2A.3 CYCLONE TYPE ANALYSIS AND FORECASTING: A NEED TO RE-VISIT THE ISSUE

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1. INTRODUCTION

Increased understanding of the nature of synoptic-scale atmospheric cyclones has occurred during the last 60 years. Conceptual models (CMs) of the early and mid-20th century had two types – the baroclinically-driven frontal cyclone (FC) and the convectively-driven tropical cyclone (TC), with the knowledge that a TC could become frontal (Richter and DiLoreto 1956). Clark and French (1958) and Spiegler (1972) recognized the existence of cyclones with mixed characteristics, while Colón (1956) noted that FCs could become TCs. Subsequently, Hebert (1973) developed the subtropical cyclone (STC) classification. Still later work by Shapiro and Keyser (1990) showed the complex structures of strong FCs, including a warm core formed by a seclusion process. Since a warm core is also a characteristic of a TC, this discovery added a new layer of complexity to the existing CMs.

Based on this and observations of several cyclones that did not readily fit earlier CMs ("hybrid" cyclones), Beven (1997) created a two-dimensional CM that included the thermal structure and the frontal nature (Fig. 1). Hart (2003) formalized this into the Cyclone Phase Space (CPS), in which numerical weather prediction (NWP) analyses and forecasts were used to determine current and future cyclone types. This was an important advance for forecasters. However, ensuing technological advances (e. g., Advanced Microwave Sounding Unit (AMSU) data (Demuth et al 2004, Herndon and Velden 2004)) have increased the forecaster's ability to observe cyclone complexity.

The increased observations have spawned new questions regarding cyclone classification. The first concerns the strength, organization, and longevity of the associated convection – how much and how long is enough to consider a system a TC or STC? Second, how can horizontal length scales, particularly the radius of maximum wind (RMW), help differentiate cyclone types? Third, concerning cyclone thermal structure, how much/deep of a warm core is required for an STC or TC, and how much low-level baroclinicity is required to call a cyclone frontal? Finally, how well defined does a cyclonic circulation have to be before it is considered a cyclone? These issues have caused sharp arguments among National Hurricane Center (NHC) forecasters in both real-time and post-event analysis. This suggests there is need for additional understanding of cyclone processes and new diagnostic tools to aid cyclone classification.

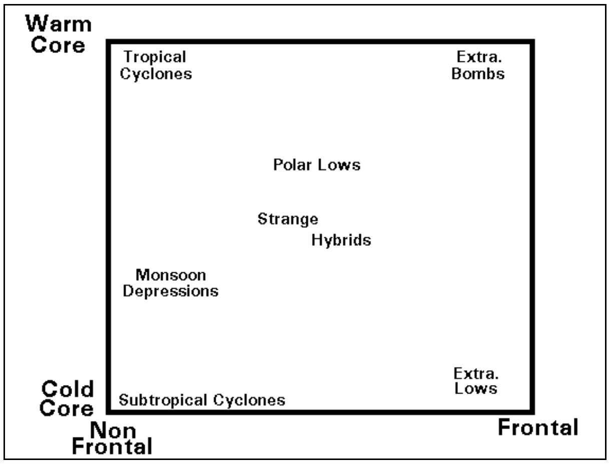

Figure 1. Two-dimensional cyclone classification model from Beven (1997).

The cyclone-type issue has great operational and climatological importance. First, the continuum nature of types contrasts sharply to the dichotomous nature of the operational warning and response process. TCs and FCs usually have different warning and response processes even for cyclones of similar strengths. Thus, operational decisions on cyclone classification have significant repercussions on how people respond. Second, for purposes of TC climatology, the handling of hybrid cyclones at tropical cyclone warning centers varies geographically and temporally. This impacts TC/STC climatology and the evaluation of how climate change affects TCs.

2. NHC DEFINITIONS

The National Weather Service (NWS) definitions of TCs and STCs underlie the following discussions. These are (from the to-be-updated NHC Glossary):

Tropical Cyclone: A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper troposphere. In this they differ from extratropical cyclones, which derive their energy from horizontal temperature contrasts in the atmosphere (baroclinic effects).

