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The modulation of tropical cyclone structure and intensity by evolving outflow layer environmental conditions

I. Introduction

At the forefront of research at the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA) is the advancement of tropical cyclone (TC) intensity forecasts. While forecasts of TC motion have shown steady improvement over the past quarter century, intensity forecasts have shown little improvement. The poor improvement of intensity prediction is reflected in the observation that statistical models utilizing climatology and persistence are superior to dynamical prediction (DeMaria and Kaplan 1999). A possible reason for the discrepancy between track and intensity forecasts might be the difference in scale of the mechanisms responsible for track and intensity changes. While the mesoscale plays a role in TC wobble, track forecasts are dominated by changes in the larger-scale, synoptic environment. The assimilation of satellite and dropsonde data into sophisticated numerical models that adequately resolve the synoptic-scale have yielded a greater understanding of the physical processes governing TC motion and the accuracy of the environmental initial condition used in forecast models. In contrast, mechanisms responsible for changes in structure and intensity are important on a wide range of scales including the mesoscale. Real time dynamic forecasts are limited to 15-25 km resolution due to computational restraints and therefore fail to resolve the heating profiles and momentum transports within individual convective elements. It is therefore reasonable to suggest that a greater understanding of structural and intensity changes in TCs will come with the further study of detailed core observations and high resolution numerical simulations which have within the past decade become readily available. The scientific investigation proposed would utilize both high resolution numerical simulations along with airborne Doppler radar and GPS dropsonde data from HRD's reconnaissance missions to explore the impact of changing outflow layer (300-100 hPa) environments on TC structure and intensity.

II. Background

Current theories recognize three fundamental mechanisms of TC intensification: 1) air-sea interaction, 2) internal dynamics and 3) external interactions. The air-sea interaction is the energy source of TCs. Wind-induced latent heat fluxes from the ocean surface along with isothermal expansion (expansion of the inflowing air parcel at constant temperature within the lowering pressure of the storm core) act to increase the moist entropy of the inflowing air and therefore generate buoyancy relative to the environment. As a TC traverses oceanic waters, intensification will continue until, in the absence of environmental flow, the saturation mixing ratio (determined by the near equilibrium of sea surface temperature and surface layer temperature) in the storm core can no longer support further pressure falls in the storm core (Emanuel 1988). When a

TC encounters high oceanic heat content and dynamical factors are not inhibitive, rapid intensification is expected. Conversely, a slow moving TC may produce upwelling beneath and mixing across the thermocline in response to strong wind stresses. The resultant lowering of sea surface temperatures would lead to weakening of the TC. Highly idealized coupled atmospheric-oceanic models utilizing the air-sea interaction have shown good success at reproducing TC intensity evolutions (Emanuel 1999).

Observations have shown that internal dynamics may result in rapid and significant intensity change. In particular, evidence of eyewall replacement cycles, in which a secondary ring of active convection strengthens and contracts at the expense of the primary eyewall, is overwhelming (Willoughby 1982). Strong radial potential vorticity gradients within the storm core, if perturbed, can support wave like disturbances similar to Rossby waves which propagate along the planetary vorticity gradient. Such waves, termed Vortex Rossby Waves (VRW), have recently been studied in a hierarchy of analytical and numerical models beginning with Montgomery and Kallenbach (1997). It is suggested that convectively generated vorticity anomalies in the core, axisymmetrized by the radial shear of the tangential flow, propagate outward along the radial potential vortictiy gradient as VRWs and that the interaction of the VRWs with the mean vortex lead to intensity changes. Furthermore, inner spiral bands may be intimately linked to VRWs (Reasor et al 2000).

The primary focus of this study will be on environmental influences of TC structure and intensity. Of course environmental interactions are not decoupled from internal dynamics as any of the three basic mechanisms regulating intensity may act independently or in concert (Bosart et al 2000). Environment influences, such as the vertical shear of the horizontal, mean vortex free wind can produce structural changes which yield intensity changes via internal dynamical processes.

Unlike the air-sea interaction, environmental interactions act only to inhibit growth as there is very little energy in the outflow layer to promote intensification. A 31-year climatology of North Atlantic basin TCs by DeMaria and Kaplan (1994) revealed that on average, the storms reached 55% of their maximum potential intensity (MPI). MPI is obtained when a TC fully utilizes the thermodynamic energy of the ocean and atmosphere available to it. Absent in MPI calculations is the contribution of environmental flow which might explain the inability of a large percentage of TCs in nature to obtain MPI.

Observations suggest that azimuthally averaged anticyclonic (radial) flow is weaker (stronger) for intensifying hurricanes than non-intensifying hurricanes while outflow jets are radially elongated for intensifying storms as opposed to more axisymmetric jets that wrap around the storm core for non-intensifying hurricanes (Merrill 1988). Examination of the satellite derived winds for intense TCs reveals a preference for asymmetric, anticyclonic jets over symmetric outflow with three general orientations: 1) flow to the north toward the anticyclonic shear side of the westerlies, 2) flow to the south and southwest toward a lower Coriolis parameter or the anticyclonic shear side of the southwesterlies and 3) flow in any direction in which there is outflow associated with mesoscale convective organization (i.e., toward the ITCZ). A common feature to all of these observations is the importance of environmental inertial stability on TC intensification. The satellite derived winds observations show an affinity for outflow jets directed toward regions of weak environmental inertial stability. This is consistent with the findings of Merrill (1988) who concluded that intensifying storms interact with regions weak environmental resistance. Azimuthally averaged anticyclonic (radial) flow is weaker (stronger) for intensifying hurricanes as the weak inertial stability favors divergence over rotation. Likewise, outflow jets are radially elongated for intensifying hurricanes as they expand into regions of weak inertial stability where there is a relatively large Rossby radius of deformation.

