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THE OVERLAND REINTENSIFICATION OF TROPICAL STORM DANNY (1997)

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1. INTRODUCTION

Conventional wisdom suggests that a tropical cyclone (TC) can only develop while over water with a relatively deep surface layer of at least 26˚C. This warm water, in conjunction with the relatively cooler and drier air above the ocean surface, provides the energy for the TC's development. TCs which move over land weaken due to the removal of this energy source and due to a spin-down of the TC vorticity because of enhanced frictional effects. TCs moving over cooler water in higher latitudes and TCs moving over land often undergo a process called extratropical transition (ET hereafter). Forty-six percent of TCs in the Atlantic basin undergo ET (Evans and Hart 2002). After becoming extratropical, these storms occasionally intensify.

Tropical Storm (TS) Danny (1997) intensified inland, while over North Carolina. Based on the preceding statements, the expected explanation for Danny's reintensification would be that Danny was either undergoing ET, or already an extratropical system, and was therefore strengthening through baroclinic processes in the presence of increased friction and a lack of a warm water surface. However, the hypothesis proposed in this paper is that Danny intensified as a *tropical system while over land* through mechanisms traditionally associated with extratropical intensification.

This presentation will provide an overview of the life cycle of Hurricane Danny through reintensification and diagnose that reintensification using observations, analyses, and model output. A brief synoptic overview is provided in section 2. In section 3, a diagnosis of Danny's reintensification as a TC while overland is given. A summary and outline for future work can be found in section 4.