Subtropical cyclone (significantly revised for 2012): A non-frontal low-pressure system that has characteristics of both tropical and extratropical cyclones. Like tropical cyclones, they are non-frontal, synoptic-scale cyclones that originate over tropical or subtropical waters, and

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have a closed surface wind circulation about a well-defined center. In addition, they have organized moderate to deep convection, but lack a central dense overcast. Unlike tropical cyclones, subtropical cyclones derive a significant proportion of their energy from baroclinic sources, and are generally cold-core in the upper troposphere, often being associated with an upper-level low or trough. In comparison to tropical cyclones, these systems generally have a radius of maximum winds occurring relatively far from the center (usually greater than 60 n mi), and generally have a less symmetric wind field and distribution of convection.

Extratropical cyclone: A cyclone of any intensity for which the primary energy source is baroclinic, that is, results from the temperature contrast between warm and cold air masses.

The definition of closed circulation refers to the earth-relative wind, and non-frontal means no surface or low-level baroclinic zones.

3. CYCLONE CLASSIFICATION ISSUES

3.1 Convective issues

A standout feature of TCs is organized deep central convection, which often occurs in the form of bands or rings. The convection releases the energy available to the TC in the form of atmospheric heating, resulting in the characteristic TC structures. However, there are two convection-related issues in cyclone classification.

First, how much convection – spatially and temporally – is needed to deliver the necessary driving energy? Dvorak (1984) somewhat quantified both of these in his TC intensity estimation technique, and while the spatial parameters work well the temporal parameters are less satisfactory. Weaker systems (including developing pre-TC disturbances) tend to have discontinuous convection. Does this signal a system is not yet a TC, or does it signal that TC energy processes can work during convection-free periods? Convection is an area where the spatial and temporal synoptic-scale requirement of the TC definition could be problematic – the convection powering the synoptic-scale cyclone is of mesoscale or smaller nature both spatially and temporally. Also, TC-like features can occur on scales significantly smaller/shorter than the synoptic.

Tropical Storm Jose of 2011 highlights this issue (Beven 2012). The pre-Jose vortex formed on 25 August from a mesoscale convective system. The convection dissipated by early on 26 August, and for most of the next 24-36 hours the system lacked sufficient convection spatially and temporally to perform TC intensity estimates (Fig. 2). However, sparse scatterometer and surface observations suggest it intensified to a tropical storm by 1200 UTC 27 August. There seem to be two possibilities: 1. Did the relatively small amount of convection intensify the cyclone? or 2. Was the cyclone actually of tropical-storm strength when the original convective system dissipated? There are not enough data to answer these questions.

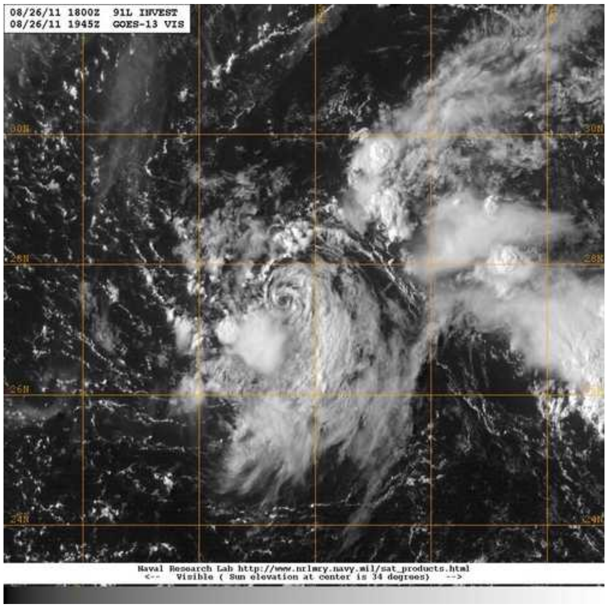

Figure 2. GOES-13 visible image of the pre-Jose vortex at 1945 UTC 26 August 2011. Image courtesy of the Naval Research Laboratory, Monterey, CA.

