P1.28 A CYCLONE PHASE SPACE DERIVED FROM THERMAL WIND AND THERMAL ASYMMETRY

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1. INTRODUCTION

It is often difficult to distinguish tropical cyclone (TC) development from subtropical cyclone development or hybrid cyclone development within operational forecast models. Yet, knowledge of the nature of the forecast cyclone development within those models is essential to quantifying the potential threat and intrinsic intensity forecast uncertainty associated with that cyclone. Further, the accurate forecasting of extratropical transition of a TC is crucial to the type and extent of marine and public warnings issued. Thus, for both the extratropical cyclone and tropical cyclone communities, diagnostics indicating cyclone phase may be helpful for providing insight into the current and forecast cyclone evolution and potential threat and forecast uncertainty given by numerical models. An objectively defined continuum of cyclone phase space is illustrated here to address this issue. The two parameters chosen to define cyclone phase here are thermal asymmetry and thermal wind magnitude. While these are not the only parameters on which to produce a phase space, they were found to provide a physically insightful description of the full range of synoptic-scale cyclones.

2. CYCLONE PARAMETERS: B, $-V_T^L$ and $-V_T^U$

The frontal nature of the cyclone and its sign are fundamental indicators of the type of cyclone and the stage of evolution. This frontal nature is defined here as the storm-motion-relative 900-600hPa thickness asymmetry across the cyclone within 500km radius, B:

$$B = h\left(\left.\overline{Z_{600hPa} - Z_{900hPa}}\right|_R - \left.\overline{Z_{600hPa} - Z_{900hPa}}\right|_L\right)$$

where Z is isobaric height, R (L) indicates right (left) of current storm motion, and the overbar indicates the areal-mean over a semicircle of radius 500km (Fig. 1). The radius for B was chosen to be consistent with the average radius over which cyclonic, convergent inflow was observed for tropical cyclones (Frank 1977). The integer h takes a value of +1 for the northern hemisphere and –1 for the southern hemisphere. The use of a layer average virtual temperature (thickness) in calculating B (instead of temperature on an isobaric surface) makes the parameter resistant to short term fluctuations in temperature that may result from transient convective activity. The definition of B successfully distinguishes asymmetric frontal zones from symmetric local extrema of temperature associated with tropical cyclones (Fig. 1). Thus, the parameter measures a gradient of mean layer temperature perpendicular to the motion of the storm, and not simply the range of temperature across the cyclone circulation. This distinction becomes important for distinguishing thermally direct circulations from indirect when diagnosing the occlusion phase of extratropical cyclones.

The determination of cold versus warm core vertical structure is the distinction of whether the magnitude of the cyclone isobaric height gradient (Z_{MAX}-Z_{MIN} within a 500km radius of surface cyclone center, proportional to the geostrophic wind magnitude) increases (cold-core) or decreases (warm-core) with height (Fig. 2). This fundamental difference of thermal wind structure between tropical and extratropical cyclones was exploited to diagnose the cold vs. warm core cyclone evolution.

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The second two cyclone phase parameters are defined as the vertical derivative of this horizontal height gradient (again within 500km radius of the surface cyclone center) which simplifies to a scaled thermal wind (V_T) magnitude, as applied to two tropospheric layers of equal mass:

$$\left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln p}\right|_{900hPa}^{600hPa} = -|V_T^L| \quad , \quad \left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln p}\right|_{600hPa}^{300hPa} = -|V_T^U|$$

Positive values of $-V_T$ indicate a warm core cyclone within the layer, while negative values of $-V_T$ indicate a cold-core cyclone within the layer (Fig. 2). For a warm-core tropical cyclone, $-V_T^L$ and $-V_T^U$ both are necessarily positive, with $-V_T^L$ having the greater magnitude. Conversely, for a cold-core extratropical cyclone, $-V_T^L$ and $-V_T^U$ are necessarily negative, with $-V_T^U$ having the greater magnitude. Hybrid and warm-seclusion cyclones may have a sign of $-V_T^L$ that is different from $-V_T^U$.

