5A.2 AN INVESTIGATION OF COMPOSITE DROPSONDE PROFILES FOR DEVELOPING AND NON-DEVELOPING TROPICAL WAVES DURING THE 2010 PREDICT FIELD CAMPAIGN

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1. INTRODUCTION

Predicting tropical cyclogenesis remains one of the great forecasting challenges to today's meteorological community. Much of our limited understanding can likely be attributed to our inability to differentiate the often subtle physical differences between developing and non-developing tropical cyclones (TCs), and any such differences, when observed, have been insufficiently documented. While the large-scale environmental parameters conducive to genesis are well known, including warm sea surface temperatures, high atmospheric moisture content, and low vertical wind shear, significant debate remains with respect to the physical processes by which genesis occurs.

Two fundamental yet differing theories of TC formation are the top-down and the bottom-up hypotheses. Bister and Emanuel (1997) propose a top-down mechanism for genesis by which the level of peak cooling descends with a stratiform rain region, thereby lowering the level of maximum potential vorticity (PV) production. A slightly differing sequence, known as bottom-up genesis, is proposed by Hendricks et al. (2004), that individual deep moist convective updrafts or vortical hot towers (VHTs) develop within the tropical wave, amplify pre-existing cyclonic vorticity, and gradually consolidate to form a low-level center of circulation. In a more recent theory, the 'marsupial paradigm', tropical cyclogenesis is favored in the critical-layer region, in which the parent wave's phase speed and the mean flow are equal, of a synoptic-scale, pre-depression wave trough in the lower troposphere (Dunkerton et al. 2009). The Pre-Depression Investigation of Cloud-systems in the Tropics (PREDICT) field campaign of 2010 sought to test the marsupial hypothesis. Dropsonde data from PREDICT area analyzed in this study.

Regardless of the exact order of processes by which genesis occurs, sufficient tropospheric instability as to allow deep convection is assumed. Molinari and Vollaro (2010) and Braun (2010) have found weak or weakening TCs to be associated with higher CAPE than strong or strengthening TCs. Nolan et al. (2007) have also found that greater CAPE did not result in greater likelihood of genesis. However, the question as to whether genesis becomes increasingly favored with increasing instability, or whether there is some threshold beyond which decreasing stability is detrimental to genesis, has not been conclusively answered via observational evidence. Additionally, the pre-genesis warm core has also been insufficiently investigated. Observational studies such as Hawkins and Rubsam (1968) have found maximum warm anomalies at around 250 hPa in mature TCs, while Hawkins and Imbembo (1976) and Stern and Nolan (2011) suggest either a primary or perhaps secondary warm core from 500 hPa to as low as 650 hPa. However, the level of maximum warm anomalies for pre-genesis disturbances remains to be determined.

Identification and quantification of several key phenomena are sought, including: the vertical level, timing and magnitude of warm core development if any warm core can be discerned at all prior to genesis, whether or not a progressive increase in moisture to near saturation is a necessary pre-requisite for genesis, if a top-down or bottom-up transition of the mean vortex is identifiable, and whether or not the presence of greater instability is associated with a higher rate of genesis.

2. DATA AND METHODS

During PREDICT, 558 dropsondes were deployed over the course of 26 aircraft missions investigating tropical waves in the Caribbean and western Atlantic (Fig. 1). Five cases of genesis, 3 cases of non-genesis, one non-developing region of convection (non-genesis frontal) over the Bahamas, and four TCs named during or prior to investigation (TC stage) comprise the PREDICT data set. The genesis category is further separated temporally into missions that occur 0-24 h pre-genesis, 24-48 h pre-genesis, 48-72 h pre-genesis and 72+ h pre- genesis. Dropsonde profiles of temperature (*T*), mixing ratio (*q*) and relative humidity (*RH*) are composited. For stability calculations, the virtual temperature adjustment $T_v = T(1 + \varepsilon q)$ will be applied, where ε = 0.608 when q is expressed in kg/kg. Buoyancy is calculated as

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$$B = g\left(\frac{T_{v\_parcel} - T_{v\_env}}{T_{v\_env}}\right) \tag{1}$$

where T_{v_parcel} is the virtual temperature of a surface parcel lifted dry adiabatically below the level of free convection (LFC) and moist adiabatically above, and T_{v_env} is the environmental profile utilizing the PREDICT mean as a reference profile. *CAPE* will be calculated from the integral

$$CAPE = g\int_{z_{LFC}}^{z_{EL}} \frac{\delta T_v}{T_v}\,dz \tag{2}$$

where *EL* is the equilibrium level for a virtual surface-based parcel, while *CIN* will be an equivalent integral except for the fact that it will be integrated between the lowest level of negative buoyancy and the *LFC*.

