Atlantic Subtropical Storms. Part II: Climatology

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ABSTRACT

A 45-yr climatology of subtropical cyclones (ST) for the North Atlantic is presented and analyzed. The STs pose a warm-season forecasting problem for subtropical locations such as Bermuda and the southern United States because of the potentially rapid onset of gale-force winds close to land. Criteria for identification of ST have been developed based on an accompanying case-study analysis. These criteria are applied here to the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) to construct a consistent historical database of 197 North Atlantic ST in 45 yr.

Because ST may eventually evolve into tropical cyclones, sea surface temperatures (SST) and vertical wind shear conditions for tropical cyclogenesis are contrasted with the conditions for ST genesis identified here. Around 60% of the 197 ST formed over SST in excess of 25°C in a region of weak static stability. Further, the mean environmental vertical wind shear at formation for these storms is 10.7 m s^{-1}, a magnitude generally considered to be unfavorable for tropical cyclogenesis.

The STs have hybrid structure, so the potential for baroclinic and thermodynamic development is explored through the baroclinic zone (characterized by the Eady growth rate σ) and SST field. Seasonal evolution in the location and frequency of ST formation in the basin is demonstrated to correspond well to the changing region of overlap between SST $>$ 25°C and $\sigma > 0.1$ day^{-1}.

This climatology is contrasted with two alternative ST datasets. The STs contribute to 12% of tropical cyclones (TC) in the current National Hurricane Center (NHC) Hurricane Database (HURDAT); this equivalent to about 1 in 8 genesis events from an incipient ST disturbance. However, with the addition of 144 ST that are newly identified in this climatology (and not presently in HURDAT) and the reclassification (as not ST) of 65 existing storms in HURDAT, 197/597 storms (33%) in the newly combined database are ST, which emphasizes the potential importance of these warm-season storms.

1. Background

At around 2300 Bermuda LT on Friday 12 October 2001 (0000 UTC 13 October), the storm that would eventually become Hurricane Karen passed close to the west end of the island. Maximum 10-min sustained surface winds were measured at 30 m s^{-1} (67 mph), with gusts to 40 m s^{-1} (90 mph) at the airport and a minimum recorded pressure of 992 hPa. Instruments at Bermuda Rescue Coordination/Bermuda Harbour Radio (at an elevation of 92 m above mean sea level) reported a sustained wind of 34 m s^{-1} with a gust to 47 m s^{-1} (76 mph gusting to 105 mph; Williams 2002). Convective bands wrapping around the central low were evident in the satellite imagery, as the storm continued its transition into a tropical system. At 2200 LT (2100 UTC) on 13 October, the U.S. National Hurricane Center designated the system ''Subtropical Storm #1''—later to become Hurricane Karen, as it continued to track north toward the Canadian Maritimes (Stewart 2001). In spite of the fact that both gale and storm warnings had been issued by the Bermuda Weather Service, the media reported this event as a ''surprise storm that caught everyone off guard'' (Breen and Mallon 2001). The 23 000

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electricity customers who had lost power were not convinced that they had been well served. Such was the dichotomy between public perception and meteorological reality—this storm did not yet have purely tropical characteristics, but it did have both intense winds and accompanying rain—that the public perceived it to be a poorly forecast tropical storm.

Oceanic storms with ambiguous origins and/or structures have often been operationally classified as subtropical. The operational definitions of cyclone types relevant to this study are a follows (as published by the U.S. National Weather Service; OFCM 2007):

Subtropical cyclone. A nonfrontal low pressure system that has characteristics of both tropical and extratropical cyclones. This system is typically an upper-level cold low with circulation extending to the surface layer and maximum sustained winds generally occurring at a radius of about 100 miles or more from the center. In comparison to tropical cyclones, such systems have a relatively broad zone of maximum winds that is located farther from the center, and typically have a less symmetric wind field and distribution of convection.

Subtropical storm. A subtropical cyclone in which the maximum sustained surface wind speed (1-min mean) is 34 kt (39 mph) or higher.

Tropical cyclone. A warm-core, nonfrontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center.

Extratropical cyclone. A synoptic scale low pressure system whose primary energy source is baroclinic.

When observing and forecasting subtropical cyclones (ST), an ambiguity often exists regarding the extent of their tropical or extratropical characteristics, despite the fact that descriptions of the characteristics of individual cases in the Atlantic have been documented in the literature for over 30 yr. Members of the public recognize no real distinctions between the effects of ST and weak tropical cyclones (TC) because the weather produced by both is similar. Indeed, the transition of systems from ST to TC is one mode of tropical cyclogenesis (Davis and Bosart 2003). For these reasons, operational forecasters have recently begun to assign names to Atlantic warm-season ST from the same list that TC are named. The intent of this study is to clarify the physical aspects of subtropical storms to aid forecasters in the detection, identification, tracking, and forecasting of ST. In the pursuit of this, we will investigate characteristics common to all ST that are not described in the operational definition (OFCM 2007), such as thermal structure and environmental controls on development.

Clearly, the process of naming ST requires an unambiguous assessment of storm type. In the remainder of this section we review historical assessments of ST in the North Atlantic. This provides context for our new approach to determination of ST, which is the subject of this paper.

a. *Hebert and Poteat (1975) satellite classification technique*

In spite of the TC-like impacts of ST, there is very little about Atlantic ST in the literature—and not much more written on the Pacific (or Kona) storms. As a complement to the Dvorak technique for TC intensity classification (Dvorak 1975), the U.S. National Weather Service (NWS) implemented a satellite recognition technique for estimating ST intensity (Hebert and Poteat 1975, hereafter HP75). HP75 distinguished three subcategories of ST: (1) ST originating from upper-level cold lows or ‘‘cutoffs’’, (2) nonfrontal lows that form east of upper troughs, and (3) frontal waves—these last two both having low-level baroclinic origins. An example of the application of the HP75 technique to determine ST storm intensity for the case of Hurricane Michael (2000) is presented in Fig. 1; schematics of IR satellite imagery taken from patterns in HP75 and examples of analyses are shown in Fig. 1, along with IR satellite images taken during the life cycle of Michael. It should be noted that there are significant elements of subjectivity to this type of categorization of subtropical storms, and the method outlined in HP75 is intended for forecasters experienced in using similar satellite classification techniques, such as the Dvorak tropical cyclone classification (Dvorak 1975). The evolution of Michael through various stages in the HP75 method is evident.

HP75 developed the first objective technique for identification of ST. Although satellite resolution has improved vastly since this technique was developed, the HP75 method provides the only guidance for remote sensing of different intensities of subtropical cyclone. Satellite imagery from the online National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) archive [National Climatic Data Center Global International Satellite Cloud Climatology Project B1 Browse System (GIBBS); available online at http://www.ncdc.noaa.gov/gibbs/] is used for the HP75 analyses of the storms in our climatology. Over the years, additional tools [e.g., satellite soundings, cyclone phase space (CPS)] for distinguishing between cyclone types have become available and are being used in operational centers. This study brings together some of these new tools and other,

