14D.9 Rapid Intensification in Tropical Cyclones: Understanding Predictability and Forecast Uncertainly Using High-resolution Stochastic Ensembles

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1. Introduction

Understanding key processes controlling rapid intensity (RI) changes in tropical cyclones (TC) is the "holy grail" of TC intensity prediction, and remains a major challenge despite recent advancements in prediction models and data assimilation.

One of the main questions related to RI is what controls RI. Two competing hypotheses exist in literature: one is that intrinsic convective and mesoscale processes determine the intensity evolution of TCs (e.g., Zhang and Sippel 2008). Another is that the TC environment plays an important role in governing storm intensity (e.g., Emanuel et al. 2004). RI would be more predictable if the latter is more dominant than the former because the predictability of the TC large-scale environment is higher than that of convective processes within the TC.

In this study, we explore the question of internal vs. environmental control of RI within a broader context of TC intensity predictability. Hurricane Earl of 2010, a long-lived TC that underwent RI, is ideal for this study. A detailed analysis of forecast error growth derived from a set of forecast ensembles is used to estimate the predictability limit of TC intensity, and current research is underway to investigate physical processes associated with forecast uncertainty during RI.

2. Methodology

a. Ensemble Technique

Three high-resolution Weather Research and Forecasting (WRF) Model ensembles using the stochastic kinetic energy backscatter scheme (SKEBS, Berner et al. 2009, 2011) were generated. The SKEBS algorithm mimics small amounts of kinetic energy that were lost to diffusion and "backscatters" them onto the resolvable scale by adding a small, stochastic term to the u, v, and T tendency equations. The model was configured with triply-nested vortex-following domains with 12, 4, and 1.33 km grid spacing, respectively. A realistic setup allowed for explicit TC-environment interactions.

b. Experiment design

The main differences between the three SKEBS ensembles (20 members each) were the spatial scale of the stochastic perturbations. The reasoning behind different

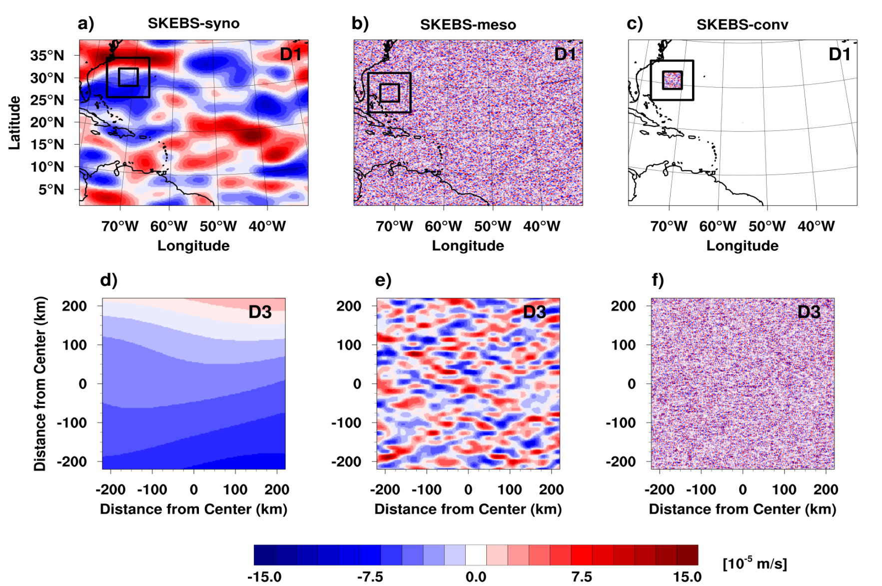

FIGURE 1. SKEBS perturbations added to the u-component of the horizontal wind in the outer model domain for SKEBS-syno (a), SKEBS-meso (b) and SKEBS-conv (c). (d)-(f) are the same, but for the innermost moving domain.

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scales is to investigate and isolate the effects of (1) synoptic-scale, (2) mesoscale and (3) convective scale uncertainty on TC predictability and RI. A list with the ensembles and their respective SKEBS characteristics follows below:

1. SKEBS-syno: "synoptic-scale" perturbations (500-3500 km), perturbations added to all domains
2. SKEBS-meso: "mesoscale" perturbations (24-500 km), perturbations added to all domains
3. SKEBS-conv: "convective-scale" perturbations (2.6-12 km), perturbations *only* added to the innermost domain.

Figure 1 provides an example of the stochastic perturbations pattern for the three ensembles. Figures. 1a-c display the SKEBS patterns on the outer domain, and Figures 1d-f zooms in on the SKEBS on the innermost domain. Note the drastic differences in perturbation scale spanning three orders of magnitude. Furthermore, SKEBS-conv was only perturbed on the innermost domain. All ensembles were initialized at 0000 UTC 27 August 2010 with identical fields from the Global Forecast System and integrated for 7 days.