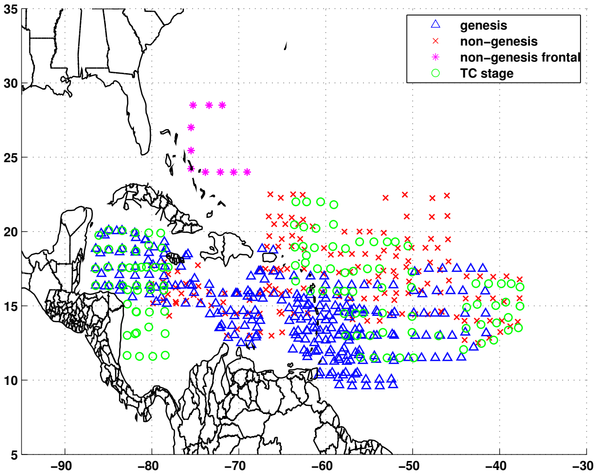

FIGURE 1. Map of all dropsonde deployment locations during PREDICT and corresponding genesis categories, from August 15 through September 30, 2010.

Vortex-relative tangential (V_{tan}) and radial (V_{rad}) components of wind are also calculated, with the parent wave's zonal phase speed removed. The mean V_{tan} profile is then computed as the sum of the cyclonic and anticyclonic contribution of each dropsonde, normalized by the number of dropsondes in a given flight. For V_{rad}, the component of wind from each dropsonde in the direction away from the center of circulation contributes positively. Computation of V_{tan} and V_{rad} requires selection of a center of circulation, which is chosen to be the point at which mean 850-700 hPa V_{tan} is maximized for each flight. Somewhat unconventionally, mean V_{tan} is computed with respect to all dropsondes, rather than only those within an RMW annulus, as the RMW for pre-genesis disturbances is poorly defined. Computation of V_{tan} is performed in one tenth-of-a-degree iterations over a 10° by 10° latitude/longitude box centered on the flight pattern. The center of circulation was found to be located to the west of most drop patterns, resulting in greatest data coverage in either the northeast or southeast quadrants of the tropical wave when plotted in wave-relative polar coordinates (Fig. 2). A sensitivity test was performed to examine the sensitivity of computed V_{tan} and V_{rad} profiles to choice of center location. It was found that the wind metrics used in this study are not particularly sensitive to latitude and longitude errors of 1°, and while errors on the order of 5° may be more problematic, they are less likely to occur.

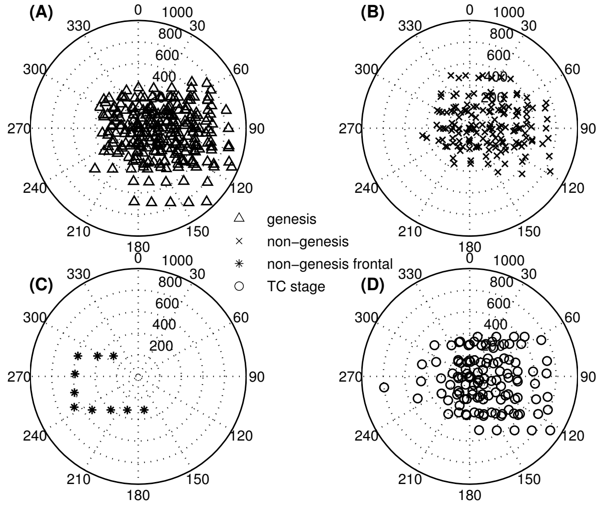

FIGURE 2. Plots of sounding locations relative to the center of circulation in polar (km, deg) coordinates for each genesis category: (A) genesis, (B) non-genesis, (C) non-genesis frontal and (D) TC stage.

