Understanding the Impact of Outflow on Hurricane Intensification through Ensemble-Based Data Assimilation and Ensemble Simulation with Multiple Models

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LONG-TERM GOALS
The long-term goal of this project is to enhance our understanding of tropical cyclone (hereafter, TC) intensification, through ensemble-based data assimilation and ensemble simulations with multiple models.

OBJECTIVES
While TC track forecasts have improved substantially in recent decades, improvements in TC intensity forecasts have been less evident (National Hurricane Center 2015). Several factors have been shown to influence the skill of TC intensity forecasts, such as vertical wind shear, sea surface temperature, and tropospheric moisture (e.g., DeMaria and Kaplan 1994). The focus of this project is the impact of upper-level outflow layer on TC intensification and its predictability. In particular, this project will
address how the TC outflow becomes coupled with the inner-core convection and how this coupling affects TC intensification. In addition, this project will examine the impact of the data collected from the 2015 Tropical Cyclone Intensity (TCI) experiment on the estimation and prediction of the outflow layer, as well as the intensity prediction of TCs. The results of this project will also address the value of using multiple models in ensemble-based data assimilation and in ensemble simulations on predicting the outflow and understanding its impact on TC intensification.

**APPROACH**

This project will use both the Hurricane Weather Research and Forecasting (HWRF) model and the Coupled Ocean-Atmosphere Mesoscale Prediction System – Tropical Cyclone (COAMPS-TC) model for the ensemble-based data assimilation and ensemble simulations of TCs to examine the impact of the outflow on TC intensification. The HWRF model uses a hybrid ensemble Kalman Filter (EnKF) – variational (VAR) data assimilation and ensemble forecast system based on the Gridpoint Statistical Interpolation (GSI) developed by the National Oceanic and Atmospheric Administration (NOAA). Wang and Lu (2015) and Lu et al. (2015) provide the descriptions of the HWRF hybrid EnKF-Variational system. The COAMPS-TC model currently uses the NRL Atmospheric Variational Data Assimilation System (NAVDAS), which is a three-dimensional variational (3DVAR) method. An experimental EnKF data assimilation system based on the Data Assimilation Research Testbed (DART) has been developed and implemented within the COAMPS-TC model to provide real-time ensemble prediction and data assimilation for TCs (e.g., Doyle et al. 2011; Reinecke et al. 2011). Both the HWRF and COAMPS-TC modeling systems have capabilities to provide skillful TC analysis and forecasts.

To advance the understanding of the outflow layer on TC intensification, accurate high-resolution observations that sample the outflow layer are needed. High-resolution Atmospheric Motion Vectors (AMVs) retrieved from satellites can capture some detailed flow structures in the upper-level regions of TCs (Berger and Velden 2007). However, AMVs can provide horizontal wind information only; thermodynamic variables are unavailable. In addition, routine hurricane research and reconnaissance aircrafts do not sample the TC outflow layer. The 2015 TCI field program can collect unique in-situ high-resolution observations of the TC outflow layer, with dropsondes released above the outflow layer that provides both wind and thermodynamic structures associated with the outflow layer. The TCI observations of the outflow layer can help improve our understanding of the outflow layer structures. Assimilating the TCI data into ensemble simulations of TCs will allow the examination of how the outflow layer influences TC intensification and its predictability.

**WORK COMPLETED**

**Diagnosing the storm-scale structures at the onset of the rapid intensification of Hurricane Edouard (2014) using ensemble simulations**

As a starting point, the operational HWRF ensemble simulations of Hurricane Edouard (2014) were analyzed. Four sets of the HWRF forecasts initialized on 12 September (0000, 0600, 1200, and 1800 UTC) when Edouard was a tropical storm were examined. In this 84-member dataset, there are a few ensemble members that closely matched the best-track data, while some members developed Edouard into a hurricane but too late; there are some other members that did not develop Edouard into a hurricane at all. Storm-scale structures at the onset of rapid intensification of Hurricane Edouard (2014) in the intensifying, late-intensifying, and non-developing members were examined and
compared with previously proposed hypotheses that involved vortex tilt and upper-level warm core. Lagged correlation coefficients between the minimum sea-level pressure (mSLP) and the aforementioned storm-scale structures were computed to determine whether the aforementioned storm-scale structures were precursors or symptoms of the rapid intensification. Results of this work has been submitted for peer review and is currently in the revision process (Moon et al. 2015). In addition, diagnostics studies revealing the differences of outflows associated with the intensifying, late-intensifying and non-developing members are ongoing.

**Developing capabilities to assimilate TC outflow layer observations**

Apart from the TCI in-situ data, the type of the remotely sensing observation dataset that can provide the most useful information about the TC outflow layer is AMVs. Since the density of AMVs prepared by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) of University of Wisconsin – Madison is greater than that of AMVs used in operation, assimilating the CIMSS AMVs is expected to yield a more accurate and realistic representation of the TC outflow layer in the analysis for TC ensemble simulations. While waiting for in-situ observations to be collected and quality controlled during the 2015 TCI field campaign, capabilities to assimilate CIMSS AMVs are developed. The efforts include a) converting CIMMS AMVs and associated observation errors and quality marks into appropriate formats, b) assimilating these data into an ensemble based data assimilation system for Gonzalo (2014) and c) initial diagnostics to examine the impact of assimilating CIMMS AMVs on the analysis of the outflow layer.

