DYNAMICS AND PREDICTABILITY OF TROPICAL CYCLONES
EVALUATED THROUGH CONVECTION-PERMITTING ENSEMBLE
ANALYSES AND FORECASTS WITH AIRBORNE RADAR AND SOUNDING
OBSERVATIONS

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Erin B. Munsell

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The dissertation of Erin Munsell was reviewed and approved* by the following:

Fuqing Zhang  
Professor of Meteorology  
Dissertation Advisor  
Chair of Committee

Marcelo Chamecki  
Adjunct Associate Professor of Meteorology

Steven J. Greybush  
Assistant Professor of Meteorology

James F. Kasting  
Evan Pugh Professor of Geosciences

Jason A. Sippel  
Contractor, I.M. Systems Group and NOAA/Environmental Modeling Center  
Special Member

Hans Verlinde  
Professor of Meteorology  
Associate Head, Graduate Program in Meteorology

*Signatures are on file in the Graduate School
ABSTRACT

The dynamics and predictability of various aspects of tropical cyclone track and intensity forecasting are explored through the use of real-time convection-permitting ensemble forecasts generated by a regional-scale model that employs advanced data assimilation techniques. Airborne Doppler radar observations, as well as sounding observations gathered during NASA’s Hurricane and Severe Storm Sentinel (HS3) are assimilated and the resulting sensitivity and uncertainty of divergent track and intensity forecasts for three Atlantic tropical cyclones (TCs; Hurricane Sandy (2012), Hurricane Nadine (2012), and Hurricane Edouard (2014)) are explored. Ensemble members are separated into groups according to their performance and composite analyses and ensemble sensitivity techniques are employed to diagnose the sources of greatest sensitivity and uncertainty, as well as to dynamically explain the divergent behavior observed in the forecasts.

The analysis of the Hurricane Sandy (2012) ensemble reveals that the divergent track forecasts result from differences in the location of Sandy that develop over the first 48-h of the simulation as a result of variance in the strength of the environmental winds that Sandy is embedded in throughout this period. Disparities in the strength and position of an approaching mid-latitude trough yield divergence in track forecasts of Hurricane Nadine (2012); an increased interaction between the mid-latitude system and the TC steers Nadine eastward, while a reduced interaction allows the TC to be steered westward ahead of the approaching trough. In addition, the inclusion of 6-h sea surface temperature (SST) updates considerably improves Nadine’s intensity forecasts, highlighting the importance of accurate SST fields when simulating TCs embedded in marginally
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Chapter 1

Introduction

The social and economic damage that tropical cyclones (TCs) are capable of is apparent. Despite the perceived recent drought of United States landfalls, by normalizing historical damage figures to today’s societal vulnerability, the decade from 2000 – 2010 still produced 8 of the 30 costliest Atlantic TCs (Blake et al. 2011). It has long been recognized that a crucial factor in mitigating some of the risks associated with these storms is lead-time prior to the storm impacting land, as the appropriate residents and businesses need time to prepare for, or in the worst cases, evacuate from the potentially affected areas. Therefore, the continual improvement of TC track and intensity forecasts is of great societal importance.

Over the past few decades, considerable efforts have been made towards the improvement of tropical cyclone track and intensity forecasting at increasingly longer lead times. In the Atlantic Basin, errors associated with track forecasts have steadily decreased over the past 25 years at all lead times, as a 48-h forecast made today is on average as successful as a 24-h forecast from 10 years ago (Cangialosi and Franklin 2013). However, the errors associated with intensity over the same time period have remained relatively unchanged (Rappaport et al. 2009). There is some evidence that decreases in intensity errors have been achieved at longer lead times but the results are uneven. Part of the reason for the discrepancy in the performance of the track and intensity forecasts can be explained by the predictability of the dynamics that govern the position and intensity of a tropical cyclone.
Before discussing the limits of tropical cyclone predictability in greater detail, an understanding of general atmospheric predictability ideas is required. The two types of predictability for a given atmospheric system are the intrinsic predictability and the practical predictability. The intrinsic predictability is defined as “the extent to which prediction is possible if an optimum procedure is used” (Lorenz 1969), while the practical predictability examines the ability to predict the system given the available resources and procedures. Differences that arise from infinitesimally small disparities in the initial conditions are limited by their intrinsic predictability, while increased uncertainty and larger errors in the initial conditions that are typically present in forecast models limit the practical predictability of a given system (Lorenz 1996).

Intrinsic and practical predictability are flow-dependent and therefore both can be limited during a regime change, as in the case of the classical Lorenz attractor. Much of the unpredictability in these cases can be attributed to chaotic behavior that occurs in the flows, particularly near the interface between the two regimes. This phenomenon has been demonstrated repeatedly in atmospheric mesoscale flows through the utilization of sensitivity experiments and ensemble simulations. Zhang et al. (2002) determined that small errors in the initial conditions of a mesoscale modeled winter cyclone led to rapid error growth that limited the predictability of the quantitative precipitation forecasts associated with the system. Furthermore, Zhang et al. (2003) utilized the winter cyclone case to highlight the intrinsic limit of predictability that is imposed on a system controlled by moist convective processes. The Zhang et al. (2006) study, in which a warm-season precipitation event was simulated using a mesoscale model, demonstrated that there was room for improvement in the practical predictability of the system through the reduction
of errors in the initial analysis fields by improved data assimilation techniques, enhanced observations or improved model parameterizations. However, an intrinsic limit of predictability remained present as a result of the importance of moist convection dynamics at these scales. The stages of error-growth dynamics in moist baroclinic wave simulations were elucidated in the Zhang et al. (2007) study, where it was exhibited that errors that grow from small-scale convective instabilities can evolve into errors that are retained in the larger-scale balanced motions. Finally, in an ensemble simulation of a squall line and bow echo, Melhauser and Zhang (2012) showed that realistic errors introduced in the initial conditions led to large variability in the forecasted convective weather. Further sensitivity experiments that employed an additional decrease in the initial condition error still produced forecasts with significant variability, demonstrating the limited predictability of the mesoscale system.

The numerous operational and experimental tropical cyclone forecasting models available to both the public and the tropical cyclone research community all have limitations on their practical predictability that result from a variety of variables. As increased computing resources become available, the grid spacing that many of these models are simulated at have become quite fine. The utilization of nested domains helps to mitigate computational costs, allowing for higher resolutions in the innermost domain, which the TC of interest is embedded. However, resolutions typically are not below a threshold of a few kilometers, and therefore cannot properly resolve all TC features. Parameterizations have been developed to characterize behavior that is not explicitly resolved, however, limitations exist in these schemes (Zhang et al. 2011).
Recent developments of more advanced data assimilation techniques have also shown promise in improving the modeling of tropical cyclones. In particular, as is used throughout this study, the ensemble Kalman filter (EnKF; Evensen 1994, 2003) has allowed for the assimilation of a wide-array of observations, including sounding (Aksoy et al. 2013, Poterjoy and Zhang 2014) and airborne Doppler radar (Zhang et al. 2009; Weng and Zhang 2012) data, leading to improvements in track and intensity forecasts in a variety of tropical cyclone cases. Although, when assimilating observations one must keep in mind the quantity and quality of the data, as observational errors will certainly impact the practical predictability of the system.

The EnKF is a simplified approach of traditional Kalman filtering, which takes advantage of the ability to carry out an ensemble of data assimilation cycles simultaneously (Houtemaker et al. 1996; Hamill and Snyder 2000; Anderson 2001). The PSU WRF-EnKF system uses a square-root ensemble filter (EnSRF; Whitaker and Hamill 2002; Snyder and Zhang 2003) algorithm, which helps address the underestimation of the posterior covariance that is typically present in perturbed-observation EnKFs. The Kalman gain is calculated as in a standard EnKF to update the ensemble mean, however, the ensemble perturbations are updated using a “reduced” Kalman gain, which is simply the Kalman gain multiplied by a coefficient between 0 and 1. This coefficient depends on the observation and background error variance at each observation location. In addition, each observation in this WRF-EnKF system is assimilated serially, which avoids the calculation of matrix square roots and therefore reduces the computational cost.
At each analysis time, the prior ensemble is generated by propagating the posterior ensemble forward in time. The posterior mean is subsequently updated by computing a weighted difference based on the innovation (difference between the observations and the model state) and adding it to the prior mean. The perturbations at this time are then updated using the EnSRF, as described above. Because of the relatively small sample size in this ensemble, localization is employed on the background error covariance in order to remove spurious correlations between variables at large distances that are likely not physically meaningful. In addition, covariance relaxation (Zhang et al. 2004) is performed in the PSU WRF-EnKF system to inflate the background error covariance and encourage the growth of the ensemble spread. These techniques contribute to the production of a sufficient amount of spread in the ensemble throughout the forecast period, which allows for the examination of the intrinsic predictability in TC forecasts through the many analyses performed in this dissertation.

The introduction of these ensemble forecasts to operational forecasters has provided potential track and intensity evolutions that may deviate significantly from a deterministic forecast. The spread of the ensemble also provides forecasters with uncertainty estimates, including probabilities of various outcomes based on the evolutions of the members. Therefore, all forecasts analyzed in this dissertation utilize ensemble forecasts to assess the predictability and uncertainty associated with the tropical cyclone of interest.

Advances in data assimilation techniques can only be beneficial for operational TC forecasting if a significant amount of observations are available. Since TCs spend the majority of their lifetimes over the open ocean, direct measurements of the TC can be
sparse. Reconnaissance missions are routinely flown in the North Atlantic and Northeast Pacific, but only when the TC of interest is within range of the aircraft. In addition, reconnaissance is not performed regularly throughout the rest of the world. Therefore, the primary source of TC observations is through remote sensing techniques such as satellite radiometers (visible, infrared, and microwave), precipitation and cloud radars (ground, airborne, and satellite), and satellite scatterometers (Laing and Evans 2011). Infrared images in particular, provide the best source of data for estimating the intensity of a TC when reconnaissance observations are not available through the Dvorak technique (Dvorak 1975; Velden et al. 2005; Olander and Velden 2007). While infrared techniques observe cloud tops, microwave imagery is sensitive to the hydrometeors in the TC, and therefore can provide additional information about the underlying TC structure that may be obscured by clouds. Radars offer additional information about the structure and intensity of precipitation in the TC, both in the outer rainband region and the intense inner-core convection in the eyewall, while microwave scatterometers measure surface wind speeds through backscatter from small-scale waves on the ocean surface. The assimilation of remotely sensed data is accompanied by numerous challenges, as many of the observations are not model variables and therefore more sophisticated data assimilation strategies must be developed. However, despite these challenges, TC satellite data assimilation has the potential for great improvements in operational TC intensity forecasting as a result of the wealth of remotely sensed TC observations that are routinely collected.

The lack of significant improvement in operational TC intensity forecasting over the past few decades can in part be attributed to the reduced predictability that is typically
observed in systems dominated by moist convection (e.g., Zhang and Sippel 2009).

Although TC intensity predictability may be intrinsically limited, previous studies have uncovered relationships between environmental variables and the resulting intensity of a TC that are in agreement with the governing dynamics. Sippel and Zhang (2008) investigated an ensemble of simulations of a nondeveloping Gulf of Mexico low from the summer of 2004 and discovered a moderate correlation between the initial moisture profile from the surface up to 300-hPa and the final intensity of the low. Uncertainty in the rapid intensification of Hurricane Humberto (2007) also resulted from variations in the midlevel moisture of the ensemble, in addition to differences in the low-level convective instability and the strength of a front to the north of the TC (Sippel and Zhang 2010). However, Sippel et al. (2011) found that initial low-level potential vorticity was the factor most strongly correlated with the final intensity of Tropical Storm Debby (2006). In an investigation of Tropical Storm Erika (2009), Munsell et al. (2013) demonstrated that the significant ensemble spread in intensity resulted from a complicated relationship between the initial strength of the vortex and midlevel environmental dry air in the vicinity of the storm. The moderate vertical wind shear that Erika was embedded in further reduced the predictability of this system as is demonstrated in Zhang and Tao (2013). Although moist convection limits the predictability of TC intensity, correlations between environmental variables such as midlevel moisture, vortex strength, and vertical wind shear and final intensity do exist in most ensemble simulations.

Given the potential increase in understanding of TC governing dynamics and their associated uncertainties provided by these ensemble analyses, this study aims to utilize
real-time convection-permitting ensemble forecasts of tropical cyclones generated by a sophisticated regional-scale model with advanced data assimilation capabilities to analyze the dynamics and predictability associated with a variety of TC evolutions. Chapter 2 uses ensemble simulations of Hurricane Sandy (2012) to investigate the sensitivity and dynamics associated with the complicated synoptic set-up that led to divergent track forecasts. Chapter 3 utilizes a similar ensemble simulation to explore the TC/mid-latitude interactions that led to divergent forecasts in Hurricane Nadine (2012), as well as examining the impacts of the lack of updated SST fields on real-time intensity forecasts, especially in TCs embedded in marginal environments. Finally, Chapter 4 focuses on the predictability associated with ensemble intensity forecasts of the near-rapid intensification (RI) event of Hurricane Edouard (2014). Chapter 5 presents a summary and the main conclusions of this dissertation.
Chapter 2
Prediction and uncertainty of Hurricane Sandy (2012) explored through a real-time cloud-permitting ensemble analysis and forecast system assimilating airborne Doppler radar observations

2.1 Introduction

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.

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 towards 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 hours 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 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.

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 towards 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 set-up 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 towards 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.

Although the track and evolution of Sandy was somewhat uncommon, as Atlantic Basin TCs typically do not curve towards 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 four 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 mid-latitude trough interaction that Sandy undergoes just prior to landfall.

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.
2.2 Methodology and data

2.2.1 PSU WRF-EnKF Real-Time System

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 (2015).

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 10200 x 6600 km (378 x 243 grid points), 2700 x 2700 km (303 x 303 grid points), and 900 x 900 km (303 x 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.

2.2.2 Operational model data

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.

2.3 Results and Discussion

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

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 2-1 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 October 26 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 lead time (Figs. 2-1a-c), 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.

At the 72-h lead time (Figs. 2-1d-f), 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 towards 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.

Finally, at the 48-h lead time the performance of the models is fairly comparable, however the PSU WRF-EnKF forecast performs the best (Figs. 2-1g-i). 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.

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

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 2-2a 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 ten 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 ten of these whose cumulative RMSE’s fall between that of GOOD and POOR became the composite group FAIR. Figure 2-2b 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.

In addition to the ensemble track forecasts, the mean intensity evolution of the composite groups also compare favorably with the best track intensity. Figures 2-2c and 2-2e 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 Figs. 2-2d and 2-2f 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.

### 2.3.3 Comparisons of the Synoptic Environments of the Composite Groups

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 2-3 shows composite plots for GOOD, FAIR and POOR of 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 (Fig. 2-3, top row) 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 mid-tropospheric 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.

At Forecast Hour 24 (Fig. 2-3, second row), Sandy has continued to move towards 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 (Fig. 2-4). The difference plots at Forecast Hour 0 (Fig. 2-4, top row) 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 (Fig. 2-4, 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 (Fig. 2-2b), 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.

By Forecast Hour 48 (Fig. 2-3, third row) Sandy has made a turn towards 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 Fig. 2-4 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 Fig. 2-4, 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.

The surface maps for Forecast Hour 96 (Fig. 2-3, bottom row) clearly show the divergence in track for this ensemble. In the GOOD and FAIR composites, Sandy has turned back towards 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 towards 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 (Fig. 2-4, bottom row) 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 hours 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.