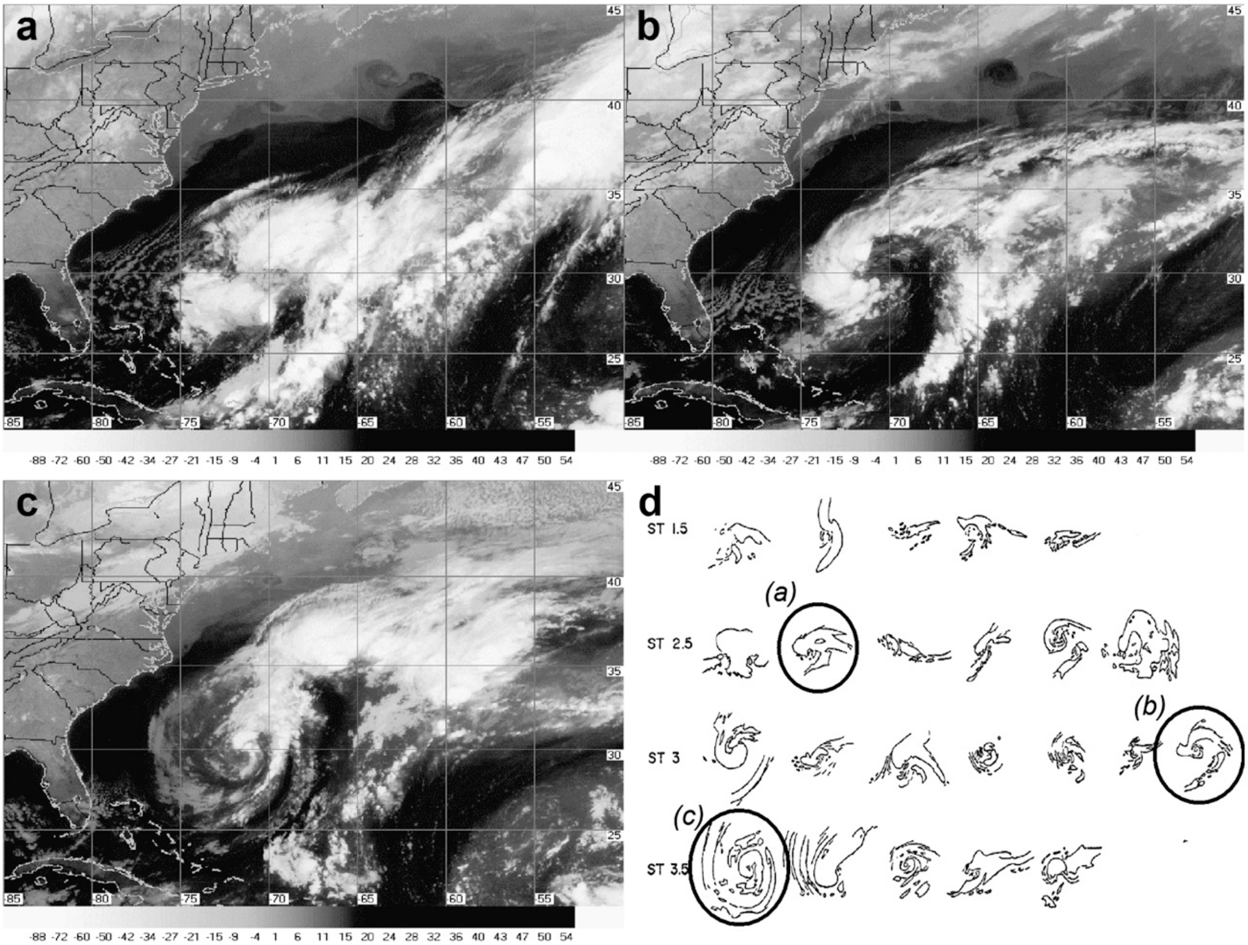

FIG. 1. Infrared (channel 2; 0.725–1.0 μm) satellite imagery for the Northwest Atlantic on (a) 1200 UTC 14 Oct, (b) 1200 UTC 15 Oct, and (c) 1200 UTC 16 Oct 2000. (d) HP75 satellite signatures for ST. Cloud patterns typical of the signatures in (a)–(c) are identified in (d). These support the intensification of Michael (2000) through the time period highlighted.

more traditional, diagnostics to provide a robust procedure for specifically identifying ST that builds on HP75.

b. A set of candidate historical ST storms

In 2002, David Roth [NWS–Hydrometeorological Prediction Center (HPC)] published a survey of 51 yr (1951–2001) of ''difficult to classify'' Atlantic storms, resulting in a database of 218 ST candidates in the Atlantic basin (Roth 2002). This database of potential Atlantic ST included storms in every month of the year, with months late in the hurricane season being the most highly populated: 17% in September, 20% in October, and 14% in November. This survey provides an abundant source of potential cases to explore for Atlantic ST. Historical variations in data quality through the period (e.g., only having surface maps in the earliest years and no satellite imagery until the 1970s) mean that potentially important variations exist across the storm list. Thus, each of these candidates is carefully scrutinized before being incorporated into our ST climatology.

c. Tropical transition: One pathway to ST development

Davis and Bosart (2003) outline a mechanism for the development of a tropical cyclone from an incipient cyclone that is initially forced baroclinically. Their conceptual model of this process, called tropical transition (TT), is supported by observations of North Atlantic storms such as Michael and Karen (e.g., Abraham et al. 2002; Stewart 2000). A baroclinically induced surface low may initiate via quasigeostrophic (QG) dynamics and amplify through convective diabatic heating, building a warm thermal core from the surface upward. The hybrid nature of these cyclones, with a cold core aloft and a warm core near the surface, is characteristic of subtropical storms. The TT mechanism can act either to 1) change an already fully cold-core (extratropical) system into a fully warm-core (tropical) system or 2) induce a hybrid cyclone in situ (Davis and Bosart 2004). Davis and Bosart do not distinguish between extratropical storms that develop warm cores and systems that develop a hybrid structure prior to the production of gale-force winds (i.e., ST). In the current study we are interested in the forecast problem associated with a rapidly intensifying hybrid storm (e.g., Karen in 2001). Thus, our study begins at the conclusion of TT-based generation of an in situ hybrid cyclone.

A uniform methodology for identifying ST over a long period of record is proposed here. This consistent methodology is necessary for the development of an unambiguous and uniform climatology of Atlantic ST. The uniform data source needed for this study is provided by the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) at 1.125° × 1.125° resolution (Uppala et al. 2005) for the period of September 1957–August 2002.

Although this study necessarily focuses primarily on model reanalyses of ST, examination of satellite observations, where available, supplements our analyses to ensure wherever possible that the storms identified here could not be classified as tropical. In addition to the HP75 technique described above, imagery from the Advanced Microwave Sounding Unit (AMSU; available online at http://amsu.cira.colostate.edu) on the NOAA polar orbiters is used to verify the thermal structure (i.e., cold core, warm core, or hybrid thermal anomaly) of systems for which these data are available—selected ST candidates from 1999–2002 were examined using AMSU.

2. Identification of Atlantic subtropical cyclones in the ERA-40 reanalyses

The ECMWF ERA-40 is freely available from the U.S. National Center for Atmospheric Research (NCAR) for research purposes. These model reanalyses are utilized for their temporal coverage (September 1957–August 2002), and high resolution relative to the National Centers for Environmental Prediction (NCEP) 2.5° × 2.5° reanalyses (also freely available). The ERA-40 data provide gridded model reanalyses with horizontal resolutions of 1.125° × 1.125°. The ERA-40 wind data at the time were, however, only available for analysis and display on a 1.4° × 1.4° resolution. Vertical resolution is fixed at 14 pressure levels plus the surface (Uppala et al. 2005). This dataset was chosen because it provided an acceptable compromise between spatial resolution of individual events (e.g., Hart et al. 2006), and the 45-yr reanalysis period allows exploration of interannual and longer variations in ST activity.

a. *General approach for identification of ST*

Utilizing high-resolution operational analyses and a variety of observational data sources, a consistent set of ST criteria has been documented that uniquely and consistently identify a set of contemporary ST over the period 1998–2002 (these criteria are enumerated shortly). Details of the development of these criteria are presented in Evans and Guishard (2009, hereafter Part I).

These criteria were then employed in an examination of the same set of systems in the ERA-40 reanalyses, with a view to attaining a typical ST signature in the ERA-40. This ERA-40 "ST template" is then applied to the identification of ST back to September 1957. This enables extending this climatology to times lacking remote sensing, high-resolution numerical models, or relevant ground-truth observations for our ST cases. In addition to the benefits of using reanalyses to extend the available data on cyclones, there are disadvantages to using the ERA-40, as outlined by Manning and Hart (2007); resolution and ground-truth observation data availability are issues that the reader should be aware of. However, the advantages of using a reanalysis dataset that resolves the three-dimensional structure of historical cyclones toward their further classification far outweigh the pitfalls inherent in using such a dataset. Although ERA-40 does not constitute a perfect representation of reality, the inclusion of observational and remote sensing data in its composition makes it the obvious choice for making meaningful conclusions about the nature of historical cyclones with societal impacts. Ongoing discussions and debates are vital to this process, and the procedure is necessarily iterative in nature. Indeed, the first author is incorporating this approach to provide supplementary ST information for the current National Hurricane Center (NHC) Hurricane Dataset (HURDAT) reanalysis of historical warm-season Atlantic storms (Guishard 2006).

b. *Automated storm tracker*

This study necessitates the development of a sizeable dataset of cyclone records. This is achieved via application of an automated detection and tracking algorithm (discussed in Hart 2003). The algorithm detects and tracks minima in the sea level pressure (SLP) analysis inside the (0°–60°N, 0°–100°W) domain of interest. The automated tracking algorithm also allows for the detection of gale-force winds (>17 m s^{-1}, or >38 mph) at 925 hPa, plus the calculation of minimum central pressure and the CPS variables of Hart (2003). The use of 925-hPa gales as a criterion for inclusion of a cyclone is consistent with previous cyclone studies involving the CPS (Hart 2003; Evans and Hart 2003;

Arnott 2004). Although this method is at odds with the operational definitions, which indicate that surface winds are used as a discriminator between subtropical cyclones and subtropical storms, 925 hPa is the lowest standard model level that is above the surface for most cyclones. However, this may make direct comparisons with datasets such as HURDAT problematic. The methods outlined above are described in detail in the following sections.

c. The CPS

The CPS is a three-dimensional descriptor of cyclone structure (Hart 2003). Structure types are classified by symmetry and strength and vertical depth of the temperature anomaly associated with the system. The CPS implies a continuum of cyclone types, typified by regimes of symmetry/asymmetry and core height anomalies (Hart 2003). The advantages of this type of diagnostic tool are evident when it is used in conjunction with synoptic fields, satellite imagery, and other analysis tools.

The CPS thermal symmetry parameter is denoted by B and is evaluated via

$$B = h[(\overline{Z_{600\text{hPa}} - Z_{900\text{hPa}}})_R - (\overline{Z_{600\text{hPa}} - Z_{900\text{hPa}}})_L]$$

where $h = -1$ for the Southern Hemisphere and $h = +1$ for the Northern Hemisphere. Two thermal wind parameters complete the CPS description. These are evaluated over layers in the lower (L; 900–600 hPa) and upper (U; 600–300 hPa) troposphere as follows:

$$-V_T^L = \frac{\partial(\Delta Z)}{\partial \ln p}\bigg|_{900\text{hPa}}^{600\text{hPa}}$$

and

$$-V_T^U = \frac{\partial(\Delta Z)}{\partial \ln p}\bigg|_{600\text{hPa}}^{300\text{hPa}}.$$

In the present analysis, the CPS is used to characterize storm structure and so to differentiate ST from other cyclone types. (Real-time CPS diagnostics are available online at http://moe.met.fsu.edu/cyclonephase.)

