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Environmental Sensitivity of Tropical Cyclone Outflow

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LONG-TERM GOALS

The overarching goal is to advance the understanding of sensitivities of tropical cyclone outflow to environmental conditions. This goal ties in with the primary objectives of the ONR Directed Research Initiative on Tropical Cyclone Intensity (TCI). Benefits to the Navy would include improved understanding and predictive skill of changes in the structure and intensity of tropical cyclones.

OBJECTIVES

1) To provide novel daily forecast products to support mission planning during the TCI field campaigns, based on ensemble predictions from the European Centre for Medium-Range Weather Forecasts (ECMWF).

2) To test the hypothesis that "the predictability of the outflow (and thereby TC structure change) is largely modulated by the environment, and in particular the amplitude and phase of upper-level troughs upstream and downstream."

Several sub-hypotheses are also proposed:

SH1: The development of poleward outflow channels is sensitive to small perturbations in the mid-latitude jet, and specifically the coupling between the outflow and the jet.

SH2: The relative phase between the TC and environmental features is critical in the establishment of outflow channels and thereby intensity change.

SH3: Modifications to the dynamic and thermal structure of the outflow influence both the radial TC structure (size; eyewall slope) and environmental features such as the mid-latitude jet.

SH4: Dynamic and thermodynamic perturbations to the outflow and sensitive environmental features are crucial in creating sufficient diversity in mesoscale ensemble predictions.

APPROACH

Forecast products to support TCI mission planning: Via a special license agreement with ECMWF, the PI received real-time ensemble forecast data initialized at 0000 UTC each day during the period of the field campaign. The forecast products were created each morning and shared on a website hosted by the PI, and uploaded to the TCI field catalog http://catalog.eol.ucar.edu/tci prior to the Daily Planning Meeting. The products were shared, as per the license agreement, with TCI participants. Other products were created when requested by TCI collaborators.

Hypothesis Testing: The hypothesis testing is being performed by Yi Dai for his Ph.D. studies. In his first year, he has conducted a literature review on environmental influences on tropical cyclone outflow, and has investigated the structure of outflow using vertical wind profiles from dropwindsondes released from the NASA Global Hawk aircraft during the 2014 field campaign. Reanalysis data and COAMPS-TC model outputs have also been investigated. Currently, an idealized modeling approach is underway to analyze the sensitivity of the outflow structure to the structure and position of an upstream jet. This approach builds upon the limited studies in the literature.

WORK COMPLETED

Forecast products

Daily products from the 0000 UTC ECMWF ensembles were produced in real-time from July-October 2015. Products include spaghetti contours of lower-tropospheric circulation, the probability that lower-tropospheric relative humidity exceeds 70%, and the probability that deep-layer wind shear exceeds 15 m/s. A new storm-relative product illustrating the different possible outflow structures in the deterministic ECMWF forecast and the 50 ensemble members was also created to assist with the mission design (Fig. 1).

PI Majumdar served as the TCI Science Director in Wallops Island VA for 5 days during September 2014. Brian McNoldy (Senior Research Associate) was involved in coordinating the model outputs for the field program plan. McNoldy and Yi Dai (Ph.D. student) led forecast briefings for three weeks during the 2015 TCI field campaign.

