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DIAGNOSIS OF BANDED PRECIPITATION PATTERNS ASSOCIATED WITH EXTRATROPICALLY TRANSITIONING TROPICAL CYCLONES USING CSI THEORY

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1. INTRODUCTION

Conditional slantwise instability (CSI) is observed to occur in saturated, statically stable atmospheres where the horizontal wind increases in magnitude and veers with height. A complete background on CSI may be found in the compendium by Schultz and Schumacher (1999). Numerous studies in the midlatitudes (e.g. Sanders and Bosart 1985, Moore and Blakely 1988, Weismueller and Zubrick 1998) have shown that CSI locally enhances the intensity of convective bands found in the midst of a larger region of convection, resulting in locally heavy amounts of precipitation, and that CSI is often found in conjunction with isentropic upglide to the north of a warm frontal structure, usually during the winter months.

In their comprehensive study on extratropical transition (ET), Jones et al. (2003) theorize that CSI may also be found in the found in the region of warm frontogenesis associated with a tropical cyclone (TC) undergoing ET, termed the “delta rain” region by Klein et al. (2000) and an area of largely stratiform precipitation found to the north of the TC and downshear of a midlatitude jet streak. This is supported by Colle (2003), who highlighted the presence of moist symmetric instability within an intense precipitation band associated with Hurricane Floyd of 1999.

To that end, three extratropically transitioning North Atlantic TCs – Bonnie (1998), Erin (2001), and Alex (2004) – are selected for analysis. Each highlights a oceanic cold-core evolution of a warm-core TC, as depicted by the cyclone phase space of Hart (2003). The analysis framework is described in detail in section 2. A synoptic overview and results from the mesoscale diagnostics associated with Bonnie are presented in section 3, with connections drawn between the other cases in conjunction with the results. Conclusions and suggestions for future expansion of this study are presented within section 5.

2. DIAGNOSTICS

Conditional symmetric instability is a slantwise instability, resulting from displacements of parcels of air in both the horizontal and the vertical. This is contrasted with convective and conditional instabilities, both of which are parcel instabilities only in the vertical. As with any upright instability, sufficient lift and moisture are also necessary to result in slantwise convection formation. Any diagnostic technique designed to analyze for regions of CSI must take into account not only other instabilities that may be present within the atmosphere but also the salient conditions necessary for convection formation. Thus, the environments in advance of each system are analyzed with respect to upright instability (e.g. convective and conditional instability), synoptic forcing (e.g. from frontogenesis), and for CSI so as to test for other mechanisms potentially influencing convection in the environments of the two cyclones.

CSI is said to occur in regions where the geostrophic momentum (M_g) lines slope more in the vertical and horizontal than do the lines of saturated equivalent potential temperature (Θ_{es}). Diagnosis can come from the use of vertical cross-sections taken perpendicular to the thermal wind or thickness lines (Bluestein 1993) or by utilizing the mathematical framework of saturated geostrophic potential vorticity (MPV_g^*; Schultz and Schumacher 1999), which takes into account the dynamical and thermodynamical conditions supporting CSI in a single mathematical formulation. These diagnostics are applied outside of the core of each tropical cyclone so as to ensure the validity of the quasigeostrophic approximation.

Using these frameworks, cross-sections are developed to diagnose for upright and slantwise conditional instability over the domain to understand their role in the convective process. Lift is diagnosed in terms of multiple physical processes, including frontogenetical forcing, quasigeostrophic forcing, ageostrophic forcing, and isentropic upglide, while moisture is diagnosed utilizing cross-sections of relative humidity. Convective energy in the form of upright or slantwise convective available potential energy (CAPE/SCAPE) is not diagnosed, as it is thought to not play an integral role with regards to CSI given the favored environments for its presence (Schultz and Schumacher 1999).

All data used were obtained from 1° resolution Aviation/Global Forecasting System (AVN/GFS) model operational analyses. It should be noted that the horizontal resolution associated with this product is on the order of 100km, resulting in mesoscale instability parameters likely being underrepresented in this analysis (following Schultz and Schumacher 1999, their section 7).

3. BONNIE (1998)

3.1 *Synoptic overview*

Bonnie was a long-lived tropical cyclone in the North Atlantic, making landfall on 27 August 1998 just under major hurricane status near Wilmington, North Carolina (NHC 2005). The system later moved towards the east and northeast in response to an approaching mid-tropospheric trough, briefly regaining hurricane intensity as it accelerated in the midlatitude westerlies. The storm gradually began to lose tropical characteristics as it moved north of the Gulf Stream and was declared extratropical by the National Hurricane Center at 1200 UTC 30 August 1998. At the time of transition, the warm core of the cyclone had evolved into a cold-core structure and frontal characteristics and the "delta rain" region of Klein et al. (2000) were evident in satellite imagery (figure 1).

