Tropical Cyclone Formation in Environments with Cool SST and High Wind Shear
over the Northeastern Atlantic Ocean (1975-2005)

THESIS

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Abstract

This work analyzes the environment conditions in which tropical cyclones have formed during the months of October, November, and December in the northeastern Atlantic Ocean. The study period begins in 1975, the year of publication for the Hebert-Poteat and Dvorak techniques for satellite classification of tropical and subtropical systems, respectively. The northeastern Atlantic Ocean is defined as the portion of the Atlantic basin north of 20°N and east of 60°W. Purely subtropical storms were excluded from the study to focus on the conditions for tropical cyclone formation. Genesis was defined as the time in the official HURDAT record when the cyclone 1) had been classified as tropical, and 2) had maximum sustained winds of at least tropical storm force (greater than or equal to 34 kt). NCEP/NCAR Reanalysis data were used for atmospheric variables, and Reynolds SST and NOAA ERSST data were used for sea surface temperatures. Dynamic and thermodynamic parameters were analyzed to determine the environmental conditions during the period prior to genesis. Wind shear (magnitude and spatial orientation), vertical temperature profiles and stability indices were computed on 6-h intervals for the thirty hours prior to genesis. Synoptic geopotential height patterns were analyzed on 12-h intervals for the thirty-six hours prior to genesis.

Seventeen of the twenty tropical cyclones in the study set had identifiable non-tropical precursors. These seventeen were subdivided into non-frontal baroclinic (NFB), frontal-weak (FW), and frontal-strong (FS) types based on the relative strength of the low- and mid-level vorticity maxima thirty hours prior to genesis. The three tropical cyclones with identifiable tropical precursors were observed to have the weakest 500 hPa vorticity maxima, consistent with the tropical wave structure. Sixteen of the seventeen storms from non-tropical precursors developed over sea surface temperatures less than 26.5°C. Local environmental wind shear varied widely among the twenty storms. Large ranges in magnitude and disparate spatial patterns were observed even among types. Wind shear was therefore determined to have secondary importance in the genesis environment. Geopotential height fields also had few discernable patterns within types. Thermodynamic variables showed distinct differences between NFT storms and the non-tropical types. Vertical temperature profiles for NFT systems were consistently warmer at all levels than the non-tropical systems. Thus storms originating from tropical precursors occurred in environments with larger convective available potential energy and higher equilibrium levels relative to those for non-tropical precursors. Static stabilities were lower for the NFT type relative to the baroclinic types when using 300 hPa as the upper level. This combination of cool sea surface temperature, moderate instability, and low equilibrium levels in the pre-genesis environments suggests that tropical cyclones from baroclinic precursors in this region are shallower than typical tropical cyclones, which would reduce the effects of high environmental shear.

Dedication

To my mother, Dr. Jacqueline Kern, who thought it was fantastic that her ten-year-old daughter wanted to go to graduate school in atmospheric science: I would not have accomplished it without your support.

To my advisor, Dr. Jay Hobgood, who always found time to talk about research and/or hurricanes in between meetings, teaching, and more meetings: I could not have a better mentor.

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Chapter 1: Introduction

In a season marked by record-shattering extremes in number and intensity of storms, the end of the 2005 Atlantic hurricane season was no less unusual. While tropical cyclone (TC) activity in the tropics finally ceased by the fourth week of November, three more TCs formed in the eastern Atlantic Ocean, the last of which survived through the first week of January 2006. In addition to the timing, these three systems were unusual in their development and structure. All three (Delta, Epsilon, and Zeta) were initially baroclinic systems and subsequently transformed into tropical systems. Despite the tropical classification by the National Hurricane Center (NHC), all three maintained features more consistent with hybrid or subtropical cyclones for some time after transition. [A fourth TC, Vince, formed in early October from an occluded low and was the first TC on record to strike the Iberian Peninsula.]

These four TCs highlighted an area that usually receives little attention: the eastern Atlantic basin. With the exception of “Cape Verde” long-track hurricanes during August and September over the southern portion of the region, this area is often an afterthought. TCs forming in this region usually remained at sea, never reaching major hurricane intensity. Such late-season TCs normally pose the greatest hazard to shipping. Figure 1 shows the locations of expendable bathythermograph (XBT) data collected during October, November, and December 2009 by ships participating in the Ship of

Opportunity Program (SOOP) managed by the National Oceanographic and Atmospheric Administration's (NOAA) Atmospheric and Oceanographic Marine Laboratory (AOML). Commercial ships collect oceanographic data during normal activities and submit it to AOML. These data points represent a fraction of the shipping traffic over the Atlantic Ocean. Even so, storms forming in and tracking through this area are clearly a threat to maritime activity. Occasionally, a TC initially from this area approached land. Lili (1990, hereafter Lili-90) prompted hurricane watches for the Outer Banks of North Carolina. Lili (1984, hereafter Lili-84) and Olga (2001) tracked southwestward towards the Caribbean, though both dissipated before reaching the islands. Vince was the first TC on record to strike Europe, albeit as a tropical depression.

Such developments over the northeastern Atlantic Ocean are exceptional in that conditions are marginally favorable for TCs at the best of times, and hostile at the worst. Cool sea surface temperatures (SSTs), relatively dry air, and high wind shear are generally not the best of environments for TC development. One question, therefore, is how tropical systems can form in these conditions. Must the baroclinic precursors encounter a favorable environment before they can transition to tropical cyclones, and how localized must it be? Or are the months in which TCs form somehow unique in this region? The overriding question, however, is whether the known necessary conditions for tropical cyclogenesis apply to all tropical cyclones. Perhaps tropical cyclones can form in inhospitable conditions if their sources are non-tropical.

This project began as an observational study of late-season tropical cyclone developments in the northeastern Atlantic basin. As sometimes happens with research, it

has morphed into an examination of TC development over cool SSTs. This is a relatively new direction in TC research: as of publication, the author was unable to find another study focusing specifically on TCs forming over SSTs below 26.5°C. The northeastern Atlantic also presents forecasting challenges due to the prevalence of TC formation from baroclinic sources, which often occur over cool SSTs. Track and intensity guidance models used by NHC to help make forecasts are optimized for systems in the deep tropics. For systems that have some hybrid characteristics, the output can be of limited use, especially for intensity.

The intent of this thesis is to describe the environments in which late-season eastern Atlantic TCs form, and to examine whether conditions significantly change in the 30 hours prior to classification as a TC. Particular attention will be given to the TCs with baroclinic precursors. Not only do they appear to be the most common type of development in this region, but NHC has the most difficulty applying guidance model output to such storms. Knowledge of the dynamic and thermodynamic environments in the hours prior to transition may help to understand the structure of such systems, which in turn may help to improve forecasts of intensity. Several questions will be explored in this study: 1) Was the 2005 quartet of late-season, not-fully-tropical Atlantic cyclones unique? If similar TCs have formed in other years, then: 2) In what environmental conditions do such TCs form, and how do they compare to the known conditions for tropical cyclogenesis in the tropics? 3) Are there any indications that tropical structures are developing? 4) Could the environment be inducing a storm structure that compensates for low ocean temperatures?

To guide this work, a hypothesis of cold-water TC formation has been constructed. Cold-water TCs compensate for low SSTs by developing in environments of anomalously high instability (which increases convection and converts the core to neutral or warm), building to a shallower vertical extent (suggested by the equilibrium levels), and retaining the ability to derive energy from baroclinic sources. This shallow structure also reduces the impact of relatively high environmental wind shear, and potentially helps to explain why guidance forecasts of weakening verify poorly.

This thesis is structured as follows. Chapter 2 is the literature review, discussing relevant research to the current work. Chapter 3, ‘Methods’, details the methodology used to conduct the research. Chapter 4, ‘Results’, describes the results of the research. Chapter 5 ‘Discussion’, summarizes the results and addresses the four questions asked in Chapter 1. Chapter 6, ‘Conclusions and Future Work’, synthesizes the results to present a picture of the environmental conditions for late-season TC formation over the northeastern Atlantic Ocean, and suggest future directions for inquiry. References in this work follow Chapter 6. Appendix A (B) contains all tables (graphics) mentioned in the text.

Chapter 2: Literature Review

2.1 Tropical Cyclones

The eastern Atlantic Ocean is a varied region in terms of timing of developments and the physical characteristics of the resulting TCs. The southern portion is best known as the birthplace of long-lived, powerful hurricanes in late summer and early autumn (the ‘Cape Verde’ long-track storms). The farther north a TC is detected, however, the more likely the storm is to have some non-tropical characteristics. Accordingly, the following discussion of relevant research will be divided into three sections: tropical cyclone research, subtropical cyclone research, and the relatively new field of tropical transition research.

2.1.1 Tropical Cyclone Structure

One of the first sections in any introductory text on TCs is a thorough discussion of TC structure (e.g. Hobgood 2005, Anthes 1982). Thus, this literature review opens with a similar discussion. Certain physical features are observed in TCs regardless of basin. In the low levels, convergent cyclonic flow is associated with an area of low pressure relative to the large-scale environment. Convection in mature TCs is organized into bands, which spiral inward toward the center of the TC. As air is pulled toward the

center, fluxes of latent and internal energy add moisture and energy to the air layer closest to the surface. These fluxes provide fuel for the TC.

A few tens of kilometers from the center, air suddenly turns upward, creating intense convection. This area is called the eyewall; the heaviest rain and highest winds are located here. Inside the eyewall is the eye, which is a small area of light winds and few clouds. Once the rising air hits the stratosphere, it is pushed horizontally outwards, creating divergence aloft. Although the upper-level circulation in the immediate vicinity of the center is cyclonic, conservation of angular momentum requires the cyclonic rotation to decrease rapidly with distance. At about 300 km radius, the circulation becomes anticyclonic. This feature is especially apparent in intense hurricanes with a cirrus canopy over the deeper central convection, since the cirrus shows the direction of movement of the outflow.

Temperature anomalies are a distinctive feature of TCs, and are often used to distinguish TCs from non-tropical cyclones. A TC is warm compared to its environment, especially at the upper levels (300-200 hPa). Positive temperature anomalies are strongest in this layer near the center of the hurricane (hence the designation 'warm-core'). In regions with intense precipitation, usually a few tens of kilometers removed from the center of circulation, temperature anomalies are less positive (more neutral).

2.1.2 Conditions for Tropical Cyclogenesis

Numerous works have tried to specify the conditions necessary and sufficient for tropical cyclone development (e.g. Gray 1968, Anthes 1982). Bosart and Bartlo (1991)

presented the following list of conditions determined to be necessary (but not sufficient) for TC formation: 1) SSTs in excess of 26.5°C, 2) a pre-existing cyclonic disturbance, 3) a sufficiently strong vertical temperature gradient to support deep convection, 4) sufficient midlevel moisture, 5) low vertical wind shear, 6) an environment capable of supporting an upper-level outflow channel.

A TC is essentially a Carnot heat engine that uses water vapor as its energy source. Warmer water provides a greater amount of energy to the engine, and thus a storm is potentially more powerful if over warmer water. Warm water is most critical in the earliest period of development, though it impacts intensity throughout the life cycle. The pre-existing disturbance is somewhat obvious, but this feature is important to distinguish a large area of convection from a developing TC, and to provide an initial source of positive (cyclonic) vorticity. Large lapse rates are necessary to propitiate rising of air parcels to create the most efficient engine pathway. A dry environment leeches moisture from the rising parcels, reducing convection and effectively halting the engine. The secondary (vertical) circulation must be vertically stacked for the engine to work properly. Wind shear can disrupt the secondary circulation structure. An outflow channel is necessary to pump the air rising from the center away from the storm to make room for more rising air, and to create a decrease in surface pressure. All these conditions together are necessary for a TC to develop, but even all of them together are not enough to guarantee TC formation.

2.1.3 Detecting Tropical Cyclogenesis

McBride (1981; M81) and McBride and Zehr (1981) examined the differences in environment and structure of developing and non-developing tropical systems in the northwest Pacific and northwest Atlantic. The authors identified two problems in studying tropical cyclogenesis: sparse data and diversity of incipient tropical cyclones (and which are still problems today). Instead of studying individual systems, the authors made composites of environmental data visualized on cylindrical grids of radius 15° centered on the systems.

There was a strong diurnal variation in the vertical velocity and mass divergence for developing cloud clusters, with larger values in the morning and smaller at night. For stronger systems, the diurnal variation was much less noticeable. Developing cloud clusters also had small temperature anomalies throughout the vertical, whereas hurricanes had strong positive anomalies at the upper levels and smaller negative anomalies near the surface. The developing cloud clusters also had asymmetric (but roughly bimodal with positive peaks at 800 and 600 hPa) moisture anomalies, whereas hurricanes had a single strong positive peak in moisture around 550 hPa.

To compare developing and non-developing systems, M81 calculated the Seasonal Genesis Parameter (SGP), which was first published by Gray (1977, 1979). This complex parameter is defined as

$$SGP = \left[\begin{pmatrix} \text{Vorticity} \\ \text{Parameter} \end{pmatrix} \begin{pmatrix} \text{Coriolis} \\ \text{Parameter} \end{pmatrix} \begin{pmatrix} \text{Vertical} \\ \text{Shear} \\ \text{Parameter} \end{pmatrix} \begin{pmatrix} \text{Ocean} \\ \text{Energy} \\ \text{Parameter} \end{pmatrix} \begin{pmatrix} \text{Moist} \\ \text{Stability} \\ \text{Parameter} \end{pmatrix} \begin{pmatrix} \text{Humidity} \\ \text{Parameter} \end{pmatrix} \right] \quad (1),$$

M81 found that the SGP for a non-developing depression was half the value of a pre-hurricane depression. For a non-developing cloud cluster $SGP = 1$, whereas for a developing cloud cluster $SGP = 12$. The magnitude of the Thermodynamic potential term was nearly indistinguishable for developing and non-developing cases, and the difference in total SGP was almost entirely attributable to the Dynamic potential term (the product of the first three terms in Equation 1). Low-level relative vorticity was the most important parameter.

McBride and Zehr (1981) compared developing and non-developing systems so that the critical features indicating genesis could be determined. The warm core was better defined for developing depressions, while the moisture anomaly was stronger in non-developing depressions. Tangential wind speeds were twice as large for developing depressions as for non-developing depressions, and the difference was noticeable over a large area. Developing and non-developing depressions had spatially similar shear patterns. Patterns were more strongly delineated for the developing depressions, however. The authors suggest the Daily Genesis Potential (DGP), defined as

$$DGP = \zeta_{900hPa} - \zeta_{200hPa} \quad (2),$$

to distinguish developing versus non-developing cloud clusters and depressions. For both types of non-developing precursors, DGP was half the magnitude of the developing equivalents. The qualification is made that the parameter is only valid for purely tropical systems because baroclinic developments from mid-latitude cold-core systems occur in different processes. The most critical finding was that developing disturbances have strong meridional gradients of vertical shear of the zonal wind and strong zonal gradients

of vertical shear of the meridional wind, and that both gradients must persist concurrently for more than one day.

Shear and vorticity compose only part of the environment necessary for genesis. DeMaria et al. (2001) created a parameter that incorporated both dynamic and thermodynamic variables to forecast favorable periods for genesis. This parameter was comprised of three measures of the large-scale environment: 850-200 hPa vertical shear, vertical instability, and midlevel moisture. All were collected as five-day running means. These components represented necessary but insufficient conditions for genesis: if any one of the variables was unfavorable, then genesis was not likely.

DeMaria et al. observed genesis in the tropical Atlantic (defined as the region from 0-20°N and the African Coast to 60°W) to peak around 29 August, with most formations occurring between early August and early October. The genesis parameter (GP) exhibited a similar distribution, partly explaining the strongly peaked distribution of genesis events. GP was also useful for predicting intra- and interseasonal variability. The findings were consistent with the theory that thermodynamic variables control the start of the season and wind shear determines the end of the season.

2.1.4 The Typical Tropical Cyclone Development Process

Hobgood (2005) described the development process of a typical tropical cyclone. Tropical waves, which are troughs of lower pressure accompanied by organized convection in the easterly flow over the tropical Atlantic, are the source for most Atlantic tropical cyclones. The convergent surface air flow associated with the tropical wave

causes water to evaporate from the ocean into the air, and the air warms. At the center of the disturbance the air is forced to rise, which leads to cooling and saturation. Then the water vapor begins to condense into clouds, releasing latent energy and warming the upper core of the system. Air is now pumped away from the center at the upper levels, and if this divergence exceeds the surface convergence, the surface pressure falls. Surface winds increase, followed by increases in the latent heat fluxes, convergence, and low-level vorticity. In the absence of unfavorable conditions, particularly strong wind shear and excessively dry air, the process becomes self-supporting. Eventually the circulation and convection organize sufficiently to form a tropical cyclone.

2.1.5 Tropical Cyclogenesis in a Sheared Environment

After decades of believing wind shear was detrimental to developing TCs, researchers realized that wind shear is necessary in some cases. Bracken and Bosart (2000) created storm-centered composites of synoptic-scale flow during tropical cyclogenesis events. Developing depressions experienced moderate (average 10 m s^{-1}) vertical wind shear. Bracken and Bosart proposed that shear is necessary to force synoptic-scale ascent and to organize the resulting convection. They also suggested that the process of tropical cyclogenesis differs among the Atlantic sub-basins.

A case study by Molinari et al. (2004) supported these results. Hurricane Danny (1997) formed in a moderate ($5\text{-}11 \text{ m s}^{-1}$) shear regime. Convective outbreaks associated with the incipient storm occurred downshear of the primary vortex. The convective cells gradually shifted closer to the center as the convection deepened. A second vortex

developed in the last outbreak. The shear created additional downshear cyclonic vorticity, which accelerated the growth of the secondary vortex. Eventually the second vortex absorbed the primary vortex, and became Danny. Without vertical wind shear the vortex would have remained weak and upshear from the convection, inhibiting tropical cyclogenesis.

2.2 Subtropical and Hybrid Cyclones

TCs fall on one side of a larger continuum of cyclone structures. The most common type is the extratropical cyclone (ETC), which is fueled by horizontal temperature gradients (Carlson 1998). TCs are the second most common type, as discussed above. There exists a third type, however, which is a combination of ETC and TC: subtropical cyclones (ST). The divisions between types are not concrete, but rather subjective. There may be a fourth type of cyclone: a ‘hybrid’, falling between subtropical and tropical, though there is no consensus on the distinction.

2.2.1 *Defining a Subtropical Cyclone*

Simpson (1952), in his pioneering work on Kona lows, first proposed the existence of an intermediate type of cyclone between extratropical and tropical. Kona lows form north of Hawaii during the winter and have both tropical and extratropical characteristics. Kona lows arise from two sources: occluded cyclones and cyclogenesis. For the first type, an extratropical system becomes secluded from the westerlies and occludes. The frontal structure dissipates and the cyclone becomes symmetrical. In cases

of cyclogenesis, a cutoff 500 hPa low merges with an approaching midlatitude trough, creating a low- and mid-level circulation. Simpson suggested the term ‘subtropical cyclone’ for these storms.

To complement the Dvorak Technique, Hebert and Poteat (1975) developed a similar method to objectively analyze subtropical storms using geostationary satellite imagery. Roth (2002) proposed a two-type system to categorize subtropical cyclones. Type A subtropical cyclones are synoptic-scale cold lows with surface circulations that have maximum winds of at least gale strength at radii of 100 mi or more from the center. Type B subtropical cyclones are mesoscale circulations (less than 50 mi radius) which spun up along dissipating fronts and have maximum winds of at least gale strength at radii of 30 mi or less from the center. Roth also created a list of candidates for the subtropical cyclone designation.