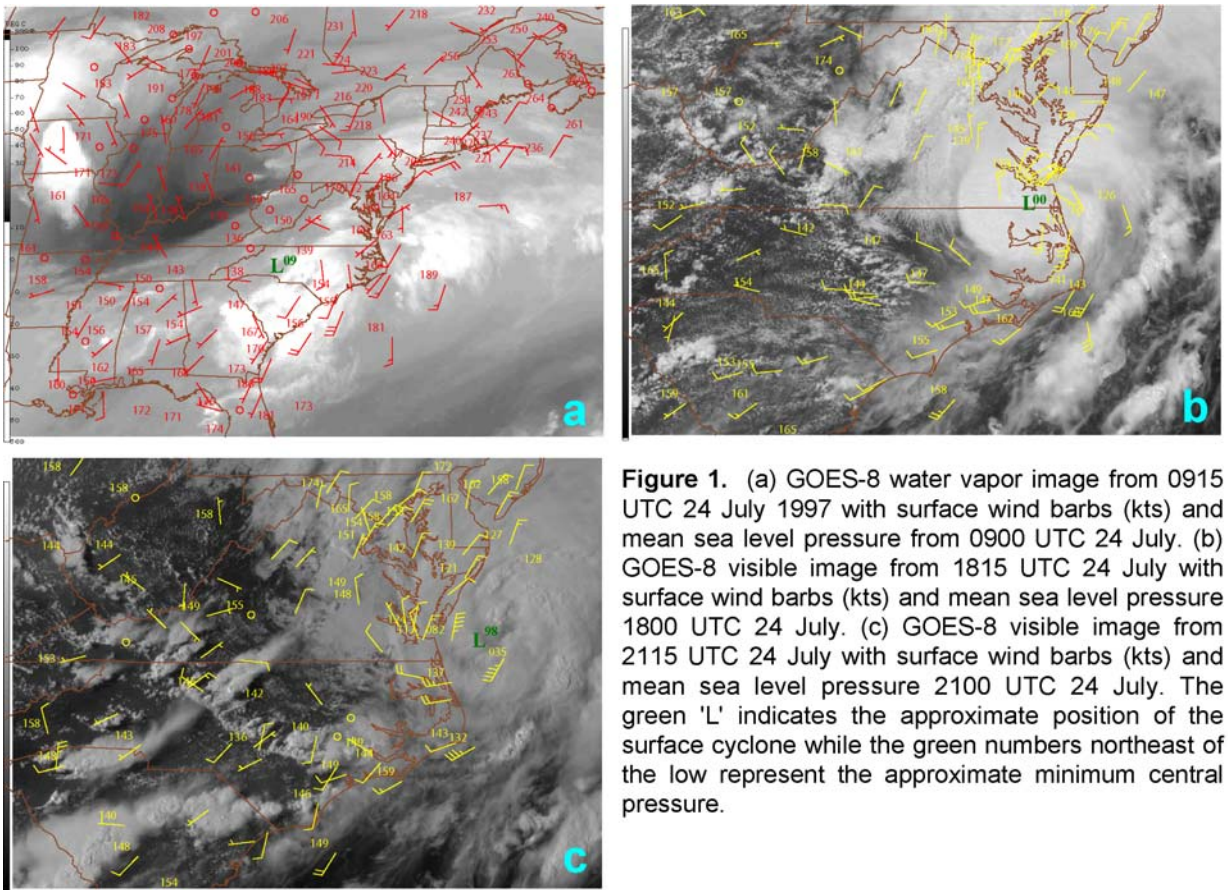

Figure 1. (a) GOES-8 water vapor image from 0915 UTC 24 July 1997 with surface wind barbs (kts) and mean sea level pressure from 0900 UTC 24 July. (b) GOES-8 visible image from 1815 UTC 24 July with surface wind barbs (kts) and mean sea level pressure 1800 UTC 24 July. (c) GOES-8 visible image from 2115 UTC 24 July with surface wind barbs (kts) and mean sea level pressure 2100 UTC 24 July. The green 'L' indicates the approximate position of the surface cyclone while the green numbers northeast of the low represent the approximate minimum central pressure.

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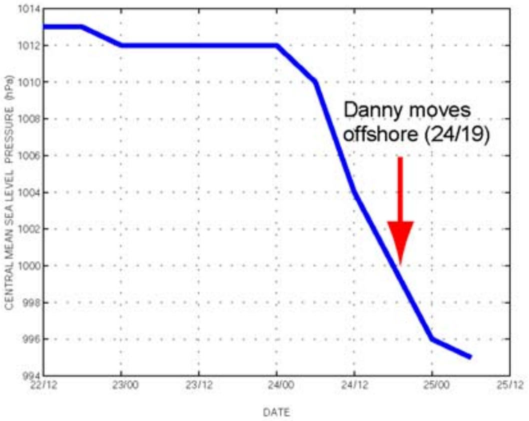

Figure 2. Mean sea level pressure as a function of time (source NHC storm summary)

2. SYNOPTIC OVERVIEW

Danny originated from an area of convection which drifted southward over the warm waters of the Gulf of Mexico and slowly organized into a surface cyclone. By 1200 UTC 16 July (16/12), the system had organized into a tropical depression and was centered 125 nautical miles south of Louisiana. The system gradually strengthened as it moved slowly northeastward and was classified a hurricane at 18/06. Shortly thereafter Danny passed over the southeastern tip of Louisiana and back into the Gulf of Mexico south of Mobile Bay. At this point Danny slowed even further and nearly stalled until making its final landfall midday 19 July as a minimal hurricane with a minimum central pressure of 984 hPa. The extremely slow movement caused torrential rainfall totals. During landfall, rainfall rates of greater than 10 cmh^{-1} were estimated from Doppler radar for nine consecutive hours in the western eyewall (Blackwell 2000). The NHC notes that rainfall totals over southeastern Alabama were as high as one meter.

Continuing its slow northeastward movement, Danny drifted for several days across Alabama and Georgia as a minimal tropical depression while maintaining a well-defined radar presentation. By 24/09, Danny was moving east-northeastward through North Carolina (Fig. 1a) near the beginning of its intensification phase after crossing the Appalachian mountains. At this time, an upper level trough was approaching Danny from the west, as evidenced by the darker colors in the water vapor image. Surface observations and visible satellite imagery at about at 24/18 (Fig. 1b) indicate that Danny's surface circulation and cloud presentation had undergone marked organization just prior to moving offshore. In fact it was at 24/18 that NHC upgraded Danny to tropical storm status. Surface reports from southeastern Virginia and eastern North Carolina indicated an extensive area of moderate to heavy rain, with thunderstorms reported near the cyclone center. The visible satellite imagery for this time was suggestive of deep convection underneath an expansive cirrus shield over southeastern Virginia and northeastern North Carolina (Fig. 1b).

