A Composite Analysis of the Dynamic and Thermodynamic Structure and Evolution of Tropical Convective Systems

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1. Introduction

A number of recent studies (e.g., Davis and Ahijevych 2012, 2013; Helms 2012; Smith and Montgomery 2012; Komaromi 2013; Zawislak and Zipser 2014) have examined the structure and evolution of developing and nondeveloping tropical convective systems (TCSs) using observations collected during field experiments such as NASA Genesis and Rapid Intensification Processes (GRIP), NSF Pre-depression Investigation of Cloud Systems in the Tropics (PREDICT), and NASA Hurricane and Severe Storm Sentinel (HS3). These studies consistently found that developing systems tend to have higher midlevel moisture in comparison to systems which fail to develop. This agrees with previous idealized modeling work (Nolan 2007) suggesting that high midlevel moisture is critical for development. Additionally, these studies highlight the presence of both a low-level and a midlevel vorticity maximum in both developing and nondeveloping TCSs. The formation of the midlevel vorticity maximum is associated with potential vorticity generation in response to the large-scale stratiform heating (e.g., Simpson et al. 1997). Helms (2012) suggested that dry air may play a role in inhibiting the spin up of the midlevel vorticity feature by keeping the air subsaturated, preventing the formation of an extensive stratiform cloud deck as well as its associated latent heating due to condensation and cooling due to melting precipitation.

In their seminal paper, Dunkerton et al. (2009) put forth a theory describing the formation of a region of closed Lagrangian streamlines, or 'pouch', within an easterly wave which is protected from dry air intrusions. Their analysis is primarily focused on the flow between the surface and 600 hPa and, as such, is most relevant to the low-level vorticity maximum. While not specifically mentioned, it is plausible to expect that the appearance of closed Lagrangian streamlines at mid- to upper levels would produce a similar protected region. Such a region would enable convection to moisten the middle and upper levels uninhibited by the detrimental effects of dry air intrusions.

Vertical wind shear has long been known to have a significant influence on the tropical cyclogenesis process. McBride and Zehr (1981) found that developing systems in the western Atlantic and west Pacific basins are typically associated with near-zero zonal and meridional vertical wind shear in the immediate vicinity of the systems. Contrary to this, Bracken and Bosart (2000) found that Atlantic developing systems experience, on average, approximately 10 m/s of total vertical wind shear in the immediate vicinity and suggested that some vertical wind shear is necessary to force synoptic scale ascent. Additionally, the role of vertical wind shear (and CAPE) in determining midlatitude convective structure is well documented (Rotunno et al. 1988) and is necessary for one method of forming the stratiform cloud deck within which the midlevel potential vorticity generation occurs (Houze 1993, p. 213).

The present study aims to examine how TCS kinematic structures influence the interactions between the TCS and its environment. To meet this goal, TCSs will be grouped according to their structure and near-system environment based on a number of metrics designed to reflect key structures and environmental qualities. Compositing TCSs in each group will enable the identification of dynamic and thermodynamic features of interest (e.g., upper-level trough axis, dry air) associated with each combination as well as those features which occur regardless of structure and environment. The next section briefly outlines the methodology used in this study. Section 3 provides some preliminary results and the future direction of the research.

2. Methodology

Based on the findings of previous studies, a number of quantities present themselves as potential met-

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rics. Currently, the environmental metrics include a measure of midlevel moisture (600–400-hPa mean relative humidity), a measure of low-level moisture (850–600-hPa mean relative humidity), and a measure of vertical wind shear (200–850-hPa zonal and meridional vertical wind shear). Three sets of metrics are used to capture the kinematic structure of a TCS: a center offset (or tilt) metric, an intensity metric, and a flow organization metric. The center offset metric is calculated as the horizontal distance between the 850-hPa and 500-hPa circulation centers. The circulation centers are identified by a maximum in the mean vortex idealization, where vortex idealization is defined as the ratio between the signed tangential velocity (positive being counterclockwise) and the unsigned magnitude of the total wind. Vortex idealization is typically expressed as a percentage with a value of 100%, 0%, and -100% indicating nondivergent cyclonic, irrotational, and nondivergent anticyclonic flow, respectively. It is worth noting that the vortex idealization measures the fractional component of the total wind in the direction of the tangential wind and, as such, is independent of the tangential wind speed itself, at least in a mathematical sense. For identifying the center, the vortex idealization is averaged azimuthally around a 111-km ($\sim 1^\circ$ latitude) radius circle. The intensity metric and the flow organization metric are both defined as the area-averaged tangential velocity and area-averaged vortex idealization, respectively. Both metrics are calculated at 850 hPa and 500 hPa and averaged over a 333-km ($\sim 3^\circ$ latitude) radius circle.

