6B.1

DYNAMICAL STRUCTURES AND PRECIPITATION DISTRIBUTIONS OF TRANSITIONING TROPICAL CYCLONES IN EASTERN CANADA, 1979-2004

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1. Introduction

From 1979-2004, 32 storms originally tropical in nature (as classified by the National Hurricane Center) have affected Eastern Canada to various degrees during or after extratropical transition (ET). This study examines the dynamical structure of these 32 cases from a quasi-geostrophic (QG) perspective using the Sutcliffe (Trenberth) approximation (Sutcliffe 1947; Sutcliffe and Forsdyke 1950; Trenberth 1978) to the QG omega equation (advection of mid-tropospheric vorticity by the thermal wind), primarily utilizing the NCEP North American Regional Reanalysis (NARR). Using the Sutcliffe approximation (Equation 1) method described above, the storms were partitioned into two groups, 'intensifying' and 'decaying', based upon the QG forcing for ascent. Composite synoptic structures, from both QG and potential vorticity (PV) views, will be presented for both partitioned groups of storms. In addition, the precipitation distribution of the cases in the study is analyzed using the 3-hour accumulated precipitation field in the NARR, in a similar to manner to the work of Atallah and Bosart (2004), which utilized the United Precipitation Dataset (UPD), for precipitation analyses over the continental United States.

2. Data and Methodology

The pursuit of a higher horizontal resolution study than allowed by the 2.5 degree grid in the NCEP/NCAR Global Reanalysis (Kalnay et al. 1996) led us to utilize the new NCEP North American Regional Reanalysis (NARR), with a 32 km horizontal resolution (Mesinger et al. 2004). This choice is important from a timeline standpoint since the NARR covers only the 1979-present period. This limited our storm selection process to the past 26 years (1979-2004). Storms were chosen by examining the National Hurricane Center (NHC) best track archive dataset, available online at http://www.nhc.noaa.gov. Thirty-two storms were found to have affected the Canadian mainland during these 26 years. We defined "affected" as the NHC track line touching some part of Canada during the storm's life cycle. The tracks of all 32 cases (1979-2004) can be found in Figure 1. The map was created using the National Oceanic and Atmospheric Agency's (NOAA) Coastal Service Center tropical cyclone track page, available online at http://hurricane.csc.noaa.gov/hurricanes. Composite plots were completed using the NCEP/NCAR global reanalysis (Kalnay et al. 1996), with a horizontal grid resolution of 2.5 degrees. This dataset was chosen for composites for the sake of expedience and the large-scale synoptic features are quite adequately represented by the NCEP/NCAR global reanalysis.

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3. Composite Methodology and Results

The primary objective of the large-scale composite synoptic analyses is to analyze the similarities and differences in synoptic structure between the intensifying and decaying storm groupings before, during, and after ET occurs. In order to partition the storms dynamically and subsequently analyze precipitation distributions, the Sutcliffe/Trenberth approximation to the QG omega equation was utilized (Equation 1). The Sutcliffe approximation allows for a diagnosis of forcing for ascent by combining vorticity and temperature advections into one term, the 400-700 mb absolute vorticity as advected by the 200-1000 mb thermal wind (Sutcliffe 1947; Sutcliffe and Forsdyke 1950; Trenberth 1978; Atallah and Bosart 2004).

$$\left(\nabla 2_p + \frac{f_0 2}{\sigma}\frac{\partial 2}{\partial p 2}\right)\omega = \frac{f_0}{\sigma}2\left(\frac{\partial \mathbf{v_g}}{\partial p}\cdot\nabla_{\mathbf{p}}\eta_{\mathbf{g}}\right) \qquad (1)$$

The steps involved in the compositing methodology are as follows:

- The four weakest vortices in the study (Alberto (1988), Chris (1988), Unnamed (1991) and Dennis (1999)) had minimum Sea Level Pressure values (SLP) more than one standard deviation above the average minimum SLP value and were therefore dropped prior to compositing. This was done so that a very weak vortex could not be classified in the intensifying category, even if it was intensifying to something not quite as weak.