As TS Danny exited the coast along the North Carolina/Virginia border around 24/19, Elizabeth City, North Carolina reported sustained winds of 42 knots with gusts of 55 knots, while two hours later sustained winds of 51 knots with gusts to 61 knots were reported at Chesapeake Light C-MAN station. While over land, between 24/00 and 24/18, the minimum central pressure of Danny decreased 12 hPa to 1000 hPa, (Fig. 2). TS Danny continued to intensify, as noted by the stronger wind observations and lower minimum central pressure at 24/21 (Fig. 1c) while moving further offshore.

3. DIAGNOSIS OF REINTENSIFICATION

In this section, the results of a diagnosis of the reintensification of Danny during the period 24/09-24/18 is presented using archived operational National Centers for Environmental Prediction (NCEP) Eta model output and forecasts available from the National Center for Atmospheric Research Data Support Section as data set ds609.2.

In order to support the hypothesis that Danny intensified as a tropical system while over land, it is first necessary to show that Danny was indeed a tropical system at the time of intensification. To begin to classify this, the definition of "tropical air" proposed by Bosart

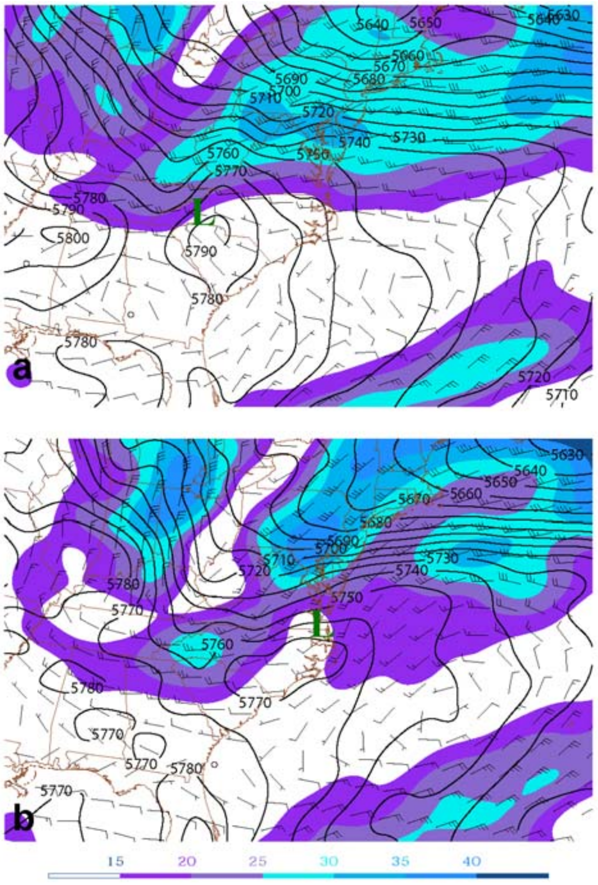

Figure 3. 250 hPa isotachs (fill, ms^{-1}), wind barbs (ms^{-1}), 500-1000 hPa thickness (interval 10 m), and approximate surface cyclone position for (a) 0900 UTC 24 July and (b) 1800 UTC 24 July.