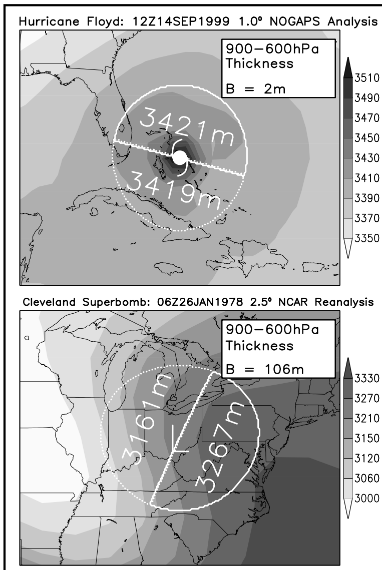

Fig.1: Derivation of B. 900-600hPa thickness (shaded) across top) thermally symmetric (nonfrontal) TC and bottom) thermally asymmetric (frontal) extratropical cyclone. Cyclone center is labeled within the 500km-radius circle and the bisecting equator indicates direction of motion. The solid semicircle lies to the right of motion and dotted semicircle lies to the left of motion. The mean thickness for each semicircle is labeled, along with their difference, parameter B.

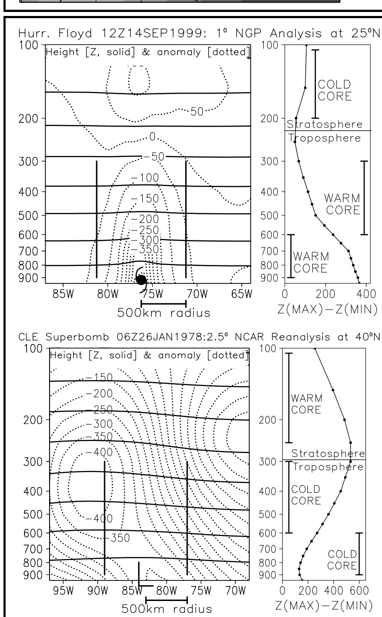

Fig. 2: Derivation of parameters $-V_T^L$ and $-V_T^U$ for top) TC exhibiting tropospheric warm-core structure and bottom) Extratropical cyclone exhibiting tropospheric cold-core structure. Left: Longitudinal cross section of height (Z, solid contour every 2000m) and anomaly from zonal mean (dotted). Two vertical lines indicate 500km radius. Right: Height difference (Z_{MAX}- Z_{MIN}) within this radius. The thermal wind parameters are derived using a linear regression fit to the vertical profile of Z_{MAX}-Z_{MIN} within the 900-600 and 600-300hPa layers.

3. PHASE DIAGRAM CONSTRUCTION & EXAMPLE

The three diagnostics (B, $-V_T^L$, and $-V_T^U$) define the three-dimensional cyclone phase space. Since a trajectory through a cube is cumbersome to visualize readily, the phase space is presented using two cross-sections: B vs. $-V_T^L$ and $-V_T^U$ vs. $-V_T^L$, examples of which are shown in Figure 3. The full lifecycle of a cyclone is defined through the trajectory through the phase diagram, with time moving forward as one moves along the trajectory, from the labeled 'A' to 'Z'. The resulting objective phase diagram is qualitatively similar to the subjective diagram proposed by Beven (1997; his Fig. 4), although the placement of cyclone types within that diagram differ from Figure 3, based upon the objective parameters chosen here.

The evolution of Hurricane Floyd (1999) from intense tropical cyclone into an extratropical cyclone is shown here through phase analysis (Fig. 3). Well-resolved deep warm core development, followed by extratropical transition (and transient hybrid status) and ultimately cold core development are shown. Insight into the tropical transition of subtropical or extratropical cyclones, and warm-seclusion within extratropical cyclones, is also found using the phase diagram (Fig. 4; see URL below). Cyclone phase climatology using 15000 western hemisphere cyclones (1986-2001 NCAR reanalysis) was evaluated (not shown), including phase frequency and mean intensity.