Prior to 2003, the classification of a system as tropical or subtropical was a subjective decision based on the satellite appearance and (if the forecaster was fortunate) ship or satellite-derived wind data. Hart (2003) developed the Cyclone Phase Space diagram to plot the vertical thermal structure of a cyclone. Initially created to assist with determining the extratropical transition time of a TC, it became a valuable tool to distinguish STs and TCs. The diagram used readily available height and temperature data from the Global Forecast System (GFS) model to analyze the symmetry and relative temperature of a cyclone’s lower and upper cores. A warm lower and upper core indicated a tropical system; cold lower and upper cores indicated an extratropical cyclone. Based on a study of previous systems, Hart developed thresholds for each

category (ET, ST, TC). This diagram has been used operationally to distinguish cyclone types (e.g. Tropical Storm Vince Discussion Number 1,

< <http://www.nhc.noaa.gov/archive/2005/dis/al232005.discus.001.shtml>>.

Two recent articles focused exclusively on subtropical cyclones. Evans and Guishard (2009, EG09) created a set of criteria to diagnose subtropical systems. These guidelines were intended for operational use to assist in determining whether a cyclone is subtropical. Criteria were then applied to the 40 year European Centre for Medium-Range Weather Forecasts Reanalysis (ERA-40; Uppala et al. 2005) to identify past subtropical storms (Guishard et al. 2009, G09). This analysis found many unidentified cyclones which fit the parameters detailed in EG09.

EG09 determined five criteria for identifying a subtropical cyclone. If a cyclone had been tracked for at least 36 h (3 consecutive 12-h model runs), it was classified as subtropical cyclone if: 1) winds were sustained at $> 17 \text{ m s}^{-1}$ (gale force) for 36 h, with genesis occurring at the first onset of gales; 2) it maintained hybrid structure for at least 36 h according to the CPS diagram; 3) it had not been tracked for more than 24 h as a cold or warm-core structure before attaining hybrid structure; 4) genesis occurred in the 20-40°N latitude belt, and 5) it was located over the ocean from the first appearance of a closed surface low to the onset of gales.

Details of subtropical structure and the usual formation environment in EG09 were consistent with previous research. The authors discussed these aspects much more thoroughly than earlier papers, however. A subtropical cyclone was defined as a cyclone with cold anomalies present in the upper core and warm anomalies in the lower core. The

authors found a common scenario when they composited the 18 storms. An upper trough moved over a region of moderately warm (23-27°C) SST and low static stability. EG09 developed a four-partition classification scheme for subtropical cyclones, demarcated by shear (10 m s^{-1}) and SST (25°C) thresholds.

G09 documented 197 subtropical cyclones from 1957-2002. This set was compared to the official HURDAT record and the Roth (2002) candidates. Only 27 storms were detected in all three datasets, highlighting the difficulties of subjective diagnostic criteria. Approximately 12% of all Atlantic TCs had subtropical origins, though this fraction depends on the accuracy of the HURDAT record. About 61% of G09 subtropical storms formed in a sheared environment ($\text{shear} > 7.5 \text{ m s}^{-1}$), supporting the idea that shear is necessary for subtropical cyclone formation.

2.2.2 Identifying Hybrids: 1950-2005

Depending on the source, the term ‘subtropical’ is either a catch-all term for any system not clearly fitting into the ETC or TC categories, or is meant to refer to a cyclone with a relatively even mix of tropical and extratropical attributes. In the latter case, another term has been used to classify cyclones that have too many tropical features to be called subtropical but still do not appear to be fully tropical. These cyclones have been called hybrids. The tone of current research suggests that hybrid systems are a new discovery. A search through the journal archives reveals references as far back as 1951 to TCs which did not completely fit the tropical definition.

Moore and Davis (1951, MD51) published an analysis of a cyclone which formed in mid-May 1951 east of Daytona Beach, FL. The cyclone eventually became a Category 2 hurricane offshore of the Carolinas. MD51 declared this event “unique” for both its structure and for its detection so close to the U.S. coast in the off-season. The authors also stated that hurricane-like systems had been detected in the subtropical Atlantic Ocean in winter.

MD51 analyzed the evolution of the environment and structure of the 1951 May storm. A surface low formed along a frontal boundary west of Bermuda. Strong cold air advection at the upper levels created anomalously cool conditions (about 7°C below normal) at 300 hPa, and a closed upper low developed just upstream of the surface system. Both features were located over the 25°C waters of the Gulf Stream, creating a relatively moist environment with low static stability. The authors suggest that these features, in combination with an area of divergence after the trough moved east, created an environment highly conducive to intensification. Their analysis of the salient environmental features in the storm’s formation was remarkably accurate, as later papers will show.

Post-season Atlantic activity summaries intermittently contained details on hybrid systems, though not every storm was included in the season count. Dunn and Staff (1964) identified two Atlantic cyclones, one in late May and another in mid September, which appeared somewhat tropical on satellite imagery and thus did not warrant a classification as subtropical. Neither was named or included in the official count. Dunn and Staff (1964) noted that a few of these “half-breed” cyclones occur each year in the Atlantic,

mostly over the open ocean. Spiegler (1971) proposed the term ‘semitropical’ for such hybrid systems instead of the ‘neutercane’ suggested by Simpson and Pelissier (1971).

[For rather obvious reasons, the term ‘half-breed’ was quietly eliminated.]

More hybrids were detected during the 1960s. Erickson (1967) described Hurricane Dorothy (1966) as an example of a half-breed cyclone. This system formed underneath a vigorous upper-level trough and over SSTs of 25-26°C, a very similar scenario to the 1951 hurricane. In contrast to the 1951 hurricane, satellite imagery was available to aid tracking of Dorothy’s evolving structure. Dorothy quickly developed the classic miniature-occluded cyclone structure with deep convection at the center. Outer convection dissipated as the central convection deepened. A weak warm core developed, and the system eventually appeared fully tropical. Interestingly, in the Best Track Dataset (HURDAT, Jarvinen et al. 1984) Dorothy is listed as a TC through its initial development. Such inconsistencies are not uncommon in the record and complicate research efforts.

2.3 Tropical Transition

Researchers have known for years that subtropical cyclones can evolve into tropical cyclones. Simpson (1952) noted that subtropical Kona cyclones could acquire the wind and rainfall patterns of TCs, suggesting that a system’s position on the continuum was not fixed. EG09 noted that 15 out of the 18 subtropical systems in their study set became TCs. The subtropical-to-tropical pathway had been discussed under a variety of names, and in 2004 one of the suggestions finally stuck. Davis and Bosart (2004; DB04)

coined the term ‘tropical transition’ (TT) for the process by which a subtropical cyclone becomes a tropical cyclone. Case studies of TT had been published years earlier, however.

Bosart and Bartlo (1991) analyzed the development of Hurricane Diana (1984), which formed just east of Florida along an old front. Initially baroclinic, the system completed the transition to a fully tropical cyclone. They determined that the development and transition process had three steps. First, a potential vorticity (PV) maximum triggered development of a wave cyclone along the front. Then strong surface and latent heat fluxes supported convection in the northeast flow along the front. Finally, positive PV advection created an environment to organize the convection around the subtropical cyclone. PV became a common way to analyze the TT process, likely because of the juxtaposition of thermal gradients, vorticity, and warm SSTs.

The 2000 and 2001 hurricane seasons sparked significant interest in TT. Ten TCs, four in 2000 and six in 2001, developed from baroclinic systems. Though all ten eventually became tropical, all had subtropical characteristics early in their existence. Hurricane Karen (2001) raked Bermuda with high winds and heavy rain, causing much damage (Stewart 2002). Davis and Bosart (2003) published an analysis of the ten TCs, focusing on wind shear and SST values experienced by the storms. They also compared the ten TCs to cyclones which remained subtropical during those months. Four of the ten tropical systems studied were analyzed in this thesis: Nadine (2000), and Lorenzo (2001), Noel (2001), and Olga. PV arguments were used in a case study of Hurricane Michael (2000) to explain the transition process.

Analyses were performed on Aviation (AVN) model data to examine the pre-tropical cyclone shear environment. The authors found that 900-200 hPa shear averaged over a 5°x5° Lagrangian (storm-centered) grid was at or above 8 m s⁻¹ in all ten cases, and exceeded the 15 m s⁻¹ limit in three of the cases. However, at some point prior to the time of transition the shear affecting each storm had decreased to 6 m s⁻¹ or less with the exception of Noel, which had shear of 10 m s⁻¹. They determined that a combination of baroclinic and diabatic processes created the intense non-tropical cyclones, which then transitioned to tropical cyclones. Intensification by baroclinic forcing most often arose from strong mid-tropospheric temperature gradients, specifically increasing warm advection with height or decreasing cold advection with height. The diabatic causes of cyclone intensification were latent energy fluxes due to phase changes of water from air-sea interaction and the development of convection. For the weaker baroclinic precursors, diabatic heating was much more critical than baroclinic cyclogenesis; the baroclinic structure only served to organize the system and did not intensify it. The cases which transitioned to tropical were those in which the baroclinic system became occluded over SSTs greater than 26°C. DB03 considered tropical cyclogenesis improbable for 850-200 hPa shear exceeding 15 m s⁻¹.

Inevitably, attempts were made to categorize TT to assist in forecasting. DB04 presented a two-category paradigm for distinguishing tropical transition (TT) cases. Strong extratropical cyclone (SEC) cases are of sufficient initial intensity to trigger wind-induced surface heat exchange (WISHE; Emanuel 1987). Weak extratropical cyclone

(WEC) cases are too weak to cause WISHE, and instead organize the convection until the cyclone is capable of self-amplification.

Once WISHE begins in SEC TT cases the vertical shear over the cyclone is reduced via diabatic processes. The cyclone takes on the appearance of an occluded cyclone, with the TC forming at the center. The four SEC cases discussed in DB04 had asymmetric rainfall patterns. The heaviest rainfall was on the west and southwest sides of the surface low. This enhanced upshear convection may contribute to the decrease in shear over the low.

Two types of WEC systems are proposed: mid-tropospheric mesoscale vortices (MTMV) and weaker baroclinic systems. Though MTMV are present in baroclinic systems, the authors distinguish the types. The difference between the two is the longevity of the vortex prior to TT. The MTMV is present for at least two days prior to tropical cyclogenesis for the MTMV type. It is implied to be much shorter for the baroclinic type. The longer-lived MTMV organizes the convection via interaction with vertical shear. The shorter-lived MTMV forms within convection associated with a weak extratropical cyclone, and convection organizes when the MTMV and area of vertical ascent are superposed.

According to the authors, forecasting SEC transitions is easier than WEC transitions. SEC cases are dependent on a favorable environment. If the environment is correctly anticipated, then the transition (or lack thereof) is likely to be correctly predicted. With rare exceptions, the cyclone must remain over water with $>26^{\circ}\text{C}$ sea surface temperatures (SSTs) for at least one day following occlusion for transition to

occur. WEC cases are more difficult because weak MTMV and baroclinic cyclones are common in the Atlantic basin. DB04 suggests WEC transitions are more likely in light to moderate shear environments ($< 10 \text{ m s}^{-1}$). A numerical simulation of Gabrielle (2001; Musgrave et al. 2008) indicated a sharp decrease in shear to less than 5 m s^{-1} over the center for about 6 h. This decrease occurred after convection erupted downshear of the disturbance. DB04 suggest it allowed the core to warm, becoming a tropical cyclone.

Papers continued to appear as the Atlantic produced more transitioning systems. Most studies focused on specific TT events, and usually employed numerical models to analyze the transition process. Researchers were mainly interested in the cause of the warm core, a feature critical to the classification of a cyclone as tropical. In 2003 Hurricane Juan hit Bermuda and Nova Scotia, causing major wind damage. McTaggart-Cowan et al. (2006a) used this hurricane as a case study for a numerical simulation of the transition. Hurricane Catarina (2004) became the first known hurricane in the southern Atlantic Ocean, making landfall in Brazil and causing major damage. This system originated from an extratropical low and underwent TT before striking as a minimal hurricane. Pezza and Simmonds (2005) and McTaggart-Cowan et al. (2006b) analyzed this record-setting TC and concluded it was due to an unusually favorable environment typical of TT.

The past year (2009) was a particularly full year for research on hybrid systems. Hulme and Martin (2009a,b) analyzed six cases of TT and simulated the transition of Hurricane Karen (2001). They presented an overview of the full TT process based on the six cases: Michael (2000), Karen (2001), Noel, Olga (2001), Delta, and Epsilon. The

precursor extratropical cyclone developed from the interaction between a surface baroclinic zone and an upper-level trough. The baroclinic zone became a frontal wave, and a closed low developed at the surface. The frontal structure evolved into an occluded cyclone with a bent-back warm/occluded front extending west and northwest of the surface center. Precipitation within the low increased low-level PV at the warm front. Latent heat release promoted growth of the low-level PV anomaly and enhanced the surface circulation. Strong southwesterly shear reduced the static stability over the occluded region of the storm. Low static stability and strong frontogenesis was conducive to convection at the center of the cyclone. This convection triggered the transition event by decreasing (increasing) the upper-level (boundary layer) PV.

In simulating the transition of Karen, Hulme and Martin (2009b) focused on the development of the upper-level warm core. Previous work (e.g. DB03, DB04) had suggested that diabatic processes isolate the cyclone's warm core. The authors theorized that the appearance of convection upshear of the cyclone signaled the beginning of TT, and was a critical part of the transition process. Low-level vorticity accumulated near the center of the cyclone in their model, intensifying the circulation. Cool and dry air was advected around the center of circulation and into the boundary layer via convective downdrafts. The temperature contrast increased across the front, promoting frontogenesis. Upshear convection redistributed PV in the vertical, which decreased the shear. This led to the formation of the upper-level warm core, completing TT.

Chapter 3: Methods

3.1 Subset Selection Criteria

This study's purpose was to analyze the formation environments of TCs similar to the 2005 cold-water quartet. Therefore temporal and spatial criteria were necessary to identify similar Atlantic TCs. Defining the selection parameters required striking a balance between having enough storms for a meaningful analysis and excluding storms which did not match the research questions.

First, the time of genesis had to be defined. Eleven of the twenty TCs were initially classified as non-tropical in the official record, so the start of tracking by NHC was not an appropriate marker. To legitimize comparisons of systems with tropical origins to systems with baroclinic origins, genesis was defined as the time at which the system was classified as tropical by NHC in HURDAT with maximum sustained winds greater than 33 kt. For the systems with purely tropical origins (and some of the weaker baroclinic systems) genesis occurred when the tropical depression became a tropical storm. For other baroclinic systems, genesis occurred when the subtropical storm transitioned to a tropical storm. For the strongest baroclinic systems (Karl (1980), Lili-84, Lili-90, and Noel), genesis occurred when the subtropical cyclone became a tropical cyclone, but at hurricane intensity (maximum sustained winds greater than 64 kt).

Defining genesis in this way assumes that each storm actually becomes tropical at the time of genesis. Given the 31-year length of the study, and the evolution of satellites and the Dvorak/Hebert-Poteat techniques over the period, this assumption is likely not always accurate. This definition minimizes the impact of technological and operational changes.

HURDAT, the official Atlantic Best Track record maintained by the National Hurricane Center (Jarvinen et al. 1984) was useful for finding similar TCs to the 2005 quartet. Storms which remained subtropical in the official record were excluded so the work could focus on TC development. Vince formed on 9 October 2005, and Zeta formed on 30 December 2005. Therefore, 1 October to 31 December became the date range for the initial classification as a TC.

By 1975 two techniques for classifying systems based on analysis of geostationary satellite imagery were being used consistently by NHC. The Dvorak technique was for tropical cyclones (Dvorak 1975), and the Hebert-Poteat technique was for subtropical cyclones (Hebert and Poteat 1975). Before 1975, identification of a system's tropical or subtropical status was largely subjective, especially when in-situ data were unavailable. An initial year of 1975 was therefore chosen to minimize the impact of classification issues, though both of the techniques have been refined since their operational introduction. A final year of 2005 was chosen because the storms which prompted this study occurred during that season. TCs forming during the 2006-2009 seasons which fit the study parameters will be used as case studies to compare to the

conclusions drawn from the study set. One TC (Grace 2009) fit the parameters, and is included as a case study at the end of the results section.

Next, spatial selection criteria were determined. The location of formation was restricted to the region north of 20°N and east of 60°W. The Climate Prediction Center (CPC; 2010) uses the region from 5°-20°N and 60°-30°W for monitoring North Atlantic SSTs. The study region is directly north of the CPC SST domain, but with unrestricted northern and eastern boundaries. Other longitudes were tested for the western boundary, but 60°W was deemed the best choice. Moving the line farther east resulted in too few storms for a meaningful analysis. Moving the line farther west increased the number of systems, but captured a higher percentage of purely-tropical systems. Since this study examines atypical TC development, 60°W was chosen as the western boundary. All TCs forming within this region which also fit the temporal parameters had unusual physical characteristics. Even the October TCs in the southwestern portion of the region, which theoretically could be purely tropical, formed in conditions different from the typical tropical environment. The twenty TCs selected for study are listed in Table 1, and the formation locations are plotted in Figure 2.

Data was collected on each storm for the 30 hours prior to genesis (36 hours for geopotential height since those fields were analyzed every 12 hours). This period captures the conditions in which the systems acquired the characteristics of tropical storms. Official positions were taken from HURDAT when available. For nine of the twenty TCs, the record did not span the required 36 hours prior to the time of genesis. Five of the nine TCs with missing positions were missing four or more points. Earlier

locations were extrapolated from existing data based on the speed and direction observed in the existing record, and confirmed with satellite imagery when available.

When discussing results for a particular time, the following convention will be used: T (for the Time of genesis) – (hr) (for the number of hours prior to transition). So a result valid at twelve hours prior to genesis will be referenced as T-12. This abbreviated notation will facilitate discussion of the results, particularly when comparing storms at different times.

3.2 Classification Scheme

Previous work had attempted to classify late-season northeastern Atlantic TC development into four categories (Types I, II, III, and IV). Type I TCs were believed to originate from non-frontal, non-tropical lows. Type II TCs developed along frontal boundaries. Type III TCs originated from occluded cyclones. Type IVs developed from tropical waves. The old scheme had been developed from written records of the storms (specifically Tropical Cyclone Reports, discussed later), with limited satellite imagery for more recent storms. Additional analysis, particularly of thermodynamic variables, and the discovery of more comprehensive satellite imagery archives, led to several modifications to the original classification scheme.

The new scheme was developed by combining subjective data (TC reports and satellite imagery) with objective parameters. The objective parameters are 850- and 500 hPa relative vorticity at thirty hours prior to genesis (T-30). Vorticity maxima were located within 5° of the grid center in nineteen of the twenty storms, which indicate

comparatively minor discrepancies between reanalysis locations and official positions. The single exception was Zeta. The vorticity maxima at both levels for this storm were located nearly 10° to the west of the grid center. This difference was maintained for the thirty hours prior to genesis. Therefore, it is reasonably certain the displaced vorticity maxima observed in the vorticity fields are actually associated with Zeta, and thus are used to classify Zeta.

Relative magnitudes of the 500 hPa vorticity maxima were consistent with a division into frontal and non-frontal TC precursors. The magnitude of the 850 hPa storm vorticity maxima was able to discriminate between weak (FW) and strong (FS) frontal TCs. Satellite imagery and TC reports in conjunction with 500 hPa vorticity data supported separation of the non-frontal systems into tropical (NFT) and baroclinic (NFB,) subtypes. These archetypes are not inconsistent with other work (e.g., DB04). Unlike DB04, however, this scheme provides a framework with quantitative guidelines for classifying TCs. A detailed discussion of the classification scheme is included at the beginning of the results section.

