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ADJOINT SENSITIVITY DIAGNOSIS OF THE INTENSIFICATION OF HURRICANE HARVEY

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1. INTRODUCTION

Improvements to tropical cyclone (TC) intensity prediction are well-known to lag in comparison to track prediction. Over the last few decades, TC track accuracy has improved considerably due to an understanding and consensus of key steering mechanisms (Chan, 2005; Hoover and Morgan, 2011) while improvements in TC intensity forecasts have generally plateaued. However, there has been a renewed focus on forecast intensity change and effective methods for further improvements.

A variety of methods have been implemented to analyze TC forecast sensitivity, including ensemble variance, ensemble transform Kalman filter, singular vectors, and adjoint diagnostics. This study uses adjoint-derived diagnostics to diagnose the sensitivity of measures of the simulated intensity to initial conditions for a simulation of the period of Hurricane Harvey's rapid intensification (RI).

2. SYNOPTIC OVERVIEW

Harvey began as a tropical wave off the west coast of Africa on 13 August 2017, and remained unorganized until it passed over the Yucatan Peninsula on 22 August. As the disturbance continued into the Gulf of Mexico, it reformed into a tropical depression (TD) and became more organized due to favorable low wind shear and deep, warm ocean water content. On 1200 UTC of 23 August, the National Hurricane Center (NHC), as well as other numerical models, forecasted Harvey would make landfall north of Corpus Christi on 25 August as a tropical storm. However, Harvey underwent RI, intensifying from TD to category 4 status in under 40 hours. The NHC's forecast at 1200 UTC on 24 August, captured this intensification, however, not the rate of intensification, forecasting Harvey to make landfall still north of Corpus Christi as a major hurricane before landfall 0000 UTC 25 August.

3. MODEL

The Weather and Research Forecasting (WRF) model (Skamarock et al., 2008) and its adjoint (Zhang et al., 2013) are run at 30km resolution on a domain centered over Harvey at the final forecast hour (Fig. 1). The model is initialized with 0.25° GFS global data at 1200 UTC 23 August for a 36-hour forecast. The response functions are defined at 0000 UTC 25 August, centered around the vortex. The WRF adjoint is run with simplified physics.

The WRF forecast under represented the intensity, as its minimum sea level pressure of 993.6 hPa at 00 UTC 25 August, approximately 20 hPa higher than observed (Fig. 2a). This is due to the WRF not capturing the RI about 15 hours into the forecast. The forecast also showed a slight southwestward bias for the lowest central sea level pressure compared to the best track (Fig. 2b). While the forecast does not closely match the analysis, it is consistent with real-time forecasts initialized at the same time, both in track and intensity.

4. RESPONSE FUNCTIONS

An adjoint model is the transpose of the tangent linear approximation to a numerical weather prediction model, linearized about a forecast trajectory of the nonlinear NWP model. Adjoint models evaluate the change in a specific forecast aspect (defined by a response function) with respect to changes in the model control variables at earlier times by evolving the response function gradient with respect to those control variables backward through time. The advantage of an adjoint study is a single adjoint model run can determine the sensitivity of a chosen response function to all input parameters (Errico, 1997). Adjoint models have limited accuracy in situations characterized by highly non-linear and moisture-dependent processes; however, tests exist to check the legitimacy of the adjoint sensitivity calculations based on linearity.

The first prescribed adjoint response functions (R_1) is the winds around a defined box centered on the TC core (i.e. vorticity) and the second (R_2) is the negative perturbation dry air mass in column within that boxed area (i.e. central sea-level pressure). As described previously, the output of an adjoint model are the sensitivities of the chosen response function (in this case two measures of intensity) to input parameters, such that perturbing the output field will intensify the storm. Multiple response functions representing the same forecast aspect allows to check for consistency. Figure 3 shows the low-level sensitivity to temperature (fill) and wind (vectors) for response functions R_1 and R_2 at forecast hour -36 (e.g. model initialization). Consistent temperature sensitivity suggests increasing temperatures to the east and decreasing temperatures west of the vortex will intensify the storm at the at the final forecast hour. Additionally, there is an enhanced sensitivity to wind near the vortex, generally suggesting a more convergent and cyclonic circulation at the initial time will lead to a more intense storm.

5. FUTURE WORK

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Continued investigation into Hurricane Harvey will involve testing the appropriateness of linearity for this case by comparing the anticipated change to the response functions based on the inner product of the initial condition sensitivity with an initial perturbation, with the difference in the response function calculated from a perturbed and control simulation. In addition, adjoint-informed optimal initial perturbations (Errico 1997) will be created to specifically intensify (and weaken) Harvey (as measured by the response function changes). A diagnosis of the impact of the perturbations on the evolution of the TC will allow for discovery of factors within the model and the atmosphere that contributed to a poor intensity simulation of Harvey. Additionally, the results of this study may inform improved strategies for targeted observations for intensity change.