The second issue is that organized central convection is not unique to a TC. The cases in section 4 show how it also occurs in FCs.

3.2 Cyclone Scale Issues

As a rule, TCs tend to be smaller in overall size than FCs. TCs also tend to have their strongest winds much closer to the center than FCs or STCs (Spiegler 1972, Hebert 1973). Indeed, at peak intensity Hurricane Wilma (2005) had an eye diameter of 5 km or less with a correspondingly very small RMW (Beven et al 2008).

However, small RMWs are not unique to TCs. Spiegler (1972) recognized that FCs could have their RMWs at a variety of distances, while Hebert (1973) defined a type of STC with a small horizontal size and RMW. In addition, Neiman et al (1993) documented a relatively small 75 km RMW in the strongly baroclinic “Ultrabomb” storm in January 1989. Complicating matters further, some TCs can develop large RMWs. Lander (1999) documented a Western Pacific typhoon with an outer eyewall diameter of 370 km and a correspondingly large RMW.

The overlap in RMW size between cyclone types is problematic. Additional research is needed to determine the relationship between the RMW size and cyclone energetics, and how to use those relationships in a cyclone classification system.

3.3 Thermal Structure Issues

TCs are also characterized by a well-defined convectively-driven warm core that is strongest in the upper troposphere (Hawkins and Imbembo 1976). As with convection and RMW size, a tropospheric warm core is not unique to a TC. Shapiro and Keyser (1990) documented the warm core seclusion in powerful FCs, and those systems can also form upper-level warm cores through tropopause folding. In addition, Douglas (1992) documented upper-level warm cores associated with monsoon depressions of the North Indian Ocean. The latter issue factored into NHC debates regarding Tropical Storm Nicole in 2010 (Blake 2011), a system in the Caribbean that somewhat resembled a monsoon depression. Based on this, how a warm core develops and persists is important in cyclone classification.

AMSU thermal data from recent STCs subtropical cyclones (e. g., Otto of 2010 (Cangialosi 2011)) suggest they have a complex thermal structure that is not well represented in the operational definitions. Additional data and research on this topic might help refine the definitions and the associated decision making.

A particularly vexing issue for NHC forecasters involves the decay of frontal structures during the tropical transition process (TT) when a FC becomes an STC or TC (Davis and Bosart 2004). NHC definitions require a potential STC or TC to be non-frontal, and this determination is normally difficult (even with the CPS) due to a lack of inner core low-level thermal data. Complicating matters is that FCs can develop organized central convection and TC-type inner wind cores before the frontal structure dissipates. How small does the low-level temperature gradient need to get before a FC becomes an STC or TC? Does it need to be near zero, or does it need only to decrease to the point where convective processes dominate? It is a rare hurricane season in which NHC forecasters do not deal with this problem, examples of which are shown in section 4.

3.4. Circulation Quality Issues

The NHC definitions state STCs and TCs must have a "closed surface wind circulation about a well-defined center". There are two types of situations in which this is an issue.

The first type is when a vorticity center is embedded in strong background flow. One example is a fast-moving Atlantic tropical wave, where strong easterly winds (possibly tropical-storm force or 17-32 ms^{-1}) exist north of the center while light winds (<5 ms^{-1}) exist to the south. Even if the winds suggested a closed circulation exists, there are questions of whether the data is representative and whether the circulation is representative on the synoptic scale spatially and temporally. (A special issue here is the use of aircraft flight-level winds, where a closed circulation does not automatically mean a closed surface circulation.) In practice, westerly winds of <5 ms^{-1} do not usually qualify as a closed circulation in the tropical wave situation.

Gruskin (2010a) documented a northward-moving system in June 2006 with a similar issue. This made landfall along the North Carolina coast with observed tropical-storm-force winds. Even after extensive post-analysis using aircraft and Doppler radar data, it is unclear whether a closed circulation developed prior to landfall, and it was not counted as a TC. The debate on this system (Beven et al. 2010, Gruskin 2010b) illustrates the difficulties of determining if a circulation exists based on potentially unrepresentative data.