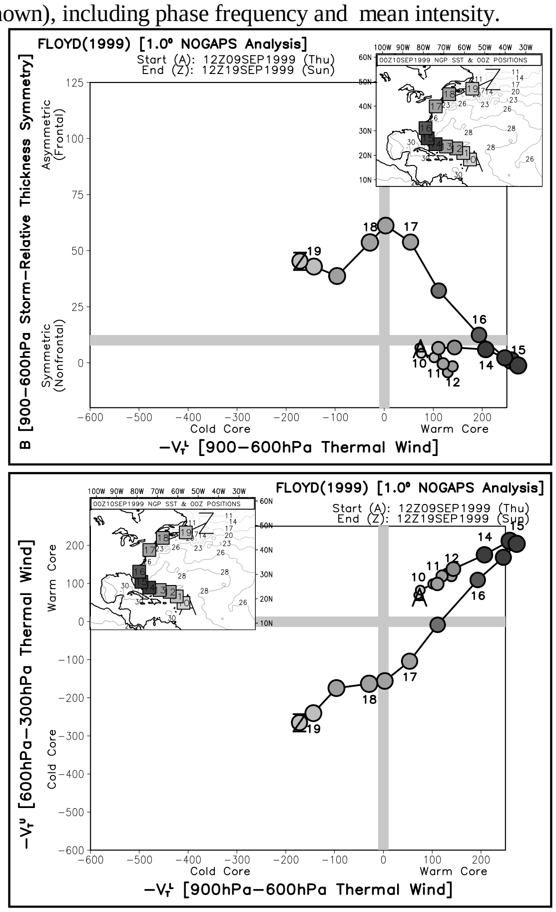

Fig. 3: Proposed cyclone phase diagram. Example is the lifecycle evolution of an extratropically transitioning TC using 1° NOGAPS analyses every 12h. top) $-V_T^L$ vs. B and bottom) $-V_T^L$ vs. $-V_T^U$. The inset frame gives the track of the cyclone and the model analysis SST field (°C). 'A' indicates the beginning of the plotted lifecycle within the available analyses and 'Z' indicates the end. A marker is placed every 12h. The shading of each marker indicates cyclone MSLP intensity (white: > 1010hPa, black: < 970hPa) and the size of the circular marker within the phase space indicates the relative size (mean radius) of the 925hPa gale-force (> $17ms^{-1}$) wind field (largest here is 400km). Positions at 0000 UTC are labeled with the day.

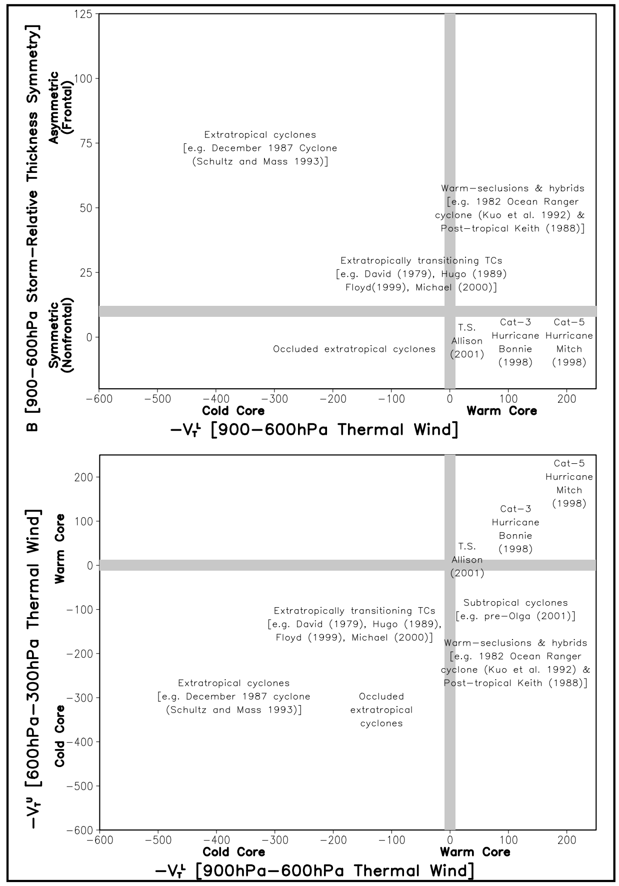

Fig. 4: General locations of various cyclone types within the phase space: top) $-V_T^L$ vs. B and bottom) $-V_T^L$ vs. $-V_T^U$. While cyclones move throughout the phase space during their evolution (e.g. Fig 3), the plotted location is that most representative of the cyclone type.

4. REALTIME PHASE ANALYSIS/FORECASTING

Phase diagrams for archived cyclones, current analyzed cyclones and operational model-forecast cyclones are available at http://eyewall.met.psu.edu/cyclonephase. Users can examine and anticipate the lifecycle evolution of existing or forecast cyclones and compare those to historic cyclones. Through the use of the URL in realtime, improved diagnosis and forecasting of tropical transition and extratropical transition was possible during the 2001 hurricane season (e.g. Gabrielle, Karen, Olga, Michelle). The cyclone phase parameters diagnosed using model forecast height fields provided substantial insight into forecast cyclone evolution when conventional model analyses may have been inconclusive. Forecast skill will be evaluated objectively in the future. Consistency in model evolution, including ensembling-based output, may provide insight into phase predictability and limits on intensity. However, the phase diagnostics are only as good as the gridded analyses upon which they are based. Thus, they should be used in concert with (rather than in place of) satellite images and observations to arrive at a more complete description of cyclone structure.

5. ACKNOWLEDGMENTS & REFERENCES

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