3.3 Storm Histories

3.3.1 Tropical Cyclone Reports

Each TC's Tropical Cyclone Report (TCR) was studied to better understand the development process. TCRs are written by NHC forecasters post-storm and contain an overview of the storm's life cycle, ship and aircraft data, satellite imagery, and verification statistics. Reports are available online at

<<http://www.nhc.noaa.gov/pastall.html>>. Few sources of in-situ data are available in the northeastern Atlantic. Aircraft reconnaissance collected data on Lili-90 when it approached Cape Hatteras, NC. Otherwise, no reconnaissance flights were made into the other TCs. Data for this study, then, is limited to satellite observations, reanalysis, and the occasional unfortunate ship.

3.3.2 Satellite Imagery

Satellite imagery was obtained from four online archives. The Naval Research Labs (NRL) Tropical Cyclone Page (http://www.nrlmry.navy.mil/tc_pages/tc_home.html) stores geostationary and polar orbiter imagery from the 1997 season to the present. NRL's coverage usually began just before or at the start of the tropical portion of each TC's life. While the NRL archive is useful for examining TC structure late in the transition period, it has limited imagery available in the early transition period. Intermittent coverage due to the nature of polar orbiters also made it more difficult to track structural changes over a short period. For some storms (e.g. Epsilon 2005), however, it was useful for tracking the center prior to HURDAT coverage.

For geostationary satellite data, two online archives were scoured. The University of Wisconsin's Space Science and Engineering Center (SSEC) maintains an archive of geostationary imagery (visible, infrared, and water vapor channels). Florence (1994) is the first TC of the study set for which satellite data was available from SSEC. This archive can be found at <<http://dcdbs.ssec.wisc.edu/inventory/>>. SSEC geostationary

imagery was usually restricted to full-disk, Northern Hemisphere, or contiguous United States (CONUS) angles, and was not useful for positioning storms. The archive was excellent for tracking structural changes, however, because of the 15-minute interval between images.

In 2003 NOAA began a project to rescue International Satellite Cloud Climatology Project (ISCCP) images. The result is an online archive of geostationary imagery accessible through the National Climatic Data Center (NCDC) at <http://www.ncdc.noaa.gov/gibbs/>. Irma (1978) is the first storm of the subset for which imagery is available through the Global ISCCP B1 Browse System (GIBBS). Images are available for visible, infrared, and water vapor channels on 3-h intervals. This archive filled in years unavailable from SSEC.

The fourth resource is also a NCDC product. The Hurricane Satellite (HURSAT) Project was an offshoot of the ISCCP project. TC imagery was collected from the ISCCP archive and cropped to only show the TC. Another archive was begun of microwave data, but the period of coverage only begins in 1993 and is thus less useful for analyzing the study set. Images are available as Google Earth files (for storms from 1978-2008) and as movies (for storms from 1978-2006). Both formats were used as an additional resource for understanding the development process. As with the NRL archives, the imagery tends to begin with the HURDAT record. Imagery for storms such as Epsilon and Zeta (both 2005) began within six hours of the time of transition. However, for storms in the late 1970s and 1980s, this archive is a valuable tool. Holly (1976) is the only TC in the study for which no satellite imagery has been found.

3.4 Sea Surface Temperature Data

Three reanalysis datasets were used in this study. A description of reanalysis methodology follows in the NCEP/NCAR reanalysis section. Reynolds OIv.2 weekly 1° gridded SST fields were used for most of the SSTs (Reynolds et al. 2002; available online through the Data Library of the International Research Institute for Climate and Society (IRI), <http://iridl.ldeo.columbia.edu/index.html>). SST data was collected for a 5° square box around the storm's location. A track-based method determined the center point of the SST grid box. Figure 3 illustrates the method with a hypothetical example. Reynolds grid points are gridded on the half-degree ($-.5$). The storm coordinates were rounded to the nearest full degree ($-.0$) to place the storm in between grid points. With this placement, the box had 6 points to a side for exactly 5° . If a storm was located halfway between lines (e.g. 30.5°N), then the previous six hours' motion determined which corner was used.

The weekly time interval required a decision for cut-off times, since some storms occurred close to the transition days. To minimize the effects of upwelling, storms forming close the beginning of the actual week of formation were analyzed using SSTs from the previous week. If a storm's genesis time ($T-0$) occurred 36 hours or less from the start of the week, the previous week was used. This rule ultimately affected only Noel: genesis occurred on 5 November at 12Z, and the week began on 4 November. The coordinates and date were entered into the IRI online interface's expert mode, which calculated the average over the box.

Five TCs—Holly, Irma, Ivan (1980), Karl, and Jose (1981)—formed prior to the Reynolds weekly dataset start date. For these TCs, SST values were determined from the NOAA NCDC Extended Reconstructed Sea Surface Temperature Version 3b dataset (Smith et al. 2008; also available online through IRI). This data is gridded every 2°. Smith et al. (2008) found a cold bias on the order of 0.01 °C in the satellite-supplemented SST fields due to residual cloud contamination. This finding led to a second version of the dataset (Version 3b) which excluded satellite data. Although the OIv.2 data included satellite observations, ERSST Version 3b was used for this work because Version 3 was removed from the NCDC archives.

SST values for these TCs were interpolated from the ERSST monthly means, assuming linear change and that the SST was valid on the 16th of the month. Various interpolation schemes were evaluated by comparing them to existing Reynolds weekly SST data. Hourly, daily, and weekly intervals were tested with different combinations of months. Daily interpolation produced the lowest squared error, calculated as

$$SE_{SST} = \sum_{i=1}^{15} (SST_{i,calc} - SST_{i,obs})^2 \quad (3).$$

Daily interpolation presented a problem, however. Reynolds SST data was stored as weekly averages, so daily and weekly values needed to be compared. This pattern seemed unnecessarily complicated and limited the internal consistency, especially when weekly interpolation of the monthly values produced a squared error only 0.1 (°C)² greater than the daily method. An offset was added at one point to account for when the mid-month

date fell in the middle of a week. This correction actually worsened the interpolation, and was removed from the final results.

Months were staggered as follows. If a TC formed in the first fifteen days of the month, the prior month and the storm month formed the basis of the interpolation. If a TC formed in the last fifteen (in October and December, sixteen) days of the month, the storm month and the succeeding month formed the basis of the interpolation. In most cases the monthly interpolated SST value was within 0.1-0.2°C of the weekly SST value, validating the proxy. The monthly SSTs had a 0.2°C cold bias overall, tentatively attributed to the upwelling along the TCs' tracks.

While the interpolation method is not complex, it should be explained in detail. To compute the estimated SSTs, the following equation was used:

$$SST_{TC} = SST_{M1} - \left[\frac{(SST_{M1} - SST_{M2})}{4.35} \times \frac{D_{TC} - D_{M1}}{7} \right] \quad (4).$$

A subscript of TC indicates a value for the storm itself. M1 indicates the value should be for the first month, and M2 for the second month. D is the Julian date. As an example, Holly formed on 23 October 1976, so the first month is October 1976 and the second month is November 1976. Net SST change between October and November was calculated, and divided by 4.35 (the approximate number of weeks between 16 October and 15 November) to derive the approximate weekly change. This result was then multiplied by the number of weeks between 16 October (the valid SST date) and 23 October (Holly's formation) to compute the SST change over the period. Finally, the SST change is subtracted from the October mean to arrive at the final estimated SST.

3.4.1 Maximum Potential Intensity

SSTs were also used in the calculation of Maximum Potential Intensity (MPI), a theoretical upper limit on a TC's intensity. DeMaria and Kaplan (1994a) found the following empirical relationship between SST and MPI:

$$V = A + Be^{C(T-30^{\circ}C)} \quad (5),$$

where V is the MPI in m s^{-1} , T is the SST in $^{\circ}\text{C}$, and A , B , and C are constants ($A = 28.2 \text{ m s}^{-1}$, $B = 55.8 \text{ m s}^{-1}$, $C = 0.1813 \text{ }^{\circ}\text{C}^{-1}$). MPI was calculated for the SST at T-0, and compared to the intensity at genesis.

3.5 Introduction to NCEP/NCAR Reanalysis

Gridded environmental data came from the NCEP/NCAR Reanalysis 1 dataset, available online from the Physical Sciences Division of NOAA's Earth System Research Laboratory at <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>. NCEP/NCAR is one of several reanalysis datasets available. It was chosen for this project because of its long record, high quality in both the tropics and mid-latitudes, and easy online access. The single major disadvantage is the large grid resolution. Many of the study TCs are small systems, and it is difficult to capture the local storm environment when the TCs are sometimes less than 150 km in diameter.

NCEP/NCAR data are available on a 2.5° grid at 6-h intervals from 1 January 1948 to the present. Individual concurrent monthly means for the month of formation of each TC (e.g. December 2005) and long-term climatological monthly means derived

from 1968-1996 data have also been calculated. Though Kalnay et al. (1996) describes the reanalysis methodology in extensive detail, a brief discussion is included here.

Reanalysis is a technique for standardizing observations that are spatially and temporally irregular. A computer model takes all available data—from ships, buoys, surface stations, aircraft, and satellites—and interpolates the observations onto various grids at 6-h intervals. Reanalysis variables are divided into four categories: A, B, C, and D. Type A variables are largely based on available observations with little influence from the model, and are considered the most reliable. Type B variables are a mix of observations and model calculations, and may have some artificial effects from the model. Type C variables are completely model-derived (no observations included) and are considered the least accurate. Type D variables have no input from the model, but are based on climatological values (e.g. land-sea mask).

This study used a mix of Type A and Type B variables. Table 2 lists the variables with levels used and the applicable units. U- and v-components of the wind, temperature, geopotential height, and surface pressure were Type A variables. U- and v-wind data were collected at 850-, 500-, 400-, 300-, 250-, and 200 hPa. Geopotential height data were collected at 1000-, 500-, 300-, and 200 hPa. Temperature data were collected at 12 levels (listed in Table 2). Concurrent monthly means and climatological means were collected for the 300- and 200 hPa levels. Relative humidity and specific humidity were Type B variables, and only appeared in calculations of dewpoint and virtual temperature, respectively. Relative humidity data was collected at the 0.995 sigma level, and specific humidity was collected for the 925-, 850-, 700-, 600-, 500-, 400-, and 300 hPa levels. The

actual surface pressure was used rather than the mean sea-level pressure (MSLP) in case one of the points was located over Europe or a Caribbean island. MSLP also introduces an unnecessary calculation.

3.5.1 Compositing Technique

Compositing was performed on some of the variables in the analysis to facilitate comparisons between types. Composites were created using the following equation:

$$X_{composite} = \frac{\sum_{i=1}^{N_T} X_i}{N_T} \quad (6) ,$$

where X is the variable being composited and N_T is the total number of systems in a type. Composites were created for shear fields (full, zonal, and meridional), upper-level winds, and 300 hPa geopotential heights.

3.6 Wind and Geopotential Height Data

3.6.1 Wind Shear: Local Average

Parameters involving data on the u- and v-wind components compose the bulk of the dynamic environmental analysis. The environmental wind shear was approximated by the vertical difference of the horizontal wind using the simple shear equation:

$$\text{Wind Shear} = \sqrt{(u_{Upper} - u_{850 \text{ hPa}})^2 + (v_{Upper} - v_{850 \text{ hPa}})^2} \quad (7) ,$$

Local shear magnitudes were averaged over a nine-point (5° square) storm-centered box for five layers: 850-500 hPa, 850-400 hPa, 850-300 hPa, 850-250 hPa, and 850-200 hPa.

The boundaries of this box exactly matched those for the Reynolds SST box.

Examination of the five layers revealed similarities between 850-500 hPa, 850-400 hPa, and 850-300 hPa. Though the magnitudes differed, the overall pattern of changes was similar, and the relative magnitudes remained similar. The 850-250 hPa and 850-200 hPa layers also showed a strong connection. Therefore, only 850-300 hPa and 850-200 hPa results were included in the results section.

3.6.2 Wind Shear: Large-Scale Contour Areal Average

The local average captured only one aspect of the shear conditions. To supplement these values, areal coverage of the 8-, 12-, 16-, and 20 m s^{-1} contours were calculated for the full 169-point (30° square) storm-centered shear field. These contour levels were chosen to represent the range of shear values most widely observed over the storms that could conceivably be low-shear environments. Only four of the twenty TCs had local 5° shear exceeding 20 m s^{-1} at any time in the 30-h pre-tropical period, so it seemed reasonable to use this magnitude as the last contour. Only three of the twenty TCs had shear less than 4 m s^{-1} at any time in the 30-h pre-tropical period (and none for the 850-200 hPa layer). Hence the first plotted contour was 8 m s^{-1} .

Areal coverage was estimated using the geographic information system (GIS) software ArcGIS version 9.2. First, the text shear data were converted into ArcGIS rasters with a geographic coordinate system of WGS 1984. This is a standard representation of Earth's surface. Then the rasters were converted to the Mollweide projection, which is an equal-area projection intended for small-size, global-scale maps. Although these data are

not global-scale, using an equal-area projection was critical for accurately calculating area, and this projection worked well at all latitudes. ArcGIS was then instructed to contour the wind shear data every 4.0 m s^{-1} from 8.0 - 20.0 m s^{-1} . Figure 4(a) is an example of the map produced by ArcGIS. To confirm the relative accuracy of the contours, ArcGIS results were compared to the IDL contour plots (shown in Figure 4(b)). Differences in the projections created slightly distorted maps, especially in the far northern section of the maps, but the overall pattern was similar enough that the results were considered usable.

Each contour's coverage area was calculated using the measuring tool in ArcGIS, and divided by the total area of the box. These percentages are not meant to be absolute thresholds, but as a means to distinguish between types. The number of points in the local 5° boxes which exceeded 8.0 -, 12.0 -, 16.0 -, and 20.0 m s^{-1} was also counted, to be presented as a percentage.

3.6.3 Wind Shear: Storm-Relative Locations of Low Shear

Locations of low-shear areas were also studied. The 850 - 300 hPa and 850 - 200 hPa shear fields were plotted in IDL with the storm position at the current time ($t-0$) and six hours before ($t-6$) and after ($t+6$). For a T-24 field, the locations at T-30, T-24, and T-18 would be plotted. Three circles (radii 250 -, 400 -, and 500 km , centered on the position at the current time) were plotted on the image as well. If a shear contour (4.0 m s^{-1} and 8.0 m s^{-1}) intersected with a circle, it was recorded as a hit. If the circle was tangential to the shear contour, or the intersection was likely due to the contouring

routine, a ‘miss’ was recorded. The percentages are thus probably lower than in reality, but underestimation was considered the better of the two possible decisions.

The location of the low-shear area was also determined using the 12-h track and the traditional track-based quadrants. ‘Right’ (‘left’) of the storm was defined as the region to the right (left) of a line drawn from the t-6 position to the t+6 position. ‘Front’ (‘rear’) of the storm was defined as the region ahead of (behind) a line drawn through the t-0 position and perpendicular to the 12-h track.

3.6.4 Wind Shear: Zonal and Meridional Fields

McBride and Zehr (1981) examined the zonal and meridional components of shear in developing TC environments. A similar analysis was done on the TCs in this study. Shear was split into zonal and meridional components using the following equations:

$$U_{\text{shear}} = u_{\text{UL}} - u_{850 \text{ hPa}} \quad (8a) \quad V_{\text{shear}} = v_{\text{UL}} - v_{850 \text{ hPa}} \quad (8b).$$

Both 200- and 300 hPa were used for the upper wind level in computing shear. Resulting fields were composited by type, and plotted with the zero shear line and positive/negative areas highlighted. More emphasis was given to analyzing the placement of the zero shear line relative to the storm center since these storms appear to occur in high-shear environments.

3.6.5 Wind (u- and v-Components): Upper-Level Minima and Maxima

Upper-level winds at 200- and 300 hPa were plotted to determine the locations of speed minima and maxima. Locating the speed minima close to the developing cyclone was of particular interest. These plots were created by combining the u- and v components of the wind from the $30^\circ \times 30^\circ$ fields and plotting in storm-relative coordinates using IDL.

3.6.6 Wind (u- and v-Components): Vorticity and Divergence

Relative vorticity was plotted for a 121-point (25° square) storm-centered box at 850-, 500-, 300-, and 200 hPa. The 850- and 500 hPa plots ultimately proved most useful for categorizing the study TCs. The 300- and 200 hPa plots mainly revealed the strong upper-level cyclones above the developing TCs, and will not be discussed further in the results section. In addition, vorticity fields at 850- and 500 hPa were used to discriminate among types in the classification scheme.

Divergence fields were also calculated for a 121-point (25° square) storm-centered box at 850-, 500-, 300-, and 200 hPa levels. However, these plots mainly reflected the presence of upper-level cyclones above the developing TCs, and showed no signs of developing anticyclonic flow aloft. Therefore the divergence plots will not be discussed in the results section either.

3.6.7 Geopotential Heights

Examination of the large-scale geopotential height pattern was performed by plotting the heights at the 1000-, 500-, 300-, and 200 hPa levels. The 1000 hPa graphics tended to be cluttered, which was not surprising given that the storms form in the subtropics and midlatitudes in late fall and early winter. Fields at 500- and 300 hPa showed both the shortwave and the longwave features, with shortwaves more evident in the 500 hPa fields. The 200 hPa fields did not show longwave patterns as clearly as did the 300 hPa fields, so the 300 hPa fields were analyzed.

Heights at the 500- and 300 hPa levels were analyzed at 36 and 0 hours prior to formation for all storms, and height fields at 24 and 12 hours were examined if necessary to understand the evolution. The fields were plotted on a 100° longitude x 50° latitude Lagrangian (storm-relative) grid. The extent of this grid captured both the features directly affecting the developing storms, and those located upstream and downstream. Observed heights (OBS), concurrent monthly heights (MON), and climatological heights (LTM) were analyzed.

Three sets of 300 hPa geopotential height anomalies were calculated: observed height departures from the concurrent monthly mean (OBS – MON); observed height departures from the climatological mean (OBS – LTM); and monthly height departures from the climatological mean (MON – LTM). For MON/LTM anomalies, an additional comparison was made using an Eulerian grid fixed to 100°W – 0°W and 5°N – 55°N. This plot will be examined for indications that longwave patterns set up in similar locations among types. The discussion will focus on the T-36 and T-0 graphics.

3.7 Temperature Data and Stability Parameters

3.7.1 *Vertical Temperature Profiles*

Local environmental temperatures were measured by averaging the values over a 25 point (10° square) storm-centered box at the twelve levels listed in Table 2. A larger box was chosen relative to the wind shear averages to capture the storm environment. Storms are affected by temperatures over a larger area than by winds. Changes in the storm environment over the thirty hours prior to genesis were analyzed by subtracting the T-30 temperature from the T-0 temperature at all twelve levels.

One key event in the storms' development was the formation of an upper-level warm or neutral core. This feature is one of the distinguishing characteristics of a tropical system. Since at least 75% of the study set developed under the influence of upper-level cyclones (cold-core systems), analysis of the temperatures at 300- and 200 hPa was performed to look for signs of a warming upper-level core. At the time (prior to the Skew-T calculations) it was believed that the TCs likely extended no higher than the 200 hPa level in the atmosphere, and therefore these levels captured the top of the storm. As will be shown, this hypothesis is supported by calculations of the equilibrium level. Concurrent monthly means and climatological means were also calculated at these levels to compare the storm values to climatology.

