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MESOSCALE PRECURSORS TO THE HURRICANE GASTON FLOODING EVENT AS DIAGNOSED FROM OBSERVATIONS AND NUMERICAL SIMULATIONS

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1. INTRODUCTION

Freshwater flooding has been shown to be the leading cause of death in tropical cyclones (TCs) accounting for over half of the TC related deaths in the United States between 1970 and 1999 (Rappaport 2000). Recently, a greater understanding of the extratropical transition process (ET) has lead to better forecasts of TC flooding events. Comprehensive research on ET by Evans and Hart (2003), Hart and Evans (2001), Hart (2003), Klein et al. (2000, 2002), Harr and Elsberry (2000), Atallah and Bosart (2003, 2007) and numerous others has allowed forecasters to apply their understanding of quasi-geostrophic (QG) theory to more accurately predict where heavy rainfall will occur. However, rainfall forecasts have remained problematic for storms that do not undergo ET or remain too small for QG theory to apply. This study will use Hurricane Gaston (2004) to investigate the dynamics that drive heavy precipitation in these "non-traditional" storms.

2. BACKGROUND AND OBSERVATIONS

Hurricane Gaston made landfall in South Carolina on 29 August, 2004, as a minimal Category 1 hurricane. On 30 August, over 12 inches of rain fell in the Richmond, Virginia, metro area causing extensive flooding, eight deaths, and nearly $20 million in damage. While the track forecast by the National Hurricane Center proved accurate, the rainfall forecast remained problematic for both humans and computers. No extreme flooding was forecast for Virginia (Billet and Lynch 2006) and numerical models held Gaston's rainfall totals essentially steady through North Carolina and Virginia, when actual rainfall totals in Virginia were more than double those in North Carolina.

Previous research on this storm by Billet and Lynch (2006) and the authors (Brown et al. 2006) has shown the heavy precipitation to have started as a line of supercells along a surface convergence zone slowly rotating around Gaston. Convection initiated when the convergence zone entered an area of high convective available potential energy (CAPE) created by a break in the cloud-shield which allowed solar radiation to heat the surface (Figure 1). This heating occurred in an area of substantial low-level moisture advection off the Gulf Stream by the southeasterly winds of Gaston's circulation. As the convergence band entered Virginia, baroclinicity was enhanced by the temperature gradient at the cloud boundary, providing further forcing for upward motions. These ingredients resulted in an ideal environment for vigorous convection (Doswell et al 1996) and rainfall rates as high as 4.25 in/hr are observed by ASOS stations.

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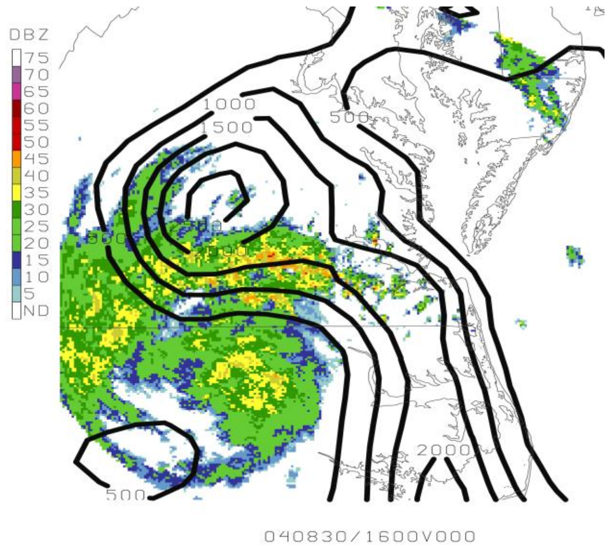

Figure 1 - NEXRAD base reflectivities (dBz in color) from radar site AKQ with CAPE values from the RUC20 (contours) plotted every 500 J kg^{-1} at 1600 UTC on 30 August.