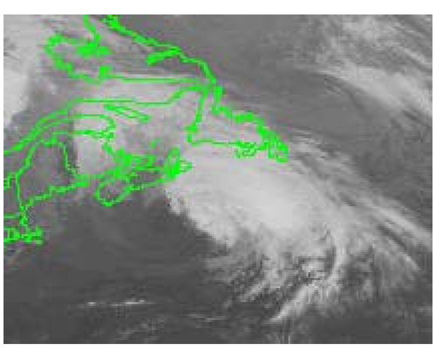

Figure 1: GOES-8 infrared satellite image at 0000 UTC 30 August 1998 of tropical cyclone Bonnie off of the coast of Nova Scotia.

3.2 *Observations*

Convective features found in the warm frontogenetical sector poleward of the center of the cyclone are the focus of this investigation, as this is the region most favored for CSI (Jones et al. 2003). Attention is paid in particular to the twelve hours leading to the completion of ET within the cyclone phase space of Hart (2003), here from 0000 UTC to 1200 UTC 30 August 1998.

Much of the layer below 700hPa was found to be favorable for CSI, as highlighted by negative MPV_g^* values (figure 2a) at the time of transition. However, conditional instability was also found in the surface-to-925hPa layer north of the developing warm front, as highlighted by Θ_{es} values increasing with height, suggesting that CSI may not be the dominant mechanism behind the observed convection or that elevated convection associated with CSI may exist. The conditional instability arose out of a decoupling of the boundary layer and mid-level circulations associated with the cyclone as it entered a region of high static stability, leading to slightly increased Θ_{es} values near the surface associated with the decaying tropical cyclone core. The observed CSI resulted primarily from vertical wind shear.

It should be noted that strong cyclonic rotation near the center of Bonnie resulted in positive values of MPV_g^*, meaning CSI was inherently only likely at large radii from the center of the storm (Bluestein 1993). Furthermore, the region directly south and east of the transitioning TC is shown to be strongly conditionally unstable in the 700-850hPa layer (figure 2c). This results from the transport of warm, moist air to the north in associated with the development of a low level jet (and, similarly, frontal structures) east of the transitioning TC.

Frontogenetical forcing (figure 2b) is observed to act in coordination with quasigeostrophic forcing and isentropic upglide (not shown) to result in strong ascent in the warm frontogenetical structure. This frontogenetical forcing is believed to have arisen primarily out of scalar frontogenesis and associated horizontal deformation processes, as highlighted by Harr and Elsberry (2000). Quasigeostrophic forcing arose due to favorable patterns of vorticity advection relating to the translation of the cyclone, while the isentropic

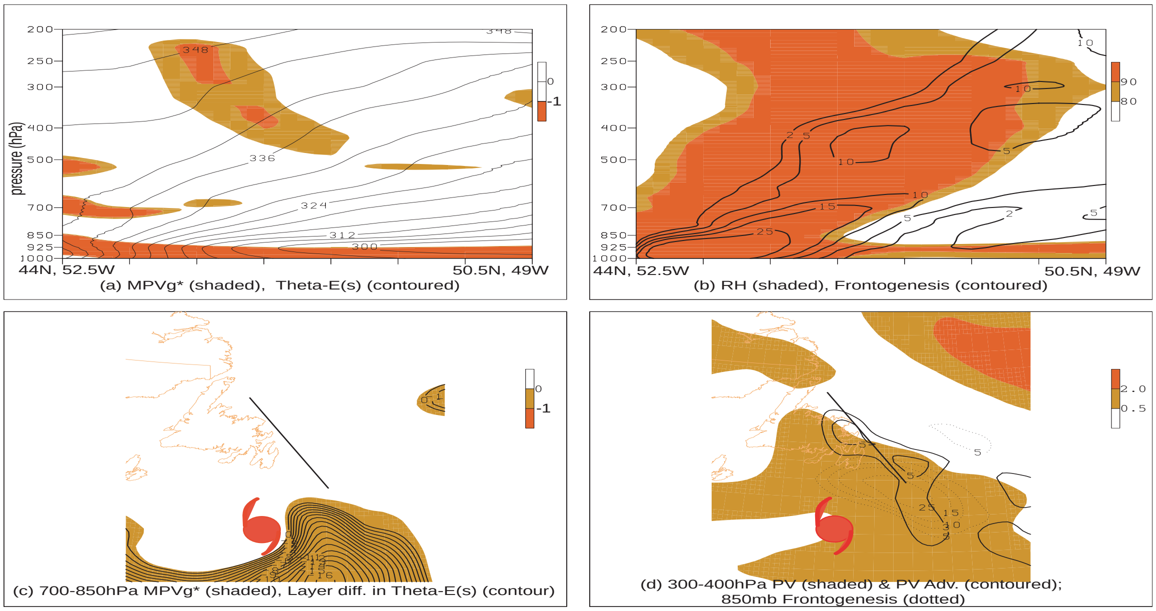

Figure 2: (a) Cross-section of MPV_g^* (shaded; units: PVU) and Θ_{es} (contoured; units: K) through the solid line depicted in panels (c) and (d); **(b)** as in (a), but for relative humidity and frontogenesis parameter (units: scaled °C m^{-1} s^{-1}); **(c)** 700-850hPa layer MPV_g^* (shaded; units: PVU) and layer difference in Θ_{es} (contoured; units: K); **(d)** 300-400hPa potential vorticity (shaded; units: PVU) and potential vorticity advection (dotted; units: PVU s^{-1}), and 850hPa frontogenesis (contoured; units: scaled °C m^{-1} s^{-1}). The center of the storm is denoted by a hurricane symbol in panels (c) and (d).

