14B.1 EVOLVING SYNOPTIC-SCALE PRECIPITATION PATTERNS IN U.S. LANDFALLING TROPICAL CYCLONES

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1. INTRODUCTION

Enhanced mid-level tropospheric moisture is among the necessary ingredients for tropical cyclone (TC) genesis (Gray 1968). However, the role of large-scale environmental moisture in modulating the intensity and structure of mature TCs is less understood. In mature TCs, inertial stability impedes the intrusion of mid-level dry air (Holland and Merrill 1984) and thus, an existing TC may be somewhat protected from dry air intrusion, even in the presence of vertical wind shear (Reasor and Montgomery 2001; Mallen et al. 2005). Yet, the TC is still vulnerable to thermodynamic changes in the boundary layer, where a warm underlying sea surface, air-sea fluxes, and moist inflow are theorized to be crucial for sustaining the symmetric vortex (Emanuel 1986)

There is mounting evidence that large-scale moisture significantly impacts TC size and structure (Hill and Lackmann 2009; Matyas and Cartaya 2009). Recent research on this topic has focused on the influence of environmental humidity on the structure of TCs over the open ocean or in idealized modeling environments (Chan and Liang 2003; Kimball 2006; Hill and Lackmann 2009; Ge et al. 2013). Relatively few studies have investigated the structural evolution of convection in historical TCs during landfall when these tropical systems move into the mid-latitudes, where they generally encounter air masses with greater vertical wind shear and reduced atmospheric moisture, in addition to decreased latent and sensible fluxes and interaction with a complex land surface.

2. DATA AND METHODS

This study evaluates synoptic-scale precipitation patterns and large-scale moisture in 2004-2012 U.S. landfalling TCs (Figure 1). The 3-hourly center positions are calculated using a spline interpolation of National Hurricane Center (NHC)'s Best Track (BT) latitude-longitude positions. The North American Regional Reanalysis (NARR: Mesinger et al. 2006) is selected for its skill in characterizing North American precipitation patterns (Bukovsky and Karoly 2007; Becker et al. 2009). When studying TCs in global and regional reanalyses, it is important to note that spatial biases exist due to the sparsely available data over the tropical oceans (Schenkel and Hart 2012; Zick and Matyas 2015a). Additionally, as a 32-km horizontal resolution dataset, the NARR is unable to resolve certain aspects of a TC, including convection and latent heating in the inner core region. However, within this dataset, the introduction of over-ocean precipitation assimilation in 2004 leads to an improved analysis of TC warm core structure, including a robust secondary circulation, which results in improved TC water budgets and precipitation rates (Zick and Matyas 2015b).

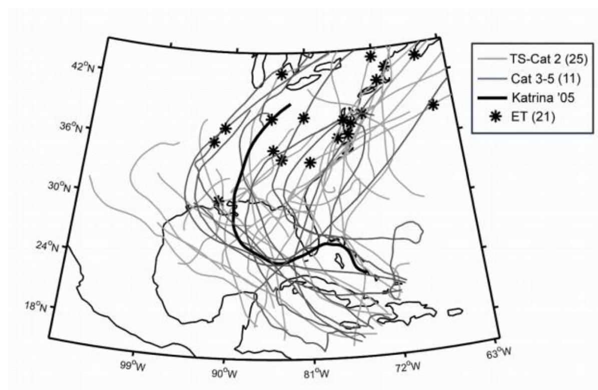

Figure 1. 2004-2012 U.S. landfalling tropical cyclone tracks (subset by maximum intensity) and the time of extratropical transition (ET), if applicable.

In this study, we utilize a shape metric methodology, which is summarized below and outlined in detail by Zick and Matyas (2016). For each of the n=36 landfalling storms, we delineate a binary precipitation region at 3-hourly timesteps by (1) limiting precipitation to distances within 600 km of the TC center and (2) retaining only precipitation greater than the 90[th] percentile of precipitation rates (Figure 2). Next, we quantify the spatial pattern of the binary image using three compactness measures that characterize TCs moving into the mid-latitudes: asymmetry (A), fragmentation (F), and dispersiveness (D) (Figure 3).

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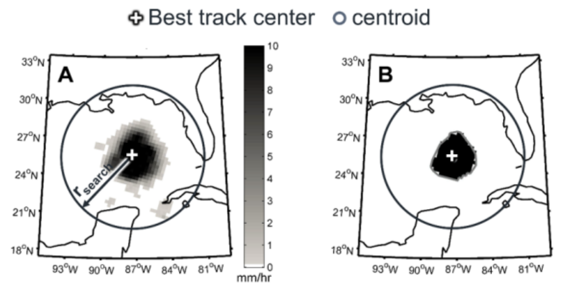

Figure 2. Example of shape delineation based on (left) NARR 3-hour mean precipitation rate within r = 600 km search radius with the corresponding (right) binary precipitation cluster(s) and associated centroids and convex hulls.