A second situation is when a cyclone has a closed circulation, but the center definition is degraded due to large RMW size, elongation, re-formation, or short-lived small-scale vorticity centers rotating inside the larger cyclonic envelope. This issue affected NHC decision making in May 2009. A persistent low pressure area developed central convection near the northern coast of the Gulf of Mexico (Fig. 3), with the center disappearing under the convective overcast for a time – a sign of TC characteristics. In addition, tropical-storm-force winds occurred along the Alabama coast. The system was not declared a TC in real time, and in post-event debates the NHC could not reach a consensus on whether to classify it as a TC. One of (several) reasons was doubts about how well-defined the center was spatially – due to an elongated circulation – and temporally – due to possible convectively-induced reformation. Regardless of the nature, the impact resembled that of a short-lived convective event, and in the real-time warning process it was handled as such.

The NHC is internally testing a method that may help quantify the center definition issue. It is unclear how the fast flow issue could be refined in a consistent and quantifiable fashion.

4. CASE STUDIES

This section examines selected cyclones that further highlight the issues presented in section 3. In

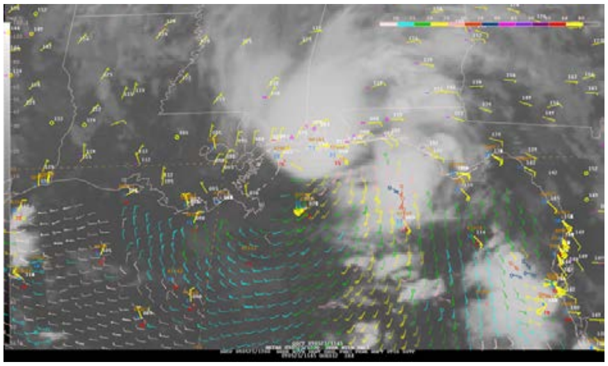

Figure 3. GOES-12 infrared image of the Gulf low at 1145 UTC 23 May 2009 along with QuikScat data (small barbs) and surface observations (station plots).

addition, during the past decade the NHC has monitored notable similar systems, including: 1. A cyclone with storm-force (25-32 ms^{-1}) near the coast of the Carolinas in September 2008, 2. A deep-layer cyclone with central convection and an eye near the Azores in June 2009, and 3. A deep-layer cyclone with persistent convection near the Canary Islands in February 2010.

4.1 *The Super Bowl Sunday Storm, 21-25 January 1989*

Cyclogenesis occurred over the Gulf of Mexico on 21 January due to the interaction of a mid/upper-level trough with a strong surface baroclinic zone (temperatures of <10^{o}C to the north and >20^{o}C to the south). As this FC moved east-northeastward, secondary cyclogenesis occurred along the east coast of Florida on 22 January. The second FC intensified rapidly into the predominant cyclone as it moved east-northeastward into the Atlantic. Convection formed near the center of the low late on 22 January (Fig. 4) and persisted into 25 January. Surface observations (not shown) suggest this accompanied the formation of a relatively small inner wind core with 20-30 ms^{-1} winds. The cyclone was absorbed by another baroclinic system over the North Atlantic later on 25 January.

Surface observations indicate this system maintained strong frontal zones during its life, and therefore it cannot be counted as a TC or STC by the NWS definitions. From a warning viewpoint, it was handled as a non-tropical low. However, the central convection and inner wind core suggest that it acquired at least some characteristics of a TC, and the Storm Data publication (National Climatic Data Center 1989) called it a “gale center which exhibited subtropical storm characteristics”. One possibility of classifying this cyclone would be as a “frontal hybrid” – a cyclone where organized convection and/or other TC characteristics were present, yet one retained too much frontal character to be counted as an STC or TC.

The cyclone is unofficially called the Super Bowl Sunday Storm (hereafter SBSS) since the Super Bowl game was held in Miami, Florida on 22 January.