upglide was forced by the tilting of isentropes into the vertical to the north of the TC by dynamically-induced rising motion associated with the secondary circulation of the tropical cyclone and the midlatitude environment. The atmosphere in the region favorable for CSI was seen to be moist throughout the depth of the troposphere, with relative humidity values exceeding 90% (figure 2b).

Owing to the lack of buoyant energy and relatively cold temperatures across the ocean, convection within the region was likely to be of a stratiform nature, as hinted at by figure 3 on the north side of the storm. However, banded structures with elevated bases inside the larger convective environment likely existed as a result of CSI. Conditional instability served to maintain the larger convective structures within the warm frontogenetical sector.

As the cyclone translated to the east, stability increased and the conditional instability weakened with a weakening of the low level warm-core of the storm, serving to weaken the overall environment for convection. This coupled with a drier midlatitude environment resulted in reduced moisture values in the column, effectively terminating the banded structures associated with CSI in the environment.

3.3 *Correlations to Erin (2001) and Alex (2004)*

Similar diagnostics were performed for two additional transitioning TCs, Erin (2001) and Alex (2004). TC Erin had a tropical lifecycle similar to that of Bonnie, while TC Alex evolved had baroclinic origins. Further, each exhibited a “delta rain”/warm frontogenetical region on satellite imagery similar to that seen in figure 1 with Bonnie. With only minor differences, the results shown with Bonnie in figure 2 above were noted with Erin and Alex as well. Frontogenetical forcing for vertical motion was found not to be as strong with either Erin or Alex; this was compensated for, however, by stronger quasigeostrophic forcing in both cases. Despite this, isentropic upglide is noted in association with both cases.

While the low levels below 700hPa were again found to exhibit favorable conditions for the presence of CSI, upright conditional instability was found at low levels in association with both cyclones, suggesting that the decoupling of the boundary layer circulation during ET over water is not an isolated occurrence and adding additional significance to the results presented here.

4. CONCLUSIONS

Operational model data were collected and analyzed to quantify the potential for convective slantwise instability within the environments of three extratropically transitioning tropical cyclones, Bonnie (1998), Erin (2001), and Alex (2004), within the North Atlantic Ocean. Environments within the region of greatest frontogenesis were found to be conducive to the presence of CSI on the mesoscale within the larger convective areas. However, the environments associated with the cyclones were also found to also be favorable for surface-based conditional instability as a result of the decoupling of the boundary layer and mid-tropospheric circulations associated with the cyclone as it entered an increasingly statically stable environment.

Dominant physical mechanisms leading to a favorable environment for CSI on both the synoptic-scale and mesoscale were similar for all cyclones. Weakly negative values of $\frac{(\partial \Theta_{es})}{(\partial p)}$ in the lower troposphere resulting from warm, moist conditions near the surface associated with the translating tropical cyclone resulted in negative values of moist geostrophic potential vorticity, a necessary condition for the presence of CSI. Regions in which this difference was strong, however, were associated with the aforementioned conditional instability near the surface. Vertical wind shear in association with each storm played a role in developing the overall convective structure (the “delta rain” region) as well as enhancing the potential for CSI within this region. Moisture necessary for convection was supplied in the diffluent outflow channel to the north of each cyclone.

Primary mechanisms forcing vertical motion were similar for each case. All of the cyclones exhibited strong quasigeostrophic and isentropic forcing for rising motion in the favored regions as a consequence of vertical shear, storm translation, and the tilting of isentropes into the vertical. Unique to the environment surrounding Bonnie was strong frontogenetical forcing at the surface in the warm frontogenetical sector resulting from scalar frontogenesis and horizontal deformation processes. The presence of CSI within the convective regions of both cyclones occurred below 700hPa, suggesting a surface-based slantwise unstable environment.

From an operational standpoint, model-based operational guidance may be used to diagnose the potential for CSI with a tropical cyclone as it approaches landfall. Depending upon the horizontal resolution of the available guidance products, specific locations favorable for CSI may be able to be depicted. Care must be exercised by also analyzing for other types of instability as well as for sufficient convective forcing to rule out other potential sources for convection (Schultz and Schumacher 1999). Future studies of additional cyclones hold the potential of further quantifying and refining the results presented here in both an operational and research environment, particularly with cases of tropical cyclones that undergo extratropical transition after landfall.

5. ACKNOWLEDGEMENTS

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