EXAMPLE OF AN ST LIFE CYCLE IN THE CPS: KAREN (2001)

An example of structure evolution in the CPS for a storm that was classified as ST during its lifetime is presented for Hurricane Karen from 11 to 15 October 2001 (Fig. 2). NWS–Global Forecast System (GFS) model fields were used to derive this CPS path through the life cycle of Karen. The system began in the GFS analysis fields on 10 October with a warm anomaly at low levels and a cold core in mid to upper levels (600–300 hPa), rapidly developing a warm-cored cyclone from near surface to midlevels (900–600 hPa). By 1200 UTC 13 October, the storm had become a deep symmetric warm-core system in the GFS analyses (cf. Figs. 2a,b), consistent with a tropical cyclone structure. A weak warm core aloft and outflow at upper levels was also evident in remotely sensed data from the Advanced Microwave Sounding Unit (not shown). This gives confidence that the GFS analyses correctly capture the broad thermal structure associated with the cyclone. The operational NHC advisories first acknowledged Karen as an unnamed subtropical storm at 2100 UTC 12 October. The system was officially named Tropical Storm Karen 12 h later. At 1800 UTC 13 October, Karen had strengthened to a hurricane and was duly upgraded by the NHC, based on reconnaissance flight data and Dvorak satellite intensity estimates. In the reanalysis, HURDAT has Karen labeled as ST at its time of maximum winds over Bermuda at 0000 UTC 12 October (Stewart 2001). This scenario highlights the difficulty posed to operational forecasters by developing ST, even with an abundance of analysis tools.

During the initial development of the hybrid system that became Hurricane Karen, a Rossby-wave break resulted in the formation of a cutoff cyclone aloft. A weak surface closed circulation was initiated by interaction of a tropical wave with the old frontal baroclinic zone at the surface, which strengthened in close proximity with the cutoff upper low. The weak surface circulation then moved under the cold upper low, destabilizing the vertical profile and allowing deep convection to initiate and become organized. The vertically stacked cyclone then intensified into a hurricane. The life cycle evolution evident on the satellite imagery shown in Fig. 3 is consistent with the GFS analyses in the CPS (Fig. 2), supporting our choice of this diagnostic approach to differentiate tropical, extratropical, and ST (hybrid) cyclones in the ERA-40 reanalysis fields.

d. Required characteristics of an Atlantic subtropical storm

The criteria used to distinguish ST included in this climatology were developed through detailed case-study analyses of a set of Atlantic ST from 1998 to 2002. These case studies are described further in Part I and Guishard (2006). For a cyclone to be included in this ST climatology, it must:

- attain gale-force winds ($>$17 m s^{-1}) on the 925-hPa surface at some time during its life cycle;
- exhibit a hybrid structure, determined by the CPS criteria of $-|V_T^L| > -10$ and $-|V_T^U| < -10$;

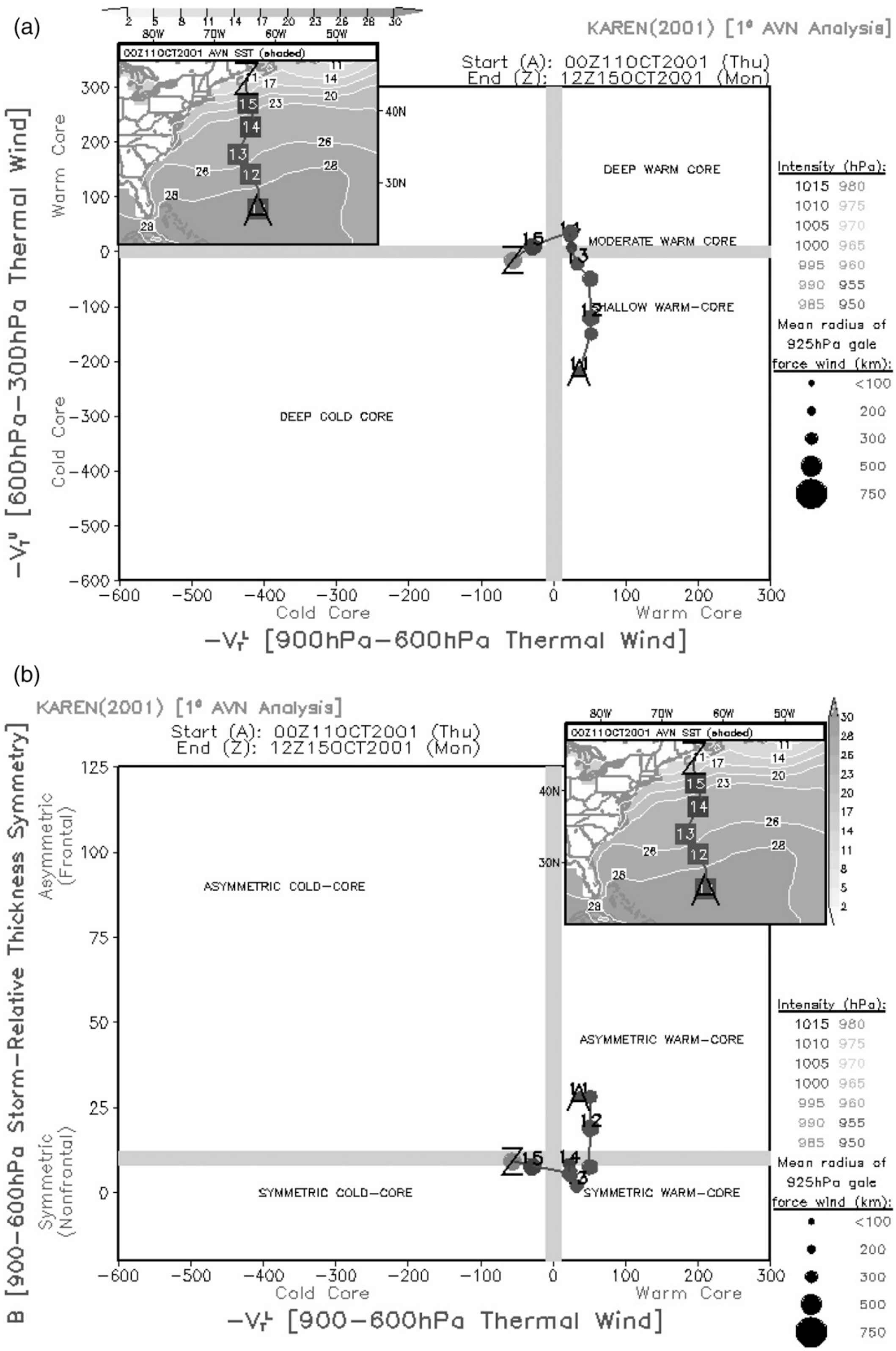

FIG. 2. GFS analyses of Karen (2001) from 0000 UTC 11 Oct to 0000 UTC 15 Oct 2001 plotted in the CPS: (a) $-V_T^L$ vs $-V_T^U$ and (b) $-V_T^L$ vs B. (Available online at http://moe.met.fsu.edu/cyclonephase.)

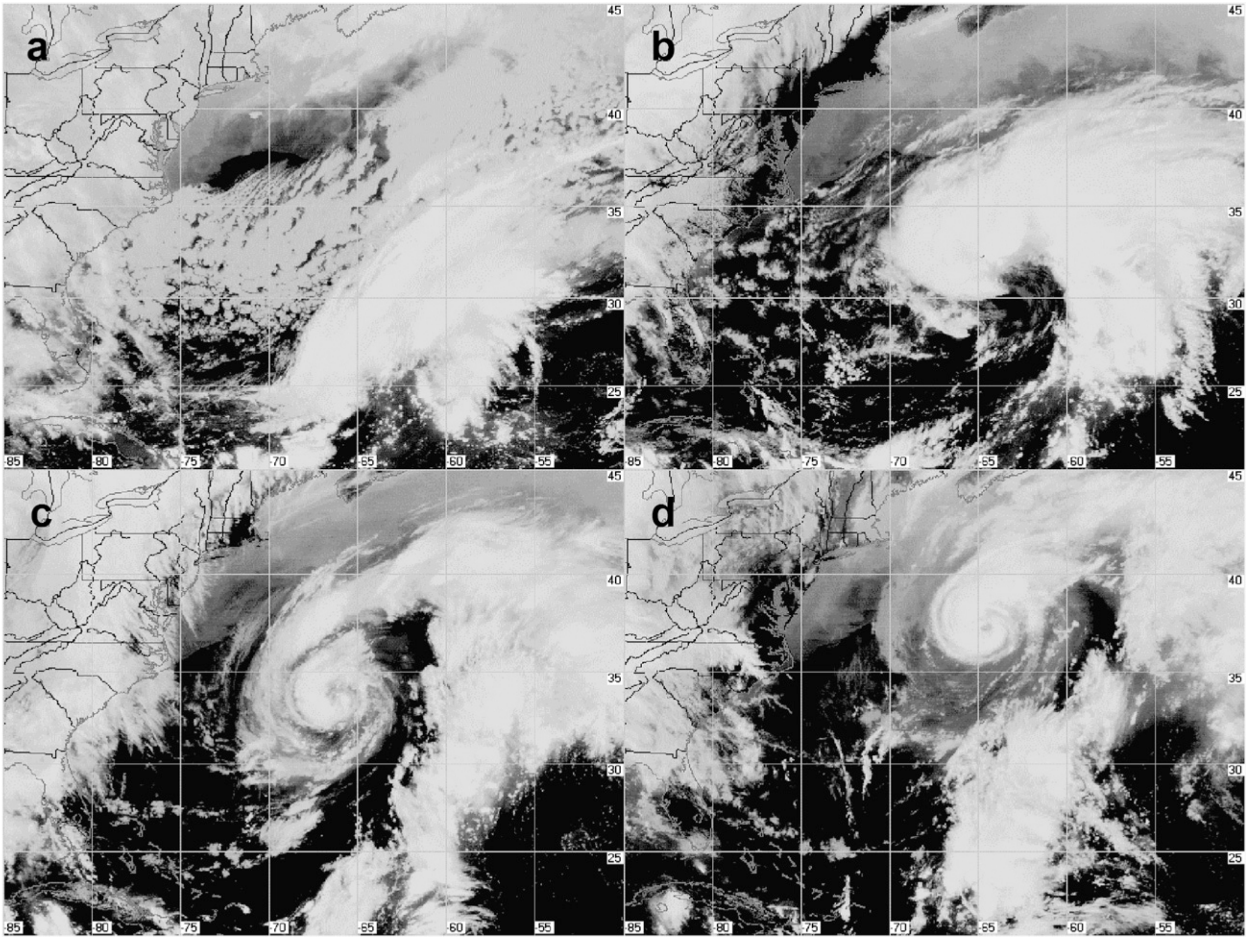

FIG. 3. Infrared imagery from GOES east of Hurricane Karen (2001) at the following times: (a) 1800 UTC 10 Oct, (b) 1800 UTC 11 Oct, (c) 1800 UTC 12 Oct, and (d) 1800 UTC 13 Oct 2001.