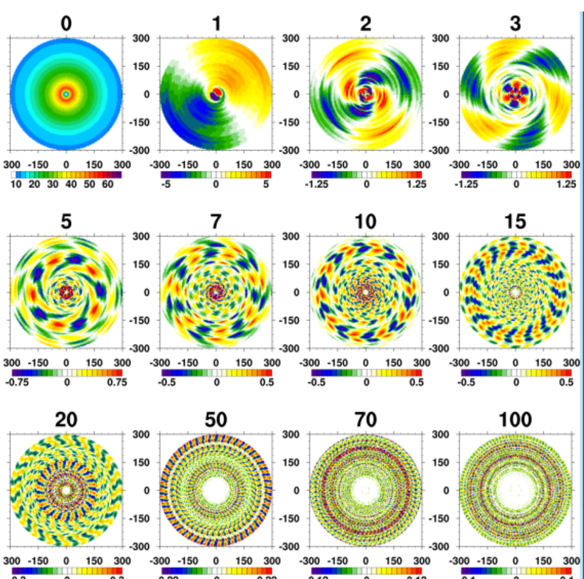

FIGURE 2. Azimuthal wavenumber 0, 1, 2, 3, 5, 7, 10, 15, 20, 50, 70, 100 components of the surface wind field. Wavenumber 0 represents the mean vortex, wavenumbers 1-3 resemble rainbands and higher order wavenumbers are associated with smaller mesoscale and convective scale elements.

c. Quantification of forecast error

Forecast errors were calculated similar to the approach described in Lorenz (1969). Here, the surface wind fields of the ensemble TCs were Fourier-decomposed into azimuthal wavenumbers (~scales, Fig. 2). The "error fraction" was defined as the ratio between ensemble mean kinetic energy (K) and variance (E), and calculated every 6 for wavenumbers 0-180. In the case of E≈K, the ensemble offers essentially no more information than guessing, which is tantamount to a loss of predictability.

3. Results

a. Track and intensity uncertainty

Figure 3 shows that track uncertainty is directly related to the spatial scale of the SKEBS perturbations. The synoptic-scale perturbations cause the largest amount of uncertainty as they project most efficiently onto the large-scale environment, which controls TC track (Fig. 3a). Figure 3c indicates that convective scale perturbations do not lead to pronounced track diversity, suggesting that upscale error growth to synoptic-scales in this flow regime is not effective on the 7 day time scale.

The SKEBS effect on the evolution of TC intensity does not show these differences between the perturbations scales as drastically. Figure 4 displays the intensity time series for SKEBS-syno (Fig. 4a), SKEBS-meso (Fig. 4b) and SKEBS-conv (Fig. 4c). The most pronounced uncertainty in Fig. 4a-c is associated with Earl's RI phase. Virtually all ensemble members show a period of RI, however the timing is very different and spread out over a 2-3 day window between forecast hours 36-96 h. Note that even small-scale perturbations induce tremendous uncertainty with respect to when RI occurs (Fig. 4c).

After all TCs intensified, the uncertainty decreases significantly and only slowly increases again towards the end of the forecast window, when the vortices begin extratropical transition.

b. Forecast error and predictability

Forecast errors on small scales (azimuthal wavenumbers 20-180) grow rapidly and saturate after 6-12 forecast hours, indicating a loss of predictability soon after initialization (not shown). Figure 5 displays the error fraction for

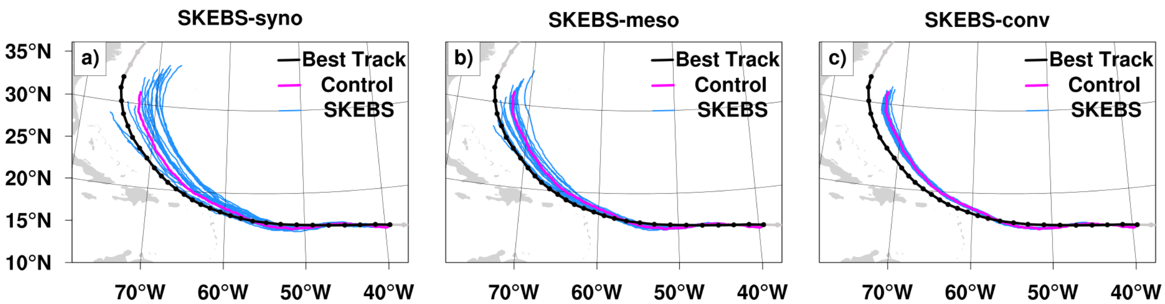

Figure 3. Best-Track estimate (black) and 7-day forecasts of Hurricane Earl (2010) tracks (blue) from (a) SKEBS-syno, (b) SKEBS-meso, and (c) SKEBS-conv ensembles. The model is initialized at 0000 UTC 27 August 2010.

wavenumbers 0-5 during the 7-day integration period. SKEBS-syno features the highest errors and most rapid error growth rate for the rainband scale wavenumbers 2-5, since the perturbations causing the uncertainty likely resonate with the TC vortex (Fig. 5a, red colors). Error growth on these scales is smaller for SKEBS-meso and SKEBS-conv (Fig. 5b,c).