- The remaining 28 storms were partitioned into two groups, "intensifying" and "decaying" based upon the slope of the low-level (700-850 mb) relative vorticity; an intensifying case is one with a minimum low-level relative vorticity increase of $5*10^{-}5$ over a time period of twelve hours, with a decreasing relative vorticity of similar magnitude defined for a decaying case.

- Ten storms were found to fit the "intensifying" criterion, while twelve cases were determined to be "decaying. Five cases had vorticity slopes too small to fit in either bin, and Juan (2003) was classified as a special case due to the NARR's shoddy representation of the storm.

All composites were done using a grid-centered method (similar to Atallah and Bosart (2004)), thus making the background geography essentially irrelevant. Quasigeostophic composite analyses were performed using the Sutcliffe/Trenberth approximation 1, with 400-700 mb absolute vorticity values ($*10^5$) shaded and 200-1000 mb thickness contours (parallel to the thermal wind) overlayed. Composite images are displayed for t=-12 hrs, t=0, and t=12, where t=0 is defined as the initial time that the low-level absolute vorticity begins to change significantly, as previously defined in the methodology. Important similarities and difference in the dynamical structures of the intensifying and decaying composites are observed and are summed up as follows:

- At t=-12, a stronger precursor trough is found over the Great Lakes in intensifying cases (Figure 2) as compared to the decaying cases (Figure 3).

- The tilt and geographical proximity of the precursor trough to the tropical cyclone are crucial; in particular, the trough has a noticeable positive tilt in the intensifying composite, as well as being physically closer to the tropical cyclone than in the decaying cases. These findings suggest that the "lean" and proximity of the trough to the cyclone are just as important as intensity.

- The baroclinic zone that sets up between the tropical cyclone and upstream trough is much more meridional in the intensifying composite (Figure 4) as opposed to more zonal in the decaying composite (Figure 5).

- The magnitude of the scale increase of the tropical cyclone is much larger in the intensifying composite (Figure 6) than is observed in the decaying storms (Figure 7).

- The downstream ridge is more amplified in the intensifying cases following the interaction of the upstream trough and the tropical cyclone. This is primarily due to latent heat release as a result of heavy precipitation and is more easily observed in the Potential Vorticity composites found later in this section.

Potential Vorticity (PV) composites are very useful in ET studies because of the conservative property of PV in an adiabatic frictionless environment (Hoskins et al. 1985; Morgan and Nielsen-Gammon 1998). In other words, areas of intense diabatic heating and ridge enhancement due to latent heat release from heavy precipitation are easily spotted on a PV map, represented as areas of non-conservative PV. In addition, the PV composites in the study (following the logic of Atallah and Bosart (2004)) allow one to observe the interaction of the low-level (tropical) and mid-level (trough) systems on one map. Thus, all PV composite maps are comprised of 200-300 mb PV (warm colors) and 850-700 mb relative vorticity (cool colors) with winds at both the upper (white) and lower (black) levels overlayed. Important conclusions about dynamic structures in the PV composites are summed up as follows:

- As seen in the quasigeostrophic composites, the upstream trough is stronger, more positively tilted and closer to the tropical cyclone in the intensifying composite (Figure 8) than in the decaying composite (Figure 9) at t=-12 hrs.

- Prior to interaction and transition (i.e. at t=-12), the tropical cyclone is actually more intense in the decaying composite (Figure 9) than in the intensifying (Figure 8). This result is similar to that found by Atallah (personal communication) and is possibly due to the storm's position directly in a large-scale ridge environment, which is a prime condition for strengthening for purely tropical cyclones.

- At t=0, while the decaying storms (Figure 11) do interact with the baroclinic zone, the intensifying composite (Figure 10) shows the tropical cyclone interaction with the upstream *trough*, within the baroclinic zone. This suggests that it is the proximity and tilt of the trough, not the strength of the mid-latitude baroclinic zone, that is the primary difference between the intensifying and decaying cases.

- The downstream ridge progressively becomes more amplified from t=-12 to t=12 in the intensifying cases, unlike in the decaying composite. At t=12, the intensifying composite (Figure 12) shows a dramatic ridge impingement on the upstream trough to the northwest of the transitioning cyclone. The enhancement of the ridge (and thus non-conservation of PV) is more than likely due to latent heat release from heavy precipitation associated with the intensifying systems. No likewise westward ridge impingement is seen in the decaying composite (Figure 13).