- persist in its hybrid form for at least 36 h (i.e., more than one diurnal cycle);
- attain gales in the 20°–40°N latitude band to reduce the possibility of tropical and extratropical systems being introduced into the dataset; and
- become subtropical (i.e., attain hybrid structure) within 24 h if identified first as a purely cold- or warm-cored system.

The intent here is to identify only systems that are clearly ST, so there is a need to exclude storms that are of an ambiguous nature, hence the criteria that limit the consideration of storms that are outside of the latitudinal band prescribed, over land, or have a deep warm- or cold-core structure. Systems that begin as robust tropical or extratropical cyclones have been rejected because they are deemed in this methodology to only be able to attain the hybrid structure via extratropical transition (ET; Hart and Evans 2001) or tropical transition (Davis and Bosart 2003), respectively. This is entirely consistent with the perspective of a continuum of cyclone types.

This last criterion results from operational forecasting considerations. As alluded to above, Davis and Bosart (2003, 2004) have identified mechanisms by which Atlantic extratropical systems may transition into tropical cyclones after moving south into the subtropics. The same mechanism operates in the transition from a subtropical to tropical cyclone, but the difference in origin is important. An extratropical storm that drifts into the subtropics and becomes warm cored—or a TC undergoing extratropical transition (and thereby gaining a hybrid structure)—may already have gale-force winds. Thus, these systems are already likely to be monitored by forecasters, limiting the chance of a ‘‘surprise’’ storm. This is the rationale for restricting the cases studied here to essentially in situ formation of an ST (hybrid structure with gales); storms initially identified

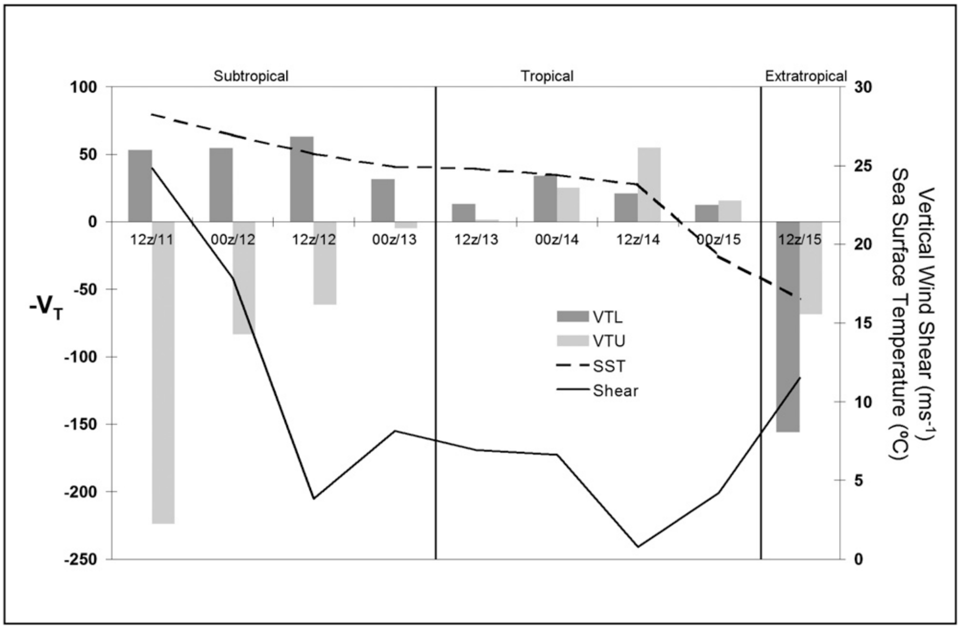

FIG. 4. Time series of 200–900-hPa vertical wind shear (solid black line), SST (dashed black line), $-V_T^L$ (dark gray bar), and $-V_T^U$ (light gray bar) following the center of Karen in October 2001. All fields are derived from GFS analyses. The phase of the cyclone (subtropical, tropical, or extratropical) based on CPS analyses is indicated at the top of the figure.

as purely cold- or warm-cored were retained in the dataset only if they developed a hybrid structure in less then one diurnal period (i.e., <24 h).

3. Diagnostics of processes potentially important to ST genesis and maintenance

Given that ST appear to develop in an environment that has aspects of both tropical and extratropical forcing (see this in later sections), a range of diagnostics is used to assess the relative likely importance of both ''tropical'' and ''baroclinic'' forcings in the developing ST system.

a. Maintenance of deep convection

In light of the importance of sea surface temperature (SST) to tropical cyclones, this study will also investigate the effects of SST on subtropical cyclogenesis. It is postulated here that the sustenance of deep convection is key to the process of subtropical cyclogenesis. The development of airmass cumulonimbi is partially limited by SST over the oceans (Graham and Barnett 1987). As a result, warm SST had been well documented as a necessary (but not sufficient) condition for tropical cyclogenesis, which depends on abundant convection (Ooyama 1963; Gray 1968; McBride and Zehr 1981; Emanuel 1986, 1995). Davis and Bosart (2003) indicate that tropical cyclogenesis of baroclinic origin is most prevalent over SST > 26°C.

GFS SST fields are averaged over a 5° × 5° grid box centered on the surface cyclonic circulation to derive a mean environmental SST around the cyclone envelope. The genesis of Karen took place over mean surface temperatures of 28°C in the GFS analyses, and subsequent analyses show a decrease in storm-centered mean surface temperature (in the GFS) with time. As Karen moved north to 40°N on 14 October, it moved through a region of rapidly decreasing SST and subsequently began to undergo extratropical transition, as verified by the CPS parameters at that time (Fig. 4). A colder core in the upper and lower layers developed with asymmetry increasing with time, which is characteristic of extratropical transition (Evans and Hart 2003).

Although SST is a significant factor to examine during cyclogenesis over the oceans, other thermodynamic considerations have been considered, including the availability of moisture and stability. Emanuel (1986) postulated that hurricanes are maintained by the process of wind induced surface heat exchange (WISHE). Diagnostics of SST and potential intensity lead to the same qualitative conclusions (see Guishard 2006), so we will focus on SST in this paper.

b. Vertical wind shear

The effect of vertical wind shear has long been debated in the tropical cyclone literature. One mechanism proposed for TC intensification in the western North

Pacific is the provision of an additional channel for outflow aloft through interaction between the TC and a tropical upper-tropospheric trough (TUTT; Sadler 1976). This additional outflow channel to the upper westerlies increases the upper-level divergence and so enhances the ''in–up–out'' circulation of the TC. In addition, Molinari et al. (1998) outlined a potential vorticity (PV) process for the intensification of TC by the influence of upper troughs in close proximity. Molinari et al. (1998) concluded that interactions with the upper-PV anomaly (associated with the trough) initially induce weakening resulting from the associated vertical wind shear and then reintensification of the lower PV anomaly (associated with the TC) resulting from enhanced forcing for convection (reduced static stability). The impact of the upper trough on the TC is consistent with the results of Kimball and Evans (2002).

Davis and Bosart (2003) present a theory for the development of tropical cyclones in a baroclinic environment, in which several case studies of incipient cyclones are described. Some of these transition into tropical cyclones in the northern tropical and subtropical Atlantic, farther north than ''classical'' tropical cyclogenesis usually occurs. The mechanism for initiating a low-level cyclonic vortex proposed by Davis and Bosart (2003) is baroclinic cyclogenesis in a vertically sheared environment (as typically occurs in the midlatitudes). Organized and persistent convection is key to the reduction of vertical wind shear in the stalled upper trough. This mechanism is discussed in more depth and with relation to North Atlantic ST in Part I.

To characterize the environments associated with the ST in this climatology, deep layer vertical wind shear (925–200 hPa) is calculated and averaged over a 5 × 5 gridbox area centered on the storm. This ensures that a representative shear across the center of the storm is captured. The vertical shear parameter is calculated as

$$\frac{\partial \mathbf{u}}{\partial z} = \left[\sqrt{\overline{(u_U - u_L)^2 + (v_U - v_L)^2}}\right],$$

where the subscript L is 925 hPa for the ERA-40 and 900 hPa for the GFS analyses; subscript U always corresponds to 200 hPa.