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

The surface maps and difference plots analyzed above revealed a connection between the location of Hurricane Sandy during the first 48 hours 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 hours 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, mid-tropospheric flow (700 hPa – 500 hPa) averaged over an area of 5 to 7 degrees of latitude from the center of the TC is highly correlated with tropical cyclone movement (Chan and Gray 1982). Figures 2-5a – c 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 Fig. 2-5 (not shown). At Forecast Hour 12, the GOOD profile is located to the left of the profiles for both FAIR and POOR. In the mid-tropospheric 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 towards 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 hours 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.

Although the vertical profiles of zonal wind provide evidence towards 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, Fig. 2-6 shows the evolution over the first 48 hours 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. 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 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 towards the northeast. This reveals that in the members composing both FAIR and POOR, Sandy has already turned towards 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 hours 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.

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 towards the northwest while the GFS steering flow has already turned towards 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.

The differences in zonal wind and the steering flow vectors among the composite groups over the first 24 hours 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 2-5d – f 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 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 (Fig. 2-6) 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 hours of the simulation. It is this difference in latitudinal position that leads to the track divergence between the composite groups FAIR and POOR.

2.3.5 Track Sensitivity and Uncertainty to the Initial Conditions: Tropical vs. Mid-Latitude

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 hours 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 McTaggert-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.

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 ten 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 Fig. 2-7. 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 (Fig. 2-4, 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 hours 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.

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 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 mid-latitude 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 mid-latitude 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 mid-latitude 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 mid-latitude 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 Fig. 2-8a.

Over the first 24 – 36 hours of the simulation, the MLGOOD_TCPOOR track turns towards 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 towards the northeast before curving back towards 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 mid-latitude 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 mid-latitude 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.

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 zonal winds are calculated and overlaid on the ensemble composite mean zonal winds at 500 hPa (Fig. 2-8b). 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 mid-level zonal winds of the frontal system are positive and relatively strong as the system is moving towards the east, while the winds in the southern portion of the domain are weak easterlies associated with the trade winds.

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 mid-level 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 mid-level 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.
2.3.6 Impacts of Ensemble Track Divergence: Differences in Rainfall Distributions and Interactions with the Mid-Latitude System

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 mid-latitude 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.
Figure 2-9 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.

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 and lower level PV can be plotted together (Fig. 2-10) 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 baroclinic zone exists and the PV associated with Sandy in GOOD is increasing.

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 2-11 shows the accumulated rainfall
over the previous six hours 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.

Since there is a shift in the timing of landfall among the composites, where GOOD makes landfall at Forecast Hour 96 or approximately 18 hours 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 2-12 shows the upper-level and lower-level PV plots for GOOD and FAIR (as in Fig. 2-10) for the forecast hours leading up to and immediately after landfall for the respective composite groups. At 24 hours prior to landfall, the 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 hours prior to landfall, while the interaction in GOOD does not begin until approximately 12 hours before landfall. The rainfall distributions (Fig. 2-13) 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 hours 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.

By 6 hours 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 hours after landfall, although at these times the members of Sandy have begun to weaken as well due to their interactions with land, which diminishes areas of convection and decreases the overall amount of rainfall.

To more clearly illustrate the differences in the total amounts of rainfall associated with each composite group, accumulations over 6 hour intervals are plotted
(Fig. 2-14a). These accumulations are also divided into total rainfall over land (Fig. 2-14b), total rainfall over water (Fig. 2-14c) and the percent of the total rainfall over land (Fig. 2-14d). 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.
2.4 Summary and Conclusions

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 four or five 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, ten 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 ten 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 hours of the simulation. In the first 24 hours 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 mid-tropospheric 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 hours 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 hours 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 mid-latitude front that Sandy eventually interacts with, as any differences that
exist among the composite groups are negligible.

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 ten 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 set-up and
position of Hurricane Sandy in the composite group GOOD allows for a near
maximization in the rainfall totals in the landfalling region.
Chapter 2 Figures

Figure 2-1: 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 0000 UTC 26 October 2012 (a-c), 0000 UTC 27 October 2012 (d-f) and 0000 UTC 28 October 2012 (g-i). 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 hours and the deterministic runs are plotted in cyan.
Figure 2-2: 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 (a)] and the 60 ensemble members of the PSU WRF-EnKF forecast initialized at 0000 UTC 26 October 2012 grouped by track performance; GOOD – the ten members with the smallest cumulative track RMSE between the member and the best track (blue), FAIR – ten members whose cumulative track RMSE fall between that of GOOD and POOR (magenta), and POOR – the ten members that do not landfall (red). A portion of the outermost domain in the WRF simulation is plotted in (a) and (b) with sea surface temperature contours every 1°C. Numbers in (b) indicate mean positions of each composite group at indicated forecast hour.
Figure 2-3: 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.
Figure 2-4: 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 Fig. 2-3 – GOOD-POOR (first column), GOOD-FAIR (second column) and FAIR-POOR (third column) for Forecast Hour 0, 24, 48 and 96.
Figure 2-5: 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.
Figure 2-6: 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).
Figure 2-7: (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.
Figure 2-8: (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).
Figure 2-9: 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 (a) and every 6 h in (b)-(d)] and the PSU WRF-EnKF composite tracks [blue in (b), magenta in (c) and red in (d) with positions marked every 6 h] are also plotted.
Figure 2-10: 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 GOOD (top row) and FAIR (bottom row) 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 2-11: 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 GOOD (top row) and FAIR (bottom row). 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 2-12: As in Fig. 2-10, but for 24, 18, 12 and 6 h prior to landfall, at landfall and 6 h after landfall.
Figure 2-13: As in Fig. 2-11, but for 24, 18, 12 and 6 h prior to landfall, at landfall and 6 h after landfall.
Figure 2-14: (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).
Chapter 3

Dynamics and predictability of Hurricane Nadine (2012) evaluated through convection-permitting ensemble analysis and forecasts

3.1 Introduction

This study examines sources of forecast uncertainty and error for Hurricane Nadine, a long-lived North Atlantic tropical cyclone that occurred in 2012. Simulations initialized at 0000 UTC 20 September 2012 with a convection-permitting hurricane forecast and analysis system (WRF-EnKF) are examined to better understand the large forecast uncertainties and errors that occurred during this period in terms of both track and intensity. The examination of this stage of Nadine’s lifetime also benefits from extensive observations taken during the National Aeronautics and Space Administration’s (NASA) Hurricane and Severe Storm Sentinel (HS3) mission, which are compared to the simulations in order to develop a better understanding of Nadine's behavior.

Nadine developed from a tropical wave that emerged from the African coast on 7 September (Brown 2013). The disturbance was classified as a tropical depression by 1200 UTC 10 September as it tracked west-northwestward around a large subtropical ridge, before being upgraded to Tropical Storm Nadine at 0000 UTC 12 September. Nadine continued to intensify, reaching hurricane strength by 1800 UTC 14 September as it moved northward through a break in the subtropical ridge. After the storm turned east, its convection began to decrease, and the system was downgraded to a tropical storm at 0000 UTC 17 September. Around this time Nadine turned northeastward towards the Azores, and it continued on this track until a blocking ridge to the north of the tropical
cyclone (TC) induced a turn towards the east-southeast on 0000 UTC 20 September. This time corresponds with the initialization time of the simulations of interest in this study. Also at this time, a mid- to upper-tropospheric trough and an associated cold front began to approach Nadine from the northwest, expanding Nadine’s wind field and causing the convection associated with the storm to diminish (Brown 2013; Figs. 3-1a-c). As a result of this interaction, Nadine was reclassified as a non-tropical low at 1800 UTC 21 September. Low-level steering flow then moved Nadine towards the south-southeast into a more conducive environment where deep convection was able to redevelop, allowing for the reclassification of Nadine as a tropical storm by 0000 UTC 23 September (Fig. 3-1d). During the remaining 48-h of the simulation window, another blocking ridge caused Nadine to complete a cyclonic loop and continue to move slowly towards the west-northwest as it slightly weakened (Figs. 3-1e-f). Beyond the simulation window, Nadine re-intensified to hurricane strength and reached its maximum intensity at 1200 UTC September 30.

Although National Hurricane Center (NHC) forecast errors for Hurricane Nadine were generally low (Brown 2013), periods of increased uncertainty and error existed. In particular, there were a few 4- and 5-day track forecasts whose errors exceeded that of the 5-year averages as Nadine initially approached the Azores on 20 September. Therefore, one goal of this study is to utilize the WRF-EnKF 60-member ensemble simulation to investigate the environmental variables that led to the uncertainty in the track forecasts. In addition, because WRF-EnKF intensity forecasts initialized during this period performed poorly, the reasons for intensity error are explored through an analysis of the
sensitivity to the sea surface temperature (SST) field and through comparisons between
the ensemble simulations and observational data.

Section 2 describes the WRF-EnKF setup and operational data utilized, while
Section 3 presents the composite analyses of Nadine’s track and intensity forecasts with
comparisons to the HS3 observations. Finally, Section 4 outlines the main conclusions of
this study.

3.2 Methodology and Data

3.2.1 WRF-EnKF hurricane analysis and forecast system

The deterministic and 60 member ensemble forecasts for Nadine are generated
using version 3.5.1 of the Advanced Research Weather and Research Forecasting (ARW-
WRF) model (Skamarock et al. 2008) and an EnKF data assimilation algorithm. The
model set-up is similar to what is described in Weng and Zhang (2012), but with the
added capability of continuous cycling assimilation of all conventional non-radiance
observations besides airborne reconnaissance measurements (Weng and Zhang 2014).
Three two-way nested domains are used with horizontal grid spacings of 27, 9 and 3 km,
which contain areas of 10200 x 6600 km (378 x 243 grid points), 2700 x 2700 km (303 x
303 grid points), and 900 x 900 km (303 x 303 grid points). The outermost domain is
fixed and encompasses the majority of the North Atlantic Ocean and North America. The
inner two domains are movable, with the center of the domain remaining aligned with the
center of the tropical cyclone of interest. The three domains have 44 vertical levels with
the top level at 10 hPa. The Grell-Devenyi cumulus parameterization scheme (Grell and Devenyi 2002) is employed in the outermost domain only. Additional parameterization schemes include the WRF single-moment six-class with graupel scheme (Hong et al. 2004) for microphysics and the Yonsei State University (YSU) scheme (Noh et al. 2003) for the planetary boundary layer. A one-dimensional ocean mixed-layer model based on Pollard et al. (1972) is also applied with an initial mixed layer depth of 50 m and a temperature lapse rate below the depth of the mixed layer of 0.14 Km$^{-1}$. The bulk exchange coefficients used to parameterize surface fluxes are obtained from the PSU option (Green and Zhang 2013). The WRF-EnKF system is initialized at 1200 UTC 9 September with the operational Global Forecast System (GFS) analysis, and the first data assimilation is conducted over all 3 domains at 0000 UTC 10 September after 12 h of ensemble integration. The system performs cycling assimilation every 3 hours until Nadine dissipates (0000 UTC 4 October). The operational GFS forecasts from 6 h prior are used as lateral boundary conditions for the deterministic forecast, while the ensemble lateral boundary conditions are generated by adding perturbations derived from the background error covariance of the WRF-VAR data assimilation system (Barker et al. 2004) to the deterministic lateral boundary conditions. The ensemble forecasts analyzed in this study are initialized with the EnKF analysis perturbations from 0000 UTC 20 September.

3.2.2 HS3 observations of Hurricane Nadine

Five HS3 flights were performed to collect observational data throughout the extensive lifetime of Hurricane Nadine by utilizing an unmanned Global Hawk aircraft.
These flights occurred on 11-12, 14-15, 19-20, 22-23, and 26-27 September. Two of these flights collected observations during the 5-day simulation window of this study (19-20 and 22-23 September), which correspond to 0 h–12 h and 72 h–84 h in the simulation. Only the Global Hawk equipped with the “environmental” instrument configuration was operational during this year of the HS3 experiment, collecting data through the utilization of NOAA/National Center for Atmospheric Research (NCAR) dropsondes (Black et al. 2011), the University of Wisconsin’s Scanning High-resolution Interferometer Sounder (Revercomb et al. 1998), and the NASA/Goddard Space Flight Center (GSFC) Cloud Physics Lidar (McGill et al. 2002). Seventy-six dropsondes were deployed during the 19-20 September flight, while 53 dropsondes were used throughout the 22-23 September flight. Since the WRF-EnKF assimilation window ends 90-min after the simulations are initialized, only 2 of the dropsondes from the 19-20 September flight were assimilated for the ensemble simulations analyzed in this study. The majority of the data collected can thus be utilized to independently verify how representative the simulations of Nadine were to the observed TC.

3.3 Results and Discussion

3.3.1 Forecast performance comparison of WRF-EnKF and operational ensemble

Given the unique and lengthy track of Hurricane Nadine, the performance of the WRF-EnKF system is first evaluated against that of an operational ensemble. Figure 3-2 shows a 126-h section (0000 UTC 20 September–0600 UTC 25 September) of the best
track of Nadine as well as the corresponding ensemble member forecast tracks from the WRF-EnKF system (Fig. 3-2a) and the European Centre for Medium-Range Weather Forecasting (ECMWF, Fig. 3-2b). There is clear divergence within both the operational ensembles (ECMWF and GFS – not shown) and the WRF-EnKF ensemble due to different forecasts of the interaction between Nadine and an approaching mid-latitude trough. Although the deterministic runs of the models at this time forecasted the southwestward turn ahead of the trough (not shown), the NHC official forecasts maintained the eastward trajectory for Nadine based on previous forecasts that had favored that scenario (Brown 2013). It is clear that as a result of the considerable spread and large uncertainty present in the ECMWF and the WRF-EnKF ensembles (Fig. 3-2), Nadine presented a significant operational forecast challenge that is worth exploring in further detail.

To help diagnose causes for the considerable uncertainty in the WRF-EnKF forecasts, the methodology employed in Munsell et al. (2013) and Munsell and Zhang (2014) was used to create two composite groups of ten ensemble members based on the performance of their track forecasts. The ten ensemble members with the smallest cumulative root mean square track error comprise the composite group GOOD, and the composite group POOR consists of the ten members whose storms are steered eastward by the approaching mid-latitude trough. Figure 3-2a highlights the members of the composite groups, as well as the mean tracks of the composites. The mean track of GOOD compares well with the best track. In addition, the mean tracks demonstrate that the members of GOOD and POOR have very similar positions over the first 24 hours of the simulation before slight variations in position begin to develop over the next 24
hours. Significant divergence in the mean tracks begins around 48 h, and therefore the analysis of the environmental influences on track uncertainty is focused on the period of time leading up to this track bifurcation.

The corresponding evolution of minimum sea level pressure (SLP in hPa, Fig. 3-3a) and maximum 10-m wind speed (in kts, Fig. 3-3b) reveals that although most of the members yielded successful track forecasts, the entirety of the ensemble predicted a steady intensification of Nadine that was not observed. Intensity errors associated with POOR were smaller than those associated with GOOD, though the tracks of POOR are completely different than the best track of Nadine so that the cyclones in these members encounter completely different environmental conditions than the observed storm. We next present a series of sensitivity experiments designed to diagnose the causes of the large intensity error from the WRF-EnKF forecasts during this period.