Lastly, we apply a moving Mann-Whitney *U* test to determine significant ($p < 0.05$) precipitation restructuring timesteps. Hurricane Katrina (2005) results are provided as an illustration of this method (Figure 4). During the Katrina lifecycle, the moving Mann Whitney *U* test (Figure 4C) identifies five evolutionary periods (EV1-5) in the synoptic-scale precipitation structure. EV1-5 correspond to genesis, landfall #1, intensification, landfall #2 and extratropical transition, respectively (Zick and Matyas 2016).

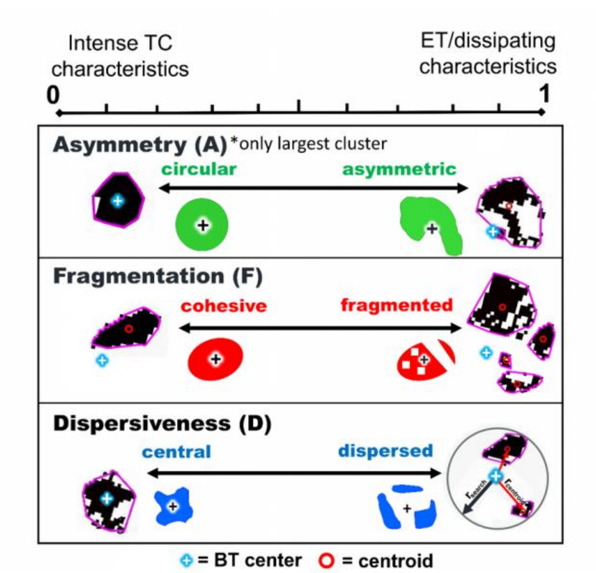

Figure 3. Summary of asymmetry, fragmentation, and dispersiveness shape metrics. Low scores indicate high compactness, while high scores indicate low compactness.

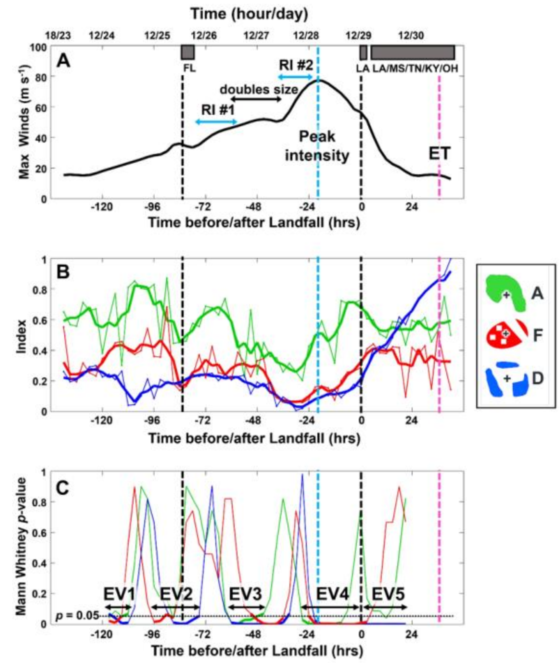

Figure 4. Time series of (A) intensity, (B) shape metrics, and (C) Mann-Whitney U test p-values for Hurricane Katrina (2005). For the shape metrics, a 6-hour running mean (bold) is applied to the 3-hourly quantities (light). Times of peak intensity, landfall, and extratropical transition (ET) are designated with cyan, black, and pink dashed lines, respectively

3. RESULTS

In Figure 5, we display the along-track positions of significant ($p < 0.05$) structural changes in all 2004-2012 landfalling TCs. Figure 6 shows these observed shape trends averaged over 2.5° × 2.5° latitude-longitude grid boxes. For a grid box to be shaded, we require significant ($p < 0.05$) shape changes in at least 2 TCs. These maps indicate preferred geographic regions for evolving precipitation patterns, with increasing (decreasing) compactness in the southern and eastern (western) Gulf of Mexico. Thus, northward moving TCs that make landfall in the panhandle and western coast of Florida are likely to increase in symmetry and cohesiveness. In contrast, westward moving TCs are likely to display more asymmetric, fragmented and dispersed precipitation patterns during the approach to landfall.