4. Precipitation Distributions

After comparing the dynamic structures of both the intensifying and decaying composite cases, one can subsequently perform a precipitation distribution analysis using the 3-hourly accumulated precipitation field from the NARR. Atallah and Bosart (2004) performed a precipitation distribution analysis by examining whether the predominant area of precipitation in a storm during and after transition was left-of-center (LOC), right-of-center (ROC), or along track. The NARR 3-hourly precipitation field is presented here for the storms with the greatest absolute vorticity increase and decrease in 12 hours, Luis (1995) and Isabel (2003), respectively.

In September 1995, Hurricane Luis underwent an extremely powerful ET into a 956 mb extratropical low near Newfoundland. In a span of nine hours during this transition, the main area of precipitation rotated cyclonically around the surface low pressure, going from a distinct ROC distribution on

9/11/95@1200 UTC (Figure 14) to a clear LOC distribution by 2100 UTC (Figure 15) on the same day. This cyclonic rotation of the precipitation distribution was found to be the case in all intensifying storms within the composite and can be related to the wrapping around of the area of warm air advection (WAA) as the storm deepens explosively. In turn, the heavy LOC precipitation that results from an explosive storm releases latent heat which helps to enable the westward impinging of the downstream ridge, as discussed in section 3.

Hurricane Isabel struck the North Carolina coast in September 2003 and at the time was considered a major threat to be a 'repeat' of Hazel over Southern Ontario as it moved northward and underwent ET. Hazel (1954) (Palmn 1958; Anthes 1990; Weese 2003) is perhaps the most infamous flooding event in the recent history Eastern Canada, devastating Toronto and Southern Ontario following an ET over the Mid-Atlantic region. However, such an event never occurred with Isabel, largely due to a lack of interaction with a slower moving than expected mid-latitude trough to the west. Consequently, the NARR precipitation analysis depicts the rainfall distribution of a rapidly decaying Isabel, which was nearly completely dissipated by friction in less than twelve hours, given the lack of a reinforcing mid-latitude feature. At 0600 UTC (Figure 16) on 9/19/03, the main area of precipitation is in the northwest quadrant of Isabel, or LOC. As Isabel rapidly weakens by 1800 UTC (Figure 17), however, the predominant rainfall area is to the east-southeast of the weak low pressure center. Consequently, the precipitation distribution has rotated *anticyclonically* in this extreme decaying case, in contrast to that which occurred during the transition of Luis. Similar results (i.e. the anticyclonic rotation) are found for other cases within the decaying composite.

5. Acknowledgements

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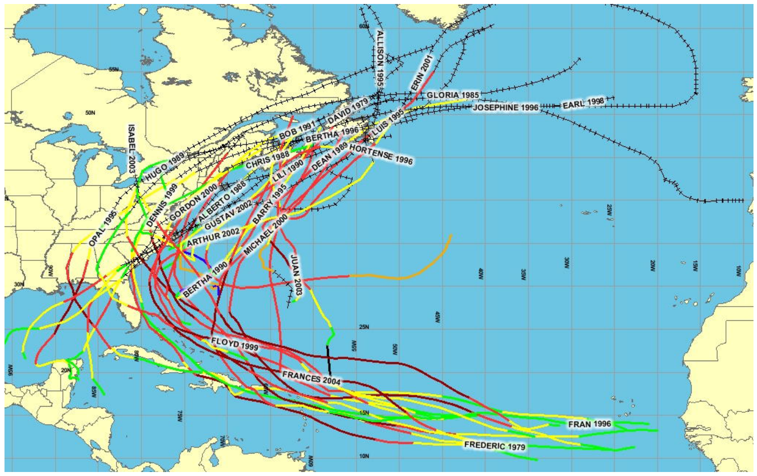

Figure 1: All 32 storm tracks (1979-2004)