### 3.3.2 Intensity errors associated with the WRF-EnKF ensemble: SST sensitivity

In the original ensemble forecast of Nadine, the sea surface temperature (SST) field was prescribed from the GFS analysis and only evolved as a result of the 1D ocean model throughout the simulation. It has long been recognized that SST has a large influence on the potential formation and intensification of a tropical cyclone (e.g., Miller 1958; Gray 1968; Emanuel 1988; DeMaria and Kaplan 1994). Given the length of this simulation, significant changes in the observed SST field could have been induced by upwelling from the storm itself (Price 1981) or by shifts in the surface wind-driven currents (Kelly 1985; Emery et al. 1986).
To determine if significant changes in SST occurred over this 5-day period of Nadine’s lifetime, the real-time, global, sea surface temperature (RTG_SST) analysis fields developed by the National Centers for Environmental Prediction/Marine Modeling Analysis Branch are plotted for the initialization time (0000 UTC 20 September, Fig. 3-4a) and the final time (0600 UTC 25 September, Fig. 3-4b) of the simulation. The initial SST field shows that the storm occupied an area of the eastern Atlantic with SST’s typically considered to be too cold (lower than 26°C) for TC development or intensification. In addition, the final SST field is noticeably cooler than the initial field, and the disparity is more clearly illustrated in the difference field (Fig. 3-4c). The largest region of cooling (up to 3°C) is located in the area to the right of Nadine’s track, which is consistent with observational studies (Stramma et al. 1986; Shay et al. 1992) that found that the largest amount of upwelling and therefore cooling of the sea surface occurs to the right of the track of the TC. Therefore, the initially cool SST’s encountered by the simulated storms continue to become cooler (as low as 22°C – 24°C) as they move southward, particularly for the members of GOOD during the latter half of the simulation.

In order to examine the impact of the changing SST field on the intensity of the members of this ensemble, a sensitivity experiment is performed. Utilizing the RTG_SST daily analysis fields beginning at 0000 UTC 20 September, the 20 ensemble members comprising the composite groups GOOD and POOR are reintegrated with an updated SST field. Updates of the SST are performed every six hours, with the intermediate fields between the daily analysis fields at 0000 UTC derived through linear interpolation.
Though updating the SST field does not substantially change the mean tracks of GOOD or POOR (not shown), there is a significant impact upon intensity (Fig. 3-5). The evolution of the means of minimum SLP (Fig. 5a) and maximum 10-m winds (Fig. 3-5b) indicate a noticeable divergence in intensity after 48 h, after which point the members of GOOD with updated SST fields have significantly weaker storms than the members of GOOD from the original ensemble. Although intensification still occurs when the SST updates are included in the simulation, which was not observed in Nadine, utilizing the SST updates significantly reduces the intensity errors. Because the utilization of the SST updates yields improved intensity forecasts, particularly for the GOOD composite group, the remainder of the analysis performed in this study uses the results from the SST update sensitivity experiment.

An additional sensitivity experiment was performed utilizing two randomly selected members from both GOOD and POOR to test the influence of the simple 1D mixed-layer ocean model on the final intensity of the members in this ensemble. The two GOOD and the two POOR members were reintegrated using both the constant SST field as well as the SST updates with the 1D ocean model turned off. The resulting intensities of the simulations without the ocean model are for the most part consistent with the intensities when the ocean model is employed for both the constant SST and the updated SST experiments (not shown). Therefore, the exclusion of the simple mixed-layer ocean model has an insignificant influence on the intensity evolution, and the presence of the SST updates far outweighs the impact of the one-dimensional ocean model on the intensity forecasts in this ensemble.
3.3.3 Influences on surface fields and subsequent intensity as a result of SST updates

This section examines the means by which the evolving SST fields impact the intensity evolution. First proposed by Riehl (1954), it has continuously been demonstrated that the sea surface acts as a source of “fuel” that aids in the development, maintenance or intensification of a tropical cyclone through the transfer of sensible and latent heat at the air-sea interface (e.g., Ooyama 1969; Emanuel 1986). Figure 3-6 shows the mean sensible (Fig. 3-6a) and latent (Fig. 3-6b) heat fluxes of the composite groups GOOD and POOR averaged over an area within 300-km of the TC surface center for the original forecast and the SST sensitivity experiment. For both experiments the sensible and latent fluxes are initially comparable, but after 6 h (the time of the first SST update) the mean surface sensible and latent heat fluxes in both composites of the SST update experiment decrease significantly. Though the fluxes increase over the next 24 h in the sensitivity experiment, they remain weaker than in the constant SST simulations.

As the simulations evolve, the surface sensible and latent heat fluxes associated with the GOOD ensemble members slowly decrease, whereas the surface fluxes of GOOD in the constant SST experiment continue to steadily increase. During this portion of the simulation, the simulated storm moves southward into a region of the Atlantic in which relatively warmer SSTs were observed in the analysis field at the initialization time. However, because an overall cooling of the SSTs throughout this region occurred over the course of the 5-day simulation window, the inclusion of the SST updates leads to the divergence in surface flux strength. Meanwhile, the surface fluxes of POOR are similar in both sets of experiments because the POOR ensemble members turn eastward
ahead of the approaching mid-latitude trough and into a region in which the SST field
does not evolve drastically throughout the simulation window.

To determine if there is a relatively uniform or asymmetric pattern in the
reduction of the surface fluxes in the SST update experiment, storm-centered composites
of the sensible heating and the latent heating field of GOOD at 24 h for both the constant
SST (Fig. 3-7a and d) and the updated SST (Fig. 3-7b and e) experiments are plotted. The
differences between the two fields (updated SST – constant SST) are also displayed (Fig.
3-7c and f). There is a clear reduction in the sensible heat flux throughout the western
portion of the updated SST experiment composite (Fig. 3-7b). The differences between
the composites are particularly noticeable in the inner-core region (within 200-km of the
surface center) of Nadine, where a reduction of up to 40 W m$^{-2}$ is seen (Fig. 3-7c). This
decrease appears to be in part driven by the comparably weaker intensity of the simulated
vortices in the updated SST composites, while the area of reduced sensible heating to the
northwest of Nadine corresponds with the observed region of greatest cooling of the SST
field, as previously shown in Fig. 3-4c. The inclusion of the SST updates also leads to a
reduction in the surface latent heat flux in the same regions of significant SST cooling
(Fig. 3-7e). The latent heat fluxes are reduced by over 100 W m$^{-2}$ in the region to the
northwest of the surface center of Nadine (Fig. 3-7f).

It is clear from the analysis of the horizontal structure of the sensible and latent
heat fluxes that the overall cooling of the SST field that results from the inclusion of
updated SST analyses throughout the simulation reduces the surface fluxes, particularly
in the inner-core region to the west of Nadine’s surface center and in the region of the
most pronounced SST cooling to the northwest of Nadine. This reduction in both the
sensible and latent heat exchange at the air-sea interface prevents the GOOD members from the updated SST experiment from intensifying as quickly as the GOOD members from the constant SST simulation.

3.3.4 Ensemble track divergence analysis: Exploration of synoptic influences

This section uses the composite groups GOOD and POOR to examine the causes for track divergence in greater detail. The overall synoptic environments of the composite groups are assessed in Figs. 3-8 and 3-9, which show the storm-centered 2-km radar reflectivity field, minimum SLP contours, 10-m surface wind vectors, the 850-hPa – 200-hPa deep-layer shear vector, and the 850-hPa – 500-hPa vortex tilt vector before track divergence at 0, 24, and 48 h (Fig. 3-8), and after track divergence at 72, 96 and 120 h (Fig. 3-9). In both composites Nadine is initialized as a tropical storm with an asymmetric precipitation structure. There is a lack of significant convection associated with the storm at this time, but the strongest convection and the majority of the precipitation is located in the northwest quadrant near the inner-core for GOOD and on the north side for POOR. Consistent with past studies (Corbosiero and Molinari 2002; Rogers et al. 2003), these precipitation regions are located in the downshear-left quadrants of the TCs.

Stark differences between the composites emerge during the first 72 h. By 24 h, an approaching mid-latitude trough has begun to interact with the members of both groups (Fig. 3-8b and e) causing an extension of the precipitation to the northeast. Stronger convection between Nadine and the trough in the POOR composite suggests a stronger interaction between the two. By 48 h, the eastward passage of the mid-latitude trough has led to a shift in the shear vector in both composites resulting in a distribution
of convection in the storm that is concentrated in the southern to southeastern part of the storm (Fig. 3-8c and f). At 72 h, the trough has passed and is no longer interacting with the GOOD composite. In POOR, the interaction between the trough and Nadine is significantly reduced but still occurring due to the more eastward motion of Nadine in the POOR ensemble members (Fig. 3-9a and d). During this period, the area encompassed by the precipitation of the simulated storm is reduced, particularly in the GOOD composite where stronger values of radar reflectivity are now observed throughout the inner-core region of Nadine.

Differences between the composites continue to grow after 72 h. Though the strength of convection increases by 96 h in both composites, in the POOR composite the convection is more asymmetric and not as compact as in the GOOD composite (Fig. 3-9b and e). Because the storm is located farther eastward in the POOR composite members, the trough and storm are closer, increasing the westerly vertical wind shear and contributing to the asymmetric structure in convection. The storm in the GOOD composite continues to intensify through the end of the simulation, and its structure becomes very symmetric and compact (Fig. 3-9c). Storms in the POOR composite are less intense and more asymmetric (Fig. 3-9f). It should be noted that because of the divergence in track (Fig. 3-2a), these storm-centered composites are embedded in completely different environments, resulting in very different structures and intensities in these ensemble members.

It is crucial to understand the environmental influences during the early stages of the simulations that lead to the divergence in the track forecasts of Nadine. Past TC ensemble sensitivity studies (Zhang and Sippel 2009; Torn and Hakim 2009; Sippel and
Zhang 2010; Tao and Zhang 2014; Munsell and Zhang 2014) have shown that small, or even unobservable environmental differences can lead to considerably different track and/or intensity forecasts. Consequently, the following analysis of factors leading to track divergence will be confined to the 24-h before the tracks of the members diverge. A potential vorticity (PV) approach will be utilized in order to better understand potential impacts that the mid-latitude trough has on the subsequent track of the members of GOOD and POOR. This technique has proven to be effective at providing insight into the complex interactions that can occur between tropical cyclones and mid-latitude systems (Hoskins et al. 1985; Morgan and Neilsen-Gammon 1998; Atallah and Bosart 2003).

Figure 3-10 shows the upper-level (300-hPa to 200-hPa) and lower-level (850-hPa to 700-hPa) layer-averaged potential vorticity and wind composites for GOOD and POOR at 3-h intervals leading up to track divergence near 48 h. Unlike the storm-centered maps in Figs. 3-8 and 3-9, the GOOD and POOR composites are created in a fixed domain. Figure 3-10 reveals very similar structures in both composites from 30-36 h. The PV plots at 30 h suggest that low-level PV is stronger in the POOR composite, however the maximum values of PV in the individual ensemble members are comparable in GOOD and POOR. This apparent difference in low-level PV is simply a result of more position spread amongst the GOOD ensemble members. Although the strongest values of PV associated with the upper-level trough are located to the northeast of Nadine, the upper level PV filament wrapping around the surface vortex in both composites suggests some degree of trough-storm interaction. This interaction continues in both composites through 36 h.
By 39 h, subtle differences begin to emerge between the GOOD and POOR PV composites. In the POOR composite the mid-latitude trough is located farther west, and the surface center of Nadine is farther east, so that the distance between Nadine and the trough is noticeably smaller. The distance between the trough and Nadine in POOR continues to decrease through 45 h, and at this time the upper-level PV filament wrapping around the storm is somewhat stronger than in GOOD, and the low-level PV within the trough is somewhat closer to the storm center. Meanwhile, the distance between Nadine and the trough in the GOOD composite has increased sufficiently so that the upper-level PV filament encapsulating Nadine has weakened somewhat. This separation between Nadine and the upper-level trough occurs immediately prior to the forecast track divergence, which suggests that the positions of the trough and Nadine in the times leading up to the separation in tracks determines the final position of Nadine.

To help illuminate the differences between the GOOD and POOR composites, Fig. 3-11 shows the difference between the PV and wind fields of the composite groups (GOOD – POOR) for the same hours as in Fig. 3-10. Although significant differences were not visually apparent between the composites at 30 h in Fig. 3-10, the difference plot at this time (Fig. 3-11a) reveals a displacement in the position of the mid-latitude trough such that the trough is farther to the east in GOOD. These differences in trough position appear to result from differences in the mean background flow. There was no variance in trough position in the initial conditions of GOOD and POOR, but stronger upper-level westerlies in the vicinity of the trough in GOOD seem to have produced quicker eastward advection of the trough so that it was positioned farther east by 24 h (not shown). By 36 h, the difference in position of the mid-latitude trough has increased
and there is also a clear difference in the location of the low-level vortex (Fig. 3-11c). These differences continue to grow from 39 to 45 h (Figs. 3-11d-f).

The PV difference plots clearly reveal that the difference in location of the mid-latitude trough develops prior to the difference in position of the low-level vortex. This suggests that because the trough in the POOR composite is located farther to the west and closer to Nadine, the storms in POOR experience more of the westerly flow in the base of the trough. This difference in flow produces the subsequent separation in the position between GOOD and POOR and ultimately leads to the eastward tracks observed in the POOR ensemble members.

In order to confirm the proposed track divergence hypothesis, the evolution of the magnitude and direction of the steering flow vectors in the composites is explicitly calculated for the times leading up to the forecasted track divergence. The mid-tropospheric flow (700-hPa to 500-hPa) averaged over radii between 5 and 7 degrees of latitude from the TC surface center is typically highly correlated with tropical cyclone movement (Chan and Gray 1982). Since Nadine was a relatively small tropical cyclone, a smaller area is chosen to average over (radii between 200-km and 500-km) in order to put more focus on the near-storm environment. Figure 3-12 shows the mid-tropospheric steering flow vectors averaged over this near-storm environment for the GOOD and POOR composites for the hours leading up to the track divergence, as in Figs. 3-10 and 3-11. At 30 h, the direction of the GOOD and POOR composite steering flow vectors is similar, as the environmental flow that Nadine is embedded in is primarily northwesterly. However, by 33 h, the POOR steering flow vector is oriented approximately 30° farther to the east than the GOOD steering flow vector. This separation in the orientation of the
vectors is maintained throughout the simulations until track divergence, which suggests that this difference in steering flow direction leads to the storms in the POOR composite being steered farther eastward, as demonstrated in Fig. 3-11. These variations in the position of the vortex center of Nadine that develop over the 24-h leading up to track divergence determines whether Nadine is picked up by the approaching trough (POOR) or is steered towards the southwest ahead of the approaching trough (GOOD), as is observed in the best track.

To further support the claim that the track divergence can be attributed to differences in the direction of the mid-latitude trough-induced steering flow between 24 and 48 h, a similar analysis is performed utilizing the corresponding ECMWF operational ensemble initialized at 0000 UTC 20 September. This ensemble is comprised of 50 members, and as was done for the WRF-EnKF ensemble, the 10 members with the smallest cumulative root mean square track error were classified as the members of the composite group EC_GOOD. Furthermore, the 10 members with the largest cumulative root mean square track error became the composite group EC_POOR. Both the individual tracks of these 20 chosen members and the mean tracks of the two composite groups (Fig. 3-2b) demonstrate that a similar evolution is observed between both the most and least successful track forecasts of Nadine in the ECMWF and the WRF-EnKF ensembles.