3.7.2 Static Stability

To quantify the environmental stability, the static stability was estimated using the following:

$$\text{Static Stability} = - (T_{\text{UL}} - T_{0.995 \text{ sigma}}) \quad (9) .$$

Calculations were done using both 300- and 200 hPa for the upper temperature level (T_{UL}). NCEP/NCAR does not include surface temperature online, so the 0.995 sigma temperature ($T_{0.995 \text{ sigma}}$) was used instead. For most storms, the height of the 0.995 sigma level was about 50 m above sea level, and was thus a reasonable approximation of the near-surface temperature. A check was done on the 0.995 sigma temperatures to confirm they were realistic in comparison to the SSTs (i.e. $\text{SST} > T_{0.995 \text{ sigma}}$), since they came from different datasets. Overall, the two datasets are consistent. There were a few cases where the temperature exceeded the SST by less than 1°C. Kitabatake (2008), in a study of extratropical transition in the northwest Pacific Ocean, found strong warm air advection in the warm sector of transitioning TCs and near-surface air temperatures greater than the underlying SSTs. It seems plausible that a similar situation could be at work here, especially since the cases in question occurred on the warm side of the storm. Because of the minus sign, ‘low’ static stability (i.e. a less stable environment) is more positive, and ‘high’ static stability (i.e. a more stable environment) is less positive.

3.7.3 Skew-T Diagrams

The largest (and possibly most important) section of this work involved the creation of Skew-T log-P diagrams (colloquially known as Skew-Ts) for the six

observations prior to formation. Skew-Ts were done by hand using temperature data at 11 pressure levels and one sigma level (see Table 2). All data were averaged for the same 10° box as the static stability calculations. The lowest sigma level (0.995) was used as the first level of the diagram. Pressure at 0.995 sigma was calculated by multiplying the surface pressure by 0.995. Since the desired features on the Skew-T require the near-surface dew point, this was calculated using the 0.995 sigma relative humidity with the following equation:

$$T_{dewpoint} = \left[\frac{1}{T} - \frac{R^*}{M_v (2.501 - 0.00237T) \times 10^6} \ln(RH) \right]^{-1} \quad (10) ,$$

where T is the temperature (K) at 0.995σ, M_v is the molecular mass of water vapor (0.018016 kg mol⁻¹), R* is the universal gas constant (8.314 J mol⁻¹ K⁻¹), and RH is the relative humidity expressed as a decimal. Because the storms occur in the tropics and into the low midlatitudes, the temperature dependence of the latent heat of vaporization must be incorporated into the equation. The approximation L_v(T) = (2.501 – 0.00237T)(10⁶) is valid for most of the temperature range in this analysis (Bolton 1980).

3.7.4 Stability Indices from Skew-T Diagrams

Four standard stability variables based on the Skew-T were incorporated into this study: the Level of Free Convection (LFC); the Equilibrium Level (EL); the Lifted Index (LI); and convective available potential energy (CAPE). The LFC is calculated on the Skew-T using the Lifting Condensation Level (LCL) and the temperature line. The EL can be calculated from the LCL or the Convective Condensation Level (CCL). Use of the

LCL assumes there is a lifting mechanism to force the low-level air to rise. Use of the CCL assumes no outside lifting mechanism, and that vertical motion is due to surface heating. Since three-quarters of the study TCs were frontal in origin and thus had a source of lift, the LCL was used.

Air is assumed to rise from the surface and cool at the dry adiabatic lapse rate. The LCL (the level at which saturation occurs) is found where the dry adiabat intersects the mixing ratio line (found using the surface dewpoint temperature). The air parcel then rises and cools at the saturated adiabatic lapse rate. There are two critical points of intersection with the observed temperature curve. The first intersection, above which the rising parcel is now warmer than its environment, is the LFC. The second intersection, above which the rising parcel is once again cooler than its environment, is the EL. Occasionally multiple LFCs and ELs are observed on a Skew-T. Such occurrences in this study will be discussed below in the main CAPE section.

LI and CAPE were two additional measures of atmospheric stability included in the thermodynamic analysis. LI is the difference between the parcel temperature and the environmental temperature at 500 hPa:

$$LI = T_{E,500 \text{ hPa}} - T_{P,500 \text{ hPa}} \quad (11) .$$

A large negative LI index indicates an unstable mid-level environment. CAPE can be calculated for any layer in the atmosphere. In this study, surface-based CAPE was computed. The calculation required that the temperatures be converted into virtual temperature to account for the water vapor in the atmosphere. Specific humidity q_v was used to calculate the mixing ratio r :

$$r = \left(\frac{1}{q_v} - 1 \right)^{-1} \quad (12),$$

which was then used in the virtual temperature formula:

$$T_v = T \left[\frac{1 + r/0.622}{1 + r} \right] \quad (13).$$

Temperature values were only available at eleven discrete levels, so the normal integration method of calculating CAPE was not applicable. Instead, a summation was performed using the following equation:

$$CAPE = -R_d \sum_{LFC}^{EL} \left[\left(\overline{T_{v,P}} - \overline{T_{v,E}} \right) \left(\ln \frac{P_T}{P_B} \right) \right] \quad (14),$$

where R_d is the gas constant for dry air ($287.05 \text{ J kg}^{-1} \text{ K}^{-1}$), $T_{v,P}(\text{bar})$ is the parcel virtual temperature, $T_{v,E}(\text{bar})$ is the environment virtual temperature, P_T is the pressure at the top of the layer, and P_B the pressure at the base of the layer. Each level's temperature was assumed to be the mean for the layer containing that level. Layers were demarcated by the pressure values exactly halfway between temperature levels (e.g., the 700 hPa temperature was the mean for the 775-650 hPa layer, since 850 (600) hPa was the next level below (above) 700 hPa). The lowest layer's component always had P_B set as the LFC pressure, and the highest layer's component always had P_T set as the EL pressure. If the LFC (EL) was equal to a temperature level, then that temperature level was removed from the sum and the level became the lower (upper) bound for the layer.

There were two equilibrium levels in some cases, resulting in a region of convective inhibition (CIN) at the mid-level of the storm. For the purpose of calculating

CAPE, the LFC and EL are based on the lower set. In recording the ELs, however, both are noted and discussed.

Chapter 4: Results

4.1 Overview of Classification Scheme

The new classification scheme is one of the more important results of this work. TCs in the study set were divided into four types according to objective and subjective criteria. These archetypes are not inconsistent with other work (i.e. DB04). Unlike DB04, however, this scheme provides a framework with quantitative guidelines for classifying TCs.

Figure 5 is a plot of the strongest T-30 500 hPa vorticity contour (interval $4 \times 10^{-6} \text{ s}^{-1}$) against the strongest T-30 850 hPa vorticity contour (interval $4 \times 10^{-6} \text{ s}^{-1}$). Satellite imagery and TC Reports appeared to indicate frontal and non-frontal categories. The magnitude of the 500 hPa vorticity maxima supports this division, with a threshold of about $40 \times 10^{-6} \text{ s}^{-1}$. Olga (2001) was an outlier with a 500 hPa vorticity maximum contour of about $28 \times 10^{-6} \text{ s}^{-1}$. Satellite imagery of Olga (2001) showed that it developed along a frontal boundary, though its 500 hPa maximum contour was more consistent with non-frontal TC precursors. Figure 6 contains four geostationary images; the upper two are IR images of Olga prior to its genesis. Figure 6(a) shows the system at T-30; the frontal low which became Olga is beginning to develop. Figure 6(b) shows the system at T-0; the low is still in the vicinity of the frontal system, but at the low's center it has become a TC. HURDAT indicates that Olga strengthened from an estimated 25 kt at 12Z

on 23 November (T-24) to an estimated 50 kt at 0Z on 24 November (T-12). Such rapid development was not observed in any other storm in the study. The 500 hPa threshold is therefore held at $40 \times 10^{-6} \text{ s}^{-1}$, with the corollary that rapidly developing frontal storms may still be weak at T-30.

Figure 5 also suggests divisions within the frontal and non-frontal types. Satellite imagery and TC reports supported separation of the non-frontal systems into tropical (non-frontal tropical, NFT) and non-tropical (non-frontal baroclinic, NFB) subtypes. Vorticity maxima at 500 hPa also suggested a threshold of about $25 \times 10^{-6} \text{ s}^{-1}$, with baroclinic systems having slightly stronger 500 hPa vorticity than tropical systems. The magnitude of the 850 hPa storm vorticity maxima was a discriminator between weak (frontal weak, FW) and strong (frontal strong, FS) frontal TCs. The strong TCs have 850 hPa vorticity above about $70 \times 10^{-6} \text{ s}^{-1}$, though there are storms occurring close to the threshold in both categories. In fact, Figure 5 suggests two subtypes within the FW subtype. Three storms—Peter (2003), Otto (2004), and Vince—had larger vorticity maxima than the other FW storms at both 850- and 500 hPa. All three stronger storms had been tracked as subtropical storms for at least 36 hours prior to genesis, and had maximum sustained winds of 40 kt at T-30. The other FW storms were at 25-30 kt at T-30 with the exception of Florence, which had maximum sustained winds of 35 kt at T-30. FW will be treated as a single type for this analysis. However, the values of the three stronger storms will be noted if there is a noticeable difference in their values in comparison to the rest of the FW storms. The next section will discuss the storms in each type, and offer an overview of the formation processes.

4.2. Non-Frontal Precursors: NFT and NFB

Small, relatively weak surface lows are common across the Atlantic throughout much of the year. Tropical waves and weak non-tropical lows are the two main examples of these features. When conditions are right, weak lows can develop into TCs.

4.2.1 *Non-Frontal Tropical (NFT)*

NFT systems developed from tropical waves in the southwestern portion of the study region. To a large extent, they followed the typical tropical development process detailed in section A(iv) of the Literature Review. Unlike TCs in the deep tropics, however, the three NFT storms in the study set—Holly, Tanya (1995), and Nadine—formed underneath upper-level cyclonic features. This environment flagged them as unusual to NHC forecasters since anticyclones were considered highly favorable for TC intensification. Based on Figure 5, the low and mid-level circulations were weak, which was consistent with tropical waves. Holly and Tanya became hurricanes, and Nadine peaked as a strong tropical storm. Figure 7(a) is a satellite image of Nadine at T-0.

4.2.2 *Non-Frontal Baroclinic (NFB)*

The second non-frontal sub-type, NFB, fit only two storms in the study set. Irma and Lorenzo were weak and short-lived TCs in the east-central portion of the study region. There was no distinct positive 500 hPa vorticity maximum over the storm center. The low-level circulation at 850 hPa was also weak. These two storms did not form from tropical waves, and thus warranted a separate classification from the NFT systems. Based

on TCRs and satellite imagery, NFBs form when a low- to mid-level circulation encounters a relatively moist low-level environment with moderate to large environmental lapse rates. Convection briefly develops and organizes into a weak tropical storm, but the mid- and upper-level circulations never intensify, and drier air and strong winds quickly erode the convection. Figure 7(b) is a satellite image of Lorenzo at T-0.

4.3 Frontal Precursors: FS and FW

TCs from frontal systems appear to be much more common than non-frontal precursors in the northeastern Atlantic. Beginning early in the boreal autumn, strong midlatitude cyclones advance eastward from the U.S. East Coast across the northern Atlantic Ocean nearly every week. In favorable conditions, a surface low developing along the frontal boundary can break away from the parent system and develop tropical characteristics in a matter of days. Olga (2001) is a very obvious example of a TC originating from a frontal system (see Figure 5(a,b), though genesis occurred over a very short period of time. For other TCs, the process occurs over a longer period of time. Figures 5(c) and 5(d) are two satellite images of Otto at T-30 and T-0, respectively. Otto had been tracked as an extratropical and subtropical system for nearly five days prior to genesis. The frontal category is been divided into Frontal-Strong (FS) and Frontal-Weak (FW) sub-types.

4.3.1 Frontal-Strong (FS)

FS systems are near their peak intensity when they transition to tropical systems. They are characterized by strong vorticity maxima at both 850- and 500 hPa. TCs of this sub-type do not necessarily separate completely from the parent frontal system. Noel and Delta remained connected to the original front for some time after transition. Figure 8(a) is a satellite image of Noel at T-0. Short-lived Noel moved northward with the extratropical system before completing ET itself. Delta eventually separated from the original frontal system and maintained tropical storm status for several days. Karl was an unusual storm (even for the northeastern Atlantic Ocean) in that it formed at the core of a larger extratropical cyclone. Figure 8(b) is a satellite image of Karl at the time of genesis. Only two other TCs have been documented with a similar developmental pathway: the Unnamed Hurricane (1991), and Tropical Storm Grace (2009, discussed as a case study at the end of the Results section).

4.3.2 Frontal-Weak (FW)

FW systems comprise the largest of the four categories. Half the study set falls into this sub-type, and accordingly it is a varied group. Some storms (e.g. Florence 1994) formed in nearly tropical environments, while others are marginally too weak in 850 hPa vorticity to be included in the strongly baroclinic FS category (e.g. Peter). A FW storm's transition intensity minimally relates to its maximum intensity. Ivan and Florence became Category 2 hurricanes after transitioning at 35 kt, yet Otto never strengthened more than 10 kt above its 35 kt transition intensity.

4.4 Spatial and Temporal Patterns of Formation

Formation locations of the 20 TCs were spread across the study area, spanning 40 degrees of longitude and 17 degrees of latitude. Table 1 contains the date and coordinates of formation, initial intensity, and the type of each storm. Figure 2 plots the locations on a map of the Atlantic Basin with the study boundaries. The three NFT storms occurred in the southwestern corner of the region, from 60°W-57°W. They also formed relatively far south: the northernmost TC (Nadine) formed at 30.4°N, and the southernmost TC (Holly) at 22.5°N. All three developed between 20-27 October.

All seventeen baroclinic systems formed east of the NFTs. NFB systems (all two of them) formed in the middle of the study region. Irma developed about 500 km southwest of the Azores, and Lorenzo formed about 1500 km east of Bermuda. It is interesting that the five TCs without strong 500 hPa cyclones formed during October.

The five FS TCs developed in the northern two-thirds of the western half of the study region. Longitudes ranged from 56°W to 41°W. Noel and Karl formed at about 37.5°N, and Lili-84 and Lili-90 formed at about 31°N. Delta was the southernmost FS at 27.4°N.

Consisting of ten TCs, FW was the largest type. Storms in this type form in three regions: the western, southern, and northeastern Atlantic basin. The western region produced five storms: Jose, Florence, Olga (2001), Otto, and Epsilon. They formed in a cluster from 53°-47°W and 26°-32°N. Florence and Jose formed in late October/early

November about 5° south of the genesis latitude of Olga, Otto, and Epsilon. These three developed during the last seven days of November around (30°N,50°W).

The three storms in the southern region were very late-season storms even by this study's standard. Nicole (1998) formed in the last week of November, Peter in the second week of December, and Zeta on 30 December. Lastly, the two storms that developed in the northeastern region were Ivan and Vince. Both formed in the first ten days of October around 35°N and east of 25°W.

Table 3 contains T-0 data for all twenty storms for the major environmental variables: SST, wind shear, 200- and 300 hPa temperature, 200- and 300 hPa static stability, equilibrium level, convective available potential energy, and ratio of maximum potential intensity to observed intensity.

4.5 Results for Sea Surface Temperature Analyses

SSTs varied widely under the twenty study systems. Figure 9 is a histogram of the 120 6-h SST measurements for all twenty storms, binned by 1°C, expressed as a percentage of the type total, and color-coded. The three NFT storms had the warmest 30-h average SST. All three remained over SSTs warmer than the 26.5°C tropical threshold stated in Bosart and Bartlo (1991) for the thirty hours prior to transition. Nadine, the coolest NFT system, developed over water an average of 0.9°C warmer than that under Florence, the warmest of the baroclinic precursors. The three baroclinic classes were mixed in the rankings. Sixteen of the seventeen baroclinic storms formed over 30-h average SSTs below the 26.5°C threshold.

Twelve of the twenty storms were located over SSTs at least 0.3°C cooler at T-0 relative to the T-30 SST, indicating they encountered cooler water as they neared genesis. Thirty-hour averages for FW and FS types had ranges of 4.6°C and 5.2°C respectively. Averages for the two NFB systems were separated by 2.1°C , and NFT systems had a range of 0.2°C . For the NFBs, Irma tracked northward over water that decreased from 24.2°C to 22.8°C . Pre-Lorenzo moved mainly westward, and stayed over water 25.0 - 26.2°C .

The TCs that developed from frontal systems were the most interesting. FS SSTs were spread over seven bins with peaks at 21°C and 25°C . Karl developed over the coldest water and Lili-90 over the warmest. The three remaining storms were scattered across the bins. The FW TCs were spread from 21.1°C - 27.0° . This distribution appears like a normal distribution for the lower five bins, with a large second peak in the uppermost bin (26.1 - 27.0°C). Most FW storms occurred over SSTs of 23.0 - 25.0°C . At no time was an FW storm over SSTs cooler than 21.1°C .

Figure 10 is a scatterplot of 30-h average anomaly against 30-h average SST. Most of the analyzed TCs formed over SSTs slightly warmer than climatological values. SST anomalies exceeded 0.2°C for ten of the twenty storms. Anomalies exceeded 0.5°C for five of the twenty storms. Only Karl and Lili-90 (both FS) formed over SST anomalies less than -0.3°C .

4.5.1 Maximum Potential Intensity

Maximum potential intensity (MPI) was calculated at the time of transition.

Figure 11 plots MPI against the transition intensity. In general, a negative trend is evident on the graph. Lower MPIs are associated with higher transition intensities. Lili-90 is the obvious outlier on the right edge of the plot; this storm formed over 25.4°C SSTs in early October. The three NFTs are in the upper left-hand corner of the plot. Though over warm SSTs, they transitioned as minimal tropical storms of 35 kt.

Ratios of MPI to transition intensity were also calculated (see Table 3). The ratios match the classification scheme quite well, even for the FW and FS systems. Delta had a higher ratio than Vince, but Vince intensified by 15 kt from T-30 to T-0 whereas Delta intensified by only 5 kt in the same time span. NFT systems have the highest ratios, which is consistent with their location and structure. The placement of Irma and Lorenzo in the rankings is interesting. Lorenzo's ratio was close to the tropical ratios, and indeed the storm formed in a nearly tropical environment. Its precursor was not a tropical wave, however, and thus did not warrant the NFT classification. Irma formed in a baroclinic environment and moved northward into an even more baroclinic environment. Thus its placement in the middle of the FW spread seems appropriate.

4.6 Results of Wind and Geopotential Height Analyses

4.6.1 Wind Shear: Local Averages

Wind shear is generally believed to be the second-most critical factor (after SST) for TC genesis (e.g., DeMaria et al. 2001). Distinctive shear patterns exist across all four

types. Figure 12 is a four-panel plot (one panel for each type) of the 30-h 850-200 hPa shear time series for each storm. Figure 13 is in the same style as Figure 12, but for the 850-300 hPa layer.

NFTs formed in the strongest shear environments, followed by FW and FS. [NFB comprises two very different storms, and is thus difficult to compare as a type to the others.] For all types both the mean and median composites cluster in a small range of shear values at T-6 (both 1.6 m s^{-1}) and T-0 (0.7 m s^{-1} mean, 1.6 m s^{-1} median). The next section will examine individual patterns within types.

All three NFT systems (Figures 12(a), 13(a)) had dynamic shear patterns. With the exception of T-12, shear over the 850-300 hPa layer remained less than 7 m s^{-1} . There was a peak at T-12 of 9.1 m s^{-1} . At T-30, Holly and Tanya had 850-200 hPa shear of 18 m s^{-1} , but decreased to 8 and 13 m s^{-1} respectively at T-0 with a minimum at T-18 of $8\text{-}9 \text{ m s}^{-1}$. The incipient Nadine experienced steadily increasing shear in the 850-200 hPa layer from T-30 (10 m s^{-1}) to T-0 (13 m s^{-1}). This is consistent with the description in Nadine's TCR, which mentioned an upper-level trough northwest of the developing system.