**RESULTS**

**Storm-scale structures at the onset of the rapid intensification of Hurricane Edouard (2014)**

Figures 1a,b show the track and mSLP of four sets of HWRF Edouard forecasts, initialized at 0000, 0600, 1200, and 1800 UTC on 12 September, with the thick black lines showing the NHC best-track data. There are 84 thin lines (four sets of one deterministic and 20 ensemble forecasts) on each plot. Green lines mark the deterministic forecasts. Edouard became a hurricane on 14 September and a major hurricane on 16 September.

Figure 1a shows that the majority of the track forecasts have a westward bias, and Fig. 1b shows that most of the intensity forecasts lag 12 to 36 hour behind the best-track data. However, there are a few ensemble forecasts that closely match the best-track mSLP, such as ensemble member 16 from the 1200 UTC initialization (12UTC#16; red line in Fig. 1). In addition, there are some members that do not develop Edouard into a hurricane at all (magenta lines in Fig. 1), while some other members develop Edouard into a hurricane but too late (blue lines in Fig. 1). All of the aforementioned intensifying members have the rapid intensification (RI) periods at some point during the forecasts. For Atlantic basin TCs, the RI implies a 22 hPa decrease in minimum SLP (mSLP) during a 24-hour period in the 1989-2011 NHC best-track data (e.g., Silver and McFarquhar 2013).
Recent studies examined storm-scale structures associated with rapidly intensifying TCs. Several features were found to be important, including upper-level temperature anomalies or warm core (e.g., Chen and Gopalakrishnan 2015) and vortex alignment (e.g., Rogers et al. 2015). Whether upper-level warm core formation or vortex alignment precedes the onset of the RI periods remains debatable, partly because the aforementioned studies were based only on individual cases. Analysis of additional TC cases is necessary to generalize the results of the previous hypotheses. This project contributes to this key topic of TC intensification by examining storm-scale structures associated with the onset of the RI periods in the HWRF ensemble simulations of Hurricane Edouard (2014).

Figure 2a shows the time series of mSLP and tilt vector magnitude of the 12UTC#16 run that closely matches the best-track data. The tilt vector is calculated as the difference in the potential vorticity-weighted centroids between 500 and 900 hPa, similar to Jones (2004). Comparing the time series of mSLP and tilt magnitude suggests that a large reduction in the tilt magnitude appears to occur before the onset of the RI period in this Edouard forecast. Figure 2b shows the time-height diagram of temperature anomaly near the TC center. Temperature anomaly is defined as the difference from the far-field environment, which is the average of a 100-km thick annulus centered at $r = 600$ km, as in Knaff et al. (2004). The upper-level temperature anomaly that becomes associated with the well-developed Edouard at later times appears to form sometime between $t = 48$ and 60 h, which is close to the beginning of the RI period. Figure 2c is the time-height diagram of moist static energy (MSE) averaged within 150 km from the storm center. Warming and moistening in the mid-tropospheric layers – thereby increasing in mid-tropospheric MSE – were noted in tropical disturbances that developed into TCs (e.g., Zawislak and Zipser 2014). The inner-core mid-tropospheric MSE minimum begins to increase with time near $t = 48$ h, close to the beginning of the RI period. Late-intensifying members (blue lines in Fig. 1) show qualitatively similar results.
Figure 2: (a) mSLP and tilt vector magnitude of the intensifying member 16 initialized at 1200 UTC. (b) Time-height plot of temperature anomaly averaged within 10 km from the storm center. White lines show 12 and 14 K contours. (c) Time-height plot of moist static energy (MSE = \(c_p T + gz + L_v q\), where \(c_p\) is the specific heat at constant pressure, \(T\) is temperature, \(g\) is gravitational acceleration, \(z\) is altitude, \(L_v\) is the latent heat of vaporization, and \(q\) is water vapor mixing ratio) averaged within 150 km from the storm center. Solid black lines in (b) and (c) show the temperature anomaly averaged between 100 and 500 hPa and the moist static energy averaged between 400 and 700 hPa. Black vertical line in (a) marks the beginning of the rapid intensification period.

To examine how closely each processes is associated with the RI onset, linear correlation coefficients are computed between mSLP and tilt magnitude, upper-level warm core, and inner-core mid-tropospheric MSE. Since the importance of the upper-level warm core has been emphasized in previous studies (Chen and Gopalakrishnan 2015), the time series of the upper-level warm core averaged between 100 and 500 hPa (e.g., black lines in Fig. 2b) is compared with the mSLP. Inner-core MSE is averaged between 400 and 700 hPa (e.g., black line in Fig. 2c), as the most evident feature before and after the onset of the RI periods appears to be the difference in the mid-tropospheric layers. To determine which processes precede the RI onset, linear correlation coefficients are computed with the mSLP time series data shifted 0, 3, 6, … 24 hours earlier than the tilt vector, upper-level warm core, and inner-core mid-tropospheric MSE data.