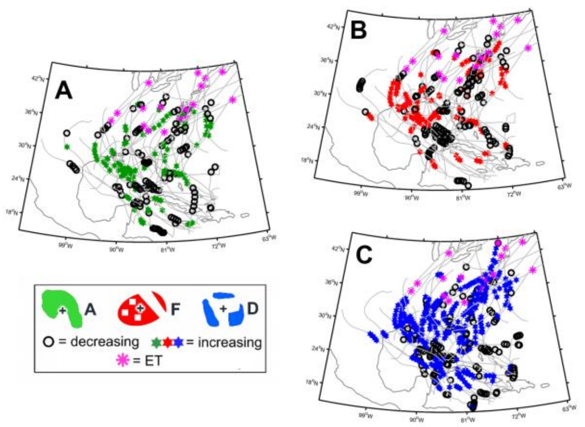

Figure 5. Along-track placement of time steps when moving window Mann-Whitney *U* test indicates an evolving precipitation structure with $p < 0.05$ for (A) asymmetry, (B) fragmentation, and (C) dispersiveness.

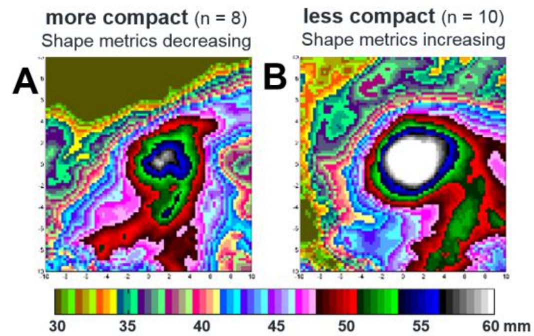

Figure 7. Composite precipitable water in the vicinity of TCs becoming (A) more and (B) less compact

Finally, we calculate TC composite precipitable water in two subsets: storms in which all three shape metrics indicate (A) increasing (n=8) and (B) decreasing (n=10) compactness (Figure 7). In TCs becoming more compact (Figure 7A), we frequently observe a prominent principal rainband that is co-located with an equatorward corridor of enhanced moisture flux convergence and precipitable water. Additionally, a strong moisture gradient exists to the northwest of the TC center, often to the front of storm motion. In the decreasing compactness subset (Figure 7B), spiral banding is reduced, the circulation is cut-off from large-scale moisture sources, and moisture flux convergence is confined to the inner core region (not shown). These precipitable water composites indicate the complex role of environmental moisture in TC structural changes. In particular, these results support recent research that intensity and structural changes depend strongly on the location of dry air with respect to storm motion (Wu et al. 2015) and/or the direction of vertical wind shear (Riemer and Montgomery 2011; Ge et al. 2013).

4. CONCLUSIONS

In this paper, we present a geospatial method that may be a useful tool for identifying and forecasting structural and, potentially, intensity changes during landfall as the TC encounters unfavorable environmental conditions in the mid-latitudes. Based on these results, TCs can evolve rapidly in the approach to landfall. In fact, structural changes are observed prior to landfall while the TC inner core is over warm Gulf of Mexico waters. Furthermore, composites of TCs becoming more versus less compact show striking differences in the large-scale moisture content and outer rainband features, as indicated by the NARR. Due to the coarse resolution of the NARR dataset and its parameterization of convective and other sub-gridscale processes, we plan to use high resolution models and observational datasets to conduct future research into the evolving TC structure in the approach to landfall.

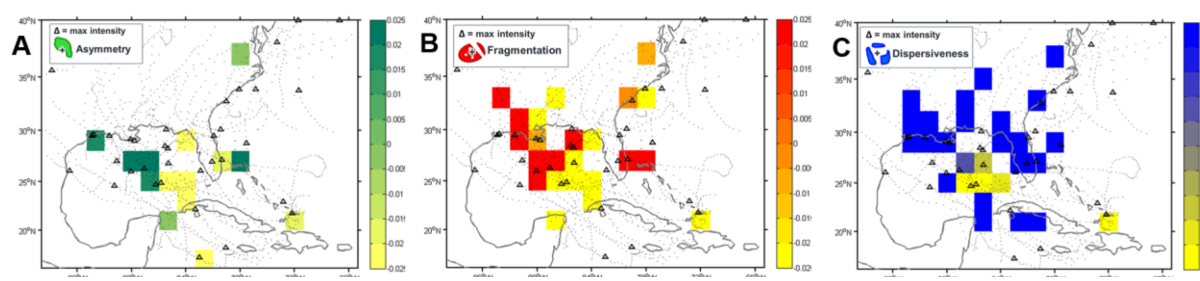

Figure 6. Average shape metric trends within 2.5° × 2.5° latitude-longitude grid boxes, calculated by averaging 3-hourly positions when Mann Whitney U-test indicates a significantly ($p < 0.05$) evolving pattern.

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