Pre-Irma and pre-Lorenzo (Figures 12(b), 13(b)) were in shear environments of similar magnitude from T-30 to T-18 ($4.0\text{-}8.0 \text{ m s}^{-1}$ for 850-300 hPa, and $6.0\text{-}10.0 \text{ m s}^{-1}$ for 850-200 hPa). While Lorenzo remained in an area of low shear through T-0, Irma entered a shear environment nearly double the previous magnitude at T-12. The 850-300 hPa layer increased from 10.3 m s^{-1} at T-12 to 13.5 m s^{-1} at T-0, and the

850-200 hPa layer had shear of about 17 m s^{-1} . While the sharp increase might in part have been due to the northward shift at T-12 in the reanalysis center grid point, satellite imagery revealed a strong trough approaching from the northwest. Therefore Irma likely entered a greater shear environment around T-12.

With the exception of Delta, the FS set had similar patterns (Figures 12(c), 13(c)). Over the 30 h prior to transition, Karl, Lili-84, Lili-90, and Noel had 850-300 hPa environmental shear of less than 12 m s^{-1} , and with the exception of Karl at T-30, less than 8 m s^{-1} . At T-6 (T-0) the range decreased to $6\text{-}7 \text{ m s}^{-1}$ ($6\text{-}8 \text{ m s}^{-1}$). Delta's shear time series was U-shaped, decreasing to less than 7 m s^{-1} at T-18 and T-12, but exceeding 9.7 m s^{-1} at T-24 and T-6, and 14.2 m s^{-1} at T-30 and T-0. There was greater variability in the 850-200 hPa layer. Delta again had the U-shaped pattern, but the remaining four had flat time series with slightly larger ($4\text{-}6 \text{ m s}^{-1}$ instead of $2\text{-}4 \text{ m s}^{-1}$) ranges from T-12 to T-0. All four had shear less than 10 m s^{-1} from T-24 to T-18, and less than 13 m s^{-1} at T-30 and from T-12 to T-0. Delta exceeded 16.5 m s^{-1} at T-30, T-6, and T-0, but decreased to 6.7 m s^{-1} or less from T-24 to T-12.

Most of the FW storms had flat shear patterns for both the 850-300 hPa and 850-200 hPa layers (Figures 12(d), 13(d)). Jose significantly affected the FW trend line since its 850-300 hPa environmental shear decreased from 23.4 m s^{-1} at T-30 to 7.4 m s^{-1} at T-0. The remainder of the FW set had ranges of 4.9 m s^{-1} or less, and with the exception of Nicole, 3.7 m s^{-1} or less. Florence had 850-300 hPa shear of $2.0\text{-}4.1 \text{ m s}^{-1}$, likely contributing to its quick intensification and relatively tropical appearance. Ivan,

Olga, Otto, Vince, Epsilon, and Zeta had shear values from 4.6-10.6 m s^{-1} for the 30 h period. Peter and Nicole were in high-shear environments (16.0-19.2 m s^{-1} and 11.7-16.6 m s^{-1} , respectively).

There was more variability across the type and within individual time series for the 850-200 hPa analysis. Jose again dominated the pattern, decreasing from 31.7 m s^{-1} to 11.4 m s^{-1} over the 30 h study interval. Pre-Nicole experienced moderate shear (12.8-16.3 m s^{-1}) at T-30 to T-18, but from T-12 to T-0 the shear increased to 19.4-24.9 m s^{-1} due to an approaching trough. Peter was also separated from the other FW systems, ranging from 17.6-21.7 m s^{-1} . The remaining seven FW storms were observed to have a net range of 10.6 m s^{-1} for the 30 h time series. Epsilon had the largest individual range at (7.8 m s^{-1}), and the Vince the smallest (2.2 m s^{-1}). At T-0 seven of the ten FW storms had average environmental shear of 8.2-11.4 m s^{-1} . Olga was slightly higher at 14.6 m s^{-1} , and Nicole and Peter were the two highest at 19.4 m s^{-1} and 21.7 m s^{-1} , respectively.

4.6.2 Wind Shear: Large-Scale Contour Coverage

Analysis of the 30°x30° shear coverage computations revealed a strong seasonal signal (mid-autumn and late autumn/early winter). There were fewer discernable differences between types, except that all the non-frontal systems formed in October. The switch from early to late shear environments seems to occur in early November, though an exact date was not apparent in the data. Jose and Noel (30 October 1981, 5 November

2001) were clearly late storms by their coverage percentages, yet the fields associated with Florence (4 November 1994) had consistently large areas covered by low shear.

Figure 14 is a four-panel plot of shear coverage, averaged for early and late storms in both the 850-200 hPa and 850-300 hPa layer. Percentages for the early-season storms in the 850-200 hPa layer (upper left) were similar to those for the late-season storms in the 850-300 hPa layer (lower right): 11% (8 m s^{-1}), 27% (12 m s^{-1}), 45% (16 m s^{-1}), and 62% (20 m s^{-1}). Early-season storms formed in environments with much more area covered by low shear in the 850-300 hPa layer (lower left): 24% (8 m s^{-1}), 50% (12 m s^{-1}), 74% (16 m s^{-1}), and 87% (20 m s^{-1}). Late-season storms tended to have very small areas covered by low shear in the 850-200 hPa layer (upper right). The area contained by the 20 m s^{-1} contour for this layer was less than that contained by the 12 m s^{-1} contour in the 850-300 hPa layer.

4.6.3 Wind Shear: 5° Box Point Count

Storms varied considerably in the number of low-shear points in the $5^\circ \times 5^\circ$ storm-local box. Figure 15 is a graphic of the number of points with shear of 8.0 - and 12.0 m s^{-1} or less. The tropical systems (Figure 15(a)) tended to have the fewest points with calculated shear less than 8.0 m s^{-1} . In the 850-200 hPa layer, all three storms had four or fewer points with shear of less than 8.0 m s^{-1} . The two NFB systems (Figure 15(b)) had point patterns similar to their overall shear pattern, likely due to the influence of large-scale features (or, in Lorenzo's case, the absence of such features).

On average an additional two points were covered by 8.0- and 12.0 m s⁻¹ contours in frontal environments for the 850-300 hPa layer than for the 850-200 hPa layer. FW systems (Figure 15(d)) were more variable than FS systems (Figure 15(c)), though Delta ranged from 1-9 points for the 12.0 m s⁻¹ contour in the 850-200 hPa layer.

4.6.4 Wind Shear: Radii of 4.0- and 8.0 m s⁻¹ Contours

Figures 16 and 17 displays the number of hits for the 8.0 m s⁻¹ contours at a given radii for 850-200 hPa and 850-300 hPa layers at T-0, respectively. The NFT category (Figures 16(a), 17(a)) consistently had the smallest percentage of hits at both levels and contours. Differences were particularly apparent for the 4.0 m s⁻¹ contour. Both Irma and Lorenzo (Figures 16(b), 17(b)) occurred within 400 km of an 8.0 m s⁻¹ contour for the 200- and -300 hPa layers.

Differences between the 250 km hits and the 400 km hits were largest for the 4.0 m s⁻¹ contour. FW storms had fewer hits than FS storms, especially in the 850-200 hPa layer. FW percentages for the 4.0 m s⁻¹ contour were half the values for FS storms. In the 850-300 hPa layer, the two types were more similar for the 4.0 m s⁻¹ contour, and almost identical for the 8.0 m s⁻¹ contour. An 8.0 m s⁻¹ contour fell within 250 km of FS storms over 95% of the time. Only at T-0 was a contour outside the 250 km circle.

4.6.5 Wind Shear: Quadrants

Figures 18 and 19 show the number of occurrences of the 4.0- and 8.0 m s⁻¹ contours in each quadrant of the storm's environment. Each type had a particular quadrant of the 500 km circle containing 8.0 m s⁻¹ contours most frequently. NFT storms often had contours in the right-rear quadrant, and NFB storms in the left-rear quadrant. Frontal systems tended to have low shear ahead of them. All five FS storms had 850-300 hPa 8.0 m s⁻¹ contours in the left-front quadrant, though the entire left-of-track semicircle had more hits than the right semicircle. The opposite was true for FW storms: an average of eight storms had an 850-300 hPa 8.0 m s⁻¹ contour in the right-front quadrant, and 7 storms with hits in the other quadrants. There was a shift towards more hits at T-18 in the 850-200 hPa layer.

4.6.6 Wind Shear: Zonal and Meridional Components

McBride and Zehr (1981) specifically stated the shear results from their comparison study of Atlantic non-developing and developing systems did not apply to TCs originating from baroclinic systems. While the upper-level cyclones located above most of the baroclinic systems in this work render the sign orientation invalid, the location of the zero shear line may still be relevant. Thus a similar analysis was performed on the 30°x30° shear fields. The composite fields at T-0 are plotted in Figure 20 (zonal) and Figure 21 (meridional).

NFT precursors were located near the zero-shear line in the zonal fields at T-18 and less closely at T-0. Meridional zero-shear zones in the 850-300 hPa layer occurred

near the developing TC at all times, but at only T-30 and T-24 in the 850-200 hPa layer. At other times, a strong gradient was co-located with the storm center. Non-frontal baroclinic precursors were located near the zero-shear line in the zonal fields from T-24 to T-0, and in the meridional fields from T-30 to T-18.

Zero shear zones were found closer to frontal precursors, and were closed contours instead of lines. The zonal 850-300 hPa zero shear composite was located close to the developing FS systems at T-30 to T-0, and only discernable at T-18 and T-12 for the 850-200 hPa layer. Zero shear of the meridional wind occurred over the composite center from T-30 to T-12, and was found to the east at T-6 and T-0. Areas to the west (east) of the storm center tended to have negative (positive) meridional shear. Zonal shear in the FW environments was non-zero but small (about 4 m s^{-1}). Values were positive over all six time composites. For the meridional shear, the zero line was nearly overhead at all times. Again, negative meridional shear values were negative to the west of the storm center and positive to the east. McBride and Zehr (1981) found the opposite formation in their work, but the difference is consistent with a cyclone in the upper levels instead of an anticyclone.

4.6.7 Wind (u - and v -Components): 200- and 300 hPa winds

Spatial variations were large in upper-level wind speeds. The mostly-tropical NFT systems tended to form on the edge of light-wind areas, especially in the 200 hPa fields. Areas of higher winds protruded from the northern region into the area under which the

storms were developing. The two weak baroclinic systems had small areas of light winds overhead at 200 hPa, and larger areas at 300 hPa.

Larger extratropical structures were apparent in many of the frontal maps. In four of the five FS cases, there was a small area of winds less than 12.0 m s^{-1} over the storm. Again, Delta formed in a high-shear environment, but there were areas of light upper-level winds close to the developing TC. As with the NFBs, the areas were larger and the winds lighter at 300 hPa, though the overall pattern remained the same. Two distinct patterns emerged in the FW storm fields. Most FW systems formed under the edge of light-wind areas, and the areas tended to be narrow and elongated. Bands were wider and weaker at 300 hPa compared to 200 hPa. Only Florence and Otto (and perhaps Epsilon and Zeta) formed under large areas of light winds.

4.6.8 500 hPa Geopotential Height Fields

During the months in which NFT systems formed, a strong ridge was located over the eastern and central Atlantic, though the longitude of the axis varied. October 2001 (Lorenzo) was also characterized by ridging over the eastern Atlantic. The ridge was split in October 1978 (Irma). A weak ridge was located at about 60°W and a stronger ridge at about 5°W .

The NFT storms began to develop at about 60°W , 10° west of the ridge axis at T-36. By T-0 the ridge had shifted $10\text{-}15^\circ$ east of its T-36 position. Figure 22 is a map of the 500 hPa geopotential height contours at T-0 for Holly. Tanya was still south of the ridge, but a (weaker) trough was within 10° of Holly (1976) and a (stronger) trough was

within 5° of Nadine at T-0. Precursors to Irma and Lorenzo were located south of a ridge, and slightly west of the axis. Figure 23 is a map of the 500 hPa geopotential height contours at T-0 for Lorenzo. At T-0 the ridges had moved east. Both storms were still under the western sides of the ridges, but strong troughs were located about 20° to the west in both cases. These troughs help to explain why neither storm strengthened above its transition intensity.

Months during which FS storms formed tended to have zonal flow across most of the Atlantic, broken by low-amplitude ridges in the far eastern region. For the months in which FS and FW storms formed, the pattern tended to match the more dynamic FW conditions. Baroclinic cyclones were obvious in the T-36 maps close to the location of TC formation. Four of the five FS storms had fewer closed contours at T-0 than at T-36. Delta had no closed contours at T-36, and two at T-0. Delta and Lili-90 were directly south of a ridge at T-0. The other three were on the west side of a strong ridge. Figure 24 is a map of the 500 hPa geopotential height contours at T-0 for Karl, and Figure 25 is for Delta at T-0.

Geopotential height patterns at 500 hPa for FW storms had more noticeable eastern Atlantic ridges than for the FS storms. Ridge axes were located between 20°W and 35°W (Peter 2003 is a very good example, shown in Figure 26). Florence and Vince were the exceptions. Florence developed in the southwestern part of the study region in a quasi-tropical environment. Flow aloft was nearly zonal. Vince formed from an occluded cyclone at about 20°W . In this case the ridge axis was at 55°W . At both times FW storms were generally south of ridges, though with no apparent trend to form east or west of the

axis. Shortwave troughs were passing through the ridge in two of the ten cases (Ivan and Olga (2001)), which could have triggered surface cyclogenesis. Ivan's T-30 map is shown in Figure 27. At T-0 shortwave troughs were also apparent near Florence, Olga (2001), and Epsilon. Florence's T-0 map is shown in Figure 28. Eight out of the ten FW storms had closed contours at T-36; at T-0 this number increased to nine out of ten.

4.6.9 300 hPa Geopotential Heights and Anomalies

Distinct patterns exist in the 300 hPa geopotential height and anomaly analyses. Figure 29 (30) shows observed 300 hPa geopotential heights at T-36 (T-0). NFT patterns were different from the three baroclinic patterns. The plots confirm the tendency for cold-water TCs to develop in the subtropics, between the zonal pattern in the tropics and the dynamic activity in the mid-latitudes.

NFT systems developed on the edge of the mid-latitude storm track. At T-36, ridges were evident north of both the NFT and NFB composite center. A developing TC was not discernable in the NFT composite, but a decrease in heights close to the system location was present in the NFB composite. At T-0, ridging was still apparent north of the composite center in the NFT plot, but with a decrease in heights far to the northwest. Ridging was relatively stronger for the NFB composites. A strong trough was located about 20° west of the composite center at T-0. This synoptic situation was consistent with the TC Reports for Irma and Lorenzo, which were impacted by troughs shortly after transition.

The two frontal composites showed less strong heights patterns, perhaps because of the greater number of storms in each type. At T-36, the FW composite indicated a tendency towards ridging north of the center. An upper-level (open) low with net positive tilt was also located over the center. The FS composite showed smoothed height contours north of the storm with no ridging apparent. As with the FW composite, an upper-level open low (but with net negative tilt) was located over the center. Patterns had changed perceptibly by T-0. The FW composite still showed broad ridging to the north, and slightly stronger to the east of the center. The upper-level cyclone over the center in the FS composite had one closed height contour, and ridging was more evident over the entire area.

Next, the OBS-LTM anomaly maps will be discussed. Figures 31 and 32 show the OBS-LTM composite analyses for T-36 and T-0, respectively. These analyses were nearly identical in pattern to the OBS-MON pattern, except slightly stronger in both positive and negative anomalies. Therefore only the OBS-LTM pattern is shown. Large areas of negative height anomalies were located northeast and northwest of the composite NFT center and a weak positive anomaly was located about 20° north of the center. By T-0, the area of negative anomalies to the northwest at T-36 had moved to 0° relative longitude. Latitudinal separation had decreased to 17.5° from 25° . For the T-36 NFB composite, a large area of positive anomalies was located north of the composite center. An elongated area of large negative anomalies was located about $20-40^{\circ}$ west of the center. By T-0, the pattern had shifted eastward, with the strongest positive anomalies to

the north and east of the center. The elongated negative area had become a circular region centered about 10° north and 15° west of the composite center.

The FW composite exhibited a moderate negative anomaly (~ -80 gpm) at T-36 over the developing TC, and a moderate positive anomaly (~ 130 gpm) about 17.5° north and 12.5° west of the location. Anomalies were stronger (more negative and more positive, respectively) in the LTM composite than in the MON composite. At T-0, the negative anomaly was still present at roughly the same magnitude as T-36. The positive anomaly had developed two cores about 15° north of the system. The weaker core was located 5° east of the system, and the stronger core 25° west of the TC.

Overall, FS anomalies were more extreme than for FW storms. At T-36, the composite anomaly had a minimum of -180 gpm over the developing system. Strong positive anomalies were observed in a zonal band about 15° north of the system. The positive anomalies wrapped around the western side of the negative anomaly, with 60 gpm observed at 0° storm-relative latitude. By T-0, significant changes had occurred. The negative anomaly weakened to 140 gpm, an increase of about 40 gpm. The positive anomaly located poleward of the negative anomaly increased in intensity and remained situated at roughly the same longitude as the TC signature. Positive anomalies curved southward along the eastern side of the negative anomaly.

Figure 33 shows the MON composite anomalies for the T-0 storm positions on a Lagrangian grid. The plot is nearly identical to one produced using the T-36 positions as center coordinates; this is not very surprising given that the storms moved at most about 5° of latitude or longitude over the analysis period. Only the FW and FS composites

show distinctive features. There was ridging to the east of where frontal systems developed. The ridging was slightly weaker in the FS cases than in the FW cases.

The last analysis performed on the geopotential height data was a plot of the 300 hPa height anomalies over a fixed region (100°W - 0°W , 5°N - 55°N). Figure 34 shows the resulting type-composite plots. No distinct patterns had set up during the months in which cold-water storms formed. A broad area of weak height anomalies was present over the central and eastern Atlantic Ocean in the NFT composite. There were small negative height anomalies (~ -30 to -60 gpm) over the eastern U.S. in the NFB composite, and small positive (~ 30 - 60 gpm) height anomalies over the eastern Atlantic Ocean and the eastern U.S. in the FW composite. The FS composite had weak positive anomalies (~ 60 gpm) over the north-central and northeastern U.S.

4.7 Results of Temperature Analysis

4.7.1 30-h Temperature Change (*Vertical Profiles*)

Examining the temperature profiles as a six-step time series did not produce clear results. Comparing just the T-30 and T-0 Skew-Ts was useful, however. Figure 35 contains type-composited temperature profiles plotted on Skew-T diagrams for T-30 (a) and T-0 (b). Differences between the types are apparent in these diagrams. In both cases, the NFT composite was much warmer from the surface to about 200 hPa than the non-tropical types. At 150- and 100 hPa, it decreased sharply to become the coolest of the types. This behavior is consistent with the known gradient of stratospheric temperatures towards the poles. Through about 400 hPa, lapse rates were relatively small. The

composite NFB profile was the next-coolest. Very steep lapse rates were present through the 850 hPa level. FW storms tended to be cooler than NFB storms, but warmer than FS storms. There was a distinctive kink in the temperature profile at 700 hPa for both the FW and FS composites, suggesting very small lapse rates in the layer surrounding that level. This feature was seen in many of the individual FW Skew-Ts. The FS composite profile was the coolest of the four from the surface to about 250 hPa. Above 250 hPa, it reversed position with the FW profile to become slightly warmer.

Profiles at T-0 altered in some notable respects when compared to T-30. NFT is still the warmest composite, but all the profiles have clustered. The warm region at 700 hPa is less pronounced at this time, indicating that lapse rates are larger overall. FW and FS composites have nearly merged below about 400 hPa, and are slightly more separate at 400 hPa and 300 hPa. Although it is difficult to estimate tropopause heights with any precision, the tropopause is probably about 150 hPa for NFT, about 200 hPa for FW, and about 250 hPa for FS.

