Note: a set of figures accompanies this discussion. They are in the file jm1.ppt

7. Discussion

The factual aspects of the development of the pre-hurricane Danny disturbance from tropical depression to hurricane stage seem fairly straightforward. Moderate vertical wind shear from the west and northwest occurred throughout the period, and repeated episodes of downshear convection occurred. With time they became both more intense (as measured by lightning flash frequency) and closer to the center. Early on 17 July a downshear cell developed that had more lightning in two hours than had occurred the entire previous day. Within 6 hours of that outbreak it was clear that a tropical storm circulation had developed more than 100 km downshear left of the original tropical depression. A second even more intense cell then developed downshear of the newly developed tropical storm. In three hours this cell produced more lightning than had occurred (within 100 km of the center) in all previous outbreaks in the storm. Back-of-the-envelope arguments suggested that 1×10^{-3} s^{-1} vorticity could easily have been generated within this cell in three hours. Although no direct evidence of spinup was available due to the lack of reconnaissance flights during this time, considerable indirect evidence supported its presence. The reformation of the center identified in real time occurred at the location of the most intense downshear cell. The center then moved in a small cyclonic loop, as would be expected if the small dominant vortex interacted with a larger, less intense tropical storm vortex. Evolution of cloud and lightning asymmetries and analyzed vorticity fields resembled those of an idealized simulation of Enagonio and Montgomery (2001), in which the small intense downshear vortex became dominant and absorbed the other. Thereafter, no dramatic lightning outbreaks occurred, and the single, much more nearly symmetric vortex intensified to hurricane strength.

a. Role of vertical wind shear and midlevel moistening

Without question, the manner in which the storm formed was directly associated with the formation of downshear convective cells. The vortex intensified on the 15th and 16th despite highly asymmetric convection. The mechanisms of Montgomery and Enagonio (1998; see also Möller and Montgomery, 2000), in which vortex Rossby waves redistribute convectively-generated asymmetric vorticity to the mean vortex, are likely to be relevant during this stage. Later intensification occurred by apparently new vortex development downshear on two separate occasions. Because the downshear vortices became much more intense than their parent vortex, the subsequent interactions resembled those shown by Guinn and Schubert (1993; their Figure 10) and Enagonio and Montgomery (2001; their Figure 12). Examination of Figure 8 suggests that the intense downshear cells on the 17th grew near the radius of maximum winds of the previous vortex, where vorticity would likely be largest and spinup of a new vortex would be most intense. It is conceivable that the formation would have been delayed, or not have occurred at all, had the local forcing associated with vertical wind shear not been present. By this argument, *moderate* vertical wind at early stages of storms might be favorable for subsequent development. This is supported by the results of Bracken and Bosart (2000), who found that western Atlantic tropical depressions formed in environments with a composite vertical wind shear of 10 m s^{-1}.

Bister and Emanuel (1997) and Raymond et al. (1998) have argued that midlevel moistening and stabilization must occur before hurricanes can develop, because otherwise cold downdrafts interrupt the intensification process. Raymond et al. (1998) noted that as pre-depression disturbances developed into depressions and storms, the level of maximum upward motion became lower and lower, which they attributed to a reduction with time of cold downdrafts . In the current study, it is possible that repeated downshear convection over 48 hours moistened the column sufficiently that when the first strong downshear cell erupted on 17 July, cold downdrafts were weak and ineffective. By this reasoning, the further moistening and stabilization resulting from the first downshear cell made the next cell even less affected by downdrafts, and thus able to grow by a local feedback between convergence and convection. A key aspect of the lack of downdrafts is that convection can lead directly to spinup at the *surface*. In the presence of midlevel vorticity generation associated with the stratiform remains of convective systems, the process might not be so immediate (e.g., Harr et al. 1996; Ritchie and Holland 1997), and downdrafts could inhibit the growth of a surface circulation.

b. Relevance of WISHE

Smith (2003) showed results from an axisymmetric hurricane boundary layer model in which convective downdrafts were not present. These assumptions resemble those made in the WISHE hypothesis, and Smith argued that the distribution of winds and surface fluxes in the model supported the WISHE hypothesis. Smith found a distinct radial variation of θ_e at hurricane stage: maximum θ_e occurred at the center; θ_e increased inward faster than linearly in the vicinity of the eye wall; and θ_e increased inward slowly outside the core. The gradients of θ_e in this study will be compared to those of Smith to evaluate the possible role of WISHE in the development of Hurricane Danny.