Figure 5 also shows that wavenumbers 0 and 1 feature much smaller error fractions at all times, and there is no saturation throughout the 7-day forecast period (error fraction < 0.7). These vortex scale components are thus predictable for at least 7 days in the case of Hurricane Earl.

c. Rapid Intensification

As Fig. 4 has indicated, most of the uncertainty is associated with the period of RI. In order to shed light on the physical processes determining the timing of RI, the 5 earliest and 5 latest RI members of SKEBS-syno have been grouped into two categories (Fig. 6). Figure 7 shows two surface wind field from a member of each category valid at t = 60 h, when the intensity spread between the groups is maximum. Member 2 (Fig. 7a) features the pronounced wavenumber 1 asymmetry of a weak TC, while the strong symmetric vortex of member 3 (Fig. 7b) is indicative of a mature hurricane. The goal is to investigate TC or environmental characteristics ("precursors") leading to RI that can be identified before the two groups diverge around t = 36 h.

Figure 8 displays the ratio of wavenumber 0 to 1 power of the members of the two groups for the first 48 h, and the dashed lines are the respective means of the two groups. This ratio is essentially indicating whether the mean vortex or wavenumber 1 asymmetry is more dominant. It is generally > 1 before t = 24-30 h because the nascent TCs are just starting to develop a well-defined circulation and the mean vortex is still weak. The interesting thing to note is that the "late

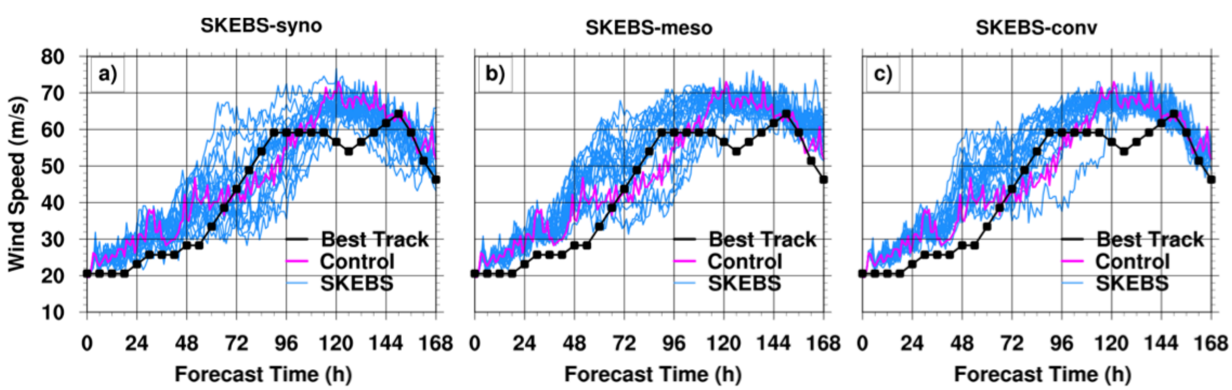

Figure 4. Same as in Fig. 3, except for 7-day forecast of maximum wind speed.

intensifiers" (Fig. 8, blue) feature relatively more power in their wavenumber 1 component compared to the "early intensifiers" (Fig. 8, red). The largest difference between the groups is most pronounced around t = 18-24 h, which is about 24 h before the actual separation in intensity occurs

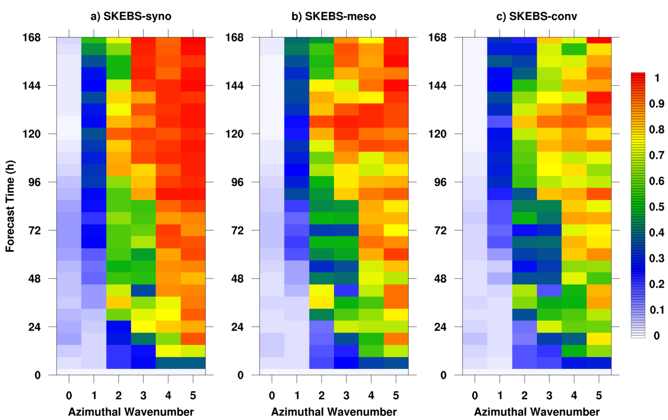

Figure 5. Error fraction (color) as a function of azimuthal wavenumber and forecast time from (a) SKEBS-syno, (b) SKEBS-meso, and (c) SKEBS-conv ensembles.