Since a very similar track divergence was observed in both ensembles, the mid-tropospheric steering flow vectors for the composite groups were calculated in the same manner as the WRF-EnKF steering vectors for the times leading up to the departure in forecasted tracks. Since the ECMWF ensemble data is only archived at 6-h intervals, the steering flow vectors for each composite group are presented at 30, 36 and 42 h (Figs. 3-
13a-c). The direction of the steering flow at 30 h in both EC_GOOD and EC_POOR is northwesterly, as was observed in the WRF-EnKF ensemble. However, by 36 h the EC_POOR vector is approximately 20° farther east than the EC_GOOD steering flow vector. This difference in orientation increases by 42 h and appears to lead to the divergence of the forecasted tracks. Although the steering flow vectors are not identical in the WRF-EnKF and ECMWF ensembles, the difference between the composites is consistent. In particular, the EC_POOR steering vector is approximately 20° – 40° farther east (to the left) of the EC_GOOD vectors, further supporting the track divergence hypothesis.

3.3.5 Deviations amongst intensity forecasts: WRF-EnKF simulations versus HS3 observations

Though inclusion of 6-h SST updates significantly reduces intensity errors in the WRF-EnKF ensemble, substantial errors still remain. In order to explore what additional factors may have contributed to the erroneous intensification, observational data that was collected during the 19-20 September HS3 flight was examined. Figure 3-14 displays comparisons between vertical profiles of relative humidity, temperature and the zonal component of wind for 3, 6, 9 and 12 h from the NOAA/NCAR dropsondes deployed during HS3 and the GOOD composites. Although there is limited data availability at 0 h, the initial condition comparisons are consistent with the analysis at the other times (not shown). The dropsondes that were deployed within 90 minutes of the given time were utilized to create the observational composite profiles. The GOOD composite profiles were generated by averaging the profiles from the model grid points in each of the
ensemble members that were closest to the geographical location at which the dropsonde was deployed. Because the focus of this section is to examine the incorrect intensification of GOOD during the latter stages of the simulation, analysis of POOR is not included.

At all times, the temperature and the zonal wind profiles compare very favorably between the HS3 observations and the GOOD composites. Differences between the observational and GOOD temperature composite profiles are mostly below 2 K, while discrepancies between the zonal wind composite profiles rarely exceed 2 m s\(^{-1}\). The relative humidity profiles of the composite groups at 3 and 6 h are similar to the observed profiles at these times, except in the upper troposphere where dropsondes used in HS3 are known to have a dry bias (DeSlover et al. 2013). At 9 and 12 h, there is a bigger difference between the observed and simulated moisture profiles, particularly in the mid-to-upper troposphere. Though it is possible that the increased mid-level moisture present in the simulations leads to later intensity error, the simulated storm still intensifies in sensitivity experiments in which the mid-level moisture is lowered (not shown). It should also be noted that the corresponding POOR profiles compare very favorably to the GOOD profiles at these times (not shown), providing further evidence that the near-storm environment and intensity of the TC itself do not contribute to the subsequent track divergence.

Because the temporal range of the HS3 observations is somewhat limited, the evolution of the thermodynamic environment of GOOD is compared to relative humidity values obtained from the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) throughout the simulation window (Fig. 3-15a). Consistent with the SHIPS calculations (from the NCEP GFS analysis), the composite mean area-averaged
(between 200-km and 800-km from each member’s surface center) relative humidity of GOOD is calculated over the low-levels (850-hPa to 700-hPa), mid-levels (700-hPa to 500-hPa) and upper-levels (500-hPa to 300-hPa) of the atmosphere. The GOOD mid-level and upper-level relative humidity evolutions are very similar to the SHIPS data, as dry environmental air (relative humidity of ~30-35%) surrounds Nadine throughout the 5-day period. There is a slight discrepancy between the simulated and observed low-level relative humidity evolution with the GOOD low-level moisture being lower than the SHIPS data. In addition, the GOOD storm-centered composite mean of a horizontal cross-section of 700-hPa relative humidity from 06 UTC 20 September and observational 700-hPa moisture values obtained from the NOAA/NCAR dropsondes throughout the 19-20 September HS3 flight demonstrate that the spatial distribution of the simulated and observed relative humidity fields are for the most part in agreement (Fig. 3-16a). As was first indicated by the vertical profiles, there is some evidence that the mid-level environment was drier than in the simulations, particularly in the region to the west of the storm’s surface center. However, the general agreement between the evolution of the observed and simulated vertical and horizontal moisture fields suggests that WRF-EnKF intensity bias cannot be attributed to disparities in the thermodynamic environments.

Since the thermodynamic profiles of temperature and moisture are unable to explain the WRF-EnKF intensity error, we turn our focus to vertical wind shear, which has long been acknowledged to have a negative influence on the intensity of tropical cyclones (e.g., Simpson and Riehl 1958; Gray 1968; DeMaria and Kaplan 1994, 1999). Figure 3-15 shows the magnitude (Fig. 3-15b) and direction (Fig. 3-15c) of the area-averaged (between 200-km and 500-km from the surface center) deep-layer wind shear
(850-hPa to 200-hPa) for both the ensemble members and the resulting mean of the composite group GOOD. Observational data is also plotted from the Advanced Microwave Sounding Unit (AMSU; Zehr et al. 2008) and SHIPS. The mean initial shear magnitude is fairly large (approximately 18 m s\(^{-1}\)), but it decreases over the next 42-h to approximately 2–3 m s\(^{-1}\), and it does not significantly exceed 5 m s\(^{-1}\) through 68 h. Shear subsequently began to increase to a more moderate magnitude of approximately 10 m s\(^{-1}\) by the end of the simulation. The only discrepancy between the observed and simulated shear occurs after approximately 72 h, when the GOOD composite shear magnitude is 2–5 m s\(^{-1}\) weaker than the observational shear. While it is possible that this difference in shear is contributing to the intensity bias present in the WRF-EnKF simulations, by this time much of the bias is already present (Fig. 3-5). It is therefore not clear how much the shear discrepancy is a cause or result of the pre-existing intensity bias. In addition to and consistent with the above analysis, the POOR composite shear evolution is nearly identical to that of GOOD prior to track divergence (not shown), indicating that environmental shear does not play a role in determining the final track in this ensemble.

Since the observational and simulated thermodynamic and dynamic environments compare favorably, the evolution of the structure of Nadine’s vortex will next be investigated as a possible source of the erroneous intensification seen in the WRF-EnKF simulations. It is first important to note that the initial intensity of the WRF-EnKF storm is stronger than the observed storm in terms of both minimum SLP (by approximately 5–10-hPa; Fig. 3-5a) and maximum 10-m winds (by approximately 10 kts; Fig. 3-5b). Previous ensemble sensitivity studies in particular have shown that a bias in the initial intensity can have a significant impact on the final intensity of the vortex (Sippel et al.}
To examine this initial intensity discrepancy further, a storm-centered horizontal cross-section of the GOOD composite mean 950-hPa tangential winds at 6 h is plotted along with the NOAA/NCAR dropsonde 950-hPa tangential wind observations from the 19-20 September HS3 flight (Fig. 3-16b). At distances outside the TC inner-core (greater than 200-km from the surface center), the observations for the most part compare favorably with the simulated composite vortex. However, in the region to the northwest of the surface center, it appears that simulated wind speeds are slightly too strong. Furthermore, in the region closer to the inner-core of the vortex, greater differences in the tangential winds and the associated surface circulation arise. Although the dropsonde locations are somewhat spatially limited in the area of strongest tangential wind to the west of the surface center, it appears that the simulated vortex is approximately 5 m s$^{-1}$ stronger than was observed. More noticeably, in the area to the north and east of the surface center, the dropsonde tangential winds are as much as 10 m s$^{-1}$ weaker than the simulated tangential winds. Based on this comparison, the simulated GOOD composite circulation is at least 5 m s$^{-1}$ too strong near the center, too broad, and is distinctly more symmetric than the observed vortex of Nadine.

An initially stronger simulated vortex can contribute to the eventual erroneous intensification in the WRF-EnKF ensemble in a variety of ways. As a result of the dependence on both the temperature and wind speed difference across the air-sea interface, a stronger surface circulation will yield stronger surface sensible and latent heat fluxes, and in general, increase the rate of intensification. In addition, stronger and larger vortices are not only more resistant to dynamic environmental influences, such as vertical wind shear (Jones 1995; Reasor et al. 2004), but they also are able to more effectively
insulate themselves from adverse thermodynamic conditions, such as environmental dry air (Riemer and Montgomery 2011). Given the increase in vertical shear observed after 72 h, as well as the substantial amount of dry environmental air that surrounded Nadine throughout this period of its lifetime, the disparity in initial intensity between the observed and simulated vortex is the most likely cause of the erroneous intensification of the WRF-EnKF ensemble. It is further hypothesized that the primary reason for the initial intensity bias present in the WRF-EnKF simulations may at least in part result from errors that have developed over time from the continuous cycling present in the system. These cycling experiments utilized a constant SST field, which as was shown above, is most likely not sufficient for accurately simulating intensity in this case.

3.4 Summary and Conclusions

A 60-member ensemble simulation initialized at 0000 UTC 20 September 2012 by a WRF-EnKF hurricane analysis and forecast system has been utilized to explore the governing dynamics and predictability of long-lived Hurricane Nadine. The performance of the 5-day track forecasts in this ensemble are at least comparable to that of other operational models initialized at this time and were for the most part successful, with 50 of the 60 members correctly predicting Nadine’s turn towards the southwest ahead of an approaching mid-latitude trough approximately 48 – 72 h into the simulation. However, 10 members forecast Nadine to be carried eastward by the trough, and the resulting track divergence was investigated to assess aspects of the predictability of this system.
To investigate the causes for track divergence, two ten-member composite groups were created based on the cumulative track root mean square error (GOOD and POOR). The synoptic environments of these groups were explored in detail for the times leading up to the location of forecast divergence, which began at roughly 48 h (0000 UTC 22 September). It was discovered that differences in vortex location developed amongst the members around 36 h, with the centers in POOR located farther east than the centers in GOOD. In addition, a difference in the location of the mid-latitude trough was also observed as early as 30 h, with the trough of POOR positioned farther west than in GOOD and therefore closer to the simulated cyclone. The reduced distance between the TC and the mid-latitude trough led to a stronger interaction between the two systems so that TCs in the POOR members experienced a stronger eastward component of steering flow. This was confirmed through the utilization of upper- and lower-level PV compositing techniques and the calculation of the mid-tropospheric steering flow vectors. The vectors revealed that in the near-storm environment, there was a clear distinction in the direction of the steering flow between the GOOD and POOR composite groups, with the POOR vector consistently oriented approximately 30° farther east.

Despite the successful track forecast, the associated intensity forecasts of the WRF-EnKF ensemble were not as skillful. Although Nadine slowly weakened during this period, all 60 members forecasted a steady intensification, particularly after track divergence at 48 h. In an attempt to explain the intensity errors associated with these forecasts, a series of sensitivity experiments examined the influence of the SST on storm intensity. In the original simulations of Nadine, the SST field remained constant and was prescribed by the GFS analysis field at the initialization time. In the sensitivity
experiment, the simulations of the ten members of GOOD and POOR were reintegrated with the inclusion of updates to the SST field every 6-h. The intensity errors associated with the simulations of Nadine were significantly reduced as a result of the SST updates, particularly for the GOOD composite members. This reduction in intensity occurred primarily as a result of an overall cooling of the SST field that occurred throughout the 5-day simulation window in the vicinity of Nadine. It was shown that this cooling led to a reduction in the surface sensible and latent heat fluxes at the air-sea interface. As the fluxes remained weaker than had been seen in the original simulation, the rate of intensification of Nadine was not as strong.

The inclusion of updates to the SST field considerably reduced the intensity errors, but the simulated storms still remained too intense. Utilizing observational data collected during the 2012 phase of NASA’s HS3 experiment, comparisons between vertical profiles of moisture, temperature and winds from the NOAA/NCAR dropsondes and the GOOD composites yielded no significant differences between the observations and the model. In addition, limited variations were discovered between the observational and simulated environmental shear; a discrepancy of approximately 2 – 5 m s⁻¹ exists after 72 h. However, by this time an intensity bias was already present between the simulated and observed storms that could be traced back to initialization. The simulated storm was initially stronger by approximately 5 – 10-hPa in minimum SLP and 10 kts in maximum 10-m winds. A comparison of the 950-hPa tangential wind fields also suggested that the simulated circulation was too strong and too large. Most notably, the simulated vortex was more symmetric, with tangential wind speeds up to 10 m s⁻¹ stronger than the observations on the northern and eastern sides of the circulation.
Therefore, the stronger and slightly larger simulated vortex appears to have been more resilient to both adverse dynamic and thermodynamic environments that Nadine experienced during this period, and is the most likely cause of the intensity errors in the WRF-EnKF ensemble.

The results suggest that in similar cases of track divergence, particularly when there is a bifurcation point present in the ensemble, attention should be given to short-term forecasts or current observations of steering flow influences such as synoptic-scale features or large-scale environmental flows. Based on the analysis of this ensemble, it is probable that small yet noticeable deviations in track occur as much as 24 – 36 h prior to the TC reaching the bifurcation point. This information could provide forecasters with additional confidence towards one solution over the other. In addition, in cases where the TC occupies a region with a sharp SST gradient, operational models include SST updates as frequently as possible, as an improvement in intensity forecasts seems attainable.
Chapter 3 Figures