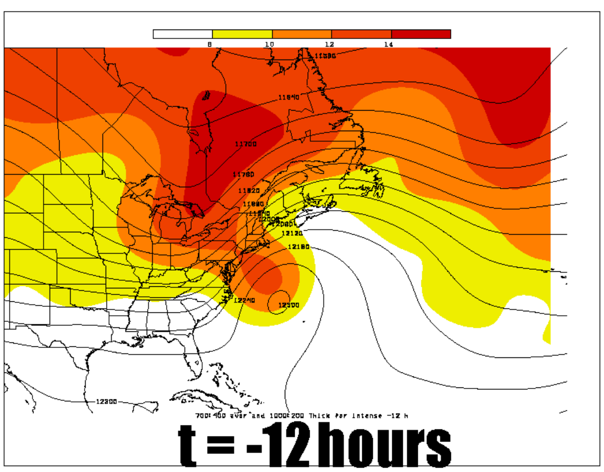

Figure 2: Intensifying quasigeostrophic composite at t=-12 hrs

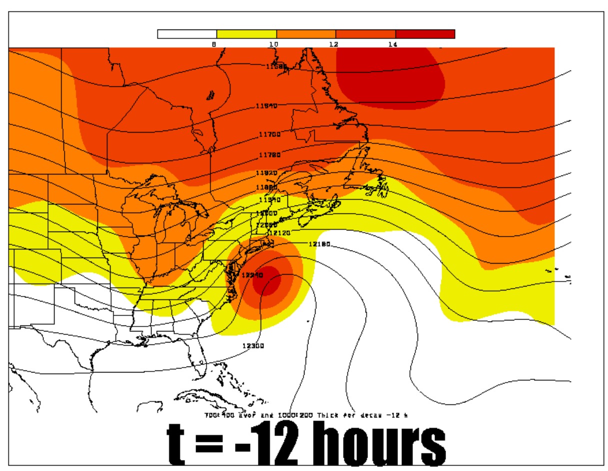

Figure 3: Decaying quasigeostrophic composite at t=-12 hrs

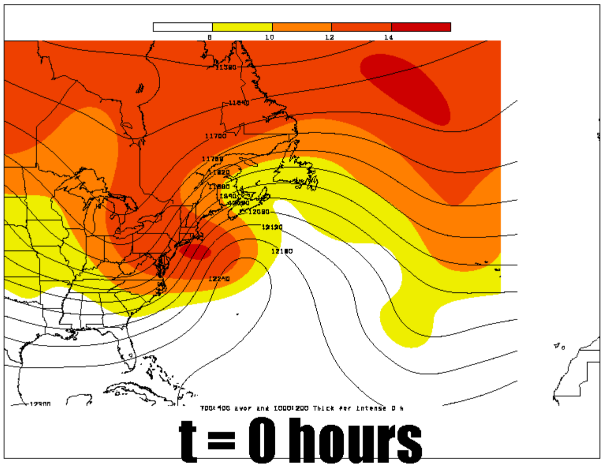

Figure 4: Intensifying quasigeostrophic composite at t=0 hrs

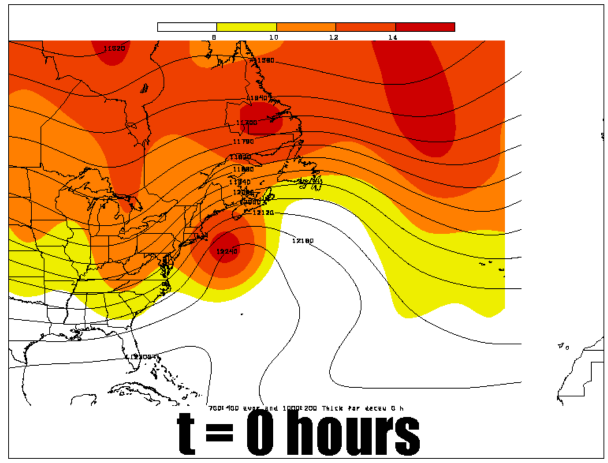

Figure 5: Decaying quasigeostrophic composite at t=0 hrs