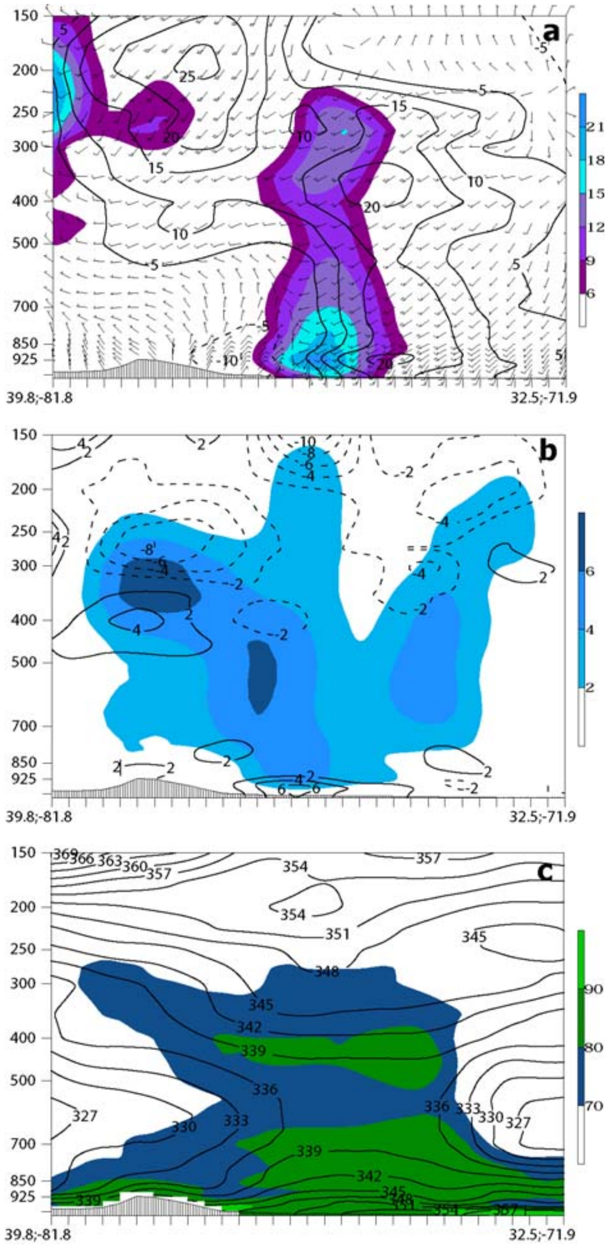

Figure 4. Cross section from 1800 UTC 24 July of (a) relative vorticity (fill, 10^{-5} s^{-1}), winds normal to cross section (interval 5 ms^{-1}), and analyzed wind barbs (ms^{-1}); (b) upward vertical motion (fill, 10^{-6} mbs^{-1}) and convergence (positive (negative) values solid (dashed) line, 10^{-5} s^{-1}); (c) relative humidty (fill) and equivalent potential termperature (interval 3 K).

and Lackmann (1995; hereafter BL95) will be used to show that Danny existed in a tropical environment during reintensification. According to BL95, these characteristics include: 500 hPa wind speeds of less than 15 ms^{-1}, 500 hPa temperatures approximately -4˚C, and a 500-1000 hPa thickness of approximately 5780 m. Although not shown, values of 500 hPa winds above Danny are roughly 10 ms^{-1} and 500 hPa temperatures are between -5˚C and -4˚C throughout the intensification period. At 24/09, the 500-1000 hPa thickness above Danny (Fig. 3a) is about 5790 m, while at 24/18 (Fig. 3b) this value is approximately 5770 m. Furthermore, a relative warm anomaly as indicated by the 500-1000 hPa thicknesses exists above Danny from 24/09 to 24/18, which is indicative of a warm core system. Therefore, it has been established that Danny existed in a tropical environment throughout its reintensification period, and was likely a tropical entity during this reintensification, although this will be more rigorously shown shortly.

Throughout the time period from 24/09 to 24/18 (defined as the period of intensification in this study), an upper trough (noted in Fig. 1a) approached Danny from the west. One important feature of this trough in relation to Danny is that it moves approximately in step with Danny during the reintensification period. This trough would be classified as a “weak” trough by Ritchie and Elsberry (2001) based on the magnitude of the 500 hPa winds associated with the trough. Even weak troughs have the potential to induce an intensification of a surface cyclone given the right conditions, as shown by Ritchie and Elsberry (2001) and BL95. Downstream and associated with this trough is a jet streak (Fig. 3). Of significance is the relative position of Danny in relation to the right jet entrance region. This region effectively follows Danny during the reintensification period. Both the positive vorticity advection (PVA, not shown) of the approaching upper trough as well as the position of the jet appear favorable for the deepening of Danny through vortex tube stretching.