Figure 3-1: Enhanced infrared imagery of Hurricane Nadine from a NOAA satellite at (a) 1200 UTC 20 September 2012, (b) 1200 UTC 21 September 2012, (c) 1200 UTC 22 September 2012, (d) 1200 UTC 23 September 2012, (e) 1200 UTC 24 September 2012, and (f) 1200 UTC 25 September 2012.
Figure 3-2: 5-day track forecasts for the 60 member (a) WRF-EnKF and 50 member (b) ECMWF ensemble forecasting systems for Hurricane Nadine initialized at 0000 UTC 20 September 2012 grouped by track performance. The WRF-EnKF composite groups are GOOD—the 10 members with the smallest cumulative track RMSE between the member and the best track (blue in (a)) and POOR—the 10 members that curve eastward by the mid-latitude trough (red in (a)), while the ECMWF composite groups are EC_GOOD—as in GOOD but for the ECMWF ensemble (blue in (b)) and EC_POOR—10 members that are curved eastward by the mid-latitude trough (red in (b)). The remaining members in each ensemble are plotted in cyan and the thick lines indicate means of the composite groups (position marked every 12 h). The NHC best track for Hurricane Nadine is overlaid in black, with positions marked every 12 h.
Figure 3-3: Evolution of (a) the minimum SLP (hPa), and (b) the maximum 10-m wind speeds (kts) of the best track of Hurricane Nadine (black) and the 60 ensemble members of the WRF-EnKF forecast initialized at 0000 UTC 20 September 2012 grouped by track performance; GOOD (blue), POOR (red), and the remaining members of the ensemble (cyan). The thick lines indicate means of the composite groups GOOD and POOR.
Figure 3-4: Real-time, global sea surface temperature (RTG_SST) analysis fields developed at the National Centers for Environmental Prediction/Marine Modeling and Analysis Branch (NCEP / MMAB) at (a) 0000 UTC 20 September 2012 and (b) 0600 UTC 25 September 2012 contoured every 1°C with the best track of Hurricane Nadine (black line with position marked every 12 h). The dashed line indicates the 26°C contour. The difference between the two SST fields are plotted in (c) with contours every 0.5°C, as well as the best track and the mean tracks of the composite groups (GOOD–blue, POOR–red).
Figure 3-5: Evolution of (a) the minimum SLP (hPa) and (b) the maximum 10-m wind speeds (kts) of the best track of Hurricane Nadine (black) and the means of the composite groups GOOD (blue) and POOR (red) for the original forecasts (thin) and the simulations with the 6-h updates of SST (thick).
Figure 3-6: Evolution of the mean 300-km area-averaged (a) sensible and (b) latent heat fluxes (W m$^{-2}$) for the composite groups GOOD (blue) and POOR (red) of the original forecasts (thin) and the simulations with the 6-h updates of SST (thick).
Figure 3-7: Storm-centered composites (750-km by 750-km box around each ensemble surface center) of surface sensible and latent heat flux (W m\(^{-2}\)) (contours filled every 10 W m\(^{-2}\) and every 25 W m\(^{-2}\)) overlaid with the 10-m wind speeds (vectors) of the GOOD composite group at 24 h for the (a), (d) constant and (b), (e) updated SST experiment. The difference fields are plotted in (c) and (f) with contours every 10 W m\(^{-2}\). 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.
Figure 3-8: Surface maps of storm-centered composite 2 km simulated radar reflectivity (filled contours every 5 dBZ beginning at 5 dBZ), minimum SLP (gray contour lines every 10-hPa), and 10 m winds (vectors) for the GOOD and POOR composite groups at 0, 24, and 48 h for a portion of the outermost domain in the forecast system. Composite deep-layer (850–200-hPa) shear vectors (red) and 850–500-hPa vortex tilt vectors (magenta) originate from the composite surface center. The minimum SLP 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.
Figure 3-9: As in Fig. 3-8 but for 72, 96, and 120 h. The data to the right of the gray line in (e) and (f) indicates data outside the 9-km inner domain.
Figure 3-10: 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 0.3 PVU) potential vorticity (PV) composites for GOOD and POOR at 30, 33, 36, 39, 42 and 45 h. Upper-level winds (black vectors) and lower-level winds (gray vectors) are also plotted.
Figure 3-11: Differences between the upper-level (filled color contours every 0.5 PVU) and lower-level (filled gray-scale contours every 0.1 PVU) PV and wind (vectors) composites shown in Fig. 3-10 for (a) 30, (b) 33, (c) 36, (d) 39, (e) 42, and (f) 45 h.
Figure 3-12: Evolution (every 3 h between 30 and 45 h) 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) and POOR (red). 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$^{-1}$).
Figure 3-13: As in Fig. 3-12 but for the ECMWF ensemble, environmental steering flow vectors of EC_GOOD (blue) and EC_POOR (red) at (b) 30, (c) 36, and (d) 42 h.
Figure 3-14: Composite vertical profiles of relative humidity (first row), temperature (second row) and zonal winds (third row) for the NOAA/NCAR dropsondes (black), GOOD (blue), and the differences between them (Dropsondes–GOOD, red) at 3 (first column), 6 (second column), 9 (third column), and 12 h (fourth column). The number of profiles used to create the composite profiles for each time is indicated in the bottom-left corner of the plots in the first row.
Figure 3-15: (a) Area-averaged (between 200-km and 800-km from the surface center) low-level (850-hPa–700-hPa; magenta), mid-level (700-hPa–500-hPa; green), and upper-level (500-hPa–300-hPa; orange) relative humidity evolution of the composite group GOOD (solid) and SHIPS (dashed). Evolution of the (b) magnitude (m s\(^{-1}\)) and (c) direction (degrees) of deep-layer (850-hPa–200-hPa) wind shear for the mean (thick) and the individual ensemble members (thin) of the composite group GOOD (blue). The AMSU (gray) and the SHIPS (black) deep-layer shear are also plotted.
Figure 3-16: (a) Storm-centered horizontal cross-section of 700-hPa relative humidity (contours filled every 5%) for the GOOD composite group at 6 h. Markers indicate storm-centered positions of the NOAA/NCAR dropsondes that were deployed during the 19-20 September HS3 flight and are filled according to the value of relative humidity recorded closest to 700-hPa (white indicates no data available). (b) As in (a), but for 950-hPa tangential winds (contours filled every 2 m s$^{-1}$).
Chapter 4

Dynamics and predictability of the intensification of Hurricane Edouard (2014)

4.1 Introduction

Over the past five years, considerable efforts have been directed towards improving tropical cyclone (TC) intensity prediction, as errors associated with these forecasts have remained relatively unchanged over the past few decades (Rappaport et al. 2009). In addition, the operational prediction of tropical cyclone formation and significant changes in intensity, such as rapid intensification (RI) or decay remain particularly challenging (Elsberry et al. 2007). This study utilizes a 60-member real-time convection-permitting ensemble forecast of Hurricane Edouard (2014) initialized at 1200 UTC 11 September 2014 to examine the forecast uncertainty and errors associated with the period of near-RI that Edouard underwent throughout this time. The Pennsylvania State University (PSU) real-time hurricane forecast and analysis system benefits from its capability to assimilate airborne Doppler radar observations, as well as other more traditional reconnaissance observations in near real-time using an ensemble Kalman filter (EnKF). The ensemble forecasts of Edouard in particular are improved by the assimilation of extensive observations taken during the National Aeronautics and Space Administration’s (NASA) Hurricane and Severe Storm Sentinel (HS3) mission (Braun et al. 2016). These same observations, when not assimilated, can be used for model verification.

The tropical wave that eventually became Edouard exited the African coast on 6 September (Stewart 2014). A broad area of low pressure and disorganized convection
traveled westward for ~4 days, until convection began to increase near the surface center late on 10 September. Edouard was subsequently designated as a tropical depression the following day, and slow but steady strengthening lead to Edouard becoming a tropical storm early on 12 September. Upper-level winds and sea surface temperatures remained favorable for further intensification, although dry air in the surrounding environment may have slowed the intensification rate as Edouard tracked northwestward. As Edouard reached hurricane status on 14 September, a period of near-RI occurred, in which the maximum 10-m sustained winds increased by 25 kts over the succeeding 24 h period\(^1\). Just prior to the end of the simulation window, Edouard reached peak intensity as a major hurricane, the first in the Atlantic basin since Hurricane Sandy in 2012. Just beyond the simulation window, Edouard maintained major hurricane status only briefly before sharply weakening during an eyewall replacement cycle as the storm began to move northward. As the TC accelerated towards the northeast and became embedded in the mid-latitude westerlies, a period of rapid weakening commenced, and by 19 September Edouard had degenerated into a remnant low.

Although the official forecast intensity errors were lower than the mean official errors for the previous 5-year period at all forecast times, there was a persistent bias leading up to Edouard’s near-RI period in which the official forecast underestimated the intensity of the TC (Stewart 2014). The PSU deterministic forecast and the majority of the members analyzed in this study were more successful at capturing the correct rate and peak intensity of Edouard, although considerable uncertainty existed in the exact timing of RI-onset. Therefore, the primary goal of this study is to utilize the 60-member PSU

\(^1\) Although Edouard did not officially undergo RI (according to the NHC criterion), the period of intensification was significant (a “near-RI event”). Therefore, we look at RI timing in this ensemble as it is traditionally defined, because it is more straightforward to do so.
real-time forecast of Edouard to examine both the environmental factors and the variance in the structural evolution of the ensemble vortices that resulted in the considerable RI-onset uncertainty.

Section 2 describes the PSU real-time hurricane forecast and analysis setup, operational data examined, and the sensitivity experiment methodology. Section 3 presents the composite analyses of Edouard’s intensity forecasts according to RI-onset time, as well as results from a series of sensitivity experiments. Finally, section 4 highlights the main conclusions from this study.

4.2 Methodology and data

4.2.1 PSU Atlantic hurricane forecast and analysis system

The deterministic and 60-member ensemble simulation of Hurricane Edouard analyzed in this study was originally a real-time forecast generated by the PSU real-time Atlantic hurricane forecast and analysis system (Zhang et al. 2009, 2011; Zhang and Weng 2015; Weng and Zhang 2016). The 2014 version of this system employed version 3.5.1 of the Advanced Research version of the WRF model (ARW; Skamarock et al. 2008) and an EnKF data assimilation algorithm. Data that can be assimilated into this system include Global Telecommunication System (GTS) conventional data, reconnaissance data (including superobservations generated from airborne Doppler radar observations from NOAA’s tail Doppler radar (TDR; Weng and Zhang 2012) and satellite-derived winds (Weng and Zhang 2016). In addition, dropsondes deployed from
the NOAA/National Center for Atmospheric Research (NCAR) Advanced Vertical Atmospheric Profiling System (AVAPS) during HS3 flights are also assimilated if they were available at initialization (Braun et al. 2016). Three two-way nested Mercator-projected domains are utilized with horizontal grid spacings of 27, 9 and 3 km, which contain 378 x 243, 297 x 297, and 297 x 297 grid points respectively. The outer domain is fixed and includes the majority of North America and the North Atlantic Ocean, while the inner domains move with the surface vortex of the TC of interest. All three domains contain 43 vertical levels with the top level at 10 hPa. The WRF model physics configurations are identical to those in Munsell et al. (2015) and Zhang and Weng (2015).

Using operational Global Forecast System (GFS) analysis, the PSU WRF-EnKF system was first initialized at 0000 UTC 4 September; Edouard had recently been designated as an NHC invest area at this time. After 12 h of ensemble integration, the first data assimilation is performed on all three domains at 1200 UTC 4 September and continuous cycling is performed every 3 h until the dissipation of Edouard. As in all forecasts produced by the PSU WRF-EnKF system, ensemble initial and lateral boundary conditions are generated by adding perturbations derived from the background error covariance of the WRF variational data assimilation system (Barker et al. 2004) to the geopotential height, minimum sea level pressure (SLP), temperature, moisture, and horizontal wind fields of the deterministic initial and boundary conditions. The EnKF analysis perturbations from 1200 UTC 11 September are utilized to initialize the ensemble forecasts analyzed in this study.
4.2.2 HS3 observations of Hurricane Edouard

Four flights utilizing an unmanned Global Hawk aircraft were performed throughout all stages of the lifetime of Hurricane Edouard during the 2014 HS3 campaign. Braun et al. (2016) describe the structure and evolution of Edouard during the period of the first two flights that are of most relevance here. These two flights were performed during the 5-day simulation window analyzed in this study. A total of 61 usable AVAPS dropsondes (Wick 2015) were deployed on the 11–12 September flight, and 80 were deployed on the 14–15 September flight (Young et al. 2014). These dropsondes were not assimilated for the real-time ensemble forecast in this study (since they had not been collected yet) and thus are used to independently verify the accuracy of the Edouard simulations.

4.2.3 Composite sensitivity experiments: Initial condition construction

Results from a series of sensitivity experiments are presented in sections 4.3.5 and 4.3.6 in this dissertation, whose initial conditions are generated according to the following methodology. First, groups of members are created according to their RI-onset time (GOOD_EARLY, GOOD, and POOR) in order to test the impacts of various factors on the RI-onset. Next, composited initial conditions created by averaging the initial conditions in each group are used to initialize additional simulations. For each composite, more sets of initial conditions are generated by replacing all fields at all vertical levels within a given radius from the surface center of Edouard with the fields from different sets of composited initial conditions. Linear blending is performed about the radius at which the initial conditions are combined in order to prevent sharp discontinuities, and
the resulting initial conditions are simulated in an otherwise identical experiment to that of the original ensemble. Descriptions of the sensitivity experiment initial conditions are summarized in Table 4-1.

A final experiment is designed to test the sensitivity of RI-onset to the moisture field within the region of greatest sensitivity in the POOR environment. This experiment, EnvGoodTcPoor800DiffQ (Table 4-1), is identical to EnvGoodTcPoor800 except for the moisture fields within the blending radii (700–900-km). The differences between the moisture fields in this sensitivity experiment depend on the radius from the surface center of Edouard and are dictated by this set of equations:

\[
\begin{cases}
0, & r < 700 \text{ km} \\
\alpha \Delta Q, & 700 \text{ km} \leq r \leq 900 \text{ km} \\
0, & r > 900 \text{ km}
\end{cases}
\]

where \( r \) is the radius from the storm center (in km), \( \alpha \) is a scaling factor based on the radius and \( \Delta Q \) is the difference between the water mixing ratio fields from the GOOD and POOR composites (GOOD–POOR). The equation for the scaling factor is

\[\alpha = 1 - \left( \frac{900 - r}{100} \right).\]

4.3 Results and Discussion

4.3.1 Overview of the PSU real-time WRF-EnKF ensemble performance

Since the primary goal of this study is to examine the predictability of the dynamics associated with the near-RI of Hurricane Edouard, the 126-h forecast chosen for analysis was initialized at the time of the storm’s designation as a tropical depression
and was integrated through intensification (1200 UTC 11 September–1800 UTC 16 September). Figure 4-1a shows the corresponding section of Edouard’s best track as well as the tracks of the control run (APSU) and ensemble members from the PSU WRF-EnKF forecasting system. The associated minimum SLP (in hPa, Fig. 4-1b) and the 10-m maximum wind speed (in kts, Fig. 4-1c) evolution are also presented. Considering the lead-time prior to intensification, the APSU deterministic forecast is quite successful; the track closely follows that of the best track, and both the onset time and the rate of intensification (in terms of SLP and maximum 10-m winds) during the near-RI event are satisfactorily represented. A slight overintensification is present in the minimum SLP forecast likely due to uncertainty in the representation of surface fluxes (Green and Zhang 2013). In addition, the majority of ensemble members ultimately reach the correct intensity, although there is significant spread (as much as 48- to 60-h) in the timing of RI-onset. Furthermore, some ensemble members fail to intensify during the 126-h forecast. The causes for the significant spread in the timing of RI will be further investigated in order to assess the predictability associated with the governing dynamics of the near-RI event of Edouard.

As in previous ensemble sensitivity studies (Munsell et al. 2013, 2015; Munsell and Zhang 2014), the variations amongst the members that lead to the considerable divergence in RI-onset time are identified through the creation of ten–member composite groups based on the timing of their respective intensifications. In this study, the RI-onset time of each member is defined as the time at which the subsequent 24-h intensity change is maximized. The ten members whose RI-onset times are closest to that of the best track RI-onset (~1200 UTC 14 September, or 72-h simulation time) comprise the group
GOOD, while two additional clusters of ten members who begin RI 24-h prior to and 24- to 36-h after the best track RI are classified as the composite groups GOOD_EARLY and GOOD_LATE, respectively. The final composite group POOR consists of ten members who fail to intensify throughout the simulation. Therefore, 40 of the 60 ensemble members are placed in one of the composite groups. These groups are restricted to 10 members due to the limited number of simulations that fail to intensify, which allows for an equal number of members in each group when compositing.

Figure 4-1 features the ensemble members according to composite group, along with the mean track and intensity of each composite. The evolution of the mean intensities clearly illustrates that the three developing composite groups have similar rates of intensification and primarily differ only in the timing of their RI-onset (Fig. 4-1b and c). It should also be noted that the mean tracks of these developing groups is more closely aligned with the best track, while the mean track of POOR has a more westward component of motion, likely as a result of the lessened beta effect induced by the weaker POOR vortices (Kitade 1981, Chan and Williams 1987; Fig. 4-1a). Before continuing with the analysis to determine the causes of the significant ensemble RI-onset time uncertainty, the GOOD composite group is first evaluated against HS3 observations to assess the representativeness of the WRF-EnKF simulation.

4.3.2 Comparison of HS3 observations and WRF-EnKF ensemble

Further validation of the simulated storm’s structure and environment was performed through comparisons to HS3 observations. Using the available dropsonde data from the 11–12 September HS3 flight and the mean of the GOOD composite members,
observed and simulated vertical profiles of relative humidity (Figs. 4-2a and d), the zonal (Figs. 4-2b and e), and the meridional components of wind (Figs. 4-2c and f) at 18 h and 24 h are plotted. Observations collected within 90 minutes of the given time were averaged to produce the observational profiles, while the simulated profiles were generated by extracting and averaging the vertical profiles at each of the model grid points that were closest to the storm-relative location at which the observations were obtained. The structure of the observed and simulated relative humidity profiles at both 18 h (Fig. 4-2a) and 24 h (Fig. 4-2d) are quite similar throughout, with only a slight increase in moisture (~5-10%) present in the simulated profiles.