Rainfall rates of this magnitude are not unheard of in tropical cyclones impacting this region. In 1999, Hurricane Floyd brought record-breaking rainfall and widespread flooding to coastal Virginia and North Carolina. Studies of Floyd by Atallah and Bosart

(2003), Colle (2003), and others showed that phasing of a energetic polar jet streak and a coastal front were responsible for focusing and maintaining the precipitation in this area. With established forcing mechanisms in the lower and upper troposphere, heavy precipitation was fed by advection of moisture-rich tropical air from the large circulation of the hurricane. This rainfall was produced as Floyd followed a rather typical progression through the Klein et al. (2000) model in its transition from warm to cold core (tropical to extratropical).

Gaston remained warm-core throughout the event, yet the low-level ingredients for precipitation in Hurricane Gaston are similar to those in Floyd: a convergent baroclinic zone and a steady source of high theta-e air advecting into the system. However the scale of the features in Gaston is much smaller. Gaston's baroclinic zone is formed merely hours before the precipitation occurs by differential heating across the cloud boundary, making forecasting the evolution of the storm very difficult. Another unknown was the ability of the upper atmosphere to support heavy precipitation in this environment. The approaching polar jet-streak was too far north for Gaston to exploit the divergence of the right entrance region as occurred in Floyd. Complicating matters for the purpose of this study was the inconsistent representation of upper tropospheric features in the Rapid Update Cycle (RUC) analysis. This is unsurprising given the rapid evolution of the convection and sporadic nature of upper-air observations ingested into the model.

One feature of interest resolved by the RUC at the outflow level was a sharply curved ridge squeezed between the approaching midlatitude trough to the north and the tropical cyclone to the south. When absolute vorticity is plotted, a persistent area of small to negative absolute vorticity is found in a ribbon paralleling the coast at 200 mb (Figure 2). Negative absolute vorticity is rare in the mid-latitudes and is usually found in sharply curved mesoscale ridges or in areas of strong anticyclonic wind shear, such as on the equatorward side of a jet streak (Holton 1992). In Gaston, both of these features are present just north of the storm over coastal Virginia. This is significant as negative absolute vorticity indicates inertial instability, an imbalance between the pressure-gradient and inertial forces in horizontal flows. Blanchard (1998) and Seman (1994), in studies of mesoscale convective systems (MCSs) and complexes (MCCs), both concluded that areas of weak inertial stability are areas of preferred outflow divergence, resulting in less resistance to the growth of convection and the secondary circulations that sustain it. Therefore, areas of weak inertial stability can sustain deeper, stronger, more persistent convection than areas of strong inertial stability.