Thirty-hour trends, or the change in temperature from T-30 to T-0 for each storm observed on the Skew-T diagrams, were compared to investigate temperature profile trends. Warming of more than 0.5°C was important because it likely indicated a change in the storm environment conducive to a more tropical system. The warming could be due to an increase in convection within the storm, or because the storm was moving to a warmer environment. Because of the reanalysis resolution, it is difficult to ascertain how much individual processes contributed to the observed warming. For this discussion, pressure levels were paired in the following manner: 925/850 hPa (lower storm, LS),

700/600 hPa (lower-middle storm, LMS), 500/400 hPa (upper-middle storm, UMS), and 300/250/200 hPa (upper storm, US).

Thirty-hour temperature trends for the NFT storms are plotted in Figure 36. Surprisingly, only Tanya exhibited warming of more than 0.5°C at LS and LMS. No storm environment showed warming in the UMS. Both Holly and Tanya showed warming in the US, while an upper-level trough was approaching Nadine from the west. NFB temperature trends are plotted in Figure 37. Warming exceeded 0.5°C in the Irma and Lorenzo environments in the LMS, UMS, and US, and for Irma in the LS.

Warming was especially pronounced on the FS Skew-Ts (see Figure 38). Lili-90 and Delta warmed by at least 0.5°C at all four levels. In the LS Noel's environment warmed by 0.3°C , slightly less than the 0.5°C threshold. Lili-84 cooled slightly in the UMS, and Karl cooled significantly (-1.5°C at 200 hPa). Environmental temperatures warmed by at least 0.7°C at one level in the LMS for all five FS storms.

As a type, FW storms did not have consistent Skew-T trends (see Figure 39). Four of the ten (Jose, Nicole, Peter, and Otto) warmed by more than 0.5°C in the LS from T-30 to T-0. Three of the ten (Ivan, Peter, and Vince) warmed by more than 0.5°C in the LMS, and five of the ten (Nicole, Peter, Otto, Vince, and Zeta) warmed by more than 0.5°C in the UMS. At the upper levels a warming environment was common: eight of the ten showed warming of more than 0.5°C in the US. Only the Jose and Epsilon environments did not warm. Peter warmed at all levels; this storm moved from 26°N to 20°N in 30 h.

4.7.2 200- and 300 hPa Temperatures: Observed, Concurrent Monthly, Climatological

Local observed 300- and 200 hPa temperatures were compared to the monthly and long-term means to determine whether the storm's upper-level environment was warming. Figures 40 (200 hPa) and 41 (300 hPa) are plots of the 30-h time series for observed, concurrent monthly, and climatological temperatures. There were large variations in 300 hPa temperatures. The 30-h NFT time average was about -33.0°C , while the three baroclinic types ranged from -36.5°C to -40.0°C . NFT climatological mean 300 hPa temperatures were usually cooler than concurrent monthly mean temperatures, and both means were cooler than the observed temperatures. Holly and Tanya had similar temperatures and patterns. Tanya's mean and observed temperatures were separated by $2\text{-}3^{\circ}\text{C}$. Nadine tended to be cooler for all three temperatures. Irma's and Lorenzo's temperatures were about 2°C apart throughout the time series, with no similarities among any of the patterns.

Composites of the 30-h average time series for FS and FW types revealed distinct patterns. FS was the coldest (-40°C), and FW was about $0.5\text{-}1^{\circ}\text{C}$ warmer. For both types the concurrent monthly and climatological monthly temperatures were warmer than the observed temperatures. Concurrent monthly temperatures tended to be warmer than the climatological temperatures. Looking at individual storms in the types reveals a range of upper-level conditions. Karl (Lili 1990) was the coldest (warmest) of the five FS TCs. The observed temperatures for Lili-84 and Noel were similar. Delta was warmer than both of them at 300 hPa.

Most of the FW storms developed with 300 hPa temperatures of -37°C to -42°C . The range collapsed from 6°C at 30 h to 3°C at T-12, then expanded to about 5°C by T-0. There were no strong trends in the relative magnitudes of the observed and mean temperatures.

The 200 hPa environment showed patterns distinct from the 300 hPa environment. Overall, the range of temperatures decreased. The NFT composite (warmest) was about 3°C warmer than the FW composite (coldest). Holly and Tanya were still similar to each other and warmer than Nadine. Lorenzo and Irma had observed temperatures separated by 3°C .

The FS cases became less widely spaced at 200 hPa in comparison to 300 hPa. Lili-84, Lili-90, and Noel warmed from T-30 to T-0, while Karl and Noel cooled. For all five FS cases, the observed 200 hPa temperatures were warmer than the corresponding long-term means. Only Lili-84 and Delta had observed temperatures warmer than the corresponding monthly means. With the exception of Lili-84, the monthly temperatures were warmer than climatology.

4.8 Results of Stability Analyses

4.8.1 *Static Stability*

As with the 300- and 200 hPa temperatures, the static stability patterns showed significant differences at the two levels. Figure 42 (Figure 43) plots the static stability time series using 200 hPa (300 hPa) as the upper level.

NFTs were the most statically stable of the four types using 300 hPa as the upper level. The three baroclinic types could be distinguished as well, however. All climatological and monthly composites fell in the range of 59.5-60.5°C. NFB and FS had similar composites in magnitude, hovering around 61°C. FW was the least statically stable of the four types for both 300- and 200 hPa, averaging about 59.3°C over the 30 h prior to transition.

Individual storms from all types were examined. All baroclinic storms clustered in a moderate (3.8°C) range of static stabilities by the time of transition. NFTs also clustered, but at more stable values. FS TCs ranged from 57.8-62.1°C (4.3°C) at T-30. By T-12, the range had decreased to 60.1-62.2°C (2.1°C), and was still 2.3°C at T-0. This decrease represents a significant shift in the overall environment. Similarly, the FW storms had a large range at T-30 (59.2-64.3°C, 5.1°C). By T-12, the range had decreased to 60.5-62.7°C (2.2°C). A small range was observed at T-6 as well (60.4-62.3°C, 1.9°C), but it increased at T-0 to 59.6-62.4°C (2.8°C). Lorenzo and Irma, the NFB TCs, remained within 1.5°C of each other and ranged from 60.3-61.9°C. At T-0, the values were 0.5°C apart. NFTs Holly and Tanya had similar 300 hPa static stability patterns, ranging from 58.0-59.6°C across the 30 h time series. Nadine was less statically stable from T-24 to T-12 (61.2°C), but similar at T-30, T-6, and T-0. Like the baroclinic systems, all three NFTs clustered at the time of transition. At T-6 (T-0), the static stabilities ranged from 58.7-59.6°C (58.6-59.8°C), indicating more statically stable environments than those which produced the baroclinic storms.

For the 200 hPa static stability analysis, NFT was the least statically stable type. The climatological and monthly means were nearly equal to the observed values. NFB was the second least-stable type, though with only two storms it is difficult to make comparisons. Using 200 hPa as the upper level, FW storms were less statically stable than FS systems on average, though the difference between the lines was larger at 300 hPa. The two frontal types had observed curves separated by 2°C. Monthly and climatological composites were similar in magnitude to the observed composite for FW storms. FS storms showed 0.5°C-1°C differences in the mean curves in comparison to observations. Differences decreased as the storms approach T-0.

Examining individual frontal storms for the 200 hPa calculations was more worthwhile than for the non-frontal types. FS initially had a wide range (73.5-80.4°C). By T-0, the four TCs occurring in November and December ranged from 76.3-77.7°C. Lili-90, the October storm, had relatively constant static stability of about 79-80°C. The FW chart did not narrow toward T-0 as seen in the FS chart. As with the formation locations, the FW type consisted of multiple sub-types. At T-30, there were three sub-types. Olga, Peter, and Zeta were the least statically stable of the ten FW storms, ranging from 81.6-81.9°C at T-30. Jose, Florence, Otto, and Epsilon were slightly more stable, ranging from 79.5-80.5°C. Ivan, Nicole, and Vince were the three most stable storms, ranging from 77.0-77.9°C. This pattern of T-30 static stability values appears to indicate a meridional split of environments. At T-0, the values clustered into two sub-types with a zonal split. Jose, Florence, Peter, and Zeta (the southernmost storms) were the least statically stable group, ranging from 80.3-81.5°C. The remaining six northern storms

were more stable, ranging from 77.0-78.5°C. No consistent differences between the observed and the mean static stability values were seen for either FS or FW storms.

4.8.2 Lifted Index

Results from computing the lifted index (LI) also revealed differences among the types. Figure 44 is a time series plot of LI, paneled by type. NFTs tended to have more negative LIs than the baroclinic set. Holly was the most stable, oscillating around -3°C (see panel (a)). Nadine increased from about -3.7°C from T-30 to T-12 to -2.1°C at T-6 and T-0. Tanya was the least stable environment, ranging from -4.7°C to -6.0°C. Irma and Lorenzo (see panel (b)) developed in more stable environments, with Irma consistently less negative than Lorenzo. This difference is reasonable considering that Lorenzo was in a borderline-tropical environment, while Irma was downstream of a strong frontal system.

Three of the five FS storms (Karl, Lili-90, and Noel) developed in environments of similar LIs in terms of magnitude and pattern: a semi-steady increase from -2.4°C at T-30 to -0.7°C at T-0 (see panel (c)). During the 30 hours prior to transition, Lili-84 experienced decreasing LIs from -0.9°C to -2.6°C. Calculations for Delta revealed a decreasing LI from T-30 (-2.9°) to T-18 (-4.3°C), then an increase to -1.5°C at T-6, and back down to -3.2°C at T-0. The peak at T-6 was probably due to a westward shift in the center reanalysis grid point, and thus should be more negative.

FW storms predominantly occurred in environments with LIs of -1.5°C to -3.5°C (see panel (d)). There were no discernable spatial or temporal patterns in the FW LI time

series. Only Florence had two points with LIs greater than -1.5°C (T-18 and T-12). Seven of the ten experienced increasing (less negative) LIs between T-6 and T-0. Peter's environment was constant, and Ivan and Florence decreased from T-6 to T-0. This short-term increase in LI close to the time of transition indicates the lapse rates are moving toward the saturated adiabatic lapse rate, which is likely caused by warming due to increased convection. Parcel temperatures were also trending warmer, but the T_E increase was larger, which suggests an environmental change.

4.8.3 Lifting Condensation Level

Figure 45 is a time series plot of LCL, paneled by type. Frontal systems tended to have lower LCLs (by about 10 hPa) than non-frontal systems. This finding is consistent with the relative structures of frontal and non-frontal TC precursors. The frontal systems were occluded near the surface, resulting in smaller dewpoint depressions. They were also colder near the surface. Together, these conditions created low LCLs. The frontal categories also had larger ranges compared to the non-frontal categories. FW had the largest range of LCLs (927– 983 hPa). One storm, Jose, experienced high LCLs relative to the rest of the type. Removing that storm reduced the range to 942 – 983 hPa, comparable to the FS type (943– 978 hPa).

Of note in the FW type is that the southern systems (Florence, Jose, Peter, and Zeta) tended to have the highest LCLs from T-12 to T-0 (see panel (d)). This was likely due to the relatively warm, but not necessarily more moist, environments. FS systems exhibited clustering behavior through T-6. All five storms remained within 20 hPa of

each other until T-0, at which point four of the five had LCLs of 950-960 hPa, and Lili-90 had an LCL of 943 hPa. It is interesting to note that the four clustered at T-0 occurred in November or later, while Lili-90 formed in early October. At T-0, Lili-90 was moving into a warmer, drier region, causing the rise in LCL. Nothing in particular emerges about the NFT or NFB patterns.

4.8.4 Level of Free Convection

Figure 46 is a time series plot of LFC, paneled by type. LFCs varied more than the corresponding LCLs. To a large extent, however, the patterns remained similar. Frontal systems had higher LFCs than did the non-frontal systems. Both Tanya and Nadine showed an increase in LFCs from T-30 to T-18, followed by a decrease from T-12 to T-0. Holly oscillated in a 20 hPa range around 930 hPa. The LFC in Lorenzo's environment tended to be 40 hPa higher than for Irma except at T-18 and T-0.

The two frontal types exhibited different LFC patterns. FS had a 12-25 hPa range at T-30 through T-6, usually between 940-960 hPa. At T-0, Lili-90 was an outlier from the other later-season storms with an LFC of 912 hPa. The other four were between 935-950 hPa. Again, Lili-90 clearly formed in a different thermodynamic environment than the other four FS storms.

FW was an even more interesting set. Between T-30 and T-18, the range was about 60 hPa and there were no consistent outliers (except perhaps Ivan). At T-12 and T-6, however, Jose and Peter diverged from the rest of the FW storms. The Skew-Ts indicated small environmental lapse rates in the 925-850 hPa layer at these times, which

contributed to the high LFCs. At T-6 eight of the ten FW storms had LFCs between 927-955 hPa, and at T-0 nine of the 10 were between 927-966 hPa.

4.8.5 Equilibrium Level

Estimation of storm ELs was a critical part of the analysis, since it acts as a proxy for the storm height. Figure 47 is a plot of EL time series, paneled by type. NFTs appeared to have higher ELs than did the baroclinic systems. Holly and Tanya varied by no more than 20 hPa over the thirty hours prior to transition. The environmental EL for Nadine rose to 180 hPa from T-24 to T-12, and then fell to 235 hPa by T-0. [The decrease was probably due to the aforementioned approaching trough.] The effects of an approaching trough could also be seen in the Irma data: the EL was about 230 hPa for the first three times, and then fell to about 290 hPa by T-6. At T-12 and T-0, the plotted EL was the second EL found on the Skew-T. The first EL occurred in the 850-700 hPa range, and was due to a region of small environmental lapse rates. Parcel temperatures were only 0.2-0.4°C colder than the environmental temperatures, however. It is likely that parcels continued rising through this shallow warm layer to reach the colder layer above.

FS storms split into two groups in the EL plot. Lili-90 and Noel had higher ELs of around 235 hPa through T-18. Karl, Lili-84, and Delta increased from 355 hPa to 280 hPa (Delta) or 310 hPa (Karl, Lili-84) by T-18. The groups split again at that point. The EL over Karl fell to 370 hPa at T-12 and T-6, and then rose again to 325 hPa at T-0. The other four remained spread across the 240-310 hPa range at T-12 through T-0. It should

be noted here that Karl, Lili-90, and Delta had second equilibrium levels (usually at 725-525 hPa) at some times.

FW storms on average had less variable ELs than the FS storms. For only one of the ten storms (Olga (2001)), the range was greater than 50 hPa. At T-24 and T-18 the minimum and maximum ELs were separated by about 55 hPa. Eight of the ten FW storms had ELs in the 230-280 hPa range at T-30, with the other two at 310 hPa and 340 hPa (Nicole and Olga, respectively). At T-12 nine of the ten had ELs of 230-275 hPa. The FW storms spread apart at T-6 and T-0. Four out of ten FW TCs had an additional EL in the 750-700 hPa range for at least three of the six times. Peter had 895 hPa and 725 hPa ELs at T-30 and T-24, respectively. Jose had low-level ELs at five times. Skew-Ts at T-6 produced single ELs for all twenty storms in the study.

4.8.6 Convective Available Potential Energy

Figure 48 is a time series plot of CAPE, paneled by type. Similar to the equilibrium level analysis, NFTs had larger CAPEs than did the baroclinic systems. In some cases, the values were more than three times as high. CAPE values were 1700-2000 J kg⁻¹ for Tanya, the largest of the three tropical systems. All three NFTs were above 1100 J kg⁻¹ in the 30 hours prior to transition. This is consistent with the NFTs occurring in less stable, and thus more typically tropical, environments.

Lorenzo formed in a moderately unstable environment with CAPE of 800-1100 J kg⁻¹. The effect of a low-level EL was apparent in Irma's Skew-T: CAPE

decreased by half in the T-12 to T-0 period compared to T-30 to T-18. For the first three times Irma and Lorenzo were in the $800\text{-}1000\text{ J kg}^{-1}$ range.

FS CAPEs followed EL patterns from T-30 to T-12. Calculations for Lili-90 and Noel indicated higher CAPE during that period than for Karl, Lili-84, and Delta. Four of the five storm environments had T-0 CAPE of 600 J kg^{-1} or less. The FW storms also split into two groups because of second ELs. At times with two ELs, environmental CAPE was less than 400 J kg^{-1} . Environments producing FW storms had smaller ranges when the times with second ELs were excluded. Only one storm, Jose, had a second EL at T-12 and T-0. Eight (nine) of ten FW storms had CAPEs of $700\text{-}1100\text{ J kg}^{-1}$ at T-12 (T-0). The collapsed range seems to suggest a trend towards an environment of modest instability.

4.9 Case Study: Tropical Storm Grace (2009)

After three years in which at least one TC formed in the study region, TC frequency decreased in the study region after 2005. The 2006 and 2007 seasons produced no systems fitting the study criteria. In 2008 a subtropical system formed in the north-central Atlantic and was eventually classified as Tropical Storm Laura. Unfortunately for purposes of this study, transition occurred at 12Z on 30 September. Laura was a cold-water TC, but did not occur within the time frame of the study. Almost exactly one year later, however, a TC formed that fit all parameters.

Tropical Storm Grace formed from a cold extratropical low spinning just northwest of the Azores in early October. Deep convection developed at the center of the

larger low, and eventually the core circulation showed enough tropical characteristics to be classified as Tropical Storm Grace at 6Z on 4 October 2009. No other tropical cyclone has been detected as far northeast as Grace in the HURDAT record. Operationally, Grace was classified as a tropical system at 3Z on the 5th. As mentioned earlier, it is not uncommon for NHC to classify transitioning systems as tropical in the post-season analysis prior to the operational time.

The same analysis performed on the 20 late-season storms was also completed for Grace's environment. Since Grace's official intensity was 40 kt thirty hours prior to genesis, the storm fits the FW category. Satellite imagery indicates Grace's structure shared similarities with Ivan and Karl. Both were very small TCs at the core of a larger extratropical system. Karl remained within the extratropical storm, but Ivan (also on 4 October, just 29 years earlier) separated and moved southwestward. Grace was more similar to Karl because Grace and the extratropical storm remained connected.

SSTs under Grace were very cold. Karl still holds the lowest average SST in the study, but Grace was colder than both Lili-84 and Ivan. Small positive (0.2-0.4°C) anomalies characterized the SST environment under Grace, consistent with the overall study set. At the time of transition Grace's MPI was 81 kt, twice the 40-kt transition intensity. This ratio places Grace squarely in the middle of the FW range.

Environmental wind shear was low in the region around Grace. Five-degree box averages were less than 7.0 m s⁻¹ until T-0 in the 850-300 hPa layer and until T-6 in the 850-200 hPa layer. All nine shear points were 8.0 m s⁻¹ or less for the 850-300 hPa layer at T-30 through T-18, and eight, six, and five at T-12, T-6, and T-0, respectively. Shear

was computed to be 12.0 m s^{-1} or less for all nine points from T-30 to T-6. Counts were usually lower in the 850-200 hPa layer. At least seven of the nine points were less than 8.0 m s^{-1} in the 850-200 hPa layer for T-30 through T-12, and all nine points were less than 12 m s^{-1} through T-6 (with seven at T-0).

Patterns of the radii and quadrants hits for Grace were consistent with a frontal system. The 850-300 hPa and -200 hPa 8.0 m s^{-1} shear contours passed within 250 km of the storm's location at all times. Counts decreased for the 4.0 m s^{-1} contours. These contours passed within 250 km of the storm at three out of six times, with no hits at T-6 and T-0 for either layer. All quadrants were covered from T-30 to T-0 for the 850-300 hPa layer, and until T-6 for the 850-200 hPa layer.