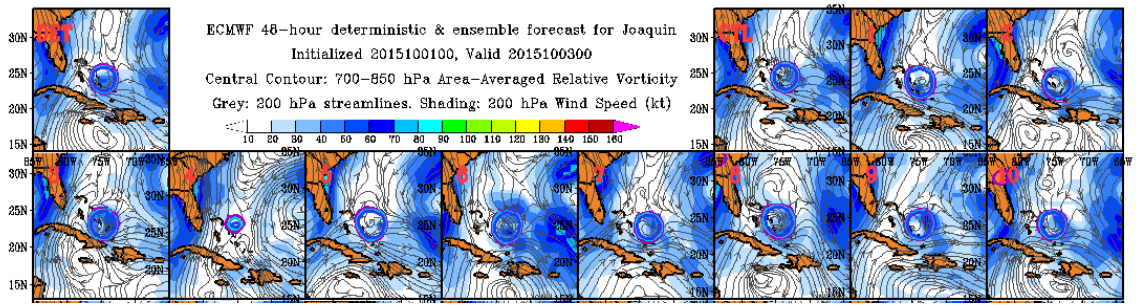

FIGURE 1. Deterministic 48-hour ECMWF forecast and the corresponding Control plus 10 ensemble forecast "postage stamps" for Hurricane Joaquin. Contours: area-averaged relative vorticity within a disk of radius 200 km, averaged between the 700 hPa and 850 hPa levels. Contours correspond to values of 8, 10 and 12 x 10^{-5} s^{-1}, respectively, commensurate with a mature tropical cyclone. 200 hPa streamlines and wind speeds are plotted, in order to illustrate the direction and strength of the outflow.

Hypothesis Testing

The main work completed comprises a literature review, an initial case study of Hurricane Edouard (2014) using observations and reanalysis data, and the initial design of an idealized modeling framework to test the hypotheses. This has been done by beginning with the basic question of how to characterize the outflow, and then to investigate its behavior and potential environmental influences.

RESULTS

The first step of the Ph.D. research is to elucidate how to characterize the outflow, and how the environmental flow is influencing the outflow. We have found that the outflow corresponds to an area of minimum inertial stability relative to the environment (Fig. 2), which is not surprising given that the relative vorticity and tangential velocity are negative, and therefore the inertial stability can be used as one diagnostic for the outflow.

(a) (b)

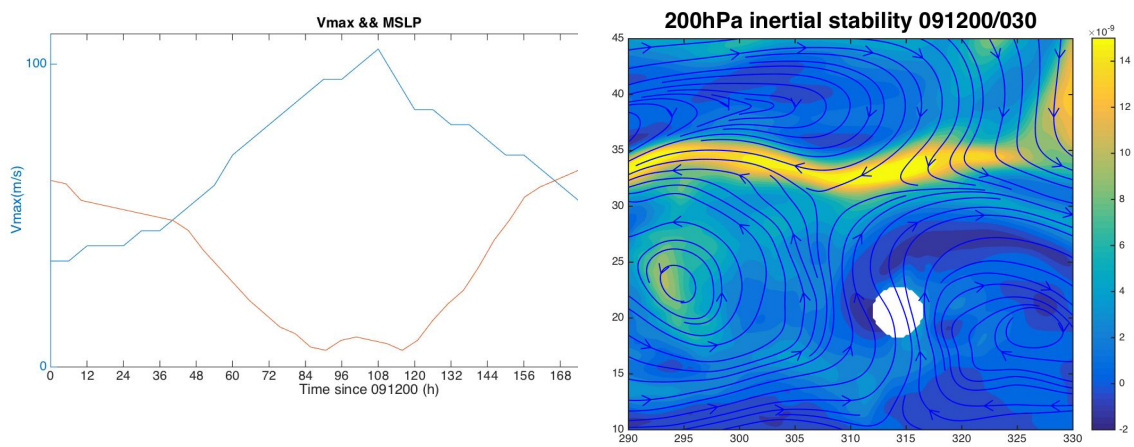

FIGURE 2. (a) Time series of (blue) maximum tangential wind and (blue) minimum sea level pressure of Hurricane Edouard (2014). (b) 200 hPa inertial stability in the environment of Edouard (2014, white circle) during its intensification stage. The region of instability, shaded in blue, is associated with the outflow

