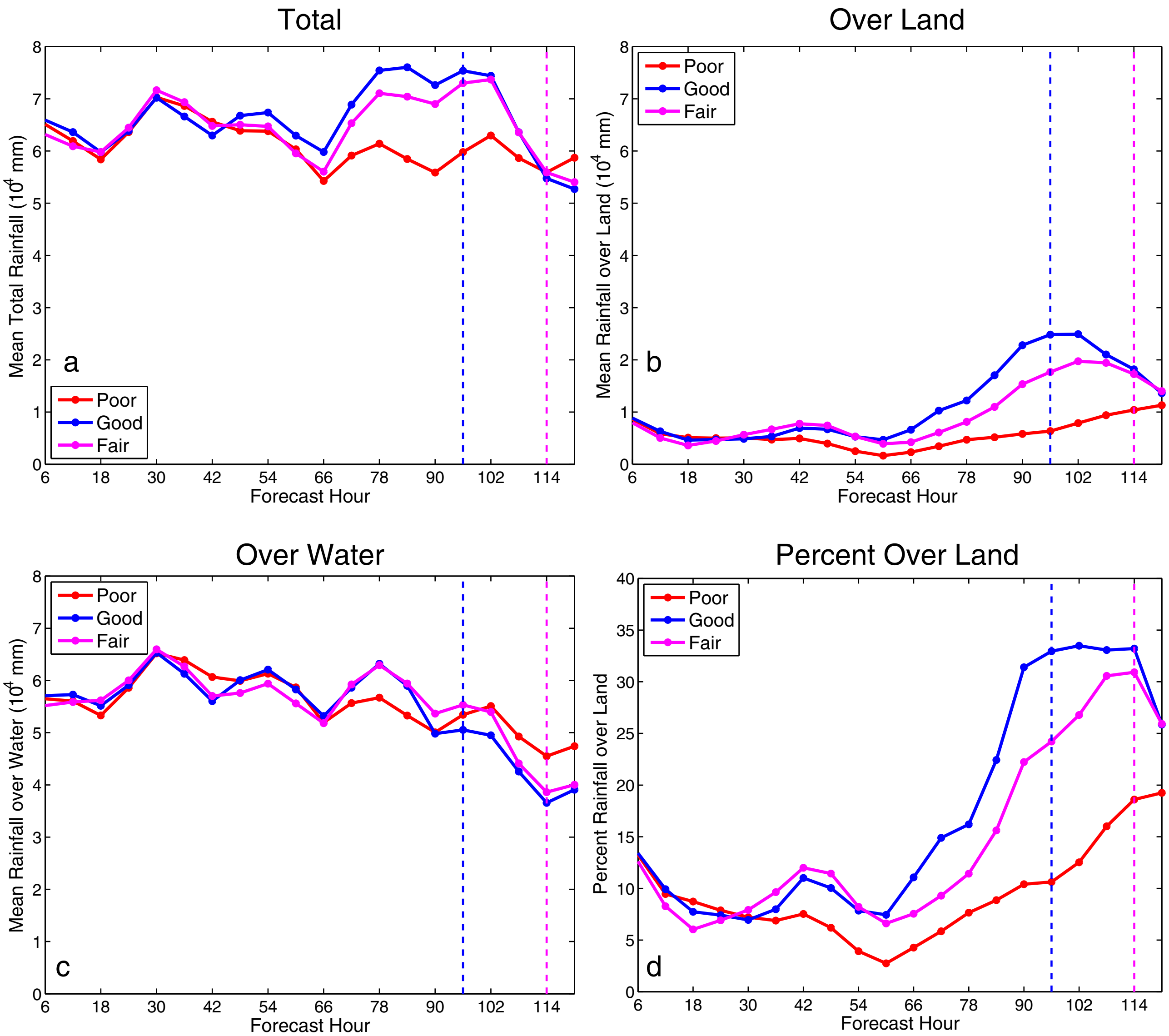

Figure 14. (a) Total, (b) over land, (c) over water, and (d) percent over land of the accumulated precipitation for 6 h intervals (marked) for the composite groups GOOD (blue), FAIR (magenta), and POOR (red). Forecast Hours indicate the amount of precipitation that was produced over the previous 6 h. The dashed vertical lines indicate the Forecast Hour in which Sandy made landfall (GOOD—blue; FAIR—magenta).

their interactions with land, which diminishes areas of convection and decreases the overall amount of rainfall.