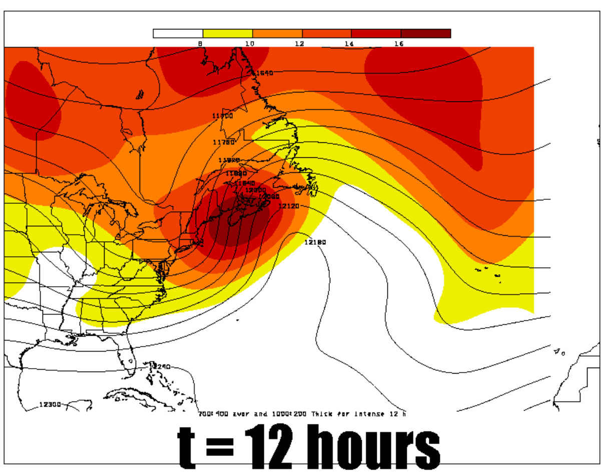

Figure 6: Intensifying quasigeostrophic composite at t=12 hrs

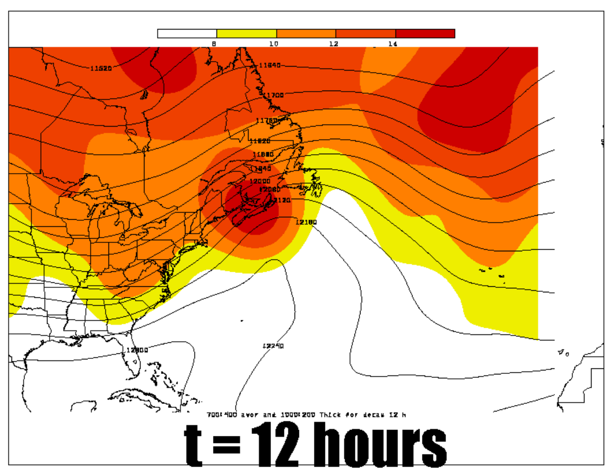

Figure 7: Decaying quasigeostrophic composite at t=12 hrs

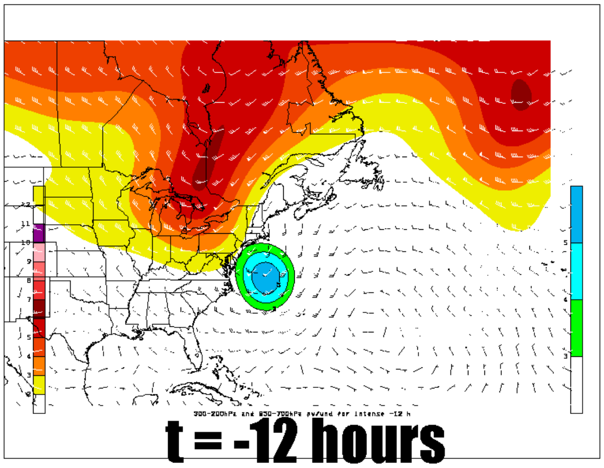

Figure 8: Intensifying PV composite at t=-12 hrs

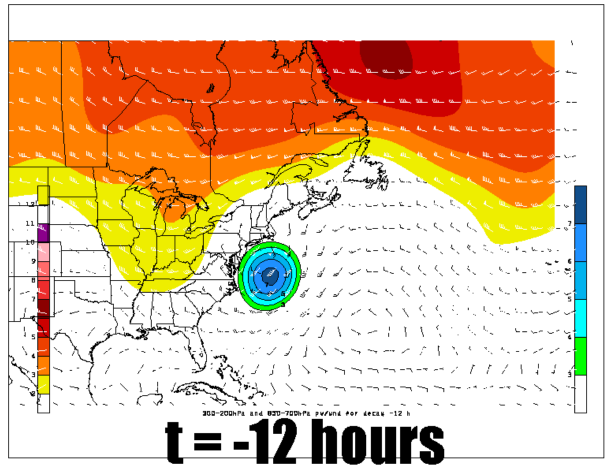

Figure 9: Decaying PV composite at t=-12 hrs

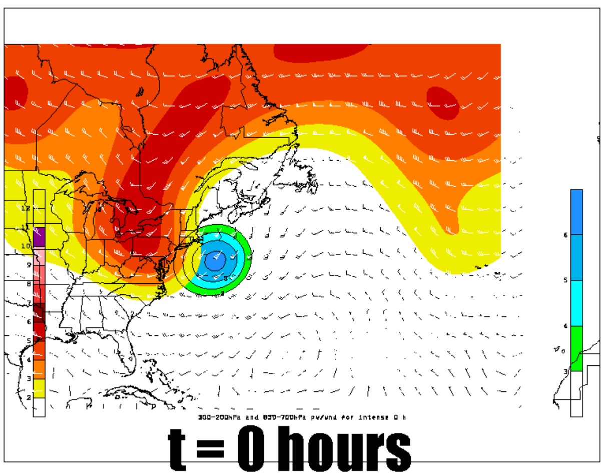

