1C.4 CONVECTION-PERMITTING ENSEMBLE FORECASTS OF THE RAPID INTENSIFICATION OF HURRICANE EDOUARD (2014): PREDICTABILITY, DYNAMICS, AND THERMODYNAMIC STRUCTURE

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1. Introduction

This study utilizes a 60-member real-time convection-permitting ensemble forecast of Hurricane Edouard (2014) to examine the forecast uncertainty and errors associated with the period of near-RI that Edouard underwent. The Pennsylvania State University (PSU) real-time hurricane ensemble forecasts of Edouard benefit from the assimilation of extensive observations taken during NASA's Hurricane and Severe Storm Sentinel (HS3) mission (Braun et al. 2016). The primary goal of this study is to utilize the 60-member PSU 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.

2. Methodology

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 (e.g. 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 ensemble Kalman filter (EnKF) data assimilation algorithm. The WRF model physics configurations are identical to those in Munsell et al. (2015). The EnKF analysis perturbations from 1200 UTC 11 September are utilized to initialize the ensemble forecasts analyzed in this study.

3. Results

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

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 1 shows the corresponding 10-m maximum wind speed of the control run (APSU) and ensemble members from the PSU WRF-EnKF forecasting system.

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 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.

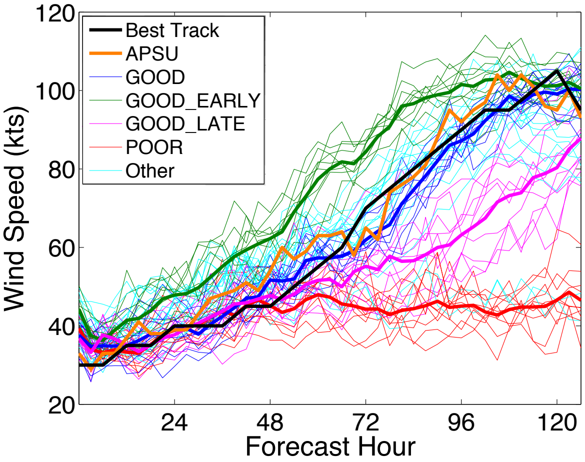

Figure 1. 5-day maximum 10-m wind speed (kt) forecasts for the 1200 UTC 11 September 2014 initialization of Hurricane Edouard from the 60-member PSU WRF-EnKF ensemble forecast system. Members are placed in composite groups of 10 according to their RI-onset time; GOOD – RI-onset at the Best Track RI (72 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), the NHC Best Track (black), and the APSU deterministic forecast (orange) are also plotted. The remaining ensemble members not classified in composite groups are in cyan.

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

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 explored by analyzing the discrepancies between the structural developments of the vortices.

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. 2a) 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.

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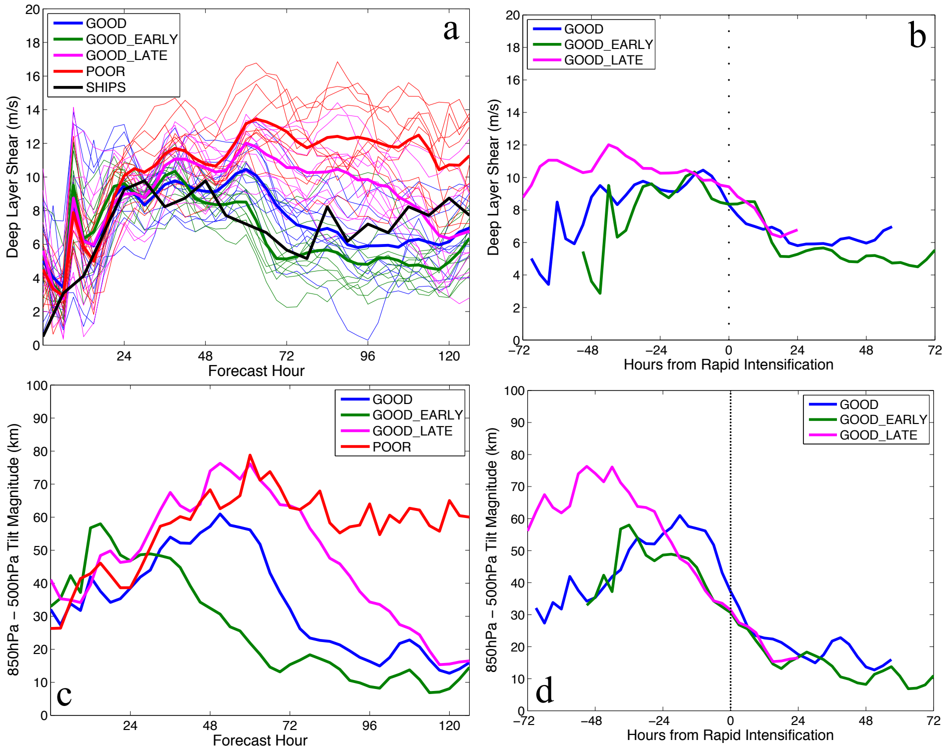