[36] To more clearly illustrate the differences in the total amounts of rainfall associated with each composite group, accumulations over 6 h intervals are plotted (Figure 14a). These accumulations are also divided into total rainfall over land (Figure 14b), total rainfall over water (Figure 14c) and the percent of the total rainfall over land (Figure 14d). At Forecast Hour 66, there is a sharp increase in the total rainfall in both GOOD and FAIR, while the rainfall totals in POOR remain relatively constant. This increase is related to the secondary peak in intensity that Sandy reaches at this time (1800 UTC 29 October 2012) and the total rainfall continues to grow as the interaction between Sandy and the midlatitude trough intensifies (primarily between Forecast Hours 72 and 84). As the total rainfall in GOOD and FAIR increases during these forecast hours, the total rainfall over land and the percent of rainfall over land also increases, however the increase is sharper for the GOOD composite. This is again primarily due to the difference in location of Sandy among the composites, as the interaction between the midlatitude trough and Sandy occurs much closer to the time of landfall and therefore in closer proximity to the coastline in GOOD than in FAIR. By the time FAIR makes landfall at Forecast Hour 114, the total rainfall has already begun to decrease, which indicates that the interaction between the midlatitude trough and Sandy has already released a majority of the available precipitation prior

to landfall. This leads to the difference in precipitation totals over land and indicates that the timing of the midlatitude trough and tropical cyclone interaction in GOOD is more favorable for producing higher cumulative rainfall totals than in FAIR.

4. Summary and Conclusions

[37] It has been shown that the PSU WRF-EnKF real-time track and intensity forecasts for Hurricane Sandy (2012) demonstrated comparable skill to operational models such as the ECMWF and GFS at lead times of up to 4 or 5 days. For the forecast initialized at 0000 UTC 26 October 2012, the majority of the 60 ensemble members accurately predict a landfall of Sandy somewhere along the Mid-Atlantic to New England coastline, however, 10 members fail and forecast Sandy to head out to sea. Based on the performance of the ensemble, determined by the root-mean-square error between the best track and the track of a given member, composite groups of 10 members are formed (GOOD, FAIR, and POOR). The differences in track amongst these composite groups result from strong sensitivity to the location of the center of Sandy over the first 48 h of the simulation. In the first 24 h of the simulation, the tropical cyclones in GOOD travel a further distance to the northwest than FAIR or POOR and therefore the composite center is located closer to the United States coastline. This divergence in the location of the composite centers occurs primarily because of stronger easterly winds in GOOD in the midtropospheric layer (700 hPa–500 hPa), which is typically the region of the wind profile that has the greatest influence on the steering of tropical cyclones. The subsequent divergence between the tracks of FAIR and POOR occurs between Forecast Hour 24 and 48 and is again caused by differences in the steering flow, where the winds that Sandy is embedded in are stronger in FAIR than in POOR. Therefore, it is the evolution of the position of Sandy over the first 48 h of the simulation that controls whether a given member makes landfall or not, with the forward motion of the tropical cyclone over the first 24 h being the most important factor for producing a track in the ensemble that most closely resembles that of the best track. There appears to be little to no influence on the tracks of the ensemble by other synoptic features in the simulation, such as the midlatitude front that Sandy eventually interacts with, as any differences that exist among the composite groups are negligible.

[38] The track divergence in this ensemble impacts other forecasts of variables that are sensitive to track. In particular, it has been shown that the PSU WRF-EnKF real-time system performs remarkably well when forecasting rainfall totals associated with Sandy, provided that the tracks of the members analyzed are most similar to the best track. The composite group GOOD, constituting of the 10 most successful track forecasts, was therefore able to accurately predict both the locations and magnitudes of rainfall in addition to correctly forecasting isolated areas of intense inland precipitation that were enhanced by phenomena such as orographic effects. The precipitation forecast of FAIR was similarly able to capture areas of localized intense rainfall, although the cumulative totals throughout the rainfall field were lower in magnitude than that of the observations or GOOD. This difference in the accumulated rainfall totals over land results from a difference in the timing of the interaction between Hurricane Sandy and the advancing midlatitude front, as the interaction occurs with the GOOD composite members closer to the coastline itself, and therefore closer to the landfall time. This causes the majority of the most intense rainfall to occur over land in GOOD, while the most intense rainfall occurs before landfall over the ocean in FAIR. Therefore, the synoptic setup and position of Hurricane Sandy in the composite group GOOD allows for a near maximization in the rainfall totals in the landfalling region.

[39] **Acknowledgments.** This work is partially supported by NOAA under the Hurricane Forecast Improvement Project (HFIP) and by NASA under grant NNX12AJ79G. The authors thank Yonghui Weng for performing the real-time forecasts. Computing is performed at NOAA and the Texas Advanced Computing Center (TACC).

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