Geopotential height contours at 500 hPa showed patterns consistent with most of the FW environments. A large closed low was located south of a ridge at T-36. By T-0 the low had weakened, as had the ridge north of the storm. Another low approached from the west, and downstream of that system another ridge was building.

Thermodynamic parameters showed the strongest frontal signals. Temperatures increased by 0.9°C (0.7°C) at 200 hPa (300 hPa) from T-30 to T-0. The 200 hPa temperatures were $1.5\text{-}4.6^{\circ}\text{C}$ warmer than the monthly means, and $3.4\text{-}5.6^{\circ}\text{C}$ warmer than the long-term monthly means, suggesting that the upper-level cyclone was only cold relative to its environment. Differences at 300 hPa were much smaller, but observed temperatures tended to be cooler than the climatological means, especially closer to transition. Static stability patterns differed significantly for each upper level. Using 200 hPa as the top level showed a more statically stable environment compared to the

monthly means, and other frontal storms. Only Karl and Delta occurred in environments as stable as Grace's. Using 300 hPa completely changed the picture. Grace's environment was less statically stable in this layer than the climatological means, and was comparable in magnitude to the other FW storms' static stabilities.

Chapter 5: Discussion

Discussion of the results of this work will be conducted as follows. First, a recapitulation of the most important finding in the analysis will be given. Second, the four questions asked in the Introduction will be addressed in the context of the study results.

5.1 Overview of Results

Twenty TCs were identified in the northeastern Atlantic Ocean during the months of October, November, and December between 1975 and 2005. Another TC, Grace (2009), formed in the study region during early October of the 2009 hurricane season. Four distinct types of precursor disturbance were identified using satellite imagery, TC reports, and a comparison of the 850- and 500 hPa storm-local relative vorticity. The study set was divided into non-frontal and frontal types. These types were further subdivided into non-frontal tropical, non-frontal baroclinic, frontal-weak, and frontal-strong. Each type was analyzed for common environmental conditions in the hours prior to TC genesis.

Dynamic and thermodynamic variables were examined during the thirty hours prior to the genesis of the twenty study storms. Wind shear in the large-scale ($30^{\circ}\times 30^{\circ}$) environment was generally higher for November and December storms than for October

storms. Regardless of month, a small area of lower shear (less than 12.0 m s^{-1}) tended to collocate with the developing storm. Even for the storms with high shear (e.g. Peter, Delta), an area of lower shear was nearby at some point during the 30-h study period. The largest difference in the hit count for the T-0 radii analysis was for the 850-200 hPa layer between 250 and 400 km for FS and NFT storms. For FW and NFB storms, the largest difference was between 250 and 400 km in the 850-300 hPa layer. For the NFT systems, the T-0 low shear areas tended to be located to the rear of the storm motion. For the frontal types, the T-0 low shear areas tended to be located on the left (FS) and right (FW) of the storm track. This difference is probably because the TCs with frontal precursors are usually breaking away from the parent extratropical system.

NFTs had consistently high local average shear relative to the other types. Shear magnitudes and patterns varied widely for the two larger baroclinic categories (FW and FS). Using 300 hPa as the upper level instead of 200 hPa resulted in a large decrease in shear such that most of the developing storms experienced shear of less than 10 m s^{-1} for at least two of the six points. Only the FW systems Peter and Nicole remained in shear environments in excess of 10 m s^{-1} throughout the transition period. The FS storms had relatively constant shear magnitudes, with the exception of Delta. Delta's dissimilar shear pattern may have contributed to another of its distinctive factors. The other four FS systems had intensities of 65 kt or higher at the time of transition. Delta, however, had maximum sustained winds of only 50 kt. It also strengthened by just 5 kts from its T-30 intensity, whereas the other four increased by 10-20 kt (Karl and Noel were at about 45 kt

as well). Higher shear early and late in the transition period probably limited the intensification process.

Geopotential height fields mainly confirmed that NFTs initially formed well south of the mid-latitude storm track, and the baroclinic types on the edge or within the track. Fields tended to be relatively high-amplitude, indicating a very active pattern. Troughs and/or lows were apparent in the vicinity of the surface system in both the 500- and 300 hPa height fields for the frontal types, consistent with their formation from extratropical systems. There were few consistencies in the location of troughs and ridges relative to the developing TCs. Most baroclinic precursors were located to the east or west of the main ridge axis over the Atlantic.

Analysis of the thermodynamic conditions in which the TCs formed revealed the strongest differences between types. NFT storms were clearly separate from the baroclinic types in terms of SST and air temperature. The small SST range for type NFT suggests that a minimum threshold applies to TCs originating from tropical waves. An SST threshold of about 26.5°C is reasonable in this case. These results also suggest both lower and upper limits to TC formation from baroclinic precursors. The lower limit is not surprising, but the concept of an upper limit has not appeared before in the literature. FS TCs were not observed to form over water warmer than about 26°C, and FW TCs over waters warmer than 27°C. The question, then, is whether this is because the frontal systems do not occur over such warm waters, or whether there is an underlying thermodynamic reason.

Months in which frontal systems developed into TCs were usually warmer at 300 hPa than the climatological temperatures, which were warmer than the observed temperatures. At 200 hPa the composite FS TC observed temperature time series was warmer than the FW time series. Type-composited temperature differences between the baroclinic and tropical systems were much more pronounced at 300 hPa than at 200 hPa. This difference could indicate the FS cyclones are not as deep as the FW cyclones. At 300 hPa the NFT composite is warmer than the baroclinic composites by 2-5°C. At 200 hPa the NFT composite is warmer than the baroclinic composites by only 1-3°C. The differences in temperature have important consequences for static stability in the local environment.

Several measures of stability in the storm-local environment provide evidence that conditions are unstable near the TC, and that structural differences exist between TCs with baroclinic precursors and TCs with tropical precursors. First, the baroclinic systems had higher values of static stability (i.e. were less statically stable) than the NFT systems when using 300 hPa as the upper level. Composites for concurrent monthly and climatological means clustered in a 1°C range, less than the baroclinic observed composites and greater than the NFT observed composites. Using 200 hPa as the upper level, both frontal observed composites were less than the non-frontal observed composites, i.e. the frontal types were more statically stable in this layer.

LI is a common measure of atmospheric stability. Nearly all times for all storms had calculated LIs that were less than -0°C (unstable for surface-based convection). NFTs were the most unstable on average, but the baroclinic systems had LIs well into the

unstable range. Strongly negative LIs are important for developing deep convection, and the storm environments were conducive by this measure.

ELs showed large differences between the tropical and baroclinic precursors. Most of the tropical precursors had ELs from 180-220 hPa. FWs had a narrow range of about 220-310 hPa in comparison to the FS systems (220-370 hPa). CAPE values were also modest for the baroclinic precursors in comparison to the tropical precursors. Baroclinic precursors peak at about 1200 J kg^{-1} , while tropical precursors peak at about 2100 J kg^{-1} .

It has been stated that forecasting TT is largely a matter of predicting the onset of a favorable environment (DB04). The implicit assumption is that a TC originating from a baroclinic system requires the same environment as a TC arising from a tropical precursor. Yet no one has thoroughly examined the environments to determine whether similar environmental conditions are needed. At least in late-season cases over the northeastern Atlantic, TT occurs over SSTs below the tropical threshold. It seemed likely that others of the six necessary-but-insufficient conditions would require caveats in cases of TT. This work attempted to fill the gap in knowledge by analyzing the environmental conditions which produced a set of cold-water TT cases and a few high-shear tropical systems. The next section will discuss the questions raised in the introduction to this thesis.

5.2 Application of Results to Research Questions

5.2.1 Uniqueness

(1) Was the 2005 quartet of late-season, not-fully-tropical Atlantic cyclones unique?

The answer to the first question posed in the introduction is an unequivocal ‘no’. Twenty TCs were identified as forming in the study region. Many had characteristics very similar to the 2005 quartet, and two other precursor types were also identified. Given the evolution of satellite technology since the first year of the study (1975), it is possible more TCs have occurred in this region but were not officially identified as TCs. While this study indicates that late-season TC development over the cool waters of the northeastern Atlantic Ocean is not uncommon, neither does TC genesis occur over this region every year. Several consecutive seasons can pass by (e.g. 1985-1989) when no developments were recorded in this region. There have been other periods (e.g. 2000-2001 and 2003-2005) when this region was very active. [No TCs developed during the 2002 season after late September due to a strong El Niño, which increased wind shear over the Atlantic basin (Pasch et al. 2004).] In 1980, 2001, and 2005, multiple storms were identified in the region (2, 3, and 4, respectively). Only one of the nine total storms from these years was non-frontal (Lorenzo 2001, NFB). Three were classified as FS and five as FW. This indicates that conditions favorable for frontal systems to produce TCs can occur multiple times in a given season. Consequently, there are undoubtedly systems which could have produced TCs but did not, for as-yet unidentified reasons.

Ten of the twenty study TCs occurred during the 2000-2005 seasons. TC activity in the Atlantic basin entered an active phase in 1995 (Zehr and Knaff 2007). Activity in the northeastern Atlantic could be related to activity in the rest of the basin: environments generally favorable for TC formation are also favorable for formation in specific regions. This argument seems to fall apart when the conditions in which the study TCs formed are considered. Such conditions are anomalous in comparison to the conditions for TC formation in the tropics. Baroclinic precursors are also the dominating source of TCs in this region, and are not known to be correlated with activity in the tropics. Another possible reason is that improvements in satellite technology have allowed forecasters to better identify TCs forming in regions where aircraft reconnaissance cannot be flown. Changes in cloud structure can be tracked via geostationary satellite imagery, but changes in the temperature profile of a cyclone require more sophisticated instruments. A third possible reason for the recent increase is a climatic shift. SSTs have warmed in the Atlantic Ocean during the last few decades (Levitus et al. 2000). Northward and eastward expansion of the warm pool may bring marginal SSTs (23-25 °C) into more frequent contact with the extratropical storm tracks. In combination with other favorable environmental conditions, the SSTs may now be sufficient to support TCs originating from baroclinic precursors. These proffered reasons are speculation at this point, however.

5.2.2 Environmental Conditions during Formation

(2) In what environmental conditions do such TCs form, and how do they compare to the known conditions for tropical cyclogenesis in the tropics?

Local dynamic environmental conditions have a greater degree of variability than do the local thermodynamic conditions. This observation makes sense given that a TC has a very specific thermodynamic structure (deep convection near the center, and a neutral/warm core, with the greatest relative warming in the upper core). Static stability profiles indicated a relatively unstable atmosphere in most cases. In particular, environmental warming was noticeable in the T-30 to T-0 temperature profile difference.

To reiterate from the literature review, the following conditions are known to be necessary but insufficient for tropical cyclogenesis: 1) SSTs in excess of 26.5°C, 2) a pre-existing cyclonic disturbance, 3) a sufficiently strong vertical temperature gradient to support deep convection, 4) sufficient midlevel moisture, 5) low vertical wind shear, 6) an environment capable of supporting an upper-level outflow channel. Since neither 4) nor 6) was investigated in this study, the following section will focus on conditions 1), 2), 3), and 5).

The results of this study indicate that several caveats should be applied when the TC formed from a baroclinic system in this region. First, the 26.5 °C SST threshold has been shown to be inapplicable. In fact, most of the cases investigated in this study developed over SSTs much less than 26.5 °C. If the SST threshold is necessary for the storm to achieve a minimum energy flux from the ocean to the air just above the surface

(thus fueling the TC) then such TCs must be supplementing the air-sea flux with energy from another source. This idea will be discussed shortly.

The seventeen baroclinic systems were shown to have positive vorticity maxima at 850 hPa located in proximity to the developing TCs and, with the exception of Olga (2001, previously discussed), greater than $30 \times 10^{-6} \text{ s}^{-1}$ at T-30 in the reanalysis data. This result is evidence of pre-existing cyclonic disturbances in all cases. Therefore the second criterion does apply to the region. The definition of a TC mandates a cyclonically-rotating area of low pressure, so this condition's applicability is unsurprising. What is more surprising is the range of 850- and 500 hPa vorticity magnitudes observed to precede TC formation. A variety of non-tropical structures can eventually become TCs, so vorticity (aside from the minimum threshold) would not be a good discriminant for predicting whether a system will become a TC.

Investigation of condition #3 produced some of the more interesting results in this study. Extratropical cyclones normally have the deepest convection well away from the cyclone center. For TCs, the opposite is true: the deepest convection is co-located with the center. In order to develop deep convection around the center, an extratropical cyclone must undergo destabilization in its core. Extratropical cyclone structure is advantageous for condition #3: cold temperatures at 300- and 200 hPa create large vertical gradients of temperature. Relative to the NFT category, vertical gradients (which were approximated using static stability) for the surface to 300 hPa layer are actually larger than for the surface to 200 hPa layer. A larger difference in temperatures between tropical and non-tropical cases at 300 hPa versus 200 hPa caused this result. This switch

likely indicates a structural difference between TCs with tropical precursors and TCs with baroclinic precursors. Exceptionally large temperature gradients could have helped to fuel convection in a marginal environment.

Temperature profiles were largely consistent with the vertical gradients. Most storm environments warmed from T-30 to T-0. Warming was spread throughout the vertical column. One area for which the warming was particularly noticeable was the 700 hPa level. In many of the TC profiles 700 hPa temperatures produced a distinct 'kink' in the vertical profile, indicating the 850-700 hPa lapse rate was exceptionally low. This feature is consistent with low-level warming due to convective processes.

Investigation of condition (5) (low vertical wind shear) produced somewhat conflicting results. Data on the coverage of shear contours during the transition periods shows seasonally dependent differences. Storms during the five weeks of the study period (with the exceptions of Jose and Noel) tend to occur in environments with greater percent coverage of the weaker contours. Later storms are in environments with lower percent coverage. This result seems to indicate the large-scale environment is less important than the local environment. In cases where the large-scale wind fields create strong vertical shears, the storm-local environment can be relatively hospitable. Upper-level extratropical cyclone structure is dynamically rather favorable for TC development. The winds are usually weak in the upper core, producing a small area of very low shear that is nearly directly above the low-level center. Even so, the 5° local box averages can be rather large in the 850-200 hPa layer. Magnitudes are lower in the 850-300 hPa layer,

however. As with the SST threshold, the low wind shear criterion appears to require some caveats in cool-water storm cases.

5.2.3 Evidence of Tropical Structures

(3) Are there any indications that tropical structures are developing?

It was difficult to identify with a high degree of certainty whether any tropical structures were present. TCs in the study set tended to be small, and were rarely co-located with a grid point. However, there were some indications that systems' structures evolved into something distinct from the typical extratropical structure during the thirty hour study period. Satellite imagery suggested an increase in and deepening of convection close to the center of circulation in most cases. [Noel 2001 was a major exception.] Convection at the center is an important component of a TC, and most of the study set showed evidence of coalesced convection.

Examination of the reanalysis vertical temperature profiles indicated that temperatures warmed at one or more levels for all storms in the study. Warming was especially pronounced in the FS systems, which were initially the coldest. By T-0 the FW and FS composite temperature profiles nearly overlap in Figure 35; at T-30, the FS composite was distinctly colder. Granted, a lot of the observed composite warming is probably due to Delta, which warmed by 2-4.5°C for the levels from 925-400 hPa (Figure 38). The other four FS systems all warmed by more than 0.5°C at three or more levels, however. Fewer FW TCs were observed to warm: the maximum number was 5/10 at 200 hPa (Figure 39). Overall, the signs of warming in the middle and upper core were

more subtle than had been anticipated, but ultimately it should have been expected given the 2.5° reanalysis resolution.

5.2.4 Effects of Sea Surface Temperature on Structure

(4) Could the environment be inducing a storm structure that compensates for low ocean temperatures?

Several pieces of evidence support the theory developed in the Introduction and restated in this question. The temperature reversal observed in the 300 hPa and 200 hPa time series for the FW and FS storms is interpreted as a sign that the FS systems are shallower than the FW systems. If the tropopause is well below 200 hPa for the FS systems and closer to 200 hPa for the FW systems, the relative warming would make sense. Temperature profiles shown in Figure 35 indicate the reduced lapse rates and eventual warming that characterize the stratosphere are not present until about 150 hPa for the NFT storms, 200 hPa for the NFB and FW storms (falling closer to 250 hPa by T-0 for the FW profile), and 250 hPa for the FS storms. ELs are relatively low for the baroclinic systems, and modest CAPE values suggest updrafts are not very strong in the vicinity of the storm. Therefore parcels are not rising upward very much farther than the EL. In contrast, ELs are high for the tropical precursors, and larger CAPE values suggest stronger updrafts. These results together are evidence that the baroclinic precursors are shallower than their tropical counterparts.

This difference in height is most likely caused by the cool SSTs. The SST threshold of 26.5°C is the minimum value for supporting deep convection in the tropics

via WISHE. The baroclinic precursors have an advantage, however, in that they are able to supplement the air-sea fluxes by converting potential energy from horizontal density gradients into mechanical energy. Strong local instability due to the cold-core cyclone aloft supports deep convection, which warms the entire core from the low levels up, and begins the transition process. Shallower structures in the baroclinic precursors are also important because of the observed reduction in shear when using 300 hPa as the upper level instead of 200 hPa. It may explain why the intensity guidance models often verify poorly for late-season northeastern Atlantic TCs.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

There is a subset of Atlantic TCs in the official record which formed over SSTs below the historical threshold of 26.5°C . This subset represents a large fraction of the late-season formations in the northeastern Atlantic basin. Such storms appear to be a minimal threat to land, as they tend to be weak and stay over the open ocean. However, the Azores, Bermuda, and Europe have been struck by TCs originating in this region during the study period. The major threat from late-season TCs in this region is to the shipping industry. As was shown in Figure 1, commercial ships track through this region through the autumn and into winter. Accurate forecasts of TC track and intensity will help mariners to avoid dangerous areas. Anecdotal evidence (e.g. J. Beven, personal communication) indicates the storms in this region and season are not handled well by the intensity guidance models, often frustrating the forecasters.

Given the likelihood that TCs have been unidentified in this region (e.g. Landsea et al., in press) this study should not be treated as a comprehensive evaluation of all possible modes of late-season TC genesis in the northeastern Atlantic. Nor should the results be treated as absolute magnitudes and thresholds. However, it has captured the major developmental pathways and the relative differences between the associated environments. The four categories (one tropical, three baroclinic) of TCs in this region

are differentiated by dynamic and thermodynamic characteristics. Thermodynamic environments particularly differ among the types in terms of temperature and stability. Interestingly, wind shear magnitude did not appear to be a consistent factor in the various environments, as magnitudes and locations of shear minima varied widely.

6.2 Future Work

While this study has provided evidence in support of the theory that cool-water TCs differ structurally from warm-water TCs, many questions remain to be answered. Specifically, questions have arisen from the study regarding the precise roles of various environmental conditions in promoting or inhibiting development. The role of shear is not clear from this analysis, as the magnitudes vary even within types. In this final section, a brief discussion of possible future research will be conducted. It will be roughly divided into three sections: expansion of the study set, the effects of specific environmental parameters, and operational implementation.

6.2.1 Expansion of the Study Set

This research specifically focused on TCs forming over the northeastern Atlantic during October, November, and December. These criteria produced a study set too small for most statistics. There is also the question of whether the results generalize to other cool-water formations, which would be important in operational forecasting. Are all cool-water developments from baroclinic precursors? Do similar environmental conditions

occur in other regions? These questions should be explored to assist in forecasting future cool-water TCs.