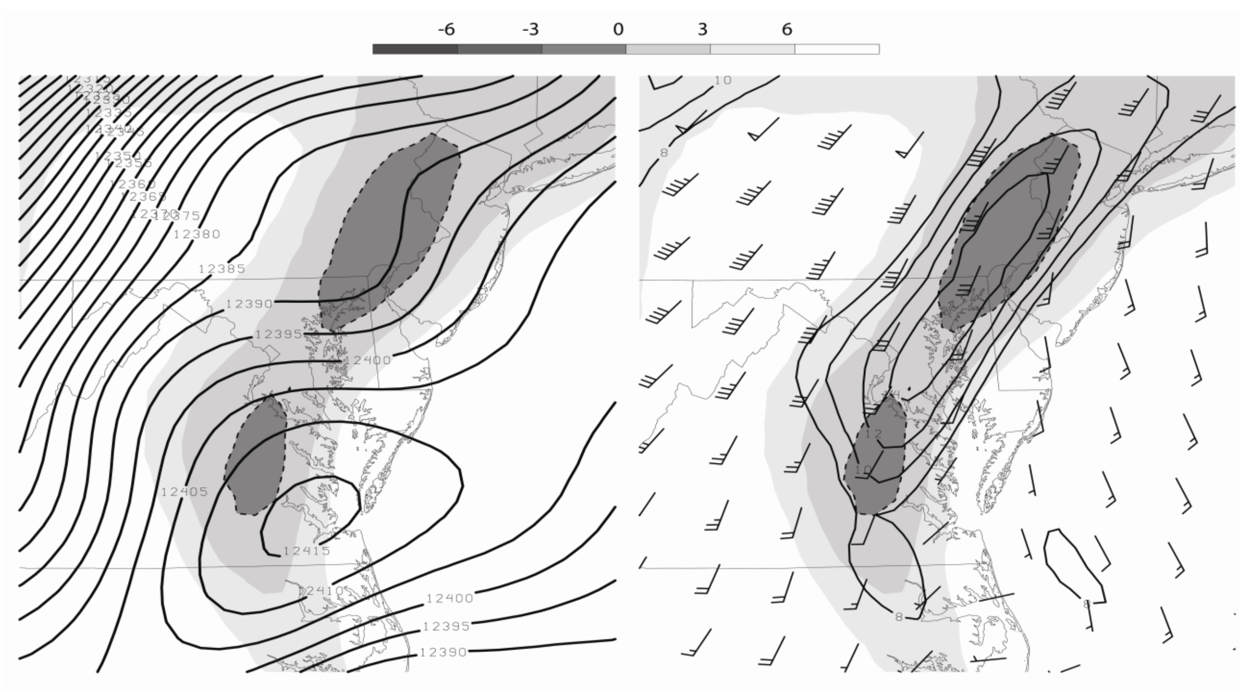

Figure 2 - 200 mb absolute vorticity (10^{-5} s^{-1}) at 1200 UTC 30 Aug shaded (lightly for positive values and darker for negative values with the zero line dashed) on both panels with heights contoured every 5 meters on the left and wind-shear contoured every 2 sec^{-1} on the right. Wind barbs (knots) are plotted on the right panel as well.

On both satellite and radar, and in general structure, the heavily precipitating feature of Gaston resembles MCCs commonly found in the Midwest and Great Plains states. The high theta-e inflow of the circulation acts like a low-level jet, the rain cooled air around the center of circulation like the cold pool, and with weak restoring forces in the upper atmosphere, an accelerative outflow jet and secondary circulation are suspected to be present. If the secondary circulations exist below the resolvable scale of the RUC analysis, this would help explain how the atmosphere could sustain such heavy precipitation for an extended duration. To address this theory, numerical simulations were run to explore the smaller scale features of this storm.

4. MODELING

The Non-Hydrostatic Mesoscale Atmospheric Simulation System (NHMASS) model (e.g., Ringley et al. 2007) was run in a 1-way nested configuration at 18 km, 6 km, and 2 km. The runs were otherwise identically configured using the Kain-Fritsch-2 CP and TKE PBL schemes, except the 2 km simulation, where no CP scheme was used and the initialization time was closer to the event. Plots of low-level fields were validated against a manual analysis and showed very good correlation to important features such as the surface baroclinic zone (Figure 3) and precipitation patterns at all resolutions.

The numerical simulations indicate that, as in Floyd, the heavy precipitation is a result of phasing of upper and lower tropospheric features. The convection in the model only becomes intense once the low level baroclinic zone and upper level inertial instability become phased, organizing the convection into a troposphere-deep mesoscale circulation (Figure 4). As proposed by Blanchard (1998) and Seman (1994), the low inertial stability of the atmosphere at the outflow level just north of the updraft in Figure 4a1 is quickly converted to inertial instability (Figure 4b1) as upper level heights rapidly rise in response to latent heating and outflow parcels begin accelerating northward. Once the restoring forces in the atmosphere are essentially eliminated by inertial instability, parcels are free to accelerate away from the updraft, efficiently evacuating mass from the column. As parcels leave the area of inertial instability, they slow and converge, sinking into the area earlier warmed by solar radiation (Figure 4c1). This subsidence helps maintain the warm boundary layer through adiabatic warming.

The circulation can be seen in the model at time 1700 UTC (Figure 4c1) extending the depth of the troposphere with the ascending branch in the convective updraft and descending branch in the warm inflow area. At this point, the circulation is self sustaining and frontogenetical, with evaporative cooling on the cold side of the baroclinic zone, subsidence enhancing the warm inflow, and latent heating driven pressure gradients in the outflow maintaining the inertial instability. As convection grows, so does the mesoscale circulation, which enhances frontogenesis, creating a positive feedback loop that enables the precipitation to persist for far longer than the expected convective lifespan.