The vertical shear over the center of Karen's low-level circulation decreases with time in the GFS analyses, consistent with the concepts in Davis and Bosart (2003, 2004), until the system is fully warm cored (tropical). Figure 4 shows a time series of V_T^L, V_T^U, SST, and the magnitude of the vertical wind shear ($|\partial \mathbf{u}/\partial z|$) over the center of Karen. The pattern fits the concept of a hybrid upper trough–lower cyclone system, with attendant moderate shear (>20 m s^{-1}) on 10 and 11 October, when the shear decreases rapidly. A deep warm core subsequently develops on 12 October, consistent with a more symmetric tropical cyclone structure and environment (McBride and Zehr 1981). As Karen undergoes extratropical transition (from 1200 UTC 13 October), the shear increases and the deep warm-core character in the CPS rapidly changes to a deep cold core on 14 October (Fig. 4). At 1200 UTC 14 October (labeled 12z/14 in the Fig. 4 graph), the cyclone has become fully cold cored, and the vertical wind shear has increased again, as one would expect in an extratropical system.

c. *Baroclinic growth rate*

A diagnosis of baroclinicity is warranted, as shear alone is not the only indicator of quasigeostrophic forcing. Eady baroclinic growth rate has been used by Hart and Evans (2001) to diagnose the potential for ET. They found that fluctuations in the time average of this parameter influenced the onset (or absence) of ET. In light of the similarities in structure between transitioning tropical cyclones and ST, the Eady baroclinic growth rate is diagnosed here following Lindzen and Farrell (1980):

$$\sigma = \frac{0.31 f}{N}\frac{\partial \mathbf{u}}{\partial z},$$

where ($|\partial \mathbf{u}/\partial z|$ is the vertical wind shear centered on 700 hPa (i.e., evaluated from 900–500 hPa only), f is the Coriolis parameter, and N is the Brunt–Väisälä frequency at 700 hPa.

4. Characteristics of subtropical cyclones in the ERA-40 climatology

A summary of the geographic and temporal distribution, structural characteristics, and synoptic indicators of the 45-yr ST climatology diagnosed from the ERA-40 analyses is presented here.

a. *Spatial and temporal distributions*

Genesis locations (onset of gale-force winds for hybrid structure) and ST tracks identified from the 45-yr (September 1957–August 2002) ERA-40 study period are plotted in Fig. 5. The mean position of the 197 origin points is 30.8°N, 59.7°W, with standard deviations of 4.7° latitude and 17.1° longitude (solid circle and dashed box in Fig. 5). Note that the geographic distribution of storms is skewed to the western side of the Atlantic, likely an effect of SST distribution (see section 4b below).

The monthly and annual breakdown of ST occurrence in the ERA-40 dataset is plotted in Fig. 6 (note that the occurrences are in the 12-hourly ERA-40 temporal

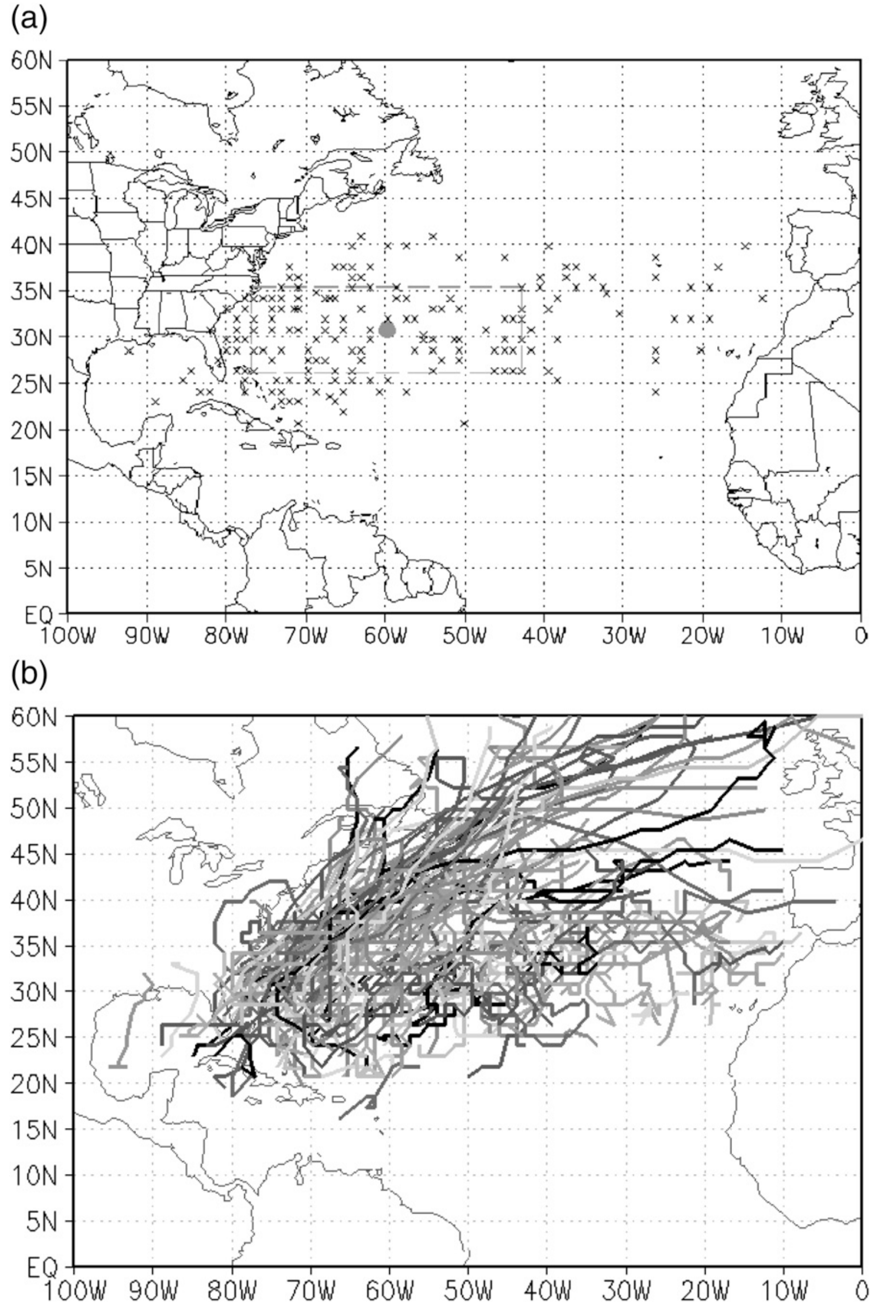

FIG. 5. Geographic distribution of Atlantic ST in the ERA-40 climatology: (a) genesis location (onset of gale-force winds) and (b) tracks. The black dot in (a) indicates the average position of all 197 ERA-40 subtropical storms at the onset of gale-force winds and the dashed-line box encloses the area within one standard deviation from this mean location.

resolution). The average number of subtropical storms per year is 4.4, with a standard deviation of 3.0. Annual peaks of ST activity are recorded in 1969 and 2001, the only two years with over 10 ST forming in the North Atlantic. Monthly peak activity is found in October with a secondary peak in June—months bracketing the peak activity of the Atlantic hurricane season.

There is a statistically significant peak of ST activity centered on October as shown in Fig. 6a. The mean daily distribution of ST occurrences (Fig. 6b) reveals that 2 November is the peak of hybrid cyclone activity, confirming the mid to late hurricane-season peak in ST activity inferred from the monthly-mean activity.