Figure 10: Intensifying PV composite at t=0 hrs

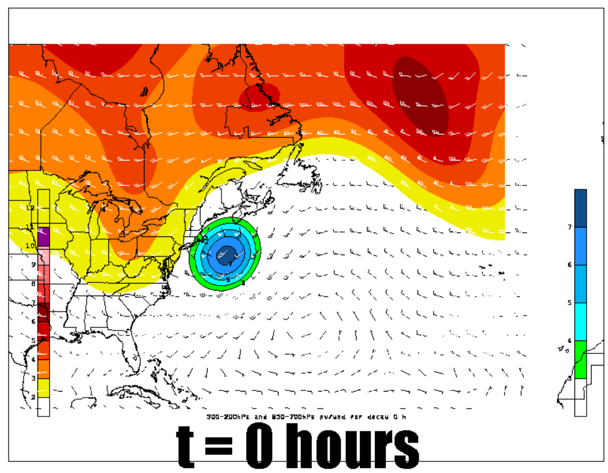

Figure 11: Decaying PV composite at t=0 hrs

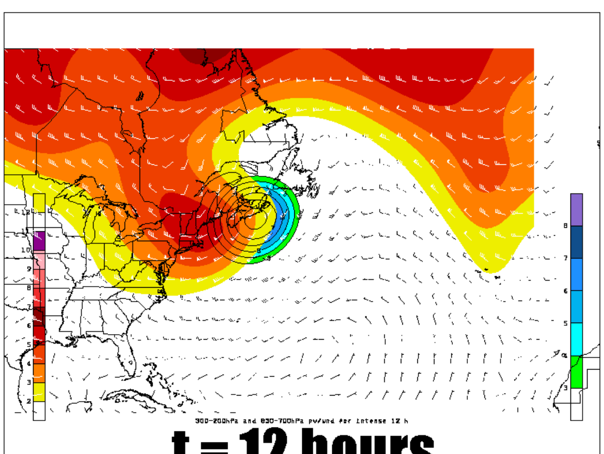

Figure 12: Intensifying PV composite at t=12 hrs

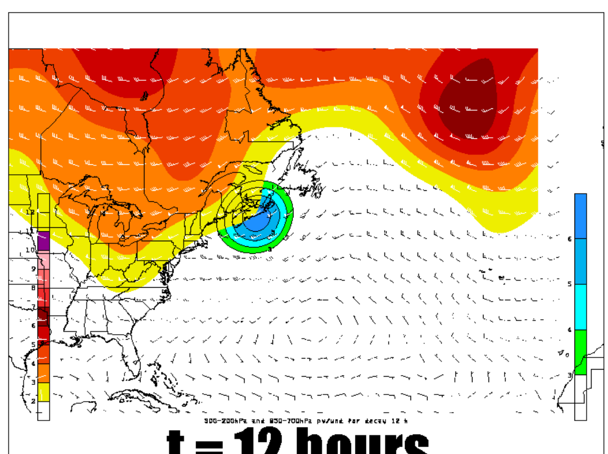

Figure 13: Decaying PV composite at t=12 hrs

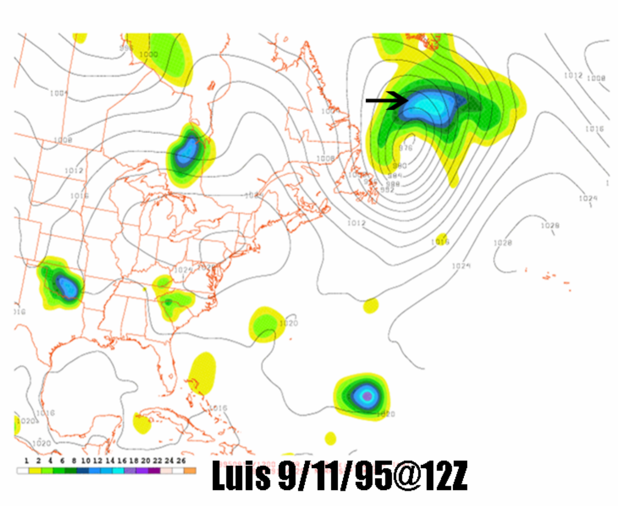

Figure 14: NARR 3-hourly accumulated precipitation (shaded); Sea Level Pressure (contoured)