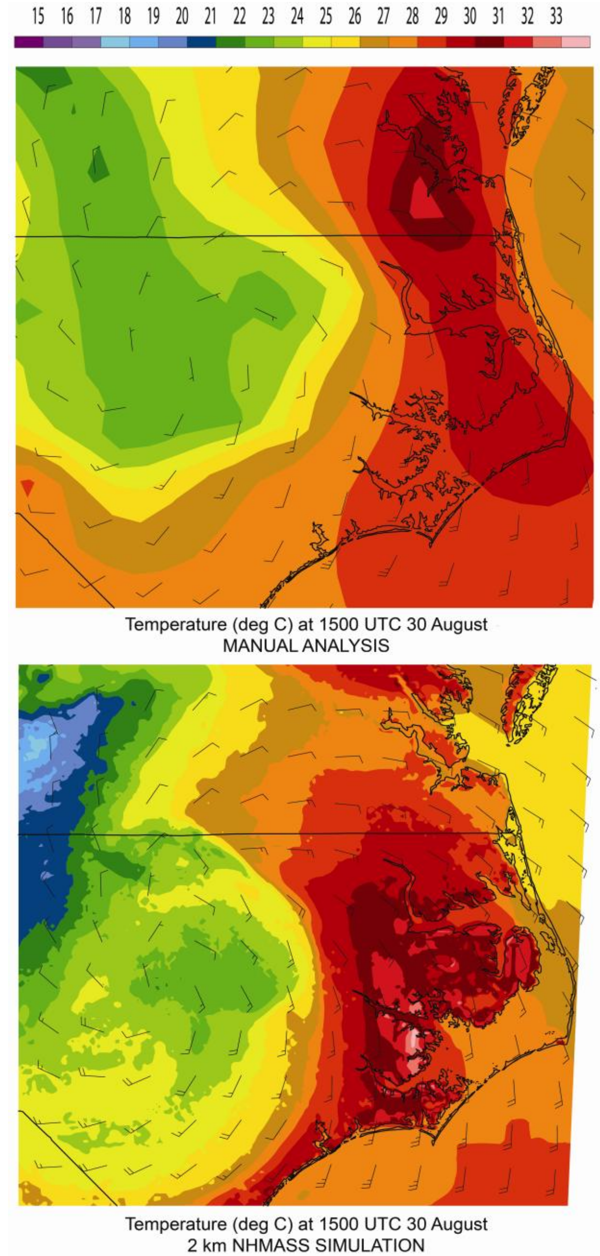

Figure 3 – Manual analysis (top) and 2km NHMASS (bottom) 2 meter temperature (degrees C) at 1500 UTC 30 August 2004