To further compare the spatial distribution of the simulated and observed thermodynamic environments, a storm-centered GOOD composite mean of the 700-hPa relative humidity field at 15 UTC 12 September is created, with observations from the AVAPS dropsondes taken during the 12 September flight overlaid (Fig. 4-3a). The spatial structure appears to primarily agree, with evidence of mid-level dry air in the environment to the north- and southwest of the TC and very moist air near the surface circulation center. The HS3 observations also confirm the presence of dry air that is beginning to wrap around the southern edge of Edouard’s outer circulation. Though there appears to be a slight 700-hPa moist bias in the simulated dry environment, a comparison between the dropsondes and the simulation of this environmental dry air at 500-hPa yields more agreement (not shown). In addition, it appears that the moist bias noted in the simulated relative humidity profile also results from excess moisture present to the east and northeast of Edouard. Overall, the spatial and vertical structure of the observed and simulated relative humidity fields compare satisfactorily for further analysis.
The vertical profiles of the zonal and meridional component of wind at 18 h and 24 h are in even greater agreement than the relative humidity assessments (Fig. 4-2). Differences in both wind components are generally smaller than 2-4 m s\(^{-1}\) and there is no obvious bias. In a manner similar to Fig. 4-3a, a comparison between the storm-centered GOOD composite mean 950-hPa wind field at 21 UTC 12 September is overlaid with observations from the AVAPS dropsondes collected during the first HS3 flight into Edouard (in m s\(^{-1}\); Fig. 4-3b) in order to evaluate the similarities between the observed and simulated near-surface vortex. The overall structure of the vortex is well represented in the model, with the maximum winds located just to the northeast of the surface circulation and embedded within a fairly broad region of tropical storm-strength winds.

There is also good agreement on the very asymmetric circulation of Edouard, with considerably weaker winds to the south of the surface center at this time. The simulated winds are also somewhat weaker than what was observed in the region of maximum winds (by ~5 m s\(^{-1}\)). Based on the environmental comparisons and the evaluation of the near-surface vortex, the WRF-EnKF simulation appears to be representative of the observed TC in these early stages of its intensification.

### 4.3.3 Significant ensemble RI-onset variability: Impacts of deep-layer shear on vortex evolution

Anticipating significant changes in intensity, such as RI, is challenging due to the increased dependence on the chaotic dynamics of the TC inner-core, in addition to the more easily observed large-scale environmental and ocean conditions. Statistical predictions of RI attempt to account for all of these influences; the rapid intensification
index (RII; Kaplan and DeMaria 2003; Kaplan et al. 2010) incorporates large-scale atmospheric influences, ocean characteristics, and some satellite-derived inner-core quantities. The RII demonstrates some skill in predicting RI; however, the RII most likely suffers due to the strong dependence on the large-scale environment, rather than more detailed inner-core information.

Although inner-core moist convection ultimately limits the predictability associated with intensification (Zhang and Sippel 2009) and more specifically RI, environmental influences, particularly moderate magnitudes of vertical wind shear, can further degrade the predictability of RI. Vertical wind shear causes the tilt of the developing TC vortex to become oriented typically in the downshear left quadrant (Corbosiero and Molinari 2002; Rogers et al. 2003), which subsequently creates an asymmetry in which convection is enhanced downshear and suppressed upshear (e.g. Black et al. 2002; Chen et al. 2006). The tilt vector of a developing TC undergoes a precession process, in which the tilt is rotated cyclonically by the primary circulation of the vortex until the angle between the shear and tilt vectors exceeds 90°. This allows for the tilt vector to proceed into the upshear quadrant, which leads to the near-immediate alignment of the vortex (e.g. Reasor et al. 2004; Rappin and Nolan 2012). An RI event begins once the alignment of the vortex has been completed, however, the speed at which a developing TC vortex completes precession can be accelerated or slowed by random moist convection near the inner-core region (Frank and Ritchie 2001; Zhang and Tao 2013; Tao and Zhang 2014), which limits the predictability under moderate shear.

Although the WRF-EnKF ensemble of Hurricane Edouard is created through the application of small perturbations to the initial conditions, the simulation produces
developing TCs with a significant range of RI-onset times. This ensemble variance is
next explored by analyzing the discrepancies between the structural developments of the
vortices. Given the strong dependence of the predictability of an RI event on the
magnitude of deep-layer vertical wind shear (Tao and Zhang 2014, 2015), the evolution
of the area-averaged (between 200-km and 500-km from the surface center) deep-layer
(850-hPa to 200-hPa) wind shear magnitude (Fig. 4-4a) and direction (Fig. 4-4c) amongst
the composite groups is examined. Observational shear values obtained from the
Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) are also
included, which are in mostly good agreement with the GOOD shear evolution. Shear
magnitude is relatively weak initially (~5 m s⁻¹) in all composite members, but it steadily
increases over the first 24 h to a relatively strong value of 10 m s⁻¹. By 48–60 h there is a
clear separation in the shear magnitudes of the composite groups such that groups with
later RI-onset time have stronger shear. There also appears to be a critical shear
magnitude threshold (~12–14 m s⁻¹) in this ensemble, above which RI does not occur
within the simulation window (as in POOR). Although this ensemble is a real-data case
with differences throughout the environment, this shear magnitude limit is comparable to
the 12.5 m s⁻¹ threshold derived from the idealized simulations of Tao and Zhang (2014)
with sea surface temperatures comparable to what Edouard experienced throughout the
simulation (~29°C; Fig. 4-1a).

Over the final 2–3 days of the simulation, the shear magnitudes for the developing
composite groups decrease steadily to a moderate value of ~7 m s⁻¹. However, because
there are differences in the times at which the shear begins to subside, the shear
evolutions are also displayed in relation to the RI-onset time of each composite group
(Fig. 4-4b). From this framework, it is clear that the shear magnitude in the developing composites begins to decrease at least ~6–12 h prior to RI. In addition, the shear magnitude of all composites at RI is very similar (~8–9 m s\(^{-1}\)). Although some of the decrease in shear likely results from a reduction in local shear that occurs as the vortices become more aligned as RI-onset approaches, a significant environmental component remains.

The evolution of deep-layer shear direction (Fig. 4-4c) also appears to be related to RI-onset time. Initially southwesterly (~240°), the shear direction is comparable amongst all composite groups through 24–36 h. However, over the next 2–3 days of the simulation the direction of the shear vectors begin to diverge as the shear vector of the members that achieve RI earlier rotate counterclockwise more significantly towards a southeasterly orientation. In addition, the direction of the shear vectors of the non-developing members (POOR) does not change significantly throughout the majority of the simulation. The precession process that the developing vortices are undergoing throughout this period likely contributes to these changes in shear direction, but as in the shear magnitude analysis, the environments that the TCs are embedded in appear to evolve as well.

Figure 4-4d shows the correlation between the deep-layer shear magnitude and the RI-onset time, which is calculated from the 30 members that comprise the composite groups who undergo RI. Although the correlation is insignificant throughout the first 24 h of the simulation, as few differences are present in the shear magnitude amongst the ensemble subset, a significant positive correlation begins to develop over the next 24–48 h. By 48 h, the correlation is moderate (~ 0.5) and by 72 h, as the majority of the
members approach RI-onset, the correlation is strong (~ 0.8). This correlation analysis confirms the previous assertion that there is a significant relationship between the shear magnitude and the RI-onset time in this ensemble, such that earlier RI-onset occurs for storms embedded in weaker deep-layer shear environments.

Figure 4-5a shows the mean tilt magnitudes for each composite group, which are defined as the distance between the 850-hPa and 500-hPa weighted horizontal circulation centers as in Zhang and Tao (2013). The tilt magnitudes of all composite groups are initially similar (~30–40-km) and all steadily increase throughout the first 24 h of the simulation, coinciding with the increase in deep-layer shear. Over the next 24 h, the GOOD_EARLY tilt magnitude begins to gradually decrease while the tilt in the other composites continues to increase. The tilt of the GOOD and GOOD_LATE vortices starts to decrease at ~60 h, while the tilt magnitude of POOR stops increasing at 48 h and remains relatively constant throughout the rest of the simulation. The developing composite tilt magnitudes continue to decrease as the storms intensify, and by the end of the simulation all three developed composites have tilt magnitudes of ~15 km.

The tilt evolution is also analyzed in relation to the RI times in the composites (Fig. 4-5b). It is clear that in all developing composites, the tilt magnitude begins to decrease ~24–48 h prior to RI-onset. In addition, despite some discrepancy amongst the composites in the magnitude of the maximum tilt, the tilt magnitude at the time of RI is ~30–40 km. This suggests that the vortices follow a very similar pathway towards intensification despite differences in timing.

Figure 4-5c shows the time mean of the tilt vectors from the composite groups in an x-y plane from 24 h to the end of the simulation. It is clear that the increasing shear
over the first 24–48 h of the simulation causes the tilt vectors of the composite groups to be oriented in the downshear direction (towards the northeast), which is consistent with the observed tilt of Edouard (Braun et al. 2016). By 48 h, as the shear magnitudes and directions begin to diverge amongst the composites, the position and magnitude of the tilt vectors diverge as well. The GOOD_EARLY tilt vector has a smaller magnitude and is oriented farther to the northwest at this time, indicating that the members of this group are further along in their precession process and closer to alignment and RI-onset. By 72 h, the GOOD vortices are also completing precession and beginning RI, while the GOOD_LATE tilt vectors are continuing to rotate counter-clockwise towards the upshear quadrant. Meanwhile, the POOR tilt vectors have the largest magnitudes (under the strongest shear conditions) and remain in the downshear quadrant throughout the simulation. The time evolution of the tilt vectors demonstrates that only the composites that precess into the upshear quadrant are able to achieve RI.

The correlation between the tilt magnitude and RI-onset quantitatively demonstrates their relationship (Fig. 4-5d). Over the first 24 h of the simulation, the correlation is insignificant as the ensemble members have comparable tilt under the steadily increasing shear. However, by 36 h the correlation is significant (~0.3), and by 48 h it is moderate (~0.5). The correlation continues to increase and remains strong throughout the simulation (greater than 0.7), suggesting that decreasing tilt magnitude leads to earlier RI-onset.

As described above, it has been shown that it is difficult for a developing TC vortex to achieve RI until the tilt vector precesses into the upshear quadrant, which leads to a tilt vector that is oriented at least 90° to the left of the shear vector (Frank and Richie
Therefore Fig. 4-5d shows the correlation between the RI-onset time and the tilt/shear angle (defined as the difference in direction between the tilt and shear vectors with a discontinuity at 180° to obtain a more representative correlation). The correlation is insignificant over the first 24 h, but it steadily increases through 72 h to a strong value of ~0.7, indicating that throughout this period earlier RI-onset is well correlated with increasingly larger differences in the direction of the tilt and shear vectors. After 72 h the correlation quickly decreases, although this primarily results from the fact that the majority of the members are aligned or nearly aligned at this time, leading to somewhat arbitrary tilt vector orientations.

In addition to the significant correlation between the shear and the evolution of the structure of the incipient vortex, the subsequent impacts on the strength and location of the developing convection is next investigated. Figure 4-6 shows the storm-centered composite maximum radar reflectivity, minimum SLP, 10-m surface winds, deep-layer shear vector and tilt vector evolutions for GOOD_EARLY, GOOD, GOOD_LATE and POOR. The composites indicate that the storms are initially somewhat asymmetric, with the majority of the strongest convection located to the north and west of the storm center. By 24 h, as the shear magnitude increases and the vortices become increasingly tilted towards the north (downshear-left), the areal coverage of convection is reduced with the strongest convection located primarily in the downtilt direction. Also by this time, the inner-core convection associated with GOOD_EARLY is stronger and accelerates precession, which leads to an earlier alignment and RI-onset. At 48 h GOOD_EARLY has essentially aligned and the inner-core convection has wrapped around the surface circulation, while the strength of the GOOD and GOOD_LATE convection has
increased. The POOR convection remains somewhat weaker in the inner-core and is aligned strictly in the downshear direction.

By 72 h, the inner-core convection in GOOD has also wrapped around the surface center as RI is commencing, while the regions of strongest convection in GOOD_LATE have begun to rotate counter-clockwise as the precession of the tilt vector has proceeded. The convection associated with POOR at this time has also increased in strength, but the strong shear keeps it primarily in the downshear-left quadrant, and the tilt vector cannot precess in the upshear direction. Finally, GOOD_LATE approaches alignment by 96 h while the POOR convection remains downshear and embedded in less favorable environmental conditions. It is possible that given more time and sufficiently low shear, storms in POOR would align and undergo RI.

Since it appears that the evolution of the composite vortices and their associated convection follow similar pathways to RI, the radar reflectivity composites are also shown in relation to the time before or after RI (Fig. 4-7). From this perspective it is clear that although there is significant variability amongst the composites in the areal coverage and the strength of the convection 48 h prior to RI, as RI-onset is approached, substantial parallels in both the position and strength of the convection and the magnitude and orientation of the tilt vector exist. Despite some differences in the tilt orientation at 24 h prior to RI, the tilt vector and convection in the composites for the most part rotates counter-clockwise. By 12 h prior to RI the inner-core convection has strengthened, particularly in GOOD_EARLY and GOOD, and depending on the composite, by RI the tilt/shear angle is ~60°–90°, while convection has wrapped around the surface circulation.
This analysis further demonstrates that despite differences in RI timing, the developing vortices undergo a similar evolution as RI is approached.

4.3.4 Exploring the significant ensemble RI-onset variability: Impacts of initial vortex strength

Although the differences in deep-layer shear can explain some of the variability present in the RI-onset times of the Edouard ensemble, it is likely that additional factors influence the timing of RI amongst the composites. In particular, past ensemble sensitivity studies have shown that initially strong vortices tend to intensify more quickly because they are able to resist negative environmental influences (Sippel et al. 2011; Munsell et al. 2015). This could potentially impact the timing of RI-onset. To examine the evolution of the strength of the TC vortices, the area-averaged mid-level (within a 250-km radius of the 500-hPa center) relative vorticity is calculated for each of the composite groups (Fig. 4-8a). Although the initial area-averaged relative vorticity amongst the members appears to be quite similar, the GOOD_EARLY composite has a noticeably stronger initial mean vortex. However, the difference in vortex strength is less apparent over the first 24 h of simulation (partly due to model spin-up), but the relative vorticity subsequently diverges mostly according to RI-onset time, with the strongest area-averaged relative vorticity in the inner-core region of the GOOD_EARLY composite members and the weakest vorticity in the POOR members. As the simulation progresses and the developing members approach and undergo RI, the relative vorticity in GOOD_EARLY, GOOD and GOOD_LATE gradually increases, while the POOR relative vorticity actually slightly decreases.
To further examine the significance of the initial intensity of the vortex on the RI-onset time in the ensemble, the correlation between the area-averaged mid-level relative vorticity and the RI-onset time is performed (Fig. 4-8b). Initially, the correlation is weak but non-zero (~0.2) indicating a weak tendency for the GOOD_EARLY vortices to be stronger when they are initialized, which could allow for a quicker alignment of the vortex and an earlier RI-onset. The correlation steadily increases as the vortices evolve, and by 24 h it reaches a moderate value of ~0.5. As the simulation progresses and more of the ensemble members commence RI, the correlation between the relative vorticity and RI-onset time increases to a strong value of ~0.8. This relationship is expected since it is well established that the mid-level relative vorticity will increase during periods of TC intensification.