Two additional metrics of interest are currently included which are not directly related to the structural or environmental qualities previously mentioned. These are a warm core versus cold core metric based on thermal vorticity (curl of 200–850-hPa vertical wind shear) and a circulation size metric (innermost radius at which azimuthally averaged 850-hPa vortex idealization drops below 20%). The thermal vorticity metric can be used to quantify the strength of the deep-layer warm core while screening out deep-layer cold-core systems if the need arises. By breaking TCS groups into large and small circulation sizes there is less chance that significant features will be washed out in the compositing process. In addition to this more practical reason, the relationship between tropical cyclone (TC) size and other characteristics has been a popular topic of scientific debate in recent years (e.g., Carrasco et al. 2014; Chavas and Emanuel 2014). Provided the 850-hPa size metric proves useful, a parallel metric for the midlevel circulation may be added.

In order to support the large number of subdivisions desired for this study, a large number of TCSs must be identified and tracked. To achieve this goal, an algorithm is being designed to track TCSs in model analysis fields. A potential TCS is identified first by the presence of a maximum in mean vortex idealization calculated at a radius of 111 km from each point. Locating TCS center fixes with vortex idealization has a distinct advantage over relative vorticity, which has been used in previous tracking algorithms (e.g., Marchok 2002), in that it is not directly dependent on the maximum wind speed of a system. As such, vortex idealization is better suited to tracking weaker systems such as TCSs. Preliminary testing suggests that a vortex idealization of 20% averaged azimuthally on a 111-km radius circle is a viable threshold for capturing a TCS.

The low-level vortex idealization center fix serves as the TCS center provided a number of additional criteria are simultaneously met at least once during the lifespan of the system. To ensure systems are capable of maintaining the large regions of upper-level stratiform heating necessary for generating the midlevel vorticity maximum, a minimum area around a TCS at 850, 700, and 500 hPa must exceed a threshold relative humidity. Although additional testing is required, preliminary examination suggests requiring 50% relative humidity covering 90, 75, and 10% of a 6° by 6° latitude box at 850, 700, and 500 hPa, respectively, is sufficient to remove the majority of nonconvective systems. At the time this moisture requirement is met, the TCS must be associated with peaks of vortex idealization (i.e. cyclonic flow) at 700 and 500 hPa as well as a peak in 850-hPa tangential velocity and sea level pressure gradient. The goal of these requirements is to include only those systems which experience a period of organization.

3. Preliminary Results and Future Work

As alluded to previously, the current study will use composite analysis to explore the influences of TCS structure on system–environment interaction. A number of atmospheric variables are of particular interest to this study for inclusion in these composites. Composited cross sections of wind speed, direction, and components as well as their vertical derivatives will help shed light on the question of whether all vertical wind shears of equal numerical value (e.g., 200–850-hPa wind shear) have equal dynamical value (e.g., impact on TC formation) and if this dynamical value is a function of the structure and environment of a system. Due to the key role the midlevel circulation appears to play in tropical cyclogenesis (e.g., Simpson et al. 1997; Ritchie and Holland 1997), understanding factors involved in inhibiting or enhancing its formation are of great interest to the proposed work. Temperature, moisture, and vorticity will be used to examine the evolution of the stratiform heating layer and its resultant midlevel vorticity maximum. As noted by Davis and Ahijevych (2012), a system which is not vertically aligned will produce flow across the low and midlevel vorticity maxima and potentially make the system more vulnerable to environmental dry air. Evidence of this interaction should appear in the composited moisture fields as well as the composited temperature anomaly fields (due to reduced latent heat release).

In addition to their use in grouping TCSs, the metrics described above can also be combined to produce a phase space similar to that of Hart (2003). Using this phase space, the structural and environmental evolution of a TCS throughout its lifespan can be visualized by its phase space trajectory. An example of the phase space with the distribution of TCSs identified in the 2010 Atlantic hurricane season and with the pre-Earl (2010) TCS phase space trajectory overlaid is presented in Fig. 1 and uses data from the 0.5° Climate Forecast System Reanalysis (CFSR; Saha et al. 2010). TCSs which become more TC-like (i.e., quasi-axisymmetric upright warm core) can be considered as strengthening while those TCSs which become less TC-like can be considered as weakening, and those without a clear trend in either direction can be considered as steady. Using this definition as a guideline in conjunction with the phase space trajectories, the favorability for strengthening of a given structure–environment configuration can be determined.

The phase space trajectory for the pre-Earl system (Fig. 1) reveals a number of interesting points about the evolution of the system. The vortex idealization is seen to be maximized at midlevels initially while the low-level vortex idealization quickly increases during the first day. This rapid increase in low-level vortex idealization is associated with the consolodation of a number of low-level mesoscale vortices into a single vortex. During this same period the mean tangential velocity at low levels increases while the midlevel mean tangential velocity decreases. Whether these wind speed changes are dynamically related to one another has not yet been determined. Another noteworthy evolution is seen in the mean relative humidities. As the pre-Earl system approaches genesis, the atmosphere tends to become drier. This trend continues after genesis until approximately the time of rapid intensification (this reversal is likely due to the system growing large enough that the TC itself covers the majority of the averaging area). This drying pattern is seen in a number of other developing systems from the 2010 Atlantic hurricane season (although not all of them) while no clear preference for drying or moistening is seen in the nondeveloping system. While reason behind this bifurcation between development and nondevelopment is not clear, it is expected that nondeveloping systems will display larger variety in their structures and it is plausible that some structural configurations may encourage this trend while others would not.