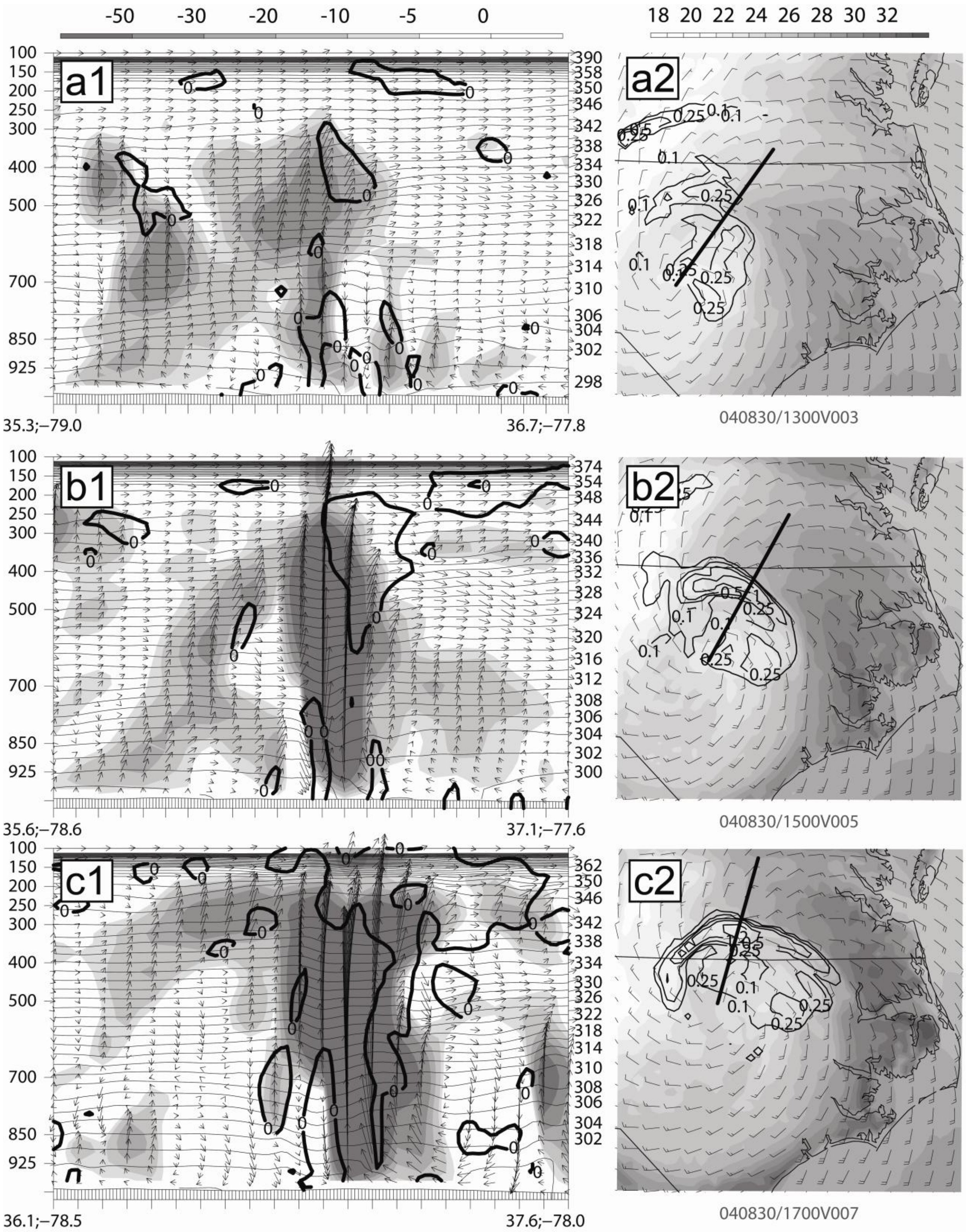

Figure 4 - Cross sections (a1, b1, c1) with omega (microbars/s, upward motion shaded), potential temperature (K, thin black lines), absolute vorticity zero line (s^{-1}, thick black line), and circulation parallel to the cross section plane (arrows scaled for readability). Plots a2, b2, and c2 show temperature (°C, shaded) and 30-minute rainfall (black contours at 0.1, 0.25, 0.50, and 1.0 inches) with the location of each corresponding cross section indicated by the thick black line. All plots are from the 2 km simulation with times, from top to bottom, of 1300 (f03), 1500 (f05), and 1700 (f07) 30 August.

Synergistic convective circulations have been found in many types precipitating systems in this region. Uccellini et al. (1984, 1987) describes a thermally indirect ageostrophic circulation over the East Coast that leads to the Presidents' Day cyclone and snowstorm of 1979. In this case, an increasingly unbalanced subtropical jet approaches the East Coast with increasing divergence along its axis. At the same time, a coastal front is developing along the Carolina coast in an inverted trough east of a cold-air damming ridge. The ascent beneath the subtropical jet initiates low-level jet formation from the southeast through isallobaric forcing. Moisture transport off the Atlantic in the low-level jet and ascent over the coastal front produces heavy rain and snow over the Carolinas and latent heating which forces further accelerations in the sub-tropical jet as geopotential thicknesses increase aloft. Sensitivity studies reveal that diabatic processes associated with condensation in the convection and PBL ocean fluxes are necessary to maintain the circulation and drive the low-level jet in the return branch of the thermally indirect circulation. The low-level jet, in turn, is responsible for the moisture advection into the convection and subsidence in the sinking branch of the circulation amplifies the baroclinic zone at the coastal front.

