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THE INFLUENCE OF AN UPPER TROPOSPHERIC POTENTIAL VORTICITY ANOMALY ON RAPID TROPICAL CYCLOGENESIS

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1. INTRODUCTION

In the North Atlantic basin, McTaggart-Cowan et al. (2013) found nearly half of all genesis events from 1948–2010 originated from a pathway that can be characterized by an environment of upper tropospheric forcing for ascent. Furthermore, the study concluded that when taking into account the frequency of a given environmental pathway, the presence of an upper tropospheric PV anomaly combined with minimal lower tropospheric baroclinicity provides the most efficient environment for TC genesis.

Proposed physical mechanisms explaining the favorability of TC genesis in an environment containing an upper tropospheric PV anomaly include increased angular momentum flux convergence (Challa and Pfeffer 1980) as well as quasigeostrophic (QG) forcing for ascent (Bracken and Bosart 2000). A numerical modeling simulation performed by Montgomery and Farrell (1993) demonstrated how an upper tropospheric PV anomaly could become vertically coupled with a lower level vortex, resulting in tropical cyclogenesis.

Tropical cyclones (TCs) that undergo rapid tropical cyclogenesis (RTCG) close to land are especially dangerous due to little advanced warning time. Many RTCG events form in the vicinity of an upper tropospheric potential vorticity (PV) anomaly. However, the role an upper tropospheric PV anomaly plays on the TC genesis rate is not well understood.

The aim of this study is to distinguish the characteristics of favorable upper tropospheric PV anomaly configurations for RTCG from those resulting in slower rates of tropical cyclogenesis.

2. METHODOLOGY

The ERA-Interim Reanalysis was utilized to examine upper tropospheric differences among newly formed TCs in the North Atlantic basin from 1980–2013. This study classifies TCs into three groups based on the maximum sustained surface wind change (ΔV_{max}) 24 h after genesis from the Best Track database. The groups are: 1) RTCG, if $\Delta V_{max} \geq 25$ kt; 2) slow tropical cyclogenesis (STCG), if $\Delta V_{max} < 25$ kt, but > 5 kt; and 3) neutral tropical cyclogenesis (NTCG), if $\Delta V_{max} \leq 5$ kt, but ≥ -5 kt. The synoptic-scale environments of the analyzed TCs and their pre-existing disturbances are examined over a 72-h period, commencing 48 h prior to genesis. Any TCs that made landfall within the 24 h following genesis were removed from the dataset if they did not meet the RTCG criteria.

PV anomalies are calculated by subtracting the 12-h time mean of PV, centered at the time of genesis, from the 30-day base state. If a PV anomaly within 1000-km from the TC center exceeds 1.5 PV units (PVU) on the 350 K isentropic surface, the TC is classified as being part of a "high-PV" subgroup, which will be the focus of this study.

In order to acquire a better understanding of the mean environment of the respective genesis groupings, RTCG, STCG, and NTCG events were composited based on the 850-hPa relative vorticity centroid, which was backtracked from the location of the TC 24-h after the genesis time. Additionally, composites were normalized by the direction of the 200–850 hPa vertical wind shear vector, calculated in an annulus of 200–800 km from the TC or disturbance center. Genesis rate groupings were determined to be statistically significant from another if values exceeded the 95% level using a two-sided Student's t-test.

Infrared (IR) brightness temperatures were obtained from the Geostationary IR Channel Brightness Temperature archive.

3. RESULTS

Each genesis rate grouping showed small to no relationship to vertical wind shear and sea surface temperature (not shown), but large differences exist in the orientation and magnitude of the upper tropospheric PV anomaly. Figure 1 shows the 250-hPa mean flow regime for all groupings. Each composite displays an upper tropospheric trough immediately upshear of the TC at the time of genesis, which is representative of all time steps throughout this study. The genesis rate groupings are negatively related to the zonal wavelength of the upper tropospheric trough and positively related to the tilt of the trough. Additionally, RTCG events feature a more amplified upstream ridge than STCG and NTCG events, with statistically significant differences existing between RTCG and STCG events, as well as RTCG and NTCG events in both the 250-hPa meridional and zonal winds, primarily upshear of the TC. These differences remain statistically significant in the 24 h before and after genesis.