6. REFERENCES

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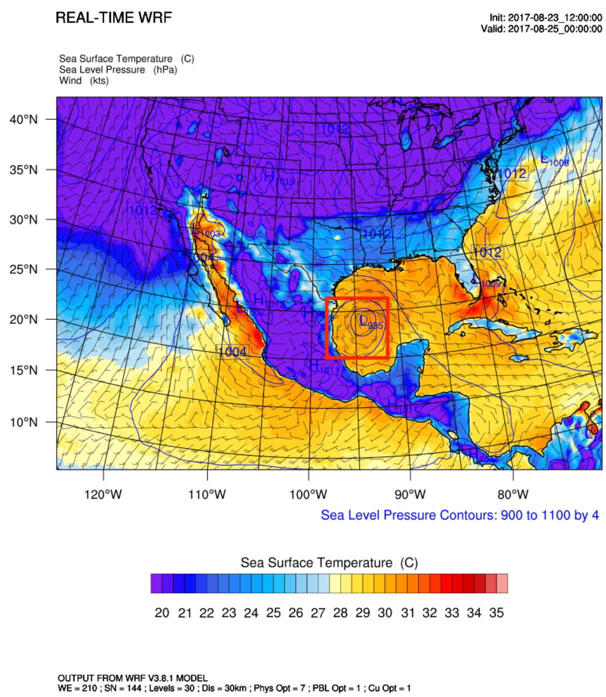

Figure 1) 0000 UTC 25 August 2017: Sea surface temperature (fill), sea level pressure (contour) and response function box (red)

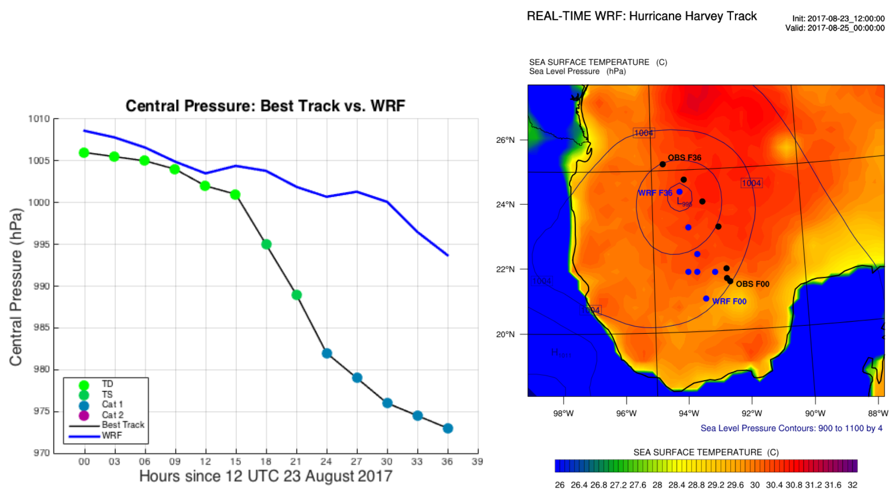

Figure 2) WRF (blue) versus Observed (black) a) Central low pressure and b) position of Hurricane Harvey every 6 hours from 1200 UTC 23 to 0000 UTC 25 August 2017 with sea level pressure (contour), sea surface temperature (fill)

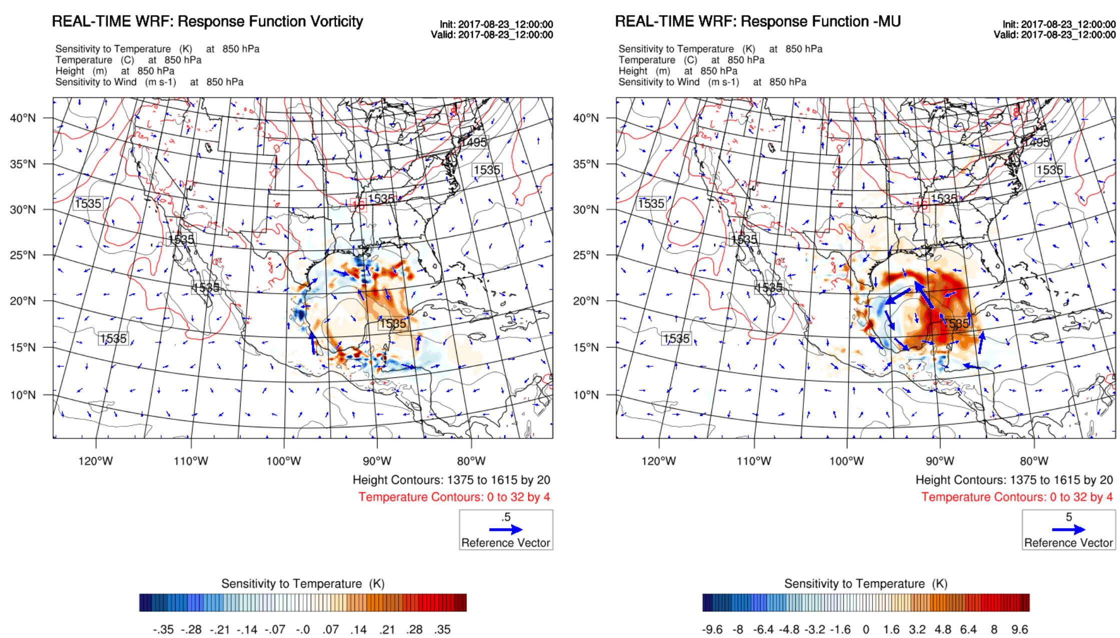

Figure 3) 00 UTC 25 August 2017 sensitivity to temperature (fill) and wind (vectors), temperature (red contour), and geopotential height (black contour) for response function a) R_1 and b) R_2