While the Presidents' Day storm is on a much larger scale than any circulation we see in Gaston, the concept is the same: a synergistic relationship between diabatically forced jets aloft and low level inflow impinging on baroclinic zones at the surface. Gaston's surface boundary is similar to the coastal front while the low-level jet in the TC circulation advects moisture into the system in the same manner as Uccellini's ageostrophic low-level jet. The secondary circulation in Gaston provides the ageostrophic push that vectors the low level inflow into a strongly convergent pattern. Gaston's outflow jet is much less powerful than the subtropical jet of the Presidents' Day storm, but can leverage inertial instability to support the scale of the precipitation. The synoptic scale subtropical jet of the Presidents' Day storm relies on geostrophic adjustments that occur in unbalanced flow to support divergent motions, but Gaston's precipitation event is sub-Rossby radius of deformation, meaning rotational influences are insignificant and geostrophic balance unattainable, thus inertial stabilities become the dominant source of divergent motions. To further relate the cases, note that Uccellini theorizes that the orientation of the indirect circulation may be due to weak inertial stability, given that the circulation is observed on the anticyclonic shear side of the subtropical jet.

The synergistic feedback process is also described by Raymond and Jiang (1990) who describe how an MCC can generate inertial instability by transporting mass upward and heating a column through latent heating. This creates sharp height rises above the storm and negative absolute vorticity and inertial instability. This inertial instability can help drive the outflow jet and encourage further convective development, just as in the mesoscale circulation seen with Gaston.

Self-sustaining instabilities of this nature are often related to "convective-symmetric instability". Note that this differs from conditional symmetric instability (CSI) often referenced in the literature. CSI should not be a dominant factor in Gaston since the growth rates of upright convection due to conditional instability and/or inertial instability will be much greater than those supported by CSI. However, CSI must be present along with conditional instability for the conditions of convective-symmetric instability to be met (Schultz and Schumacher 1999). As proposed by Emanuel (1980), convective-symmetric instability theory posits that latent heating in free-convective updrafts drives the circulation (Jascourt et al. 1988). Compensating subsidence occurs along a slanting path as to do the least work against buoyant and inertial forces. The cross sections in Figure 4 suggest the circulations expected with convective-symmetric instability including slanting downdrafts.

5. CONCLUSIONS

Due to the synoptic flow pattern that will often predicate a TC's recurvature out of the tropics and into the Mid-Atlantic States (trough digging into the eastern U.S. and a receding Bermuda ridge), an environment with weak inertial stability may be common in East Coast landfall events. The upper tropospheric jet streak that accompanies a mid-latitude trough is one of the few features that can create a region of synoptic scale inertial instability in the mid-latitudes. As seen in Gaston, a retreating ridge becoming squeezed between the mid-latitude trough and approaching TC can accentuate the inertial stability weakness created by the shear of the jet streak with sharp anticyclonic curvature, leading to an environment primed for convective-symmetric instability. With numerous options for frontogenesis at the surface (cold air damming, coastal frictional convergence, uneven surface heating, preexisting coastal and synoptic fronts), a juxtaposition of the inertially unstable atmosphere with a low level forcing mechanism becomes likely for this region. Convective-symmetric instability can be realized when synergistic phasing occurs, creating a self-sustaining precipitation machine focused on the area of greatest coupling where the convective-symmetric instability creates a low resistance path for parcel ascent. It is likely that heavy rainfall events from landfalling TCs share common ingredients that include a divergent upper troposphere, surface baroclinic zones, and lower-tropospheric moisture convergence, regardless of scale. Mesoscale circulations created by atmospheric instabilities drive the precipitation in Hurricane Gaston and may be endemic to the mid-Atlantic in TC landfall situations.

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