Expanding the study set could be done in three ways: via spatial expansion, temporal expansion, and classification expansion. It would be very surprising if cool-water TCs did not occur in other regions of the Atlantic basin, though perhaps they are not in the Caribbean Sea. But the region between Bermuda and the U.S. East Coast has produced several TCs from baroclinic precursors which likely formed over SSTs cooler than the tropical threshold (e.g. Michael (2000) and Karen (2001)). The second method of expansion is to widen the possible date range. Again, it would be surprising if cool-water TCs occurred only during October, November, and December. Combining spatial and temporal expansions would likely produce a large enough study set to run more powerful statistics. A third expansion that would likely improve understanding of the processes which create a cool-water TC is to examine subtropical cyclones over appropriately cool SSTs which did not become TCs. Such a study might help to isolate environmental characteristics which are supportive of (or hostile to) TC development.

One expansion which the author is hesitant to recommend is to go back farther in the HURDAT record. Satellite imagery was critical in identifying TC origins, and imagery is limited before the mid-1970s. Dvorak and Hebert-Poteat techniques for satellite estimation of intensity were also not developed before the mid-1970s. Thus any TCs occurring prior to the mid-1970s that were never investigated by aircraft reconnaissance would be classified entirely subjectively. In the interest of collecting a minimum amount of data per storm, the initial year should be no earlier than 1975.

6.2.2 Effects of Specific Environmental Parameters

More research is needed on the roles of several environmental parameters in cool-water developments. First, if the 26.5°C threshold is not necessary for all TCs, then what determines whether SSTs are sufficiently high to support TC formation? Is it dependent on other environmental conditions? Other thermodynamic conditions, such as the static stability and relative core temperature (and probably the moisture content, though this variable was not examined here), would seem to be more likely relevant than wind parameters given the wide range in wind field patterns and wind shear magnitudes.

SSTs are only part of the story with TC intensity. The upper-ocean structure has more of an impact than the surface temperatures on TC intensity (Mainelli et al. 2008). Ocean Heat Content (OHC) is a measure of the energy available in the upper ocean to a TC (Leipper and Volgenau 1972). It is usually measured by integrating over the vertical column from the surface to the depth of the 26°C isotherm. Because SSTs in the northeastern Atlantic tend to be cooler than 26°C, OHC in the region is broadly zero. Clearly the use of the 26°C isotherm is too limiting in this case, since TCs are forming over SSTs below 26°C. It is possible that a layer of water with relatively warm temperatures exists beneath the TCs, and is helping to fuel the storms. A better lower threshold might be 21°C; Karl was the only study TC with a 30-h average SST of less than 21.0°C, and this storm had a very unique structure (as discussed earlier). Both Ivan and Lili-84 formed over SSTs with 30-h averages of about 22°C, and were the coolest of the remaining storms. Integrating to a lower isotherm may reveal the depth of the warm layer under the TCs.

One of the foremost questions in TC research is the trigger of TC genesis. On the surface it is a simple question. Ultimately, only the general sequence of events is known (and even that is not perfectly understood). Research is still ongoing to find what triggers tropical cyclogenesis. Knowledge is even more limited for TC genesis from baroclinic sources. At the beginning there is an extratropical cyclone; at the end, a tropical cyclone. The processes in between are still largely uncertain. What factors prevent development into a TC? For example, baroclinic systems are fueled by horizontal density gradients. TCs are fueled by the evaporation of seawater into the near-surface layer and sensible heat transfer from the ocean to the atmosphere. Satellite imagery suggests that for many TCs with baroclinic precursors, a hybrid tropical/extratropical structure exists for a period around the time of transition. Is this actually happening? If so, for how long does the symbiosis between the baroclinic and tropical energy sources persist? Does the balance gradually shift towards the air-sea fluxes, or does the dominant process suddenly switch?

This study focused on the large-scale environment, which was necessary given the resolution of NCEP/NCAR reanalysis data. It would be useful to compare the NCEP/NCAR reanalysis data to a higher-resolution dataset, particularly to look for evidence of warm core formation. Such an analysis would also be helpful in determining whether storms are actually tropical at the time of NHC designation, which is important for comparing different systems.

6.2.3 Operational Implementation

This study suggests differences in structure between TCs arising from baroclinic precursors and TCs arising from tropical precursors. It would be useful, then, for NHC forecasters to have a few characteristics which they could identify as indicators of a shallow structure, and thus to be cautious of model intensity forecasts. It appears that the situation of a late-season baroclinic precursor in the northeastern Atlantic should be a large red flag, but a more specific parameter would likely be better appreciated.

Equilibrium levels are one way to approximate storm height, but they are a very rough estimate since it is the (lower) pressure at which the environmental temperature exceeds the parcel temperature. The clouds extend higher than this altitude, though given the modest CAPE values the additional height is not likely to be much. One suggestion was to look at the dynamic tropopause heights, since the convection would not exceed that altitude (R. McTaggart-Cowan, personal communication.).

Perhaps the more fundamental question for this section, however, is whether formation of a cool-water system can be predicted. Satellite imagery is very good for identifying non-tropical systems acquiring tropical characteristics, but this method is real-time at best. Identifying high-risk extratropical cyclones would be useful for NHC forecasters. One possible method of doing so would be to identify favorable conditions in the large-scale environment, and be aware of when systems enter the region. Again, the large-scale conditions would have to be known. The preceding ideas are just some questions raised by the research and some additional angles to be considered.

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Appendix A: Tables

TC	Label	Date	Time	Lat °N	Lon °W	Type	Intensity (kt)	Line color on 4-Panel Time Series Plots
Holly	H76	10/23/1976	18Z	22.5	58.0	NFT	35	Black
Irma	I78	10/4/1978	12Z	35.1	31.5	NFB	40	Black
Ivan	I80	10/4/1980	18Z	35.6	24.6	FW	40	Pink
Karl	K80	11/25/1980	18Z	37.7	44.7	FS	65	Black
Jose	J81	10/30/1981	0Z	27.7	46.6	FW	35	Red
Lili 1984	L84	12/20/1984	12Z	31.1	52.4	FS	65	Red
Lili 1990	L90	10/11/1990	0Z	31.2	55.9	FS	70	Blue
Florence	F94	11/4/1994	0Z	26.0	52.6	FW	35	Teal
Tanya	T95	10/27/1995	12Z	26.2	57.9	NFT	35	Red
Nicole	N98	11/24/1998	6Z	27.9	29.1	FW	35	Brown
Nadine	N00	10/20/2000	12Z	30.4	57.2	NFT	35	Blue
Lorenzo	L01	10/30/2001	0Z	28.5	44.6	NFB	35	Red
Noel	N01	11/5/2001	12Z	37.8	50.3	FS	65	Gold
Olga	O01	11/24/2001	12Z	29.5	49.8	FW	50	Gold
Peter	P03	12/9/2003	6Z	20.0	37.4	FW	40	Purple
Otto	O04	11/30/2004	18Z	31.7	51.0	FW	40	Gray
Vince	V05	10/9/2005	12Z	33.8	19.3	FW	55	Blue
Delta	Del05	11/23/2005	12Z	27.4	41.2	FS	50	Purple
Epsilon	Ep05	11/29/2005	6Z	31.5	49.2	FW	45	Black
Zeta	Z05	12/30/2005	6Z	24.2	36.1	FW	40	Green
Grace	N/A	10/4/2009	6Z	38.5	29.5	FW	40	N/A

Table 1. Basic data for storms in study set. Columns from left to right are storm name, label for graphics, the date and time of genesis, the coordinates at the time of genesis, the type, the intensity, and the plotting color.

Variable	Type	Units	Levels (hPa unless indicated otherwise)
Wind (u and v)	A	m s ⁻¹	850, 500, 400, 300, 250, 200
Temperature	A	K	925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100
Temperature	A	K	0.995 sigma
Geopotential height	A	gpm	1000, 500, 300, 200
Pressure (surface)	A	Pa	surface
Specific humidity	B	kg/kg	925, 850, 700, 600, 500, 400, 300
Relative humidity	B	%	0.995 sigma

Table 2. NCEP/NCAR Reanalysis variables used in analysis.

Storm	SST (°C)	WS ₂₀₀ (m s ⁻¹)	WS ₃₀₀ (m s ⁻¹)	T ₂₀₀ (°C)	T ₃₀₀ (°C)	SS ₂₀₀ (°C)	SS ₃₀₀ (°C)	EL (hPa)	CAPE (J kg ⁻¹)	MPI:IO
Holly	27.6	8.4	7.5	-54.5	-31.8	81.3	58.6	196	1262	3.6
Irma	23.0	16.9	13.5	-57.4	-37.3	81.0	60.9	(282)	215	2.1
Ivan	22.8	11.2	8.1	-55.0	-39.9	77.0	61.9	285	711	2.1
Karl	19.5	11.6	7.4	-56.1	-44.4	73.9	62.2	323	486	1.1
Jose	25.4	11.4	7.4	-56.8	-38.1	81.1	62.4	(257)	126	2.9
Lili 1984	22.3	8.2	6	-56.1	-39.2	77.7	60.8	(305)	157	1.3
Lili 1990	25.9	7.1	7.9	-54.4	-35.6	79.5	60.7	(263)	177	1.5
Florence	26.4	9.1	2.8	-57.0	-35.1	81.5	59.6	221	1052	3.2
Tanya	27.4	13.4	11.2	-52.8	-32.9	79.4	59.5	188	1821	3.5
Nicole	24.2	19.4	13.5	-57.0	-40.3	78.4	61.7	303	786	2.7
Nadine	26.8	12.8	6.9	-55.7	-34.7	80.8	59.8	233	917	3.3
Lorenzo	26.2	6.1	4.6	-54.4	-35.9	79.8	61.3	253	1073	3.1
Noel	23.5	6.4	6.2	-55.3	-40.1	76.3	61.1	287	593	1.4
Olga	24.6	14.6	9.4	-56.1	-39.1	77.7	60.7	293	697	1.9
Peter	26.3	21.7	16.7	-56.5	-36.4	80.3	60.2	248	963	2.8
Otto	23.0	11.2	9.2	-56.6	-39.2	77.7	60.3	260	915	2.1
Vince	23.0	10.8	9.1	-56.5	-39.8	77.7	61.0	261	757	1.5
Delta	24.3	16.6	14.2	-55.2	-37.5	77.6	59.9	241	1042	1.9
Epsilon	23.3	8.2	6.5	-57.9	-41.8	78.5	62.4	243	1024	1.9
Zeta	23.8	11.4	7.3	-58.1	-39.8	80.6	62.2	257	687	2.2
Grace	22.2	9.7	9.7	-51.7	-39.5	72.7	60.5	356	292	2.0
NFT	27.3	11.5	8.5	-54.3	-33.1	80.5	59.3	206	1333	3.5
NFB	24.6	11.5	9.1	-55.9	-36.6	80.4	61.1	268	644	2.6
FS	23.1	10.0	8.3	-55.4	-39.3	77.0	60.9	284	491	1.4
FW	24.3	12.9	9.0	-56.7	-38.9	79.1	61.2	263	772	2.3

Table 3. Environmental variables at T-0 (time of genesis). WS is wind shear, SS is static stability, IO is intensity observed. Subscript indicates the applicable level. Parentheses around an EL indicate there was a second EL in the lower levels.

Appendix B: Figures

Figure 1. XBT release locations from 1 October to 31 December 2009 by commercial ships participating in the Ship of Opportunity Program (SOOP). New England is in the upper-left corner, South America in the lower left corner, and western Africa in the lower right corner. Graphic created using the SEAS BBXX interface (<http://www.aoml.noaa.gov/phod/trinanes/BBXX/>). Black lines at 20°N latitude and 60°W longitude mark the study's spatial boundaries.

Figure 2. Map of formation locations for the 20 study TCs. Location of formation is indicated by a circle, labeled by storm and color-coded by type. Red – NFT; blue – NFB; gold – FS; black –FW. Dark gray lines at 20°N latitude and 60°W longitude mark the study’s spatial boundaries.

Figure 3. Illustration using Reynolds SST of the grid point selection method for gridded data. A storm's current location is rounded to the nearest full degree of latitude and longitude. Data at the surrounding thirty-six points is collected to create a $5^{\circ} \times 5^{\circ}$ storm-centered average.

Figure 4. Comparison of ArcGIS and IDL shear field contouring routines. Example is in the 850-200 hPa layer for Epsilon at 12Z, 28 November 2005 (T-18). (a) ArcGIS shear contour map. (b) IDL shear contour map. Note the similarities between the two maps, with the northern 2.5° the exception.

Figure 5. Plot of the T-30 500 hPa maximum vorticity contour against the T-30 850 hPa maximum vorticity contour. Symbols are color-coded, and individual storms labeled. Lines at $25 \times 10^{-6} \text{ s}^{-1}$ and $40 \times 10^{-6} \text{ s}^{-1}$ (500 hPa) and $70 \times 10^{-6} \text{ s}^{-1}$ (850 hPa) represent the suggested thresholds for each type.

Figure 6. IR images of FW TCs Olga (2001) at T-30 (a) and T-0 (b), and Otto (2004) at T-30 (c) and T-0 (d). Both TCs formed in late November around (30°N,50°W). Note the rapid development of Olga from a frontal low into a small TC. Otto was already an established subtropical cyclone at T-30. Images are from the NCDC GIBBS satellite archive.

Figure 7.(a) False-color GOES IR image of Nadine (2000) (NFT) at T-0. (b) False-color GOES IR image of Lorenzo (2001) (NFB) at T-0. Both images are from the NRL TC Page, <http://www.nrlmry.navy.mil/TC.html>.

Figure 8. (a) False-color GOES IR image of Noel (2001) (FS) at T-0, downloaded from the NRL TC Page, <http://www.nrlmry.navy.mil/TC.html>. (b) Visible image of Karl (1980) (FS) at T-1, downloaded from the NHC Karl Storm Wallet (http://www.nhc.noaa.gov/archive/storm_wallets/cdmp/). Note the sparse convection around Noel despite the classification as a hurricane. In contrast, Karl had a small area of relatively thick convection around the center.

Figure 9. Histogram of the 120 SST points by type, binned every 1°C (e.g. 24.5°C bin contains SSTs of 24.1-25.0°C) and expressed as a percentage of the total count for each type. Colors are the same as for the formation locations.

Figure 10. SST 30-h average anomaly plotted against the 30-h average. Horizontal line is 0°C anomaly; solid vertical line is the 30-h average SST for all 20 TCs (24.5°C), and dashed vertical line is the 26.5°C threshold.

Figure 11. Maximum potential intensity of each storm at T-0 is plotted against the T-0 intensity.

Figure 12. Thirty-hour time series for the 850-200 hPa shear calculation. Storm colors are listed in Table 1. The black dotted line is the 10 m s⁻¹ shear line.

Figure 13. Same as in Figure 12, but for the 850-300 hPa shear layer.

Figure 14. Shear areal coverage percentages for 850-200 hPa layers, early and late storms. Vertical hashes: 8 m s⁻¹ contour; triangles: 12 m s⁻¹ contour; x's: 16 m s⁻¹ contour; diamonds: 20 m s⁻¹ contour.

a)

NFT

8 m s⁻¹

12 m s⁻¹

200 hPa

2/9

22%

4/9

44%

300 hPa

4/9

44%

6/9

67%

b)

NFB

8 m s⁻¹

12 m s⁻¹

200 hPa

4/9

44%

6/9

67%

300 hPa

6/9

67%

8/9

89%

c)

FW

8 m s⁻¹

12 m s⁻¹

200 hPa

2/9

22%

4/9

44%

300 hPa

5/9

56%

7/9

78%

d)

FS

8 m s⁻¹

12 m s⁻¹

200 hPa

4/9

44%

7/9

78%

300 hPa

6/9

67%

8/9

89%

Figure 15. Thirty-hour averages of the number of points (with corresponding percentages) less than or equal to 8- and 12 m s⁻¹ in the 5° (nine-point) local shear box for the 850-200 hPa and 850-300 hPa shear layers.

Figure 16. Counts (with corresponding percentages) of the number of storms for which an 8 m s^{-1} contour intersects a circle of given radius. The inner circle is 250 km radius, the middle circle is 400 km radius, and the outer circle is 500 km radius. This plot is for T-0 in the 850-200 hPa layer.

Figure 17. As in Figure 16, but for the 850-300 hPa layer.

Figure 18. Counts (with corresponding percentages) of the number of storms for which an 8 m s⁻¹ contour fell within a given quadrant. Quadrants are based on the 12-h average storm motion. The left-front (LF) quadrant is ahead and to the left of the storm's direction of motion. The right-front (RF) quadrant is ahead and to the right of the storm's motion. The right-rear (RR) quadrant is behind and to the right of the storm's motion. The left-rear (LF) quadrant is behind and to the left of the storm's motion. This plot is for T-0 in the 850-200 hPa layer.

Figure 19. As in Figure 18, except for the 850-300 hPa shear layer.

Figure 20. Type-composited zonal wind shear at T-0 for (a) the 850-200 hPa layer, and (b) the 850-300 hPa layer. Gray dashed horizontal and vertical lines through (0,0) indicate the composite center.

Figure 22. Holly (1976) (NFT) 500 hPa geopotential height contours at T-0. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 23. Lorenzo (2001) (NFB) 500 hPa geopotential height contours at T-0. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 24. Karl (1980) (FS) 500 hPa geopotential height contours at T-0. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 25. Delta (2005) (FS) 500 hPa geopotential height contours at T-0. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 26. Peter (2003) (FW) 500 hPa geopotential height contours at T-0. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 27. Ivan (1980) (FW) 500 hPa geopotential height contours at T-36. Image provided by <http://www.esrl.noaa.gov/psd/>.

Figure 28. Florence (1994) (FW) 500 hPa geopotential height contours at T-0. *Image provided by <http://www.esrl.noaa.gov/psd/>.*

Figure 29. Plot of the type-composited storm-relative (Lagrangian) 300 hPa geopotential heights at T-36.

Figure 30. As in Figure 29, but for T-0.

Figure 33. Plot of the type-composited storm-relative (Lagrangian) concurrent monthly (MON) 300 hPa geopotential heights at T-0.

Figure 34. Plots of the type-composited T-36 300 hPa concurrent monthly (MON) geopotential height anomalies using the climatological (LTM) 300 hPa geopotential heights as a reference. The grid is Eulerian. Oranges and reds (blues and purples) are positive (negative) anomalies.

Figure 35. Type-composited temperature profiles plotted on a USAF DOD-WPD 9-16-1 Skew-T diagram for (a) T-30 and (b) T-0.

Figure 36. 30 hour temperature change at nine pressure levels, NFT storms. Storm colors are listed in Table 1. Thick dashed line represents no net temperature change. Dotted line indicates 0.5°C net 30-h warming.

Figure 37. As in Figure 36, but for NFB storms.

Figure 38. As in Figure 36, but for FS storms.

Figure 39. As in Figure 36, but for FW storms.

Figure 40. Time series of composites for observed (solid line), concurrent monthly (dashed line), and climatological (dotted) local environmental temperatures for 200hPa.

Figure 41. As in Figure 40, but for 300 hPa temperatures.

Figure 42. As in Figure 40, but for static stability.

Figure 43. As in Figure 41, but for static stability.

Figure 44. Time series of lifted indices (LI) in the storm-local environment for all storms. Dashed line (0°C) represents neutrality with respect to parcels lifted from the surface. Dotted line (-3°C) represents maximum threshold for moderate instability. Storm colors are listed in Table 1.

Figure 45. As in Figure 44, but for the Lifting Condensation Level (LCL).

Figure 46. As in Figure 45, but for the Level of Free Convection (LFC).

Figure 47. As in Figure 45, but for the Equilibrium Level (EL). Dotted line is at 200 hPa, the average of the NFT systems (and the level used for shear computation in many intensity models).

Figure 48. As in Figure 45, but for Convective Available Potential Energy (CAPE). Dotted line is 1000 J kg^{-1} , the threshold for a moderately unstable environment.