4.2 The New Jersey Coast Storm, 7 – 13 September 2009

A frontal trough near the coast of South Carolina spawned a low pressure area on 7 September. The low moved northeastward and merged with a southward-moving baroclinic zone on 9 September. The resulting FC then came under the influence of an upper-level cyclone to the west. This caused an unclimatological northwestward motion which brought it onshore over the coasts of New Jersey and Delaware on 11 September – a track more characteristic of a TC. As the cyclone approached the coast, it developed gale-force winds accompanied by bands of convection near the center and evidence of anticyclonic outflow in the northern semicircle (Fig. 5). In addition, surface data from NOAA buoy 44009 during the center passage indicated a warm core. After landfall, the low weakened as it meandered near the coast of mid-Atlantic states, and it dissipated just off the New Jersey coast on 13 September.

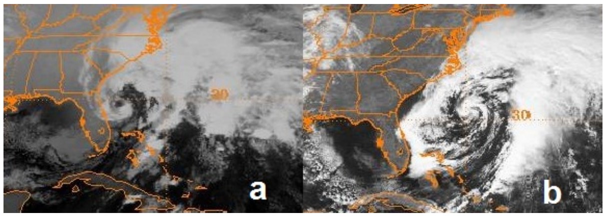

Figure 4. GOES-7 (a) infrared image at 0300 UTC 23 January and (b) visible image at 1800 UTC 23 January 1989 showing the Super Bowl Sunday storm. Images courtesy of the National Climatic Data Center.

The combination of organized convection, warm core, and anticyclonic outflow on one side, suggested the cyclone acquired some STC or TC characteristics. However, surface analyses and rawinsonde data (Fig. 6) showed distinct temperature gradients were present across the system both at the surface and aloft. Surface data and satellite imagery suggest that the warm core resulted from a seclusion process and not from the cyclone’s convection. Based on this, it is likely that this system was also a “frontal hybrid”-type cyclone.

It is interesting to compare this storm (hereafter NJCS) with the SBSS. Both cyclones maintained

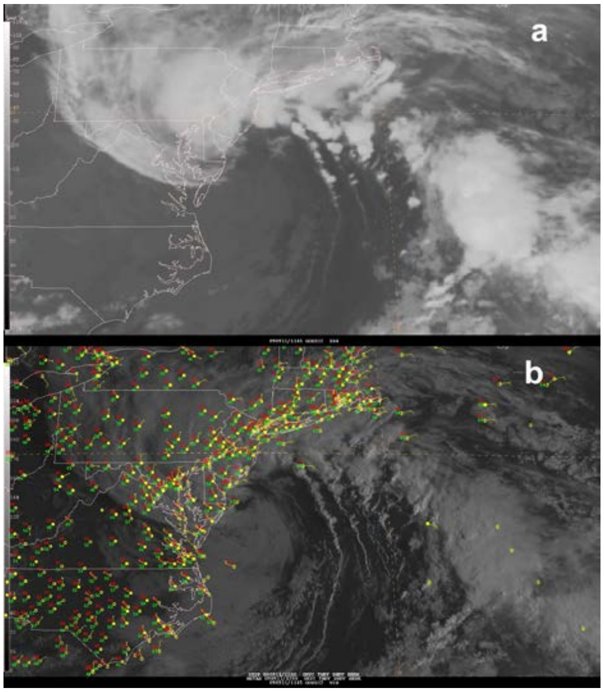

Figure 5. GOES-12 (a) infrared and (b) visible imagery of the New Jersey Coast storm at 1145 UTC 11 September 2009. Surface observations are plotted on the visible image.