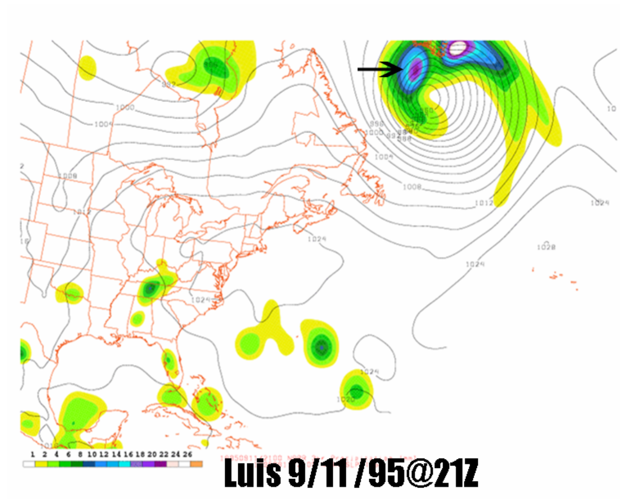

Figure 15: NARR 3-hourly accumulated precipitation (shaded); Sea Level Pressure (contoured)

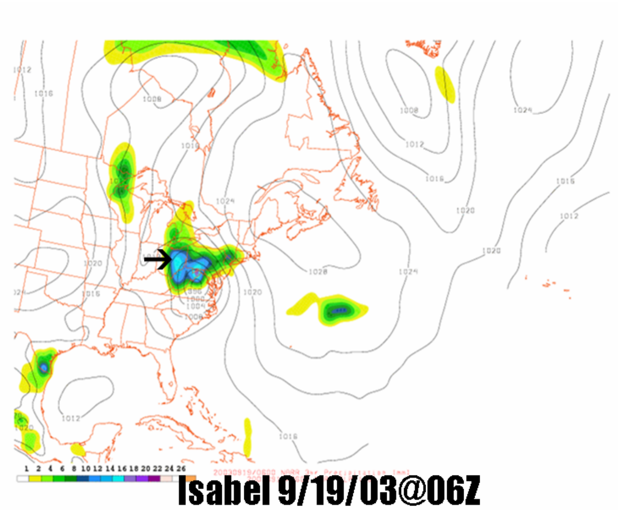

Figure 16: NARR 3-hourly accumulated precipitation (shaded); Sea Level Pressure (contoured)

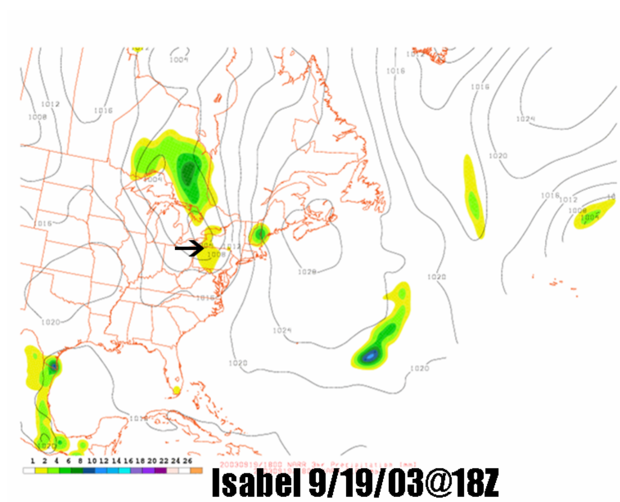

Figure 17: NARR 3-hourly accumulated precipitation (shaded); Sea Level Pressure (contoured)