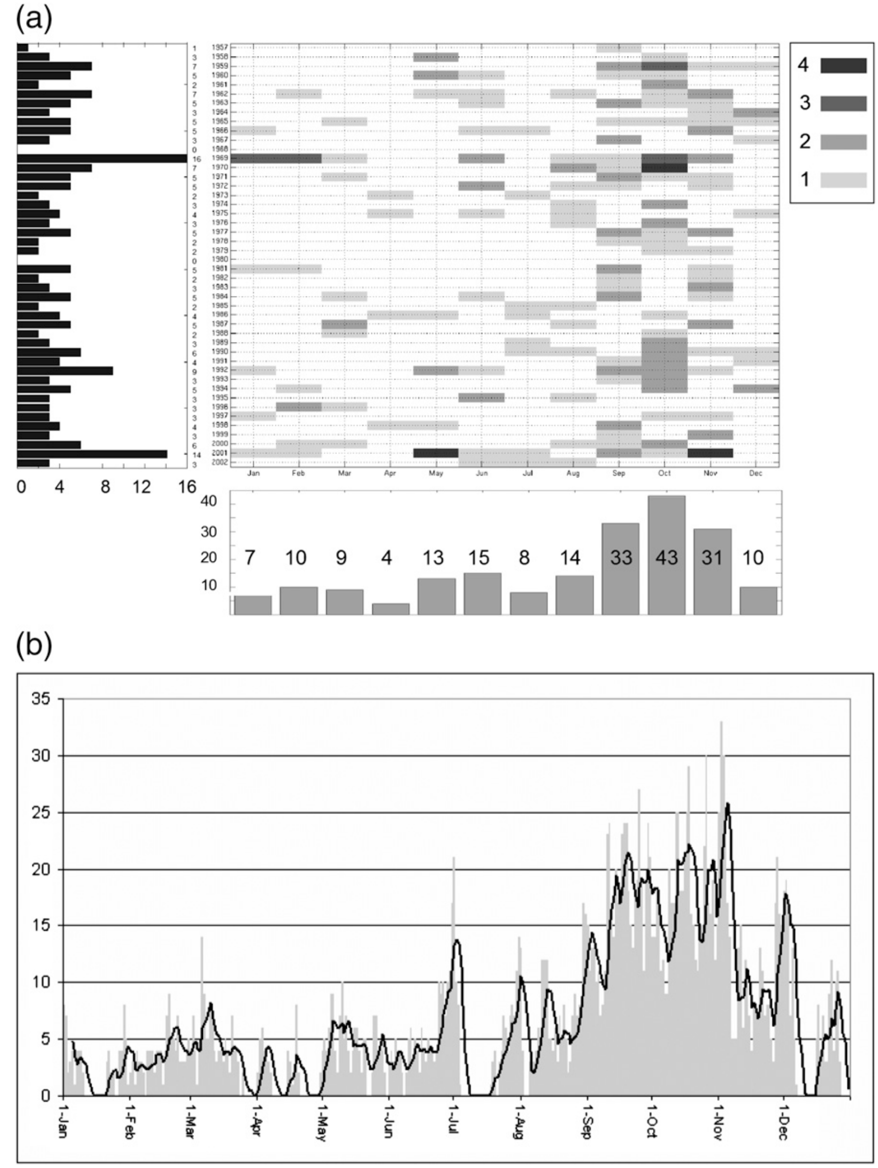

FIG. 6. Temporal distribution of ST occurrence: (a) Year vs month gridded plot of occurrence of subtropical storms. Monthly and annual histogram distributions are plotted below and to the left of the main plot, respectively. (b) Daily distribution of all ST occurrences in the 45-yr dataset (histogram) and 5-day running average (black line).

b. CPS, SST, and shear characteristics

Statistics of the temporal, spatial, CPS, shear, and SST characteristics of all storms in the ERA-40 climatology are presented in Table 1. The CPS thermal wind parameters for the genesis times of all 197 ST detected in the ERA-40 reanalyses are plotted in Fig. 7, along with the mean and the domain of ±1 standard deviation. The mean thermal signature of these cyclones is that of a neutral lower-tropospheric anomaly and a cold upper troposphere. The number of warm-lower-core structure cyclones is 113, accounting for 57% of the total. Despite this, the mean cyclone structure has a $-V_T^L$ value of −8.7 because it is heavily influenced by several outliers evident in Fig. 7, including one system that had gales form with both $-V_T^L$ and $-V_T^U$ less than −400, indicating a deep cold core. These outliers were retained in the dataset because they developed a hybrid structure in less than one diurnal period (i.e., <24 h) and obtained gale-force winds while in their hybrid phase.

TABLE 1. Population statistics for ERA-40 subtropical storm climatology for all time periods identified as ST.

	Lat (°N)	Lon (°W)	B	$-V_T^L$	$-V_T^U$	SST (°C)	Shear (m s^{-1})
Avg	30.8	59.7	11.1	−8.7	−124.7	24.6	10.7
Std dev	4.7	17.1	13.9	87.2	76.5	3.4	8.0

Frequency distributions of SST and shear for the gale onset times of all 197 storms in the ERA-40 climatology are plotted in Fig. 8. SST is skewed left with a mean of 24.6°C (median 25.5°C), and the domain bound by ±1 standard deviation is 21°–28°C. This is consistent with the hypothesis that warm SST is a contributing factor to ST genesis. However, the minimum SST of 15°C and the fact that 12% of the storms (23) formed over water that was <20°C imply that warm SST on its own is not a sufficient parameter for predicting or analyzing subtropical storm genesis.

At the time of the onset of gales, the mean vertical wind shear in the 925–200-hPa layer was 10.7 m s^{-1} with a standard deviation of 8.0 m s^{-1}. Although shear values range as high as 39.4 m s^{-1}, 75% of ST occurrences have vertical shear <12.5 m s^{-1}. Thus, the vast majority of ST form in shear regimes also conducive to tropical cyclogenesis (McBride and Zehr 1981; De Maria et al. 2001).

c. Analyses of long-term mean tropical and baroclinic forcing

Monthly-mean maps of SST, Eady growth rate, and vertical wind shear were plotted using the NCEP–NCAR reanalysis (Kalnay et al. 1996) to track the mean seasonal evolution of environmental factors that are likely important to ST development. These geographic composites are generated over a domain spanning from the equator to 60°N and from 100°W to the Greenwich meridian. The objective here is to determine the basin-scale features that are dominant during active and inactive periods of subtropical cyclogenesis.

To elucidate the differences in background environmental conditions during active and inactive ST regimes, selected monthly long-term mean composites of shear and SST are presented here (Figs. 9–11): April, the least active month for ST (Fig. 9); August, a month of near-average activity (Fig. 10); and October, the most active month (Fig. 11).

Only four ST occurred in the 45 April months. The positions of occurrence (white crosses) show a range of ST cyclogenesis over waters with 18°–24°C SST, spread across a latitude range of 24°–36°N. The shear regime is on the order of 20–40 m s^{-1} in this region; however, the average shear for the four April ST is only 11.2 m s^{-1}, indicating that a reduction from the average environmental shear occurred prior to subtropical cyclogenesis

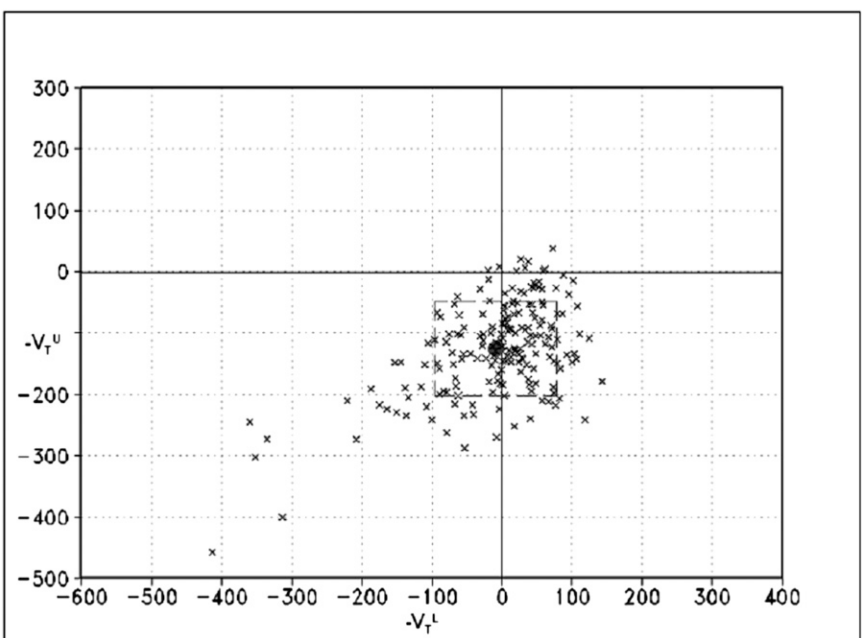

FIG. 7. Cross section through the cyclone phase space ($-V_T^L$ vs $-V_T^U$) for ERA-40 ST at the time of gale onset. The mean position is plotted as a solid circle and the dashed box encloses the domain within one standard deviation of the mean CPS location for the 197 storm set.

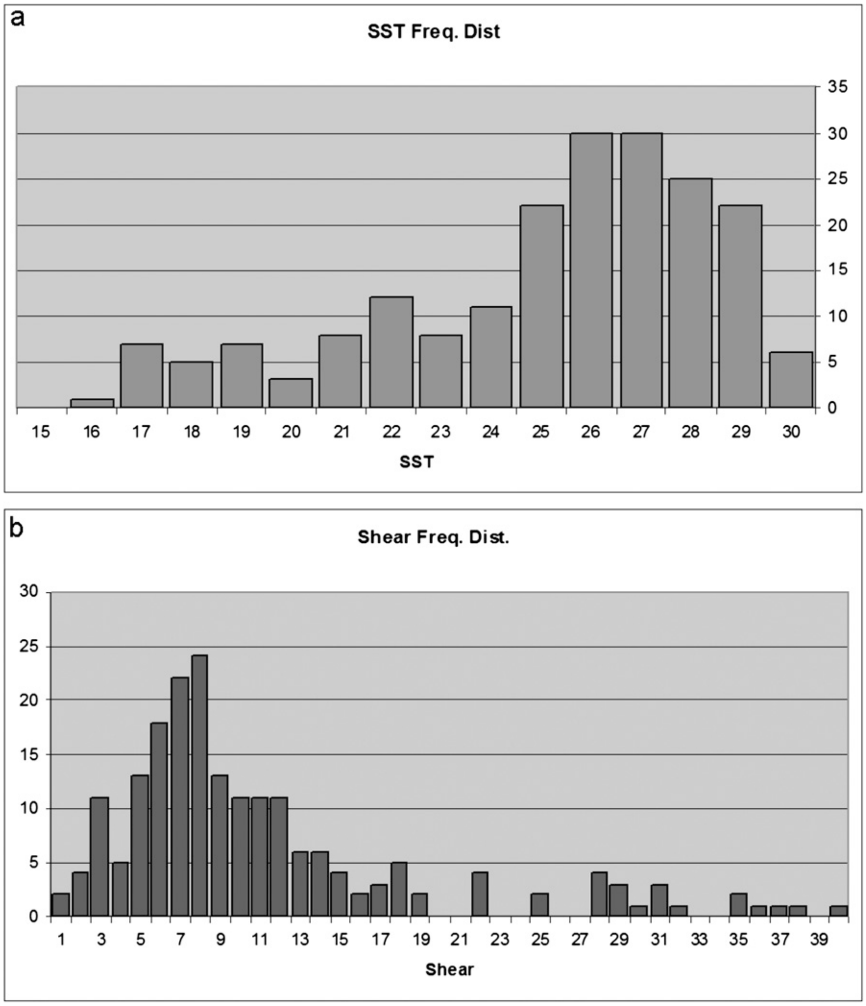

FIG. 8. Frequency distribution of the numbers of ERA-40 storms sorted by (a) SST (°C) and (b) 925–200-hPa vertical wind shear (m s^{-1} over the 725-hPa layer).