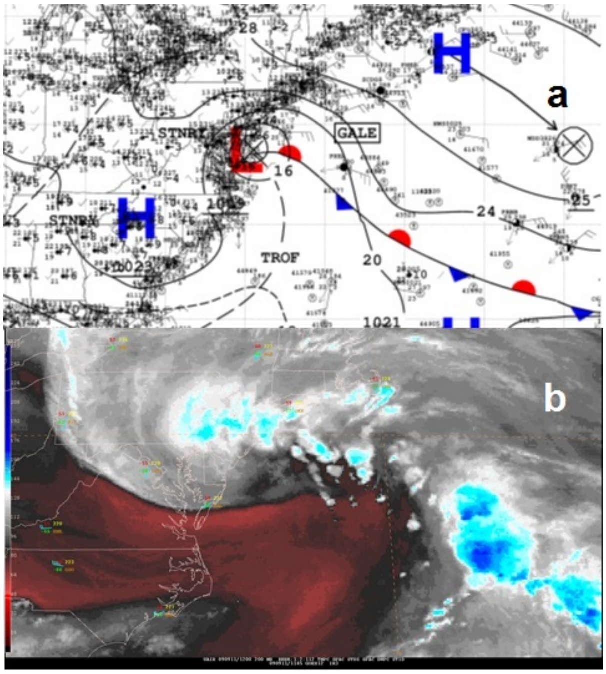

Figure 6. (a) NWS surface analysis for 1200 UTC 11 September 2009, and (b) GOES-12 water vapor imagery for 1145 UTC 11 September 2009 overlaid with 200 hPa rawinsonde data for 1200 UTC.

significant baroclinic zones at peak intensity. The SBSS featured a stronger baroclinic zone (as expected for January) compared to the September NJCS. Both storms developed organized convection, with that of the SBSS more concentrated near the center. A major contrast is in the synoptic evolution. The SBSS represented classic baroclinic cyclogenesis from a wave in the westerlies. The NJCS had a more complex evolution involving two baroclinic zones and a cut-off upper-level low. The latter part of the evolution resembled the TT process of Davis and Bosart (2004). However, there was insufficient time and too much cold air to allow this system to become an STC or TC.

The NJCS was handled operationally as a non-tropical gale. While the NHC monitored the development of the cyclone as it approached the coast, it was never given more than a “low” (<30%) chance of development in NHC Tropical Weather Outlooks.

4.3 The Brevard County, Florida Storm, 9-12 October 2011

A broad trough of low pressure and associated gale-force winds developed over the Bahamas Islands, the Florida Peninsula, and the adjacent western Atlantic on 8 October. This occurred in a weak baroclinic zone on the south side of a large low-level ridge while a large deep-layer low pressure area developed over the eastern Gulf of Mexico. A broad surface low formed over the Straits of Florida by 1200 UTC 9 October. Concentrated convection developed during the next 6 hours in the northern portion of the low, and Doppler radar data showed an associated small but well-defined circulation (Fig. 7). Shortly thereafter, surface observations indicated the development of a small-scale surface low. Maximum sustained (1-min) winds reached at least 26 ms^{-1} with a central pressure of 995-998 hPa around 0000 UTC 10 October. The center of the low made landfall near Cape Canaveral, Florida around 0345 UTC 10 October, accompanied by numerous reports of sustained tropical-storm-force winds and reports of hurricane-force (>32 ms^{-1}) gusts.

After landfall, the low moved west-northwestward across the northern Florida Peninsula. The convection diminished just after landfall. However, a second burst of convection developed after 0600 UTC 10 October, which persisted through about 1400 UTC. The small wind and pressure center was apparent in surface observations until about 1000 UTC. After that time, only a broad low pressure area was evident. The low moved to the Tallahassee-Apalachicola, Florida area later on 10 October, at which time it was first analyzed as having fronts. Subsequently, the low dissipated over northern Florida or southern Georgia early on 12 October as a baroclinic cyclone formed along the Georgia coast.

The nature of this system (hereafter the BCFS) is unclear even after extensive post-analysis. The RMW