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The shorter zonal wavelength of the upper tropospheric troughs in RTCG events is associated with greater vorticity immediately upshear of the TC. A simplified version of the Sutcliffe-Trenberth form of the QG omega equation can be applied to diagnose forcing for vertical motion due to vorticity advection by the thermal wind, similar to Bracken and Bosart (2000):

$$-\omega \propto V_T \cdot \nabla\zeta_{UL} \qquad (1)$$

where ω is the vertical velocity (*dp/dt*), V_T is the vertical wind shear between 200 and 500 hPa, and ζ_{UL} is the mean relative vorticity between 250 and 300 hPa.

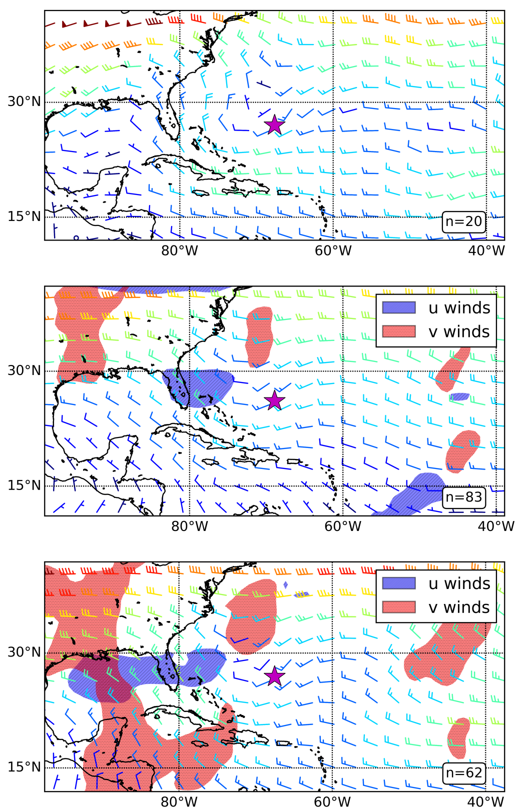

Figure 1. 250-hPa shear-relative winds (colored barbs, m s^{-1}) composited at the time of genesis shown for RTCG (top), STCG (middle), and NTCG (bottom) events. The shear direction for all composites is directed toward the right of the figure. The location of the mean 850-hPa relative vorticity centroid is denoted by the star. The number of cases in each group is denoted by n. Statistical significance between RTCG events and the respective genesis rate groupings for u (v) winds is denoted by the blue hatched (red stippled) areas.

In the RTCG composite, the vertical shear acts to provide ascent in a locally confined area immediately adjacent to, and directly over, the low level vorticity maximum associated with the future TC, as shown in Figure 2. The area of QG forcing is more symmetric and focused around the TC in RTCG cases than STCG and NTCG events throughout the period of study.