Mid-level moisture can often vary immensely over relatively small distances over the spatial extent of a tropical wave. Much of both the top-down and bottom-up literature note a general trend of increasing convection near the center of the cyclone, however, averaging over the full areal extent of any one case might lead to a net cancellation of numerous moistening and drying processes, masking mesoscale variability. Therefore, in addition to domain-wide averaging, profiles of *q* and *RH* from dropsondes located within a 100 km radius of the approximate center of circulation are composited in order to investigate localized moisture processes. This is only performed for genesis cases in which the center of circulation is well defined.

3. RESULTS

Temperature profiles reveal a progressive building of warm anomalies, relative to the PREDICT mean, of +0.3 to +0.6℃ at 24-48 h pre-genesis, increasing to +0.4 to +0.9℃ 0-24 h pre-genesis from 500-200 hPa. Overall, genesis profiles are much warmer than non-genesis profiles above 600 hPa (Fig. 3A). While the existence of a warm core in mature TCs has been well-established in previous literature, the magnitude and timing of the warm core development with respect to time of genesis has not. Maximum warm anomalies just below tropopause level are consistent with observations for mature TCs by Hawkins and Rubsam (1968), while a possible weak secondary maximum observed below 500 hPa is consistent with Hawkins and Imbembo (1976) and Stern and Nolan (2011). Mid-level warm anomalies are much weaker here due to the fact that this study examines the pre-genesis period. In contrast with the genesis cases, negative T anomalies of -0.5 to -1.0°C exist from 500-200 hPa for non-developing systems, and overall the non-genesis T profile resembled more closely the non-genesis frontal profile than the genesis mean.

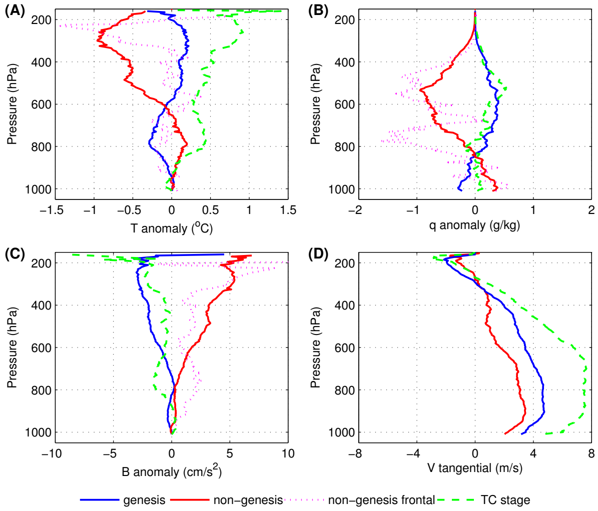

FIGURE 3. Composite vertical profiles of anomalies relative to the PREDICT mean of (A) temperature, (B) mixing ratio, (C) buoyancy, and (D) tangential component of wind for genesis, non-genesis, non-genesis frontal and TC stage categories.

In terms of moisture, positive q anomalies of +0.1 to +0.5 g/kg from 800-300 hPa are observed in developing systems, even 72 or more hours pre-genesis, but fluctuate minimally with time as genesis becomes imminent. In contrast, non-developing TCs are associated with significant dry anomalies from 800-300 hPa (Fig. 3B). When only examining dropsondes located within 100 km from the center of circulation, it is apparent that moist convective processes act to increase moisture as the tropical wave approaches genesis, as suggested by Bister and Emanuel (1997), Nolan (2007), and others. The maximum increase in moisture occurs 24-48 h pre-genesis. This trend is likely washed-out when all dropsondes are included due to the large spatial area of averaging in the full composite, possibly coupled with some large-scale entrainment of dry air into the wave circulation. Nonetheless, the full q composite still demonstrates that time-evolving genesis profiles are all significantly more moist than non-developing systems, even more than 72 h prior to genesis. Non-genesis RH profiles are on the order of 10-20% drier than the PREDICT mean from 700-500 hPa, suggesting a greater potential for dry air entrainment into convective towers. Conversely, the non-genesis mean is actually more moist than the genesis mean from the surface through 850 hPa, possibly suggesting that dry air at the mid-levels is more detrimental to genesis than dry air at the low levels. Similar to what has been demonstrated for temperature, the non-genesis moisture profile more closely resembles the non-genesis frontal profile than the profile of moisture for genesis cases.