To further compare the initial strength of the composite members, the vertical structure of the vortices is examined through an azimuthally averaged vertical cross-section of tangential winds and the associated differences between the composites (Fig. 4-9). The tangential winds of the GOOD composite vortex are maximized at ~12 m s\(^{-1}\) in the near-surface region at a radius of between 100 and 200 km. In addition, as is standard in warm-core TC precursor vortices, the tangential winds decay with both radius and height. The differences in tangential wind structure between GOOD_EARLY and GOOD reveal that the initial GOOD_EARLY near-surface circulation is as much as 3 m s\(^{-1}\) stronger than GOOD in the lowest 3 km. Furthermore, the initial vortex structure in GOOD_EARLY appears to be more organized in the vertical with stronger tangential winds extending upwards through the troposphere (Fig. 4-9a). Since GOOD_EARLY vortices are initially stronger, they are likely more resilient to environmental influences.
and thus able to align and undergo RI the earliest. Finally, a similar vertical cross-section of tangential wind differences between GOOD and POOR (Fig. 4-9b) demonstrates that the initial strength of those two vortices is quite similar. The starkly different outcomes in GOOD and POOR despite initially similar vortex strength suggest that POOR has an environment that is less conducive for intensification.

4.3.5 Ensemble sensitivity to RI-onset: Initial conditions

The sensitivity of the RI-onset times to the initial conditions is next investigated by creating simulations initialized with composite initial conditions from GOOD_EARLY, GOOD, GOOD_LATE and POOR groups (refer to Section 4.2.3 for additional details). The tracks, minimum SLP and maximum 10-m winds of these simulations are shown in Fig. 4-10. Both the GOOD_EARLY and POOR composite simulations show similar behavior to that of the original ensemble means, with the GOOD_EARLY simulation undergoing RI at ~48 h and the POOR simulation not significantly intensifying throughout the simulation window. The final intensity in both the GOOD_LATE and POOR simulations is stronger than the mean of that in the original ensembles, but this most likely results from an enhancement of the wavenumber-0 component of the initial vortex (at the expense of asymmetries) that occurs during averaging. It should also be noted that the tracks in the compositied simulations are quite similar to those in the original ensembles (Fig. 4-10a) with the exception of POOR, which takes a more northwestward track as the TC begins to intensify near the end of the simulation.
The intensity evolutions of GOOD and GOOD_LATE simulations converge to a solution with an RI-onset time of approximately that of GOOD from the original ensemble (Fig. 4-10b and c). This indicates that although there is ~24–36 h between RI for these members in the original ensemble, the differences in the initial conditions that contribute to their subsequent RI-onsets produce solutions that are within the intrinsic variability present in this ensemble, which considerably limits the predictability of the timing of RI in these members. Given that the differences between the GOOD and GOOD_LATE groups are within the ensemble uncertainty, in all remaining sensitivity experiments GOOD_LATE will not be utilized.

To further test the hypothesis that the GOOD_EARLY vortices undergo RI prior to the rest of the ensemble because they are initially stronger, additional sensitivity experiments are performed utilizing the composited initial conditions from GOOD_EARLY, GOOD, and POOR. Two experiments (EnvGoodEarlyTcGood and EnvGoodEarlyTcPoor) are created by replacing the near-storm initial conditions of GOOD_EARLY with the initial conditions from GOOD and POOR (refer to Section 4.2.3 and Table 4-1 for a description of how this was done and of the naming convention for the subsequent sensitivity experiments). The tracks (Fig. 4-11a), minimum SLP (Fig. 4-11b) and maximum 10-m winds (Fig. 4-11c) from EnvGoodEarlyTcGood and EnvGoodEarlyTcPoor are shown in Fig. 4-11. Storm intensity in these two simulations is similar to that in the GOOD simulation, and RI begins around 72 h. This demonstrates that the insertion of the initially weaker GOOD or POOR vortex in the GOOD_EARLY environment leads to a delay in RI-onset of about 24 h, providing more evidence that the initially stronger GOOD_EARLY vortex significantly contributes to the earlier RI.
The intensity evolutions of the complimentary experiments EnvGoodTcGoodEarly and EnvPoorTcGoodEarly are also shown in Fig. 4-11. Both the minimum SLP (Fig. 4-11e) and maximum 10-m winds (Fig. 4-11f) of the EnvGoodTcGoodEarly experiment indicate that this simulation undergoes RI at 48 h, which is the time of RI-onset of GOOD_EARLY. This shows that the initially stronger GOOD_EARLY vortex is not particularly sensitive to small degradations of its initial environment. Meanwhile RI in EnvPoorTcGoodEarly begins at 72 h, as in the GOOD composite. This result further indicates that the environment in POOR is not conducive for intensification to the extent that it delays RI of even initially strong vortices.

Additional composites are created to test the hypothesis that the POOR environment is detrimental to intensification (EnvGoodTcPoor and EnvPoorTcGood). The minimum SLP (Fig. 4-12b) and maximum 10-m wind (Fig. 4-12c) evolutions from this set of sensitivity experiments reveal that EnvGoodTcPoor undergoes RI at ~72 h as in GOOD, while EnvPoorTcGood does not begin to intensify until near the end of the simulation as in POOR. Given the comparable initial strengths of the GOOD and POOR vortices, these results strongly suggest that the POOR environment is less favorable for development in this ensemble.

Next we aim to identify at what radius from the storm center are the most adverse environmental conditions in POOR through sensitivity experiments initialized with linearly combined GOOD and POOR composited initial conditions at varying radii (Table 4-1). The EnvPoorTcGood650 experiment fails to develop until near the end of the simulation, while EnvGoodTcPoor650 has an RI-onset time of ~72 h. Meanwhile, EnvPoorTcGood1100 begins RI just after 72 h, while the EnvGoodTcPoor1100
experiment intensifies considerably later in the simulation (Figs. 4-12b and c). These intensity evolutions demonstrate that the area in the POOR environment of conditions unfavorable for RI is beyond 650-km but closer than an 1100-km radius from the surface center of Edouard. This result is somewhat surprising as this radial distance is farther away than the standard region of greatest environmental influence on TC evolution, however, it is conceivable that the differences in this region propagate inwards towards the TC in the ~72 h leading up to intensity divergence.

More systematic sensitivity experiments in which the radius at which the GOOD and POOR composites are combined is incrementally increased from 500-km to 900-km (Table 4-1) reveal that the region of greatest sensitivity to RI in the POOR environment is between 800-km and 900-km. EnvGoodTcPoor800 undergoes RI, while EnvGoodTcPoor900 does not. In addition, the opposite experiments exhibit the opposite behavior; EnvPoorTcGood800 does not intensify, while EnvPoorTcGood900 has an RI-onset time of ~72 h. The environmental influences in this narrow region of POOR that are inhibiting RI are next explored in detail.

4.3.6 Ensemble sensitivity to RI-onset: Assessing adverse conditions in the POOR environment

Before investigating in greater detail the unfavorable environmental influences in the sensitive region in the POOR composite, the very subtle differences in this highly sensitive region of this ensemble should first be highlighted. An example of the magnitude of these differences is shown in Fig. 4-13a, which contains vertical profiles of the root mean square differences (RMSD) in zonal wind, meridional wind, temperature
and specific humidity between EnvGoodTcPoor800 and EnvGoodTcPoor900 in the sensitive region. The differences in both the zonal and meridional winds are $\sim 0.5$ m s$^{-1}$ throughout the profile, which is comparable to the accuracy of the dropsondes used in HS3. The RMSDs in the temperature and specific humidity profiles peak near the top of the boundary layer at $\sim 0.2$ K and 0.35 g kg$^{-1}$ respectively, with both gradually decreasing in magnitude with altitude. These differences in the thermodynamic variables are also at or below the levels of accuracy obtained by the HS3 dropsondes. This demonstrates that although there is some degree of deterministic behavior with regards to the detrimental impacts on RI in the POOR environment, as there is a very specific region that appears to determine whether or not the member will undergo RI, the differences between the RI and non-RI simulations are within the accuracy of observational measurements.

Therefore, in situations similar to the Edouard ensemble, it would likely be impossible to determine operationally whether or not RI was going to occur with certainty.

Given the fact that the area of sensitivity in the POOR environment is at a large distance from the surface center of Edouard, it is hypothesized that the factor impeding RI is dry environmental air (Fig. 4-3a) that is subsequently advected towards the TC circulation. In order to test this hypothesis, the moisture fields in the initial conditions from EnvGoodTcPoor800 are modified in the region of greatest sensitivity (between 700-km and 900-km; EnvGoodTcPoor800DiffQ). An example of the differences between the experiments that result from the modifications to the moisture fields are shown in the initial 800-hPa and 500-hPa relative humidity fields (Figs. 4-13b and c). As by design, the two initial conditions only differ in the 700-km to 900-km region and these
differences are very small (at most 4–6% relative humidity and RMSD of 0.6 g kg\(^{-1}\) in specific humidity near the top of the boundary layer; Fig. 4-13a).

Despite these very small differences in only the moisture fields of the initial conditions, EnvGoodTcPoor800 undergoes RI at ~72 h while EnvGoodTcPoor800DiffQ does not begin to intensify until near the end of the 5-day simulation window. A comparison of the maximum radar reflectivity fields of the experiments reveals that over the first ~48 h of the simulations, the evolution of the location and strength of convection is essentially identical (not shown). This is somewhat expected since the initial conditions are very similar; however, given that intensity divergence exists by 72 h, the time over which the two simulations develop visible differences leading to divergence is only ~24 h. A demonstration of the substantial resemblance in storm structure over the first half of the experiments are in Figs. 4-14a and d, which show the maximum radar reflectivity, minimum SLP, 10-m surface winds, shear vector, and tilt vector at 51 h for EnvGoodTcPoor800 and EnvGoodTcPoor800DiffQ. These reflectivity fields represent the first time at which any visible differences can be detected between the experiments, and these differences are minor. At this time, the inner-core convection to the northeast of the surface center appears to be stronger in EnvGoodTcPoor800 than in EnvGoodTcPoor800DiffQ and most likely as a result of this stronger burst of convection, the tilt vector is oriented more towards the north in EnvGoodTcPoor800 as the precession process has begun to accelerate.

Additional evidence of the difference in the strength of the convective bursts can be seen in the 985-hPa \(\theta_e\) at 51 h, where there is a stronger surface cold-pool associated with the inner-core convection in EnvGoodTcPoor800 (Figs. 4-14c and f). The near-
surface $\theta_e$ also reveals the slight difference in position of the convective burst between the two simulations. In EnvGoodTcPoor800 the inner-core convection and the associated tilt vector has rotated farther in the counter-clockwise direction than in EnvGoodTcPoor800DiffQ, which appears to have helped quicken the precession process and allow RI to more easily occur. These differences in inner-core convection result in clear divergence in storm structure as RI is beginning in EnvGoodTcPoor800, as shown in the maximum radar reflectivity fields at 84 h (Figs. 4-14b and e). As RI-onset is occurring in EnvGoodTcPoor800, the angle between the tilt and shear vectors has approached 90° and convection has begun to wrap around the inner-core. Meanwhile, the tilt vector and the regions of strongest convection in EnvGoodTcPoor800DiffQ remain in the downshear quadrant. RI is still possible in this member, as the vortex appears to be slowly precessing into the upshear quadrant however, significant intensification does not occur in the simulation window. Because the only initial condition differences between these two experiments are in the moisture fields, it has been demonstrated that small perturbations in moisture can impact the strength and location of the developing deep convection, which can subsequently lead to differences in precession and therefore RI timing. It is hypothesized that the addition of similar initial condition perturbations to other variables (e.g. winds, temperature etc.) may produce similar divergent behavior.

Attempts to diagnose the sources of the difference in the strength of the inner-core convection in EnvGoodTcPoor800 and EnvGoodTcPoor800DiffQ proved to be challenging. We speculate that the small differences between the moisture fields are sufficient to cause divergent behavior in the chaotic interactions of mesoscale features, such as the development of near-surface cold pools that result from moist convection.
(Zhang and Sippel 2009). Therefore, though the Edouard ensemble displays some degree of practical deterministic predictability, since experiments that use the POOR environment fail to undergo RI, sensitivity experiments in this subsection show that the adverse conditions that prevent RI in the POOR environment may be too subtle to confidently diagnose. This primarily results from the chaotic nature of developing moist convection and is an indication of limited intrinsic predictability.

### 4.4 Summary and Conclusions

The governing dynamics and predictability of the rapid intensification of Hurricane Edouard have been explored through the use of a 60-member convection-permitting ensemble and sensitivity experiments generated by the PSU WRF-EnKF hurricane forecast and analysis system. The 5-day forecasts are quite successful as the deterministic track and intensity forecast closely follows that of the best track and the majority of the ensemble correctly predicts Edouard’s near-RI event. In addition, the representativeness of the forecasted storm structure and surrounding environment of the most successful members compares favorably to AVAPS dropsondes gathered during the 2014 HS3 campaign.

Although the majority of the ensemble captures Edouard’s intensification, there is considerable variance in the exact timing of RI with as much as 60 h between the RI-onset of the earliest and latest developing member. An examination of the evolution of the deep-layer shear vector across composite groups separated by RI-onset time reveals
that by 48 h, there is a clear separation between the groups with weaker shear corresponding to earlier RI-onset. Furthermore, ~6–12 h prior to RI in all of the developing composites, the shear magnitude begins to decrease, demonstrating that a reduction in deep-layer shear can indicate an imminent RI event if the environment is otherwise favorable.

Among the intensifying ensemble members, ~24–48 h prior to RI-onset a reduction in the tilt magnitudes of the developing composites was observed. In addition, the tilt vector and the region of strongest convection is typically aligned and initially collocated in the downshear quadrant. As RI is approached, the tilt vector and the strongest convection begin to precess in a counter-clockwise direction. Once the tilt vector is able to precess into the upshear quadrant, a significant reduction in the tilt magnitude occurs as the vortex aligns and RI is initiated. Although as much as 48 h of simulation time exists among intensifying members, the precession and alignment process of the developing vortices under similar profiles of deep-layer shear demonstrates that the simulations follow comparable pathways towards RI.

To further explore the factors that contribute to the significant ensemble variance in RI-onset, a series of sensitivity experiments was performed. Because the maximum 10-m wind speed, mid-level relative vorticity and azimuthally-averaged tangential winds of the earliest developers (GOOD_EARLY) were initially stronger, it was hypothesized that those members developed more quickly because the vortices were initially stronger and more defined. To test this, the vortex and surrounding near-environment of the GOOD_EARLY composited initial conditions was replaced with the initial vortex of both the GOOD (RI similar to best track) and POOR (non-intensifying) composited
vortices. The resulting simulations produce storms with RI-onsets at 72 h, or 24 h after the RI-onset of the original GOOD_EARLY composited simulation. Likewise, when the GOOD_EARLY vortex was inserted into the composited initial conditions of either the GOOD environment, the resulting storm achieved RI earlier. In addition, when the GOOD_EARLY vortex was placed in the POOR environment, the vortex was able to intensify as quickly as that in GOOD. These results indicated that the initially stronger GOOD_EARLY vortex accelerates the precession process and allows for an earlier RI-onset, regardless of the environment.