during each individual event. The strong background shear and cold SST are both detrimental to ST formation. The range of SST in the region of active ST occurrence has increased dramatically to 24°–29°C by August, and the area over which ST cyclogenesis is favored has shifted northward. Mean locally composited shear for the August ST cyclogenesis events is 13.1 m s^{-1}, which is more representative of the long-term mean environmental shear for this region. The increase in ST activity between April and August is consistent with the necessity for thermodynamic support for cyclogenesis (warmer SST), and the typical magnitudes of environmental shear are more similar to the regime demonstrated here that are favorable for ST genesis (see Fig. 8). The region of subtropical cyclogenesis has expanded outward by October, and the mean local shear for each event has decreased to 8.1 m s^{-1}. On the composite map, the regional shear regime is one of horizontal divergence aloft, with a 20–30 m s^{-1} southwesterly flow to the north of the mean position and a westerly 10–15 m s^{-1} shear to the south. This is consistent with an upper trough being present to the northwest of the mean position and shear reduction (as in the April mean) being over the mean position of cyclogenesis.

In their climatology of extratropically transitioning Atlantic tropical cyclones, Hart and Evans (2001) mapped the evolution of the Eady baroclinic growth rate and the 26°C isotherm as measures of baroclinic and tropical cyclogenesis potential. They hypothesized that ET was most favored in the region of overlap where both convectively driven and baroclinic forcing were supported. This was based on the hybrid structure of the evolving ET system, a structure similar to the ST being considered here. Hart and Evans (2001) noted good agreement between the seasonal migration of the prime location for ET and the region of warm SST–high Eady

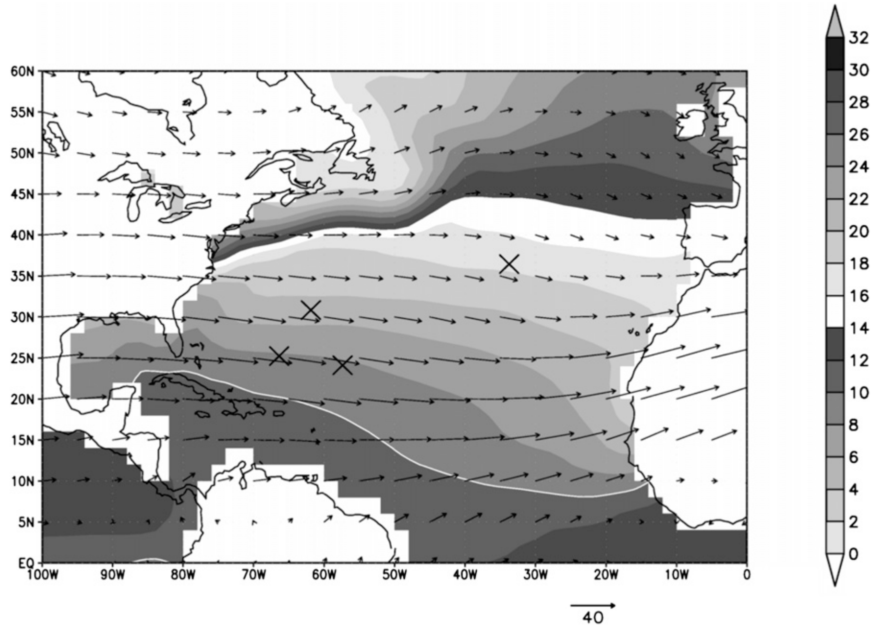

FIG. 9. April long-term means NCEP–NCAR Reanalysis composite 925–200-hPa shear (vectors; m s^{-1}) and SST (shaded; °C). The crosses indicate the April position of ST storm (gale) onset.

growth rate overlap. We perform a similar analysis here for the ERA-40 dataset of 197 ST events.

Composite maps of Eady baroclinic growth rate (σ) overlain on SST maps for April, August, and October are presented in Figs. 12, 13, and 14, respectively. There is some overlap of the shaded contours for Eady growth rate of 0.25 day^{-1} and the SST threshold of 22°–26°C, but only in October do they overlap, indicating the highest potential for coincident baroclinic development and deep convective activity. In April, the cooler SSTs and stronger shear (as discussed above) explain the relative lack of ST activity, although the baroclinic forcing

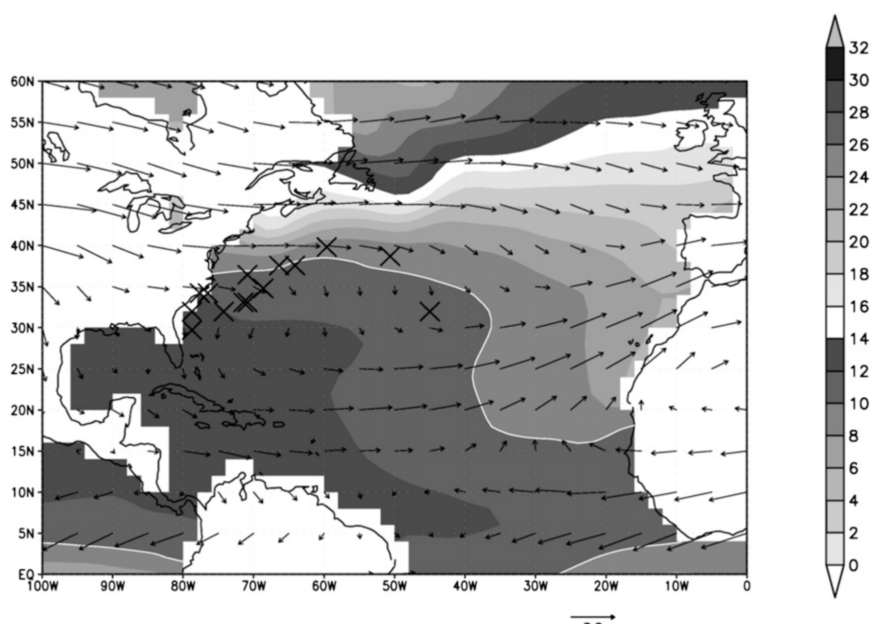

FIG. 10. As in Fig. 9, but for August.

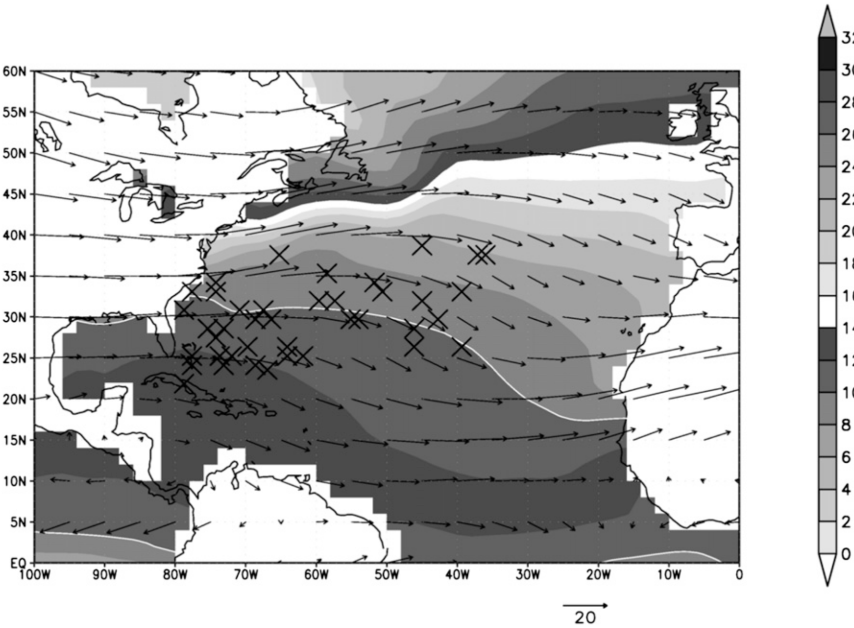

FIG. 11. As in Fig. 9, but for October.

may be in place. In August, the SSTs in the Atlantic have warmed basinwide, but the maximum Eady growth rate has retreated northward. The warmer SSTs and lower shear environment are conducive to more ST development in August, although the baroclinic development zone has moved north and contracted (Fig. 13). As the seasons transition and the baroclinic zone once again moves south, the Eady growth rate extends farther south again, reaching its southernmost extent in October. Because the SST lags the atmosphere and remains warm, the area of overlap between the warm SST and the baroclinic zone increases dramatically (Fig. 14), consistent with the observed increase in ST activity in September and October (Fig. 6).