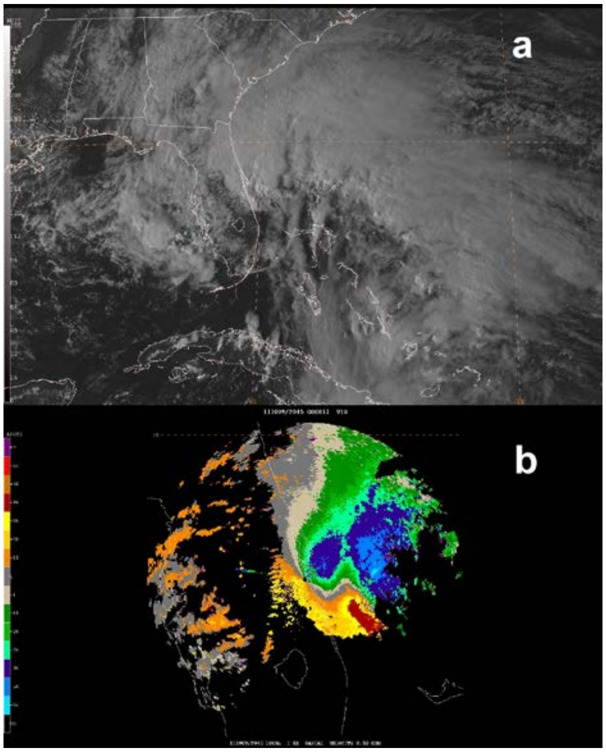

Figure 7. (a) GOES-13 visible image of the Brevard County storm at 2045 UTC 9 October 2011 and (b) coincident Melbourne, Florida WSR-88D base velocity data. Blue/green colors indicate winds blowing toward the radar at the center of the image while orange/red colors indicate winds blowing away from the radar.

was as small as 20 km at landfall, and this combined with the organized central convection suggests TC characteristics. However, the presence of the baroclinic zone and the lack of other TC characteristics argues otherwise. The baroclinic zone and interaction with the upper-level low suggests the possibility the system was an FC. However, surface and rawinsonde data (not shown) indicate only about $3^{o}C$ of temperature gradient between north and south Florida at the surface and 850 hPa, and NWS surface analyses showed no fronts with the system until well after landfall. At the very least, the baroclinic energy available to the BCFS was far less than in the SBSS and the NJCS. In addition, available upper-air data suggests the vortex was confined to the lowest 4 km, with no evidence of the vertical tilting characteristic of a FC.

The synoptic pattern also suggests the possibility the BCFS was an STC, and after landfall it most resembled one in satellite imagery. An STC evaluation is supported by radar wind profile data from the Melbourne WSR-88D (Fig. 8), which show decreasing winds above the boundary layer to 4 km indicative of a low-level warm core. Above this is a layer of increasing southerly/southwesterly flow that eventually becomes southeasterly. This is due to the upper-level low and it is indicative of a cold core aloft. It should be noted that AMSU data (not shown) also indicates a warm core, although at a greater altitude than that suggested by the radar winds. On the other hand, the strength of the convection and the location of the center under the convective overcast argue against the STC designation.

The temporal scale further complicates the classification. The BCFS developed very rapidly over a 10 h period before landfall, and the associated convection occurred primarily in two bursts of several hours duration. It is thus possible the cyclone was some type of mesoscale severe-local-storm event. Arguing against that, however, is that the convective pattern in radar data (not shown) more resembled TC bands than mid-latitude supercells or squall lines. Also, surface observations suggest that the system did not produce strong pools of cold/dry downdraft air characteristic of a severe-local-storm event.

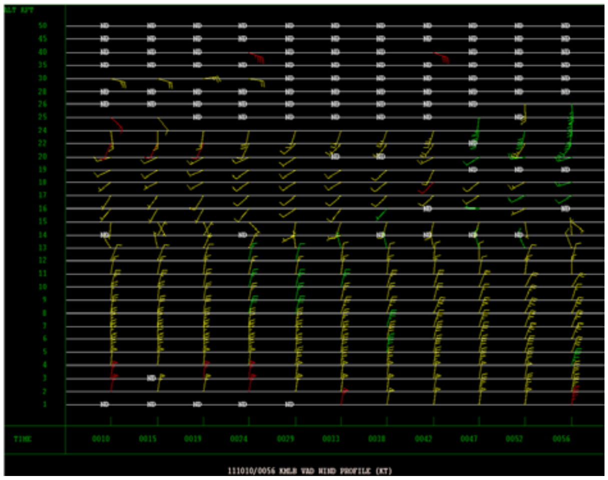

Figure 8. Vertical wind profiles from the Melbourne WSR-88D from 0010-0056 UTC 10 October 2011. Vertical scale at left is in 1000's of ft.