The delay in development of the initially stronger GOOD_EARLY vortex embedded in the POOR environment suggests that the POOR environment is somewhat detrimental to RI. To identify the most detrimental region of the POOR environment, additional blended initial conditions were created utilizing the GOOD and POOR composites. The radius at which the inner-core and environmental regions were combined was steadily increased from 500 to 900-km for both the GOOD inner-core embedded in the POOR environment and vice-versa. These experiments revealed that the region most detrimental to RI in the POOR environment was between 800 and 900 km from the surface center of Edouard.

To examine this region in the POOR environment in greater detail, an additional experiment was performed in which only the moisture field was perturbed in the sensitive region of the EnvGoodTcPoor800 initial conditions. These small adjustments to the moisture field yielded an experiment that failed to undergo RI, while the original experiment began RI at ~72 h. A comparison of the radar reflectivity and vortex structure evolutions revealed that the two simulations were extremely similar throughout the first
48 h, with the first observable differences occurring at 51 h. In the EnvGoodTcPoor800 experiment, a stronger burst of convection near the surface center of Edouard appears to strengthen the circulation, allowing for the tilt vector to precess counter-clockwise farther towards the upshear quadrant. This difference in convection strength allows for the completion of precession and alignment of this experiment within the 5-day simulation window. Attempts to diagnose the sources of the difference in moist convection strength between the experiments proved to be difficult, which highlights the intrinsic predictability that is present in these RI scenarios.
Chapter 4 Tables

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<td>GOOD</td>
<td>POOR</td>
<td>500–800</td>
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<td>POOR</td>
<td>800–1000</td>
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<td>GOOD</td>
<td>700–900</td>
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Table 4-1: Summary of the Edouard sensitivity experiments that are discussed in Chapter 4.
Figure 4-1: 5-day (a) track, (b) minimum SLP (hPa), and (c) maximum 10-m wind speed (kt) forecasts for the 1200 UTC 11 September 2014 initialization of Hurricane Edouard from the 60 member PSU WRF-EnKF ensemble forecast system. Members are placed in composite groups of 10 according to their RI-onset time; GOOD – RI-onset at the Best Track RI (72 h; blue), GOOD_EARLY – RI 24 h earlier than Best Track RI (48 h; green), GOOD_LATE – RI 24 h after Best Track RI (96 h; magenta), and POOR – RI does not occur in the simulation window (red). The composite means (thick; positions marked every 12 h in (a)), the NHC Best Track (black; positions marked every 12 h in (a)), and the APSU deterministic forecast (orange) are also plotted. The remaining ensemble members not classified in composite groups are in cyan. Sea surface temperatures (constant throughout simulation) are contoured (filled every 1°C starting at 15°C) in (a).
Figure 4-2: Composite vertical profiles of (a, d) relative humidity (\%; first column), (b, e) zonal winds (m s\(^{-1}\); second column) and (c, f) meridional winds (m s\(^{-1}\); third column) for the AVAPS dropsondes (black) and GOOD (blue) at 0600 UTC 12 September 2014 (18 h; first row) and 1200 UTC 12 September 2014 (24 h; second row).
Figure 4-3: (a) Storm-centered horizontal cross-section of 700-hPa relative humidity (contours filled every 5%) for the GOOD composite group at 0900 UTC 12 September 2014 (21 h). Markers indicate storm-centered positions of the AVAPS dropsondes that were deployed during the 12 September HS3 flight and are filled according to the value of relative humidity recorded closest to 700-hPa. (b) As in (a), but for 950-hPa winds (contours filled every 2 m s$^{-1}$).
Figure 4-4: (a) Evolution of the magnitude (m s\(^{-1}\)) of deep-layer (850-hPa–200-hPa) wind shear for the mean (thick) and the individual ensemble members (thin) of the composite groups GOOD (blue), GOOD_EARLY (green), GOOD_LATE (magenta), and POOR (red). SHIPS (black) deep-layer shear is also plotted. (b) As in (a), but only for the mean evolutions of GOOD (blue), GOOD_EARLY (green), and GOOD_LATE (magenta) plotted in relation to the RI-onset time of the composite groups. (c) As in (a), but for direction (degrees). (d) Evolution of the correlation between deep-layer shear magnitude and RI-onset time calculated from the 30 ensemble members that comprise the developing composite groups.
Figure 4-5: (a) Evolution of the mean tilt magnitude (distance between weighted horizontal circulation centers at 850-hPa and 500-hPa; km) for the composite groups GOOD (blue), GOOD_EARLY (green), GOOD_LATE (magenta), and POOR (red). (b) As in (a), but only for the composites that undergo RI, shown in relation to RI-onset time. (c) Tilt vector evolution starting at 24 h for GOOD (blue), GOOD_EARLY (green), GOOD_LATE (magenta), and POOR (red) with positions marked every 6 h (dots) and every 24 h (squares with simulation day indicated). (d) Evolution of the correlation between RI-onset and the tilt magnitude (black) as well as the angle between the tilt and deep-layer shear vector (red). Correlations calculated using the 30 members of the developing composite groups.
Figure 4-6: Surface maps of storm-centered composite maximum simulated radar reflectivity (filled contours every 5 dBZ beginning at 5 dBZ), minimum SLP (gray contour lines every 10-hPa), and 10 m winds (vectors) for the GOOD_EARLY (first column), GOOD (second column), GOOD_LATE (third column), and POOR (fourth column) composite groups at 0 (first row), 24 (second row), 48 h (third row), 72 h (fourth row), and 96 h (fifth row) for a portion of the 9-km inner domain in the forecast system. Composite deep-layer (850–200-hPa) shear vectors (red) and 850–500-hPa vortex tilt vectors (magenta) originate from the composite surface center. The minimum SLP 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.
Figure 4-7: As in Fig. 4-6, but composites (GOOD_EARLY–first row, GOOD–second row, and GOOD_LATE–third row) shown in relation to RI onset time.
Figure 4-8: (a) Evolution of the area-averaged (within a 250-km radius of the 500-hPa center) 500-hPa relative vorticity ($10^{-5}$ s$^{-1}$) for the mean (thick) and individual ensemble members (thin) of the composite groups GOOD (blue), GOOD_EARLY (green), GOOD_LATE (magenta), and POOR (red). (b) Evolution of the correlation between the area-averaged 500-hPa relative vorticity and the RI-onset time utilizing the 30 members of the developing composite groups.
Figure 4-9: (a) Azimuthally-averaged vertical cross-section of tangential winds at 0 h for the GOOD composite (contoured every m s \(^{-1}\)) overlaid with differences (filled contours every 0.5 m s \(^{-1}\) between -3 and 3 m s \(^{-1}\)) between the GOOD_EARLY and the GOOD initial vortex (GOOD_EARLY–GOOD). (b) As in (a), but differences are between the initial vortex of GOOD and POOR.
Figure 4-10: (a) Tracks, (b) minimum SLP (hPa), and (c) maximum 10-m wind speed (kt) evolutions for the composited initial condition sensitivity experiment (thick; GOOD–blue, GOOD_EARLY–green, GOOD_LATE–magenta, and POOR–red) and the composite group means from the original ensemble (thin). NHC Best Track is in black (positions marked every 12 h in (a)).
Figure 4-11: (a) Tracks, (b) minimum SLP (hPa), and (c) maximum 10-m wind speed (kt) evolutions for the sensitivity experiment in which the initial vortex in the GOOD_EARLY composite is replaced by that of GOOD (EnvGoodEarlyTcGood; thick blue) and POOR (EnvGoodEarlyTcPoor; thick red). Results from the composited initial condition sensitivity experiment (GOOD_EARLY—thin green; GOOD—thin blue; POOR—thin red) and NHC Best Track (black; positions marked every 12 h in (a)) are also included. (d)–(f) As in (a)–(c), but for the sensitivity experiment in which the GOOD_EARLY vortex is placed in the GOOD (EnvGoodTcGoodEarly; thick blue) and POOR (EnvPoorTcGoodEarly; thick red) environment.
Figure 4-12: (a) Tracks, (b) minimum SLP (hPa), and (c) maximum 10-m wind speed (kt) evolutions for the sensitivity experiments that replace the initial vortex in the GOOD composite with that of POOR (EnvGoodTcPoor; red) and vice-versa (EnvPoorTcGood; blue). The experiments vary according to the radius at which the composites are blended (between 200-km and 300-km; solid, between 500-km and 800-km (650); dashed, and between 1000-km and 1200-km (1100); dashed-dot). The NHC Best Track (black; positions marked every 12 h in (a)) and the composite initial condition sensitivity experiment evolutions (GOOD–thin blue; POOR–thin red) are also included.
Figure 4-13: (a) Vertical profiles of the root mean square differences (RMSD) of zonal wind (m s$^{-1}$; blue), meridional wind (m s$^{-1}$; green), temperature (K; red) and specific humidity (g kg$^{-1}$; magenta) between the experiment whose initial conditions transition from POOR to GOOD at 800-km and those that transition at 900-km. Accuracy of observations for each of the variables as obtained by the AVAPS dropsondes is indicated by the dashed lines [Accuracy information from: https://www.eol.ucar.edu/instruments/avaps-dropsonde]. The RMSD profile of specific humidity between EnvGoodTcPoor800 and EnvGoodTcPoor800DiffQ (g kg$^{-1}$; orange) is also included (RMSD between other variables are zero by design in these experiments). Differences (filled contours every 4% between -40% and 40%) between the initial (b) 800-hPa and (c) 500-hPa relative humidity fields of EnvGoodTcPoor800 and EnvGoodTcPoor800DiffQ.
Figure 4-14: (a) Surface maps as in Fig. 4-6 for EnvGoodTcPoor800 at 51 h and (b) 84 h. (c) 985-hPa $\theta_e$ fields (filled contours every 1 K) and surface winds (vectors) for EnvGoodTcPoor800 at 51 h. (d–f) As in (a)–(c), but for EnvGoodTcPoor800DiffQ.
Chapter 5

Summary and Conclusions

The primary goal of this dissertation is to examine the dynamics and predictability of tropical cyclones through the use of convection-permitting ensembles generated by a real-time regional-scale WRF-EnKF analysis and forecasting system. The predictability of various aspects of the governing dynamics associated with tropical cyclone track and intensity forecasting for Hurricanes Sandy (2012), Nadine (2012), and Edouard (2014) are explored through the use of composite analyses and ensemble sensitivity techniques.

In Chapter 2, the PSU real-time convection-permitting hurricane analysis and forecasting system (WRF-EnKF) that assimilates airborne Doppler radar observations, is utilized to assess the sensitivity and uncertainty of forecasts initialized several days prior to landfall of Hurricane Sandy (2012). 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 mid-latitude 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, ten 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 mid-latitude trough. Though the mid-latitude 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.

In Chapter 3, the governing dynamics and uncertainties of an ensemble simulation of Hurricane Nadine (2012) are assessed through the use of a regional-scale convection-permitting analysis and forecast system based on the Weather Research and Forecasting (WRF) model and an ensemble Kalman filter (EnKF). For this case, the data that is utilized was collected during the 2012 phase of the National Aeronautics and Space Administration’s (NASA) Hurricane and Severe Storm Sentinel (HS3) experiment. The majority of the tracks of this ensemble were successful, correctly predicting Nadine’s turn towards the southwest ahead of an approaching mid-latitude trough, though ten members forecasted Nadine to be carried eastward by the trough. Ensemble composite and sensitivity analyses reveal the track divergence to be caused by differences in the environmental steering flow that resulted from uncertainties associated with the position and subsequent strength of a mid-latitude trough.

Despite the general success of the ensemble track forecasts, the intensity forecasts indicated that Nadine would strengthen, which did not happen. A sensitivity experiment performed with the inclusion of sea surface temperature (SST) updates significantly reduced the intensity errors associated with the simulation. This weakening occurred as a result of cooling of the SST field in the vicinity of Nadine, which led to weaker surface sensible and latent heat fluxes at the air-sea interface. A comparison of environmental
variables, including relative humidity, temperature, and shear yielded no obvious differences between the WRF-EnKF simulations and the HS3 observations. However, an initial intensity bias in which the WRF-EnKF vortices are stronger than the observed vortex appears to be the most likely cause of the final intensity errors.

Finally, in Chapter 4, the dynamics and predictability of the intensification of Hurricane Edouard (2014) are explored through a 60-member convection-permitting ensemble initialized with an ensemble Kalman filter that assimilates dropsondes collected during NASA’s Hurricane and Severe Storm Sentinel (HS3). The 126-h forecasts are initialized when Edouard was designated as a tropical depression and include the storm's near rapid intensification (RI) from a tropical storm to a near Category-3 hurricane. Although the deterministic forecast was very successful and many members correctly forecasted Edouard’s intensification, there was significant spread in the timing of intensification amongst the ensemble.

Utilizing composite groups created according to the near RI-onset times of the members, it is shown that for increasing magnitudes of deep-layer shear, RI-onset is increasingly delayed; the TC will not intensify once a critical shear threshold is exceeded. Although the timing of intensification varies by as much as 48 h, a decrease in shear is observed across the intensifying composite groups ~6–12 h prior to RI. This decrease in wind shear is accompanied by a reduction in the magnitude of the vortex tilt, as the precession and subsequent alignment process begins ~24–48 h prior to RI. Sensitivity experiments reveal that some of the variation in RI time can be attributed to the initial vortex intensity, as the earliest developers intensify regardless of their environment. In addition, the non-developing members fail to undergo RI because of a less conducive
environment, although significant sensitivity exists in which minute differences in moisture fields distant from the storm center (up to 900-km) produce divergent forecasts.

This dissertation has demonstrated the benefit of ensembles for TC operational forecasting as a means of assessing the uncertainty associated with a given forecast. In addition, as a result of the chaotic nature of TC dynamics, particularly concerning TC intensity changes that are governed by moist convective processes that are intrinsically less predictable, ensembles are effectively necessary for providing reliable TC forecasts. Communicating the uncertainty associated with a forecast to the general public is challenging but essential, as an intrinsic limit of predictability will always exist in TC forecasting as a result of the governing dynamics. Despite this intrinsic limit, a practical predictability constraint exists as a result of limitations within the current state of numerical weather prediction. This lack of practical predictability primarily results from insufficient model resolution, inadequacies in necessary parameterizations of physical processes, and the lack of efficiency in certain data assimilation techniques and strategies for all available TC observations. Ensembles therefore demonstrate a means for analyzing the practical predictability associated with a given forecast, in addition to the intrinsic limitations. The regions of greatest sensitivity that have been diagnosed in the ensemble forecasts analyzed in this study can in particular highlight the processes that are contributing to the divergence in the model, suggesting that forecasts may improve if for example, additional observations are collected and assimilated in these areas (referred to as observation targeting). In addition, if the verifying truth of a TC track or intensity evolution lies outside of the spread of the ensemble forecast (e.g. as in the original Nadine intensity ensemble), the ensemble forecast can be utilized to isolate the
deficiencies in the model. In summary, this dissertation presents numerous examples of ensemble TC forecasts that can be employed to examine forecast uncertainty, identify the regions and dynamical processes that produce that greatest sensitivity, as well as reveal deficiencies in the forecasting system, all of which provide support towards the improvement of operational TC forecasting.
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EDUCATION:

The Pennsylvania State University, 2016
Doctor of Philosophy: Meteorology

The Pennsylvania State University, 2012
Master of Science: Meteorology

Massachusetts Institute of Technology, 2009
Bachelor of Science: Earth, Atmospheric, and Planetary Science

PUBLICATIONS:


PRESENTATIONS:


“Dynamics and predictability of tropical cyclones evaluated through convection-permitting ensemble analysis and forecasts with airborne radar and sounding observations.” *Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division*, Miami, Florida; 11/2015.