Examination of the wind field reveals a progressive strengthening of the vortex around 500 hPa, with an initial delay in intensification from 850-700 hPa. Tangential wind at these levels fluctuates between 3-5 m/s from 72 through 24 hours pre-genesis, before jumping suddenly to 6-7 m/s less than 24 hours pre-genesis. This sudden intensification of the vortex appears to lag the greatest increase in moisture by 24 hours. The lack of a trend in the level of maximum V_{tan} does not provide a clear answer regarding whether development is from top down or from bottom up. Differences between genesis and non-genesis V_{tan} also reveal than developing waves are, on average, associated with a slightly stronger circulation than non-developing waves (Fig. 3C). Radial wind profiles suggest that many cases of genesis may have been delayed by low-level outflow. Alternatively, an initial stage of low-level outflow may be an intricate part of the genesis process, as suggested by Bister and Emanuel (1997). During the final 48 hours before genesis, low-level inflow of 1-2 m/s develops and strengthens with time.

Mean virtual $CAPE$ and B profiles indicate much greater instability associated with non-genesis and tropical frontal convection profiles than with either pre-genesis or TC-stage profiles (Fig. 3D). Results suggest that 2000 J/kg of $CAPE$ may be sufficient for tropical cyclogenesis, and additional instability does not aid in the genesis process (Table 1).

A brief comparison with the Dunion (2011) moist tropical (MT) mean sounding indicates that the mean genesis profile is much more moist than the MT mean, while the much drier non-genesis profile is only slightly drier than the MT mean and only from 450-200 hPa. Therefore, while the non-genesis profile is dry amongst tropical wave soundings, it is nonetheless not particularly dry against Caribbean summer climatology.

Non-genesis profiles tend to be associated with slightly greater buoyancy than the MT mean, while the pre-genesis mean is significantly less buoyant than the MT mean above 800 hPa, due primarily to the large positive warm anomalies aloft. Caveats aside, this simple comparison implies that the non-genesis profile is not unusually unstable, but rather that the genesis and TC stage profiles may instead be unusually stable for the tropical Caribbean during the summer months.

Sounding	No. Cases	LFC (hPa)	EL (hPa)	CAPE (J/kg)	σ (J/kg)
PREDICT mean	13	928	199	2104	537
Genesis	5	920	200	1925	298
Non-genesis	3	940	196	2433	314
Non-gen frontal	1	940	211	2501	---
TC stage	4	932	202	2054	571

TABLE 1. Instability data for different subsets. Included are the LFC, EL, CAPE, and standard deviations (σ) of CAPE.

4. CONCLUSIONS AND FUTURE WORK

Observations from the 2010 PREDICT field campaign, when analyzed from a composite mean framework, offer discernible differences between developing and non-developing tropical waves that may be advantageous to the understanding and prediction of tropical cyclogenesis. Temperature, mixing ratio, relative humidity, radial and tangential components of wind, CAPE, and buoyancy are examined.

Significant results include the development of positive temperature anomalies from 500-200 hPa two days prior to genesis in developing waves. This is not observed in the non-genesis mean. Progressive mesoscale moistening of the column is observed within 100 km of the center of circulation, prior to the onset of genesis. The genesis composite was found to be significantly more moist than the non-genesis composite at the middle levels, while comparatively drier at low levels, suggesting that dry air is more detrimental to genesis when located at the middle levels. Initial circulations are slightly stronger in developing than non-developing cases. Time-varying tangential wind profiles also reveal an initial delay in intensification, followed by an increase in organization 24 hours pre-genesis. Finally, and somewhat unexpectedly, CAPE values are much greater for non-genesis than genesis profiles, indicating that greater instability does not necessarily favor genesis.

While other recent studies have examined and compared individual cases sampled during PREDICT, we have presented an alternative perspective in comparing genesis to non-genesis cases via creating composite vertical profiles for all sampled tropical waves, as well as examining the day-to-day evolution of multi-case pre-genesis composites. Further in-depth investigation of tropical waves with new aircraft data and corroboration with model analyses could potentially increase the robustness of these results.

Acknowledgements

The author acknowledges funding from NSF Grant No. ATM-0848753. The author is also grateful to professors Sharan Majumdar, Brian Mapes and David Nolan for their comments and advice throughout the study.

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