The questions from the BCFS are thus: Did the center and convection exist long enough for the low to be considered an STC or TC? Was this an FC, and was the observed temperature gradient strong enough to be considered frontal? What was the interaction of this system with the upper-level low (and associated surface low) over the Gulf of Mexico? The NHC could not reach a consensus on these questions, and it decided not to classify this system as an STC or TC.

In real time, the NHC, in coordination with the National Weather Service Forecast Office (WFO) in Melbourne, Florida, decided to handle the cyclone as a non-tropical storm center with appropriate local warnings issued by the WFO. However, the impact very much resembled that of a TC.

Interestingly, the NHC data archive has a record of a similar storm near Daytona Beach, Florida on 17-18 October 1965. This system will eventually be examined as part of the Atlantic Hurricane Re-Analysis Project (Landsea et al. 2012)

5. DISCUSSION AND FUTURE DIRECTIONS

The NHC definition of a TC includes a warm core and organized convection requirement, while other known structural features of a TC include a normally small RMW and anticyclonic outflow in the upper levels. The examples shown above, however, suggest that none of these features are unique to TCs! This seriously complicates cyclone classification and the associated warning/ response processes. An increased understanding of these issues would benefit the NHC.

On convective issues, there are two interesting areas for future research. First, how much convection is required spatially? Is the Dvorak Technique (1984) minimum diameter criteria (155 km) good? Or can some TCs survive/thrive on less, as might have happened with Jose? Second, how persistent and continuous does the convection need to be? With the BCFS, the cyclone formed in an almost instantaneous response to the convection. On the other hand, numerous other TCs and disturbances exhibit a much slower response time.

In regards to thermal issues: First, as highlighted by the BCFS, is how strong of an associated baroclinic zone does it take to disqualify a cyclone from being an STC or TC? Second, how can current/future tools better account for both the structure and process involved with a warm core – i. e. differentiating between a seclusion warm core and a diabatic warm core?

Circulation quality issues may not be as good of a possibility for future research as convection and thermal issues, but there is one intriguing question: If a cyclone center is poorly defined due to being large or elongated, is this a sign that TC energy process are not yet the dominant influence on the system?

Cyclone size and scale issues also need additional research to relate cyclone size parameters (particularly the RMW) to cyclone energetics. Is there too much overlap in various cyclone size parameters to use this as a classification parameter? Is there a relationship between the cyclone's vertical depth and horizontal extent that could be used as a classification parameter (Stewart 2011)?

Finally, it is time for a new cyclone classification CM? Synoptic-scale cyclones are driven by baroclinic, diabatic, or barotropic energy sources, and the observed mixed structures are related to multiple sources contributing simultaneously. A potential new classification method could use a three-dimensional system with the three main energy sources as the axes (Fig. 9). Real-time energy budgets would be calculated from NWP analyses and forecast models, and the cyclones would be classified by the relative contribution from each source. (TCs would be most aligned with the diabatic axis, FCs with the baroclinic axis, and monsoon cyclones with the barotropic axis.) This methodology was not possible at the time of Beven (1997). However, increases in computing power, data, and NWP systems since then may make real-time analysis and forecasting of cyclone energetics feasible.

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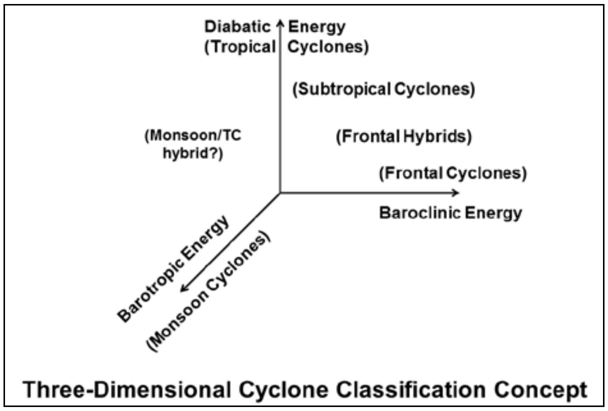

Figure 9. Conceptual model for a three-dimensional cyclone classification system.

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