Several published papers have motivated the role of Eddy Flux Convergence (EFC) as a controller of the outflow and environmentally driven intensity change. Conflicting ideas exist about whether the inward or outward movement of the EFC is necessary for intensity change. Based on observational and reanalysis data from Hurricane Edouard (2014), our hypothesis is that the EFC may play a different role, and that its position relative to the tropical cyclone may be important. In the case of Edouard, if the strongest positive EFC is within around 5 degrees of the tropical cyclone center to its north, it can serve to increase the outward radial wind and induce a secondary maximum of vertical wind speed. This flow could then serve to intensify the tropical cyclone circulation. On the other hand, if the EFC and associated circulation are further away from the center, they may weaken the tropical cyclone. This is illustrated in Fig. 3, where the maxima of EFC at a large distance from Edouard at +120-144 h and moving inwards (Fig. 3a) correspond to a sharp increase in outward wind speed (Fig. 3b) and upward motion in the

same locations on the northern side of Edouard. This is at the time of Edouard's weakening in Fig. 2a, and in the area in which Edouard is interacting with a trough. We hypothesize that the remote EFC is serving to influence the remote secondary circulation and in particular act to reduce the low-level inflow into Edouard. However, the causality and sensitivity still needs to be established, and this has only been explored for one tropical cyclone. Our next stage is to test this hypothesis via investigating more cases together with idealized modelling.

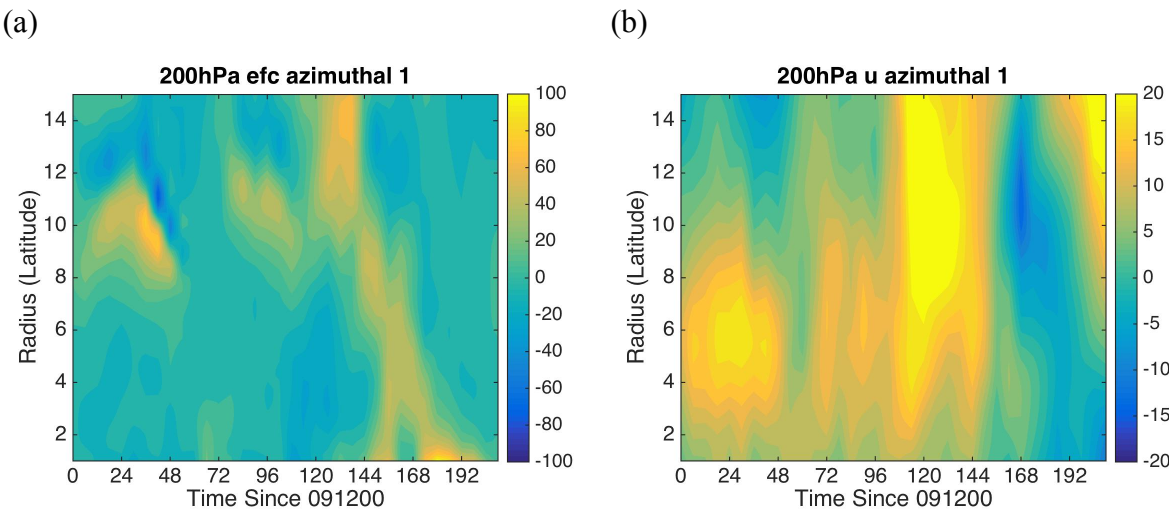

FIGURE 3. Time series of (a) averaged 200 hPa Eddy Flux Convergence (EFC) and (b) averaged 200 hPa outward radial wind in the northern sector of Edouard.

IMPACT/APPLICATIONS

Novel ensemble forecast products have been developed during the 2014 and 2015 field campaigns, which may influence how Navy ensemble forecasts are used and interpreted.

An improved understanding of the mechanisms behind how the outflow is connected to the environment and affects tropical cyclone intensity will lead to improved specification of ensemble predictions and thereby better predictions of uncertainty.

RELATED PROJECTS

This project is related to the DRI grant entitled "Importance of the Coupling of Tropical Cyclone Outflow Vents with the Environment: Observational and Model Sensitivity Studies" (PI Chris Velden and Co-PI Brett Hoover), on which Majumdar is a Collaborator. This project is also related to projects conducted at NRL Monterey, and in particular the sensitivity studies conducted by Dr William Komaromi, a postdoc in Jim Doyle's group at NRL Monterey. Additionally, The paperwork for an Educational Agreement is in progress, in order for the U. Miami team to use the COAMPS-TC model.