A northwest to southeast cross section taken across the cyclone center at 24/18, normal to the direction of movement, shows a vorticity maximum indicative of a warm core, tropical system in that it has a nearly vertical appearance with the vorticity decreasing with height (Fig. 4a). Furthermore, no significant wind shear is present above the cyclone. The entrance to the jet streak to the north of Danny, as noted on Fig. 3b, is evident at the upper left of Fig. 4a. Figure 4b shows a divergence maximum associated with this entrance region. The effect of this divergence, in combination with the convergence maximum collocated with the surface cyclone below 900 hPa, is to produce locally strong ascent over the cyclone center, generating intense vortex tube stretching, and thus intensifying the cyclone[1]. While it is evident from the satellite observations (Fig. 1b) and surface reports (not shown) that vigorous convection is occurring at 24/18, it should be noted that the analyses being used likely underrepresent the magnitude of the upward vertical motion, and thus the intensity of the concomitant vortex tube stretching.

An accompanying aide to intensification is a result of latent heat release. Figure 4c depicts a classic “tree-trunk” structure in the equivalent potential temperature (θ_e) typical of tropical systems. The atmosphere is characterized by convective instability between the surface and 500 hPa. The zone between 450 hPa and

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[1] The vertical motion shown in this cross section was diagnosed using the kinematic method with an O’Brien correction.

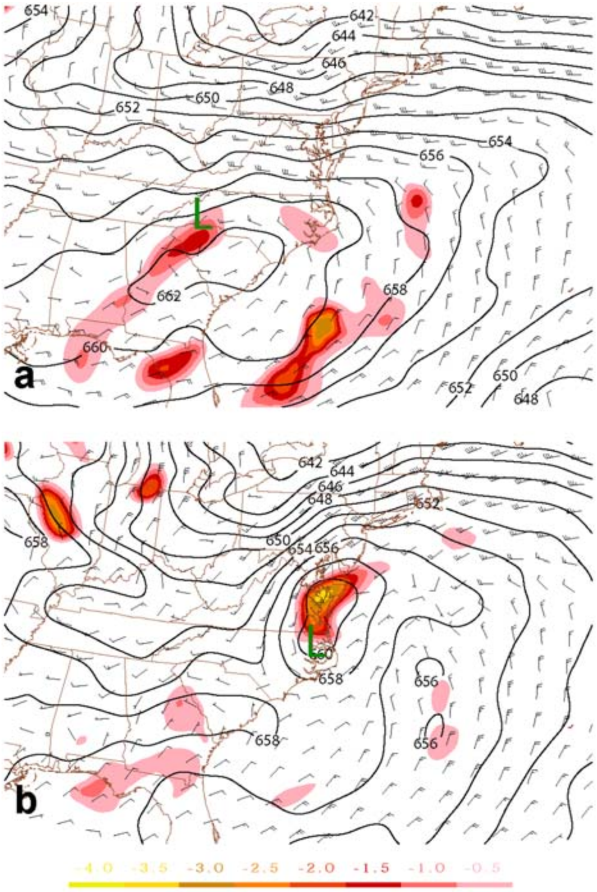

Figure 5. 354-360K negative PV (fill, PVU), 200-500 hPa thickness (interval 2 dam), 200-500 hPa layer difference wind (kts), and approximate location of surface cyclone for (a) 0900 UTC 24 July and (b) 1800 UTC 24 July.

750 hPa of nearly constant θ_e is suggestive of an atmosphere having recently experienced (or currently experiencing) moist convection. Such a moist-neutral environment would be conducive for intense upward vertical motions. Furthermore, intense upward vertical motion in the presence of saturated or nearly saturated conditions will produce large amounts of latent heat. Not only can the presence of convection be inferred from Fig. 4, but it is known to be occurring as seen on Fig. 1b. We note that given the evidence for on-going convection, the analysis is deficient in its depiction of relative humidity.