The exploitation of weak resistance to convective outflow in explaining upscale growth of mesoscale convective disturbances is not new. Blanchard et al (1998) showed that a pre-existing region of weak inertial stability in the outflow layer of an idealized, mid-latitude, mesoscale convective system led to stronger divergent outflow yielding a more rapid onset of convective-symmetric instability and enhanced circulation strength. Mecikalski and Tripoli (1998, 2003) considered the role of upper level environmental inertial stability on the dynamics of tropical plume formation. Using the diagnostic parameter, inertial available kinetic energy (IAKE), a quantity analogous to CAPE and near zero (minimal outflow energy drain) when the difference between outflow potential vorticity and environmental potential vorticity is small, they found that the convective structures in a tropical plume region are modulated so as to produce convective plumes that access the least environmental inertial stability.

Using the observational evidence of Merrill (1988), the theoretical foundations of Blanchard (1998) and Mecikalski and Tripoli (1998, 2003), and the theoretical work of Emanuel (1986) in which the TC secondary circulation is treated as an idealized Carnot cycle where the energy input by the air-sea interaction is balanced by frictional dissipation in the boundary layer and outflow layer (energy is drained expanding the outflow anticyclone against the ambient cyclonic rotation of the environment), Rappin (2004) showed that by availing itself of regions of diminished inertial stability, the work done by the TC outflow to expand away from the cyclone center is lessened. In regions where the environmental potential vorticity (angular momentum) is nearly equal to the TCs outflow potential vorticity (angular momentum), the energetic drain of outflow expansion into these regions (asymmetric outflow channels) is minimized, and consequently tropical cyclone intensity is maximized.

Environmental flow regimes may also leave low environmental inertial stability inaccessible to TCs. A band of westerlies that lie significantly beyond the Rossby radius of deformation will result in the dominance of outflow rotation and the development of a quasi-symmetric outflow jet. Ambient environments may slow intensification, but they will not prohibit growth to MPI, given sufficient time, as the low potential vorticity generated by convective outflow gradually “condition” the outflow layer to low inertial stability. Environmental flow, however, often prevents such conditioning, by constantly ventilating the storm outflow away from the storm’s immediate environment..

Rappin (2004) showed how an ensemble of convective clouds could utilize low environmental stability to produce rapid intensification of idealized TCs. Further research should be conducted to better understand more precisely just how the hurricane core responds to organized, asymmetric outflow. Merrill and Velden (1996) suggested that vertical transports of momentum may have a significant influence on outflow direction. If outflow direction is determined by the outflow environmental flow field (Merrill and Velden 1996; Rappin 2004) it is reasonable, in light of the low inertial stability of the outflow, that the structure and orientation of convection in the core, as well as the inner and outer bands, is influenced by the environmental flow field. Mecikalski and Tripoli (2003) showed how the outflow environment of tropical cloud clusters influences the structural characteristics of individual clouds through the evolutionary selection of cloud structures that resonate with the environmental weaknesses. Similarly within the hurricane core, storms that are under the influence of westerly vertical shear often exhibit successive bands emanating or developing on the northern flank of the storm where their radial outflow points in the direction of low environmental inertial stability. The tendency for westerly shear to produce a wavenumber one asymmetry in the core with eyewall convection enhanced downshear left (northeast) and suppressed upshear right (southwest) may result in the axisymmetrization and the associated vorticity filamentation (Reasor et al 2000) of both eyewall convection and bands. With convective asymmetries located in the northeastern quadrant of the storm, convective downdrafts produced by melting ice and sub-cloud evaporation with produce density currents predominately on the north side of the storm and therefore will tend to initiate further upward motion to the north of the TC core.

III. Methodology

In pursuit of a greater understanding of TC structure and intensity change in response to evolving outflow layer environmental flow fields, two objectives are presented.

-Develop an Atlantic basin climatology of TC core structure as a function of outflow layer asymmetry. Core structure will be subjectively evaluated on a scale ranging from highly asymmetric to axisymmetric with particular attention being paid to asymmetry wavenumber and height dependence (if possible). While an infinite number of outflow layer structures are possible, the tendency for TC outflow to form asymmetric outflow jets should yield a correlation between changes in the horizontal and vertical outflow layer structure and the evolving TC core structure. The large scale outflow environment can be constructed from atmospheric analyses supplemented with dropsonde data and satellite derived winds (Merrill and Velden 1996). High resolution data sets of the core can be constructed from the myriad of data products available at HRD including surface wind analyses, aircraft radar and the G-IV and P3 GPS dropsonde data base (reference Black et al 2002).

-Perform high resolution simulations on several test cases to provide clean, accurate and complete data sets for an in-depth study of TC structural and intensity changes. Complete data sets provided by numerical simulations on the Hurricane Weather Research and Forecasting (HWRF) model currently being utilized by HRD will permit the isolation of outflow plumes in order to study their horizontal and vertical structure as well as their influence on core structure. Such a study is accomplished by trajectory analysis or even the implementation of a potential vorticity tracer. Construction of angular momentum budgets will assist in understanding of convective momentum transports in the generation of eyewall asymmetries and/or support in the development of bands

It is expected that a relationship, if existent, will be found on the organization of hot towers in the eyewall and asymmetric outflow structure. Any role of convective momentum transport in linking core and outflow layer structure should be elucidated. It is the author's anticipation that eyewall convective cells will show a strong affinity for an asymmetric distribution (perhaps partially attributed to vertical shear that is not strong enough to overcome the resiliency of the cyclonic vortex) and that the resultant vorticity filamentation and/or density current induced vertical motion will initiate an eyewall replacement cycle.

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