On the 16th the evidence from Fig 11a suggests that no WISHE-like process was occurring. No maximum in θ_e occurred at or near the RMW, and no inward increase was present. On the 17th it was argued that intense downshear cells created additional vortices downshear, and the interaction of these vortices initially created a complex disorganized mix of high vorticity and high θ_e over a broad region. Figure 11b shows that θ_e was elevated from before, but no WISHE signature was present. Some high values existed at almost all radii over the inner 100 km. In contrast, late on the 17th and early on the 18th, 10-15 hours after the vortex interactions began, Figure 11c shows that a WISHE-like profile was developing. This is attributed to the development of a single, quasi-symmetric dominant vortex on the ocean surface. Lightning also decreased to nearly zero during this time of vortex interactions. The conditions were thus met for WISHE to be satisfied. Figure 11d shows that during the first full flight at hurricane intensity, a dramatic difference in θ_e distribution occurred: low values almost vanished from the storm core, and high values almost vanished from outside the storm core. The result was a monotonic, and increasingly rapid, inward increase of θ_e with radius, similar to that attributed to the WISHE process by Smith (2003). It is argued that the latter stages of the development of Hurricane Danny fit the WISHE hypothesis.

c. Stages of hurricane development

Zehr (1992) proposed a two-stage development in hurricanes. Each was distinguished by intense convective outbreaks, the first creating a depression and the second leading eventually to hurricane intensity. Emanuel (1993) provided a physical basis for these arguments. He argued for triggering/gestation/ignition/intensification: triggering denoted the first convective outbreak; gestation stood for the quiescent period after convective downdrafts had stabilized the boundary layer; ignition represented a renewal of convection once the boundary layer had recovered, and intensification followed via the WISHE mechanism. Davis and Bosart (2001) proposed a somewhat different three stage development for a particular storm (Diana, 1984). The first phase involved axisymmetrization of convectively-generated potential vorticity anomalies, following the reasoning of Montgomery and Enagonio (1998); the second involved a 12-hour period of moistening, but little deepening; and the third stage involved rapid development. It would seem that another proposal for stages of hurricane development is unneeded. Nevertheless, one will be given here that is perhaps somewhat broader than those proposed above.

The hypothesized phases of hurricane development are simply two: pre-WISHE and WISHE. In the pre-WISHE stage, little direct coupling exists between convection and ocean fluxes as postulated in WISHE: storms are highly asymmetric, multiple interacting vortices may be present, vertical shear may often exceed 5 m s^{-1}, and transient highly buoyant convection occurs. Due to the infinite variety of pre-existing disturbance structure, vertical wind shear profiles, convective outbreaks, and multiple mesovortices, all storms are likely to differ in their details during the pre-WISHE stage. Owing to the chaotic nature of this stage, predictability is low and only probabilistic forecasts can be made, similar to the arguments of Ooyama (1982), Simpson et al. (1997), and Davis and Bosart (2001). The work of Montgomery and Enagonio (1998), Möller and Montgomery (2000) and related papers may be most relevant for describing the dynamical aspects of this stage. The thermodynamic aspects remain somewhat obscure.

In storms that develop, the result of the pre-WISHE stage is a quasi-symmetric tropical storm with much less buoyant convection. It is hypothesized that the axisymmetry arises as a natural outcome of the interaction of two or more vortices, and the reduction in convective instability arises from mixing by previous highly buoyant convection. These processes were seen in Danny by the development of a single dominant vortex and the sharp drop in lightning frequency late on 17 July. The disturbance then meets the requirements of the known finite-amplitude WISHE instability, and development follows unless the underlying surface changes to a less favorable state, or vertical wind shear increases dramatically. It is argued that, unlike the pre-WISHE stage, in the WISHE stage all storms behave similarly.

Such a classification allows for the possibility that the pre-WISHE stage can last for one day or several days, and may never attain rapid development. Whether the conceptual classification proposed here can benefit operations is open to question, because the transition from pre-WISHE to WISHE can be very rapid, and important processes like midlevel moistening and mesovortex interactions are very difficult to observe. It is apparent that a great deal more work is needed to understand and predict the early stages of tropical cyclogenesis.