The effect of latent heat release is to erode the potential vorticity (PV) directly above the layer of maximum heating, which has two effects. First, it acts to create and/or intensify the horizontal PV gradient along the periphery of this upper level anticyclone, consequently increasing the magnitude of the observed winds. Second, it produces an upper level anticyclone above the surface cyclone, creating an upper tropospheric, low-shear environment. To diagnose any effect this had on the surface cyclone, PV was analyzed in the isentropic layer 354-360K at the beginning and end of the defined intensification period. For reference, this layer would be centered approximately at 150 hPa above the surface cyclone at 24/18. Figure 5a shows a small area of negative PV to the south of Danny, which is likely a result of the convection to its southeast as evident on Fig. 1a. However, by 24/18, a very strong localized negative PV anomaly is located above and to the north of the surface cyclone as seen on Fig. 5b. The creation of this negative PV is a direct result of the convection alluded to previously. The dramatic increase in negative PV ahead of the upper trough greatly increases the horizontal PV gradient, acting to intensify the jet, which in turn can contribute to greater divergence over Danny, thus leading to intensification. This effect can be seen by a comparison of Fig. 3a and 3b. Notice that not only does the intensity of the jet increase, but the along flow speed change increases between 24/09 and 24/18, both of which would be conducive for increased divergence above the surface cyclone.

An alternative, though dynamically complimentary view of the role of latent heating and jet intensification focuses on the convective outflow: the convective outflow of high θ_e, if properly phased with the right jet entrance region, will produce an increase in tropopause height adjacent to the jet streak (note the existence of an elevated tropopause in Fig. 4c), thereby intensifying the jet streak (Klein et al. 2002). This is an example of self-development, since the storm's own outflow intensifies the jet and creates a more favorable divergence pattern for more uplift and convection and therefore more outflow, etc.

Another result of the creation of an area of negative PV above the surface cyclone is a reduction in the wind shear above the surface cyclone. This is evident by comparing Fig. 5a and 5b. The upper level wind shear above the surface cyclone relaxes from 20 kts to about 5 kts from 24/09 to 24/18. Furthermore, Fig. 5 shows that the position of the upper level anticyclone, based on the thickness fields, moves from several hundred kilometers southeast of the cyclone at 24/09 to directly over the surface cyclone by 24/18. Again, this acts to create a low-shear environment above the surface cyclone conducive for intensification. Additionally, the production of negative PV allows for the development of inertial instability above the cyclone, which would act to sustain convection by further providing a method of evacuating mass at the top of the convection.

A final contributor to Danny's reintensification is related to the Appalachian Mountains of which the tallest peaks are located in western and southwestern North Carolina. The cyclone center at 24/09 is located on the eastern fringe of the Appalachian Mountains after having previously passed over the southern portion of the mountain range. Associated with the movement away from higher elevations will be vortex tube stretching and a corresponding spin-up in cyclonic vorticity.

4. SUMMARY AND FUTURE WORK

Tropical Storm Danny's reintensification while over land is an example of many factors, traditionally viewed favorable for extratropical cyclogenesis, coming together at once. Many of the factors: PVA, favorable trough and jet locations, and vortex tube stretching due to orography, produce conditions favorable for the development of cyclonic vorticity at the surface. Essentially that is the most important aspect of the physical mechanisms previously described. The surrounding environment and storm structure dictate whether the development will be one of tropical or extratropical nature. The reintensification of Danny shares many similarities to that of Hurricane David (1979) as analyzed by BL95 - both existed in a tropical environment and the cyclones at the onset of reintensification both possessed tropical characteristics. The essential ingredients for David's rapid cyclonic spinup were identified by BL95 as low-level convergence and broad, nearly moist adiabatic ascent in the presence of cyclonic vorticity. This is a scenario identical to that of Danny. Also, as with David, Danny exhibited self-development (i.e., the "David Effect"). Given our understanding of David's behavior, and given the similarities between David and Danny it is not surprising that Danny developed in the manner it did. The only reason it may even be considered a surprise is that an event such as this occurs so rarely due to the infrequency of all of the correct factors combining at once.

Future work will require a dynamically consistent, high resolution in space and time data set derived from either or both analyses that are more faithful to the observations or a numerical simulation which accurately captures the observed evolution of Danny.

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Acknowledgements

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