The TCS tracks, trajectories, and composite analyses will be produced using a number of gridded data sets. These data sets will include both reanalyses (e.g., CFSR) and operational analyses (e.g., NCEP GFS). By producing parallel analyses from a variety of data sources, the results will be able to better account for biases inherent in any single source.

Given the planned inclusion of operational model analyses in this study, a natural use of the TCS phase space is as a forecasting aid. By processing forecast data from a number of the operational models, comparisons can be made between each model as well as between individual runs of the same model in much the same way as has been done with the Hart Cyclone Phase Space (Hart 2003) and the Real-time Multivariate MJO phase space (RMM; Wheeler and Hendon 2004). Furthermore, the uncertainty in forecasted TCS structure can be examined by processing ensemble forecast data.

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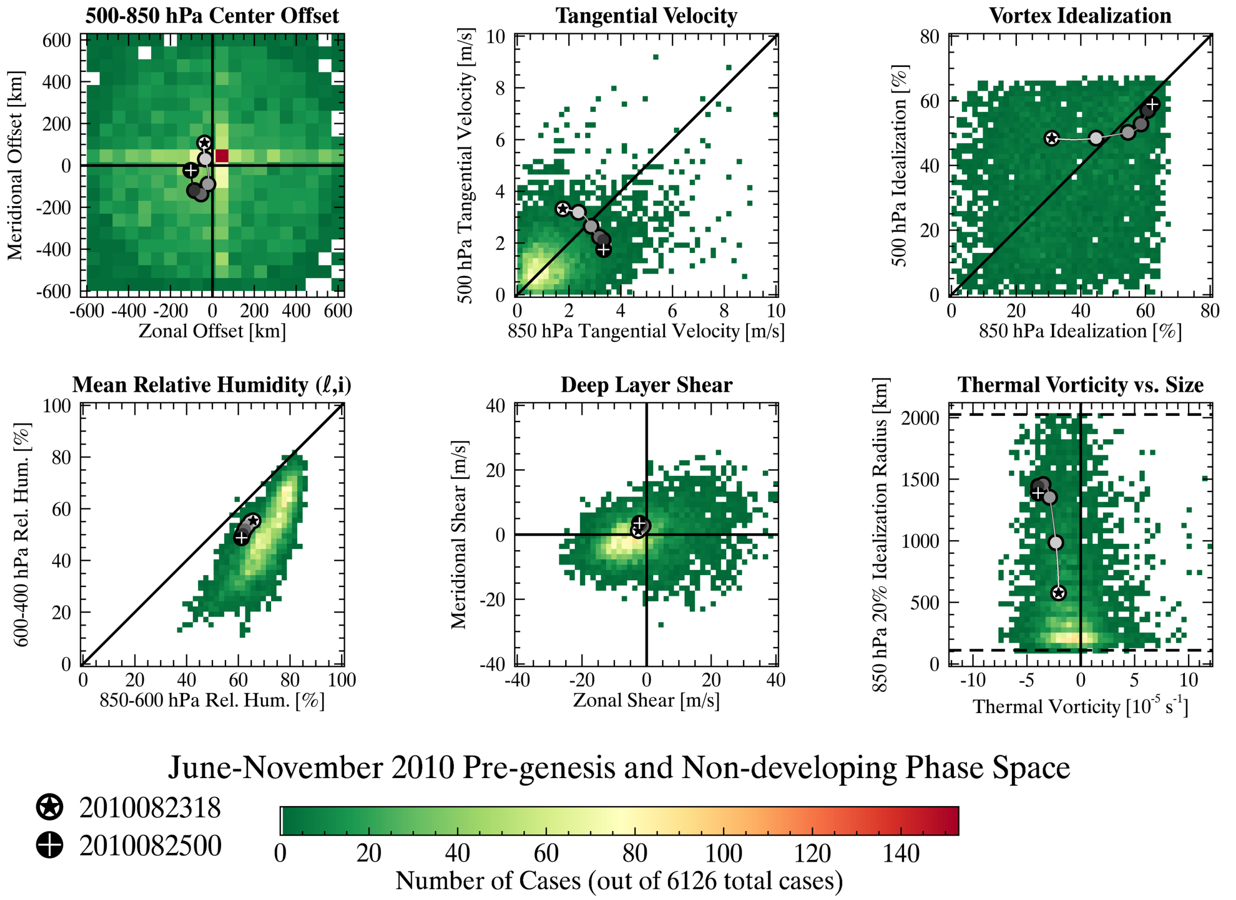

Figure 1: TCS phase space with the trajectory of the pre-Earl (2010) TCS overlaid (filled circles). Color shading indicates the total number of TCSs analyzed in a bin. The six-hourly pre-Earl phase space metrics are plotted in shaded circles (becoming darker with time). The black star and white plus denote the initial time and the final pre-genesis time, respectively.

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