Figure 3 shows correlation coefficients between the mSLP and the tilt vector magnitude, upper-level warm core, and inner-core mid-tropospheric MSE of the intensifying and late-intensifying members in which Edouard underwent the RI period, with differently color-coded lead-times. The correlation coefficients of mSLP are positive with the tilt magnitude but are negative with the upper-level warm core and inner-core mid-tropospheric MSE. The correlation coefficients between the mSLP and the tilt magnitude (Fig. 3a) and the upper-level warm core (Fig. 3b) are high, at over 0.82. In Fig. 3a, the strongest correlation between the mSLP and tilt magnitude is found when the mSLP data is shifted 12 to 24 hours. However, in Fig. 3b, the highest correlations between the mSLP and upper-level warm core are found at the lead-times of 0 or 3 hour. The correlation decreases with increasing lead-times of
greater than 3 hour. This indicates that decrease in the tilt vector likely precedes mSLP decrease and the RI period within it. However, the formation of the upper-level warm core occurs concurrently with mSLP deepening in the rapidly intensifying Edouard forecasts. The correlation coefficients between mSLP and mid-tropospheric MSE in Fig. 3c are highest at the non-zero lead-times between 6 and 18 hour, suggesting that increase in the inner-core mid-tropospheric MSE likely precedes mSLP decrease associated with the RI period.

Therefore, it is likely that the formation of the upper-level warm core is a symptom of the RI process, as the highest correlations are found very close to the lead-times of 0 hour. However, the tilt and inner-core mid-tropospheric MSE have the largest correlations at the lead-times of 9 hours or longer. This suggests that reducing the vertically tilt structure and warming and moistening in the mid-tropospheric layers in the inner-core region of the storm could be important in initiating the RI period in Edouard. Additional work will be conducted in the future to clarify which kinematic and thermodynamic processes are responsible for initiating the intensification period in Edouard, in particular the upper-level outflow layer of TCs.

![Figure 3: Correlation coefficients between mSLP and (a) tilt vector magnitude, (b) upper-level warm core temperature, and (c) inner-core mid-tropospheric moist static energy, with different colors showing different lead times.](image)

**Impact of assimilating CIMMS AMVs on the analysis of the TC outflow layer**

Fig. 4 and Fig. 5 show the horizontal and vertical distributions of the CIMSS AMVs data within a 6-hour window centered at 12Z, Oct. 16th, 2014 for hurricane Gonzalo (2015). Apparently, CIMSS AMVs data has much more coverage and higher resolutions than the AMVs in data stream that are operationally assimilated. It is also noted that the number of CIMMS AMVs data peaks around 200hPa (dominated by IR and WV) and 900hPa (dominated by SWIR and VI).
As an initial step of analyzing the impact of assimilating CIMSS AMVs on the analysis of TC outflow layer, Fig. 6 shows the 200hPa horizontal wind increments before and after assimilating the AMVs data. The wind increment made by assimilating CIMSS AMVs data reduced the speed around the roots of the north-northeastward outflow and in the regions where northward outflow interacted with the mid-latitude trough. Additionally, the wind increment made by assimilating CIMSS AMV data increased the speed around the exit of the southeastward outflow and the easterly wind zone to the south of the storm (66W~70W, 20N). In comparison, assimilating the operational AMVs was not able to bring as much corrections to the background as assimilating the CIMSS AMV data. For example the correction of wind speed around the roots of the north-northeastward outflow was completely missing.
Fig. 6 a) CIMSS AMV observation for Gonzalo (2014); b) Background wind field at 200hPa; c) wind increment at 200hPa by assimilating CIMSS AMV data; and d) wind increment at 200hPa by assimilating the AMV data in operation data stream. Shaded are the horizontal wind speed (a, b) and horizontal wind speed increments (c, d). The arrows in b), c) and d) are all the background wind vectors.

IMPACT/APPLICATIONS

The results described in the previous section have identified a few structures that act as precursors to rapid intensification of Hurricane Edouard – vortex tilt and mid-tropospheric MSE. Additional work will be necessary to test the robustness of the results with multiple ensemble simulations of multiple storms in the HWRF and COAMPS-TC models. Additional work is ongoing to identify the kinematic and thermodynamic processes responsible for initiating the intensification period, in particular the upper-level outflow layer of TCs. Such robust precursors will be extremely useful in enhancing TC intensity prediction.
The capability developed for assimilating TC outflow layer observations such as CIMSS AMVs laid the foundation to further improve our understanding of the outflow layer structures and to allow the examination of the impact of outflow observations and how the outflow layer influences TC intensification and its predictability.

**RELATED PROJECTS**

None

**REFERENCES**


PUBLICATIONS