Figure 2. (a) Evolution of the magnitude (ms^{-1}) of deep-layer (850-hPa–200-hPa) wind shear for the mean (thick) and the individual ensemble members (thin) of the composite groups GOOD (blue), GOOD_EARLY (green), GOOD_LATE (magenta), and POOR (red). SHIPS (black) deep-layer shear is also plotted. (b) 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 the evolution of the mean tilt magnitudes (distance between weighted horizontal circulation centers at 850-hPa and 500-hPa; km). (d) As in (b), but for tilt magnitude.

Shear magnitude is relatively weak initially (~5 m s^{-1}) in all composite members, but by 48–60 h there is a clear separation in the shear magnitudes of the composite groups. Due to 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. 2b). From this perspective, it is clear that the shear magnitudes in the developing composites follow a similar evolution and begin to decrease ~6–12 h prior to RI.

A similar analysis of the tilt magnitude evolution (Fig. 2c) shows that the tilt magnitudes of all composite groups are initially similar (~30–50-km); however, differences arise after 24 h as shear increases. When plotted in relation to the RI times in the composites (Fig. 2d), 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.

3.3 Ensemble sensitivity to RI-onset: Initial conditions

It is hypothesized that the GOOD_EARLY vortices undergo RI prior to the rest of the ensemble because they are initially stronger. To test this, sensitivity experiments are performed utilizing 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 composited initial conditions from GOOD and POOR. The maximum 10-m winds from EnvGoodEarlyTcGood and EnvGoodEarlyTcPoor are shown in Fig. 3a. 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 (Fig. 3b) demonstrate that the initially stronger GOOD_EARLY vortex is not particularly sensitive to small degradations of its initial environment and that the environment in POOR is not conducive for intensification to the extent that it delays RI of even initially strong vortices.

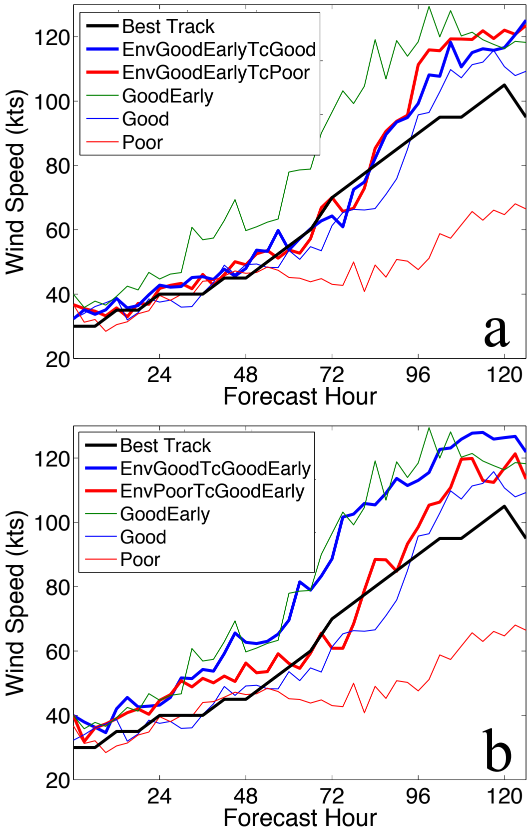

Figure 3. (a) Maximum 10-m wind speed (kt) evolutions for the sensitivity experiments in which the initial vortex in the GOOD_EARLY composite is replaced by that of GOOD (EnvGoodEarlyTcGood; thick blue) and POOR (EnvGoodEarlyTcPoor; thick red). Results from the composited initial condition sensitivity experiment (GOOD_EARLY–thin green; GOOD–thin blue; POOR–thin red; not discussed) and NHC Best Track (black) are also included. (b) As in (a), 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.

4. Summary and Conclusions

Utilizing composite groups created according to the near RI-onset times of the members, it is shown that for increasing magnitudes of deep-layer vertical wind shear, RI-onset is increasingly delayed. In addition, a critical shear threshold appears to exist in which the TC will not intensify once it is exceeded. Although the timing of intensification varies by as much as 48-h, a decrease in wind 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 tilt of the vortex, 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 intensity of the vortex, 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.

5. References

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