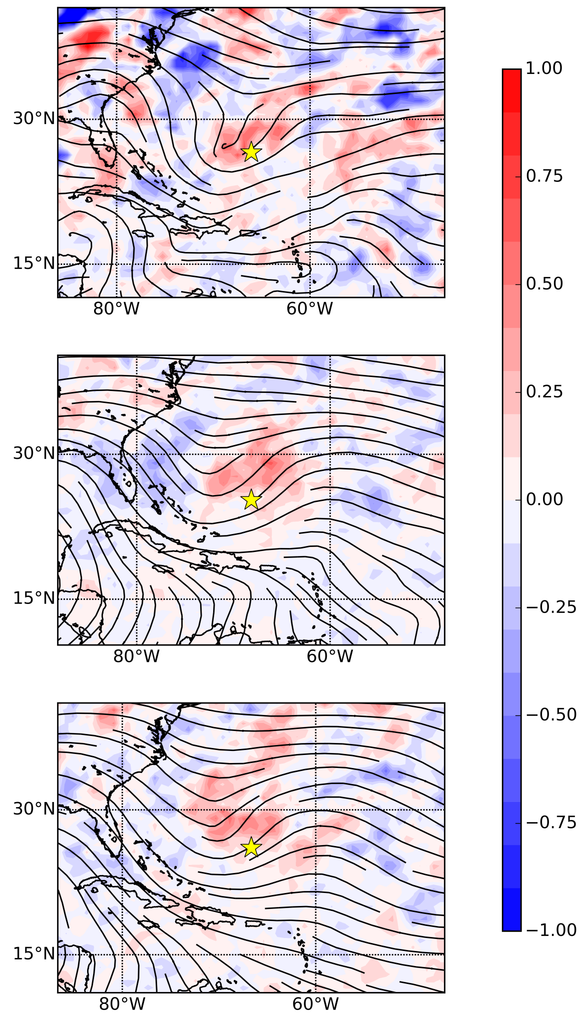

Figure 2. Composite median, layer averaged 250–300-hPa shear-relative streamlines and QG forcing (color shaded, x10^{-9} s^{-2}) 18 h prior to genesis, shown for RTCG (top), STCG (middle), and NTCG (bottom) events. The shear direction for all composites is directed toward the right of the figure. Positive values (red) denote forcing for ascent, while negative values (blue) depict forcing for descent. The location of the mean 850-hPa relative vorticity centroid is denoted by the star.

Furthermore, a comparison of regions of enhanced QG forcing for ascent to IR brightness temperatures reveals a close correlation between the two, with many instances involving only a six-hour lag between areas of enhanced QG forcing and colder cloud top temperatures, as demonstrated in Figure 3. The more confined and symmetric regions of positive forcing for ascent result in more symmetric convection about the TC center in RTCG events, particularly in the upshear quadrants 24 h prior to genesis (not shown). This discovery agrees with aircraft reconnaissance observations, which have shown more symmetric precipitation to be favorable for TC intensification (Rogers et al. 2013).

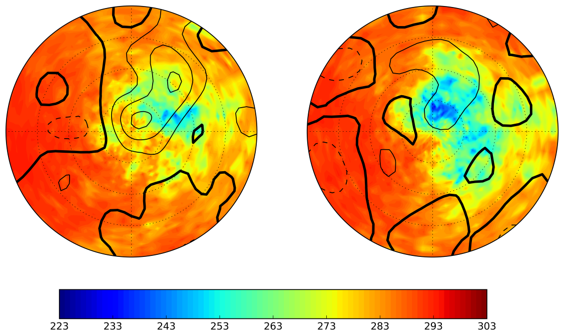

Figure 3. Composite median, shear-relative IR brightness temperatures (color shaded, K) and smoothed QG forcing (contoured every 1.0x10^{-10} s^{-2}) for RTCG events 24 h prior to genesis (left) and six hours later (right). Thick contours represent the zero line, while solid (dashed) contours indicate positive (negative) values. The shear direction is toward the right of the figure.

It is hypothesized that the more symmetric and concentrated region of forcing for ascent in RTCG events focuses convection in a confined area near the proto-TC, resulting in moistening of the troposphere, diabatic heating via convection, and pressure falls to occur over a more organized region. The orientation and spatial scale of the upper tropospheric trough relative to the lower tropospheric vortex facilitates more symmetric forcing for ascent, and thus more symmetric and sustained convection, which is a configuration favorable for intensification and rapid tropical cyclogenesis.

4. ACKNOWLEDGEMENTS

We thank Dr. Kristen Corbosiero for providing valuable insight throughout this analysis.

5. REFERENCES

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