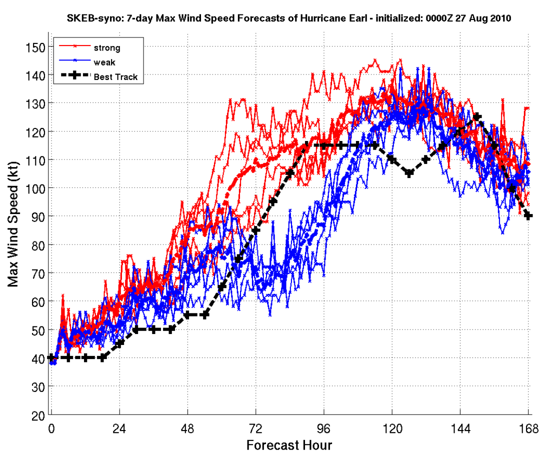

Figure 6. Intensity forecasts of five "early intensifiers" (red) and five "late intensifiers" (blue) from the SKEBS-syno ensemble.

(Fig. 6). This indicates that there is a characteristic signal about a day before the "early intensifiers" undergo RI. The relatively stronger wavenumber 1 component of the "late intensifiers" may have been related to a temporary increase in shear during the early TC stage (not shown). This finding is in agreement with the results from idealized simulations in Zhang and Tao (2013), who noticed an increase in RI uncertainty under stronger shear.

4. Conclusion

The main findings of this study related to RI are:

- The TC environment seems to be in control over whether RI will happen or not.
- The exact timing of RI is highly uncertain, but may be predictable if it is determined by environmental factors

It was found that the "late intensifiers" feature a relatively stronger wavenumber 1 component about a day before the "early intensifiers" undergo RI, indicating that there is a subtle signal even before the intensity of the two groups diverges significancy. The goal of ongoing research is to identify physical processes associated with these signals, such as shear during the early TC development stage.

The error growth analysis showed that small scales within the TC are not predictable beyond a few hours. This is possibly a reason for why the timing of RI is inherently uncertain. Rainband scale motions (wavenumbers 2-5) are predictable for a few days, however the mean vortex and wavenumber 1 asymmetry can be predictable beyond 7 days for long-lived non-landfalling TCs. This result furthermore hints at the environmental control of the intensity and strength of the mean vortex.

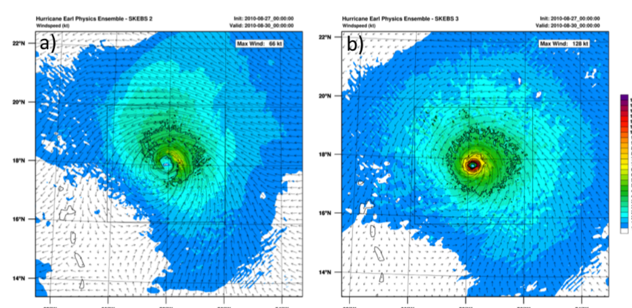

Figure 7. Surface wind field (kt) of SKEBS-syno member 2 (a) and member 3 (b) at 0000 UTC 30 August 2010.

The TC vortex seems to be resistant to error growth and upscale propagation, implying that the *predictability limit* of the mean vortex intensity and size is in line with synoptic scale features. However, even convective scale uncertainty is able to affect the timing of RI. This result indicates

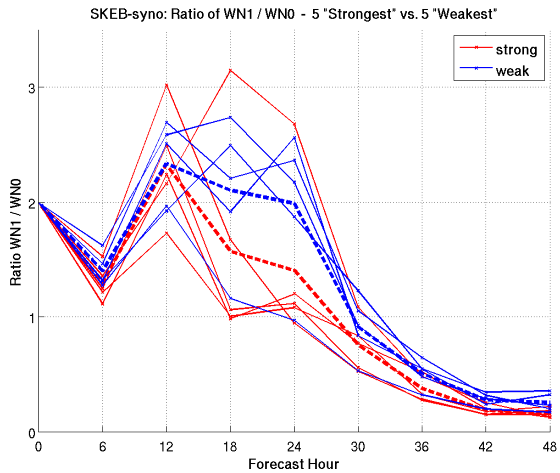

FIGURE 8. Ratio of power of wavenumber 0 and 1 as a function of forecast time. "Early intensifiers" are in red and "late intensifiers" are in blue. Dashed lines denote the average of each group.

that, although the environmental conditions are conducive for RI, a deterministic prediction of RI may be inherently difficult. Based on this unique data set of 60 high-resolution forecast ensemble TCs featuring RI, current research investigates physical processes that control the timing and magnitude of RI in more detail, and how they contribute to forecast uncertainty. Composites of all TC RI events from the three ensembles may shed some lights on the conditions leading to RI.

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