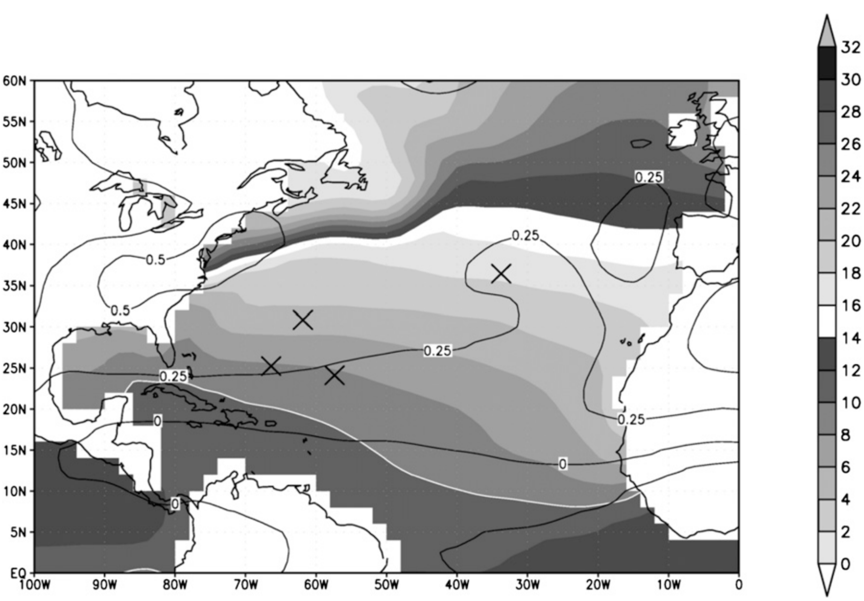

FIG. 12. April long-term mean NCEP–NCAR Reanalysis composite Eady baroclinic growth rate (contoured; day^{-1}) and SST (shaded; °C). The crosses indicate the April positions of ST storm (gale) onset.

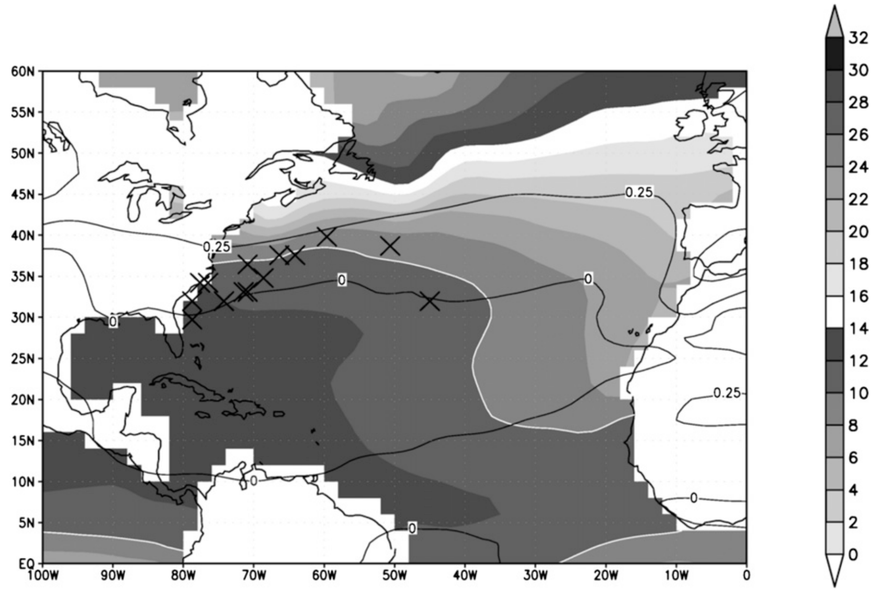

FIG. 13. As in Fig. 12, but for August.

5. Comparison of this ERA-40 climatology with other Atlantic ST datasets

Previous records of ST candidates have been listed by Roth (2002) and have been mentioned in the HURDAT (also called the best track) dataset (Jarvinen et al. 1984). These two datasets are derived primarily from operational data that have been reanalyzed and quality controlled, referencing all the available observational data. Although there are portions of HURDAT that have not yet been fully reanalyzed, it forms the most complete record of Atlantic cyclones with tropical or subtropical segments of their life cycles (Landsea et al. 2004). Because of the evolution of observing techniques and numerical model guidance, they may be inconsistent and subject to the biases and differences in available information and also the knowledge of the operational personnel performing the analyses. For example, about one cyclone per year has been added to the HURDAT dataset since 2002 because of advancements in technology

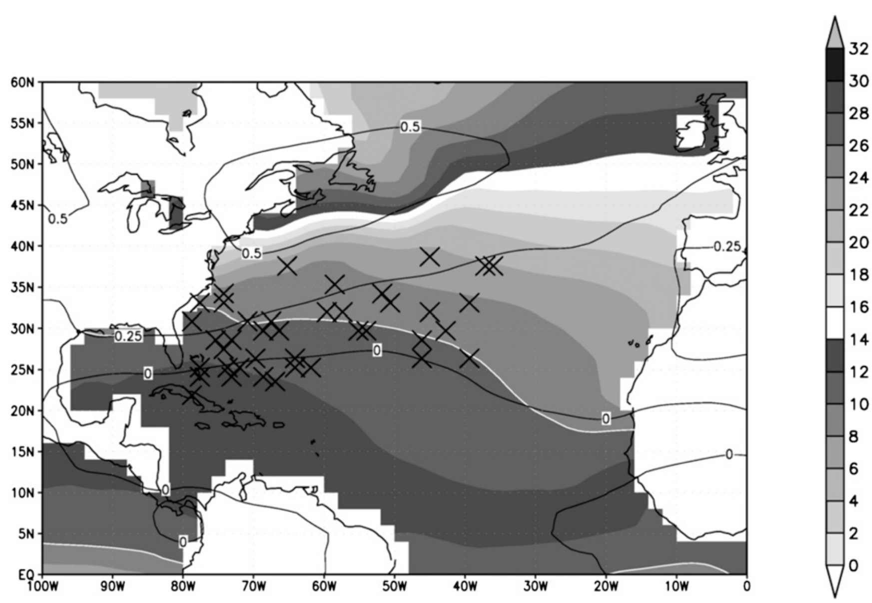

FIG. 14. As in Fig. 12, but for October.

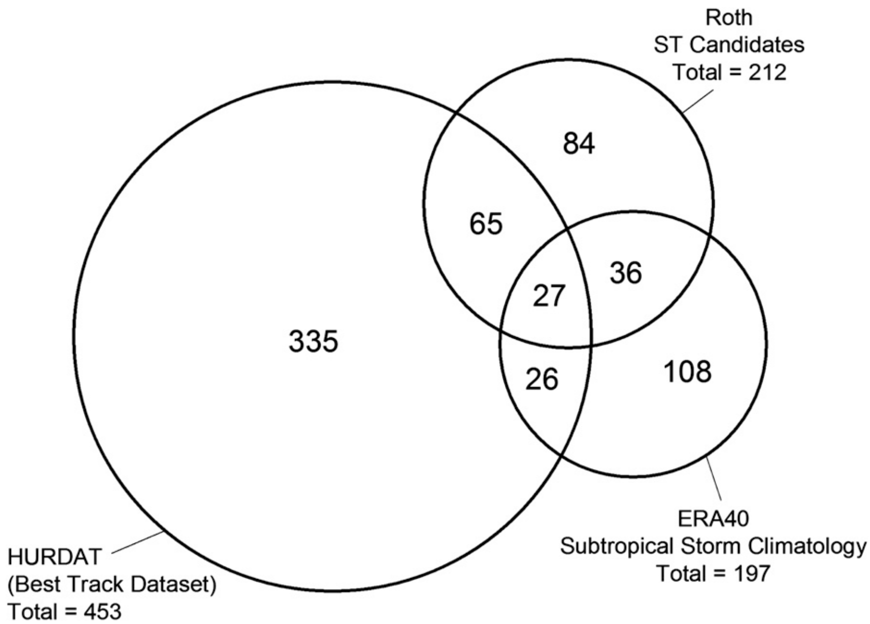

FIG. 15. Venn diagram to show the relative numbers of cyclones in the ERA-40 climatology, NHC HURDAT best-track dataset, and Roth's (2002) list of ST candidates.

and analysis methods (Landsea et al. 2007). Although the NOAA–NWS policy for classification of ST may have been the same since 1975 (HP75), the policy for naming or issuing advisories on them has not been consistent. Indeed, there are no named storms corresponding to ST found in the ERA-40 analyses for 11 out of 43 active ST years and, at most, 2/3 of the ERA-40 ST correspond to storms recorded in HURDAT in any year (Guishard 2006). However, it should be noted that the criteria for inclusion in each dataset mentioned here are different. The intent of this study is to use model reanalyses and the CPS to isolate cyclones that are unambiguously ST via an objective, consistent, and largely automated method. The techniques used for the reanalysis of HURDAT are not the same, and therefore it is to be expected that the overlap between the two datasets is not perfect. However, as a reference dataset, HURDAT is the most appropriate to make comparisons against.

It is not the intention of the authors to criticize the efforts by operational forecasters and observers to analyze and predict a rapidly evolving real-time system accurately. Ongoing efforts to reanalyze the historical tropical cyclone dataset in the Atlantic (Landsea et al. 2004) and efforts to normalize satellite-based records of tropical cyclone winds (Kossin et al. 2007) aim to address the inconsistencies in methodology that may have impacted the current historical record. The methodology presented here for identifying and classifying ST is being incorporated into the Atlantic HURDAT reanalysis process.

There is a considerable overlap between the ERA-40 climatology presented here, the Roth (2002) list of candidates, and the HURDAT dataset (Fig. 15). Fifty-three of the 197 ST in the ERA-40 climatology are named cyclones in the HURDAT database (Guishard 2006). Sixty-five of the 92 cyclones operationally deemed subtropical in the NHC HURDAT met the ST criteria in our ERA-40-based climatology. However, those systems were included in the Roth list of ST candidates by default (one of his criteria was that a storm was classified as ST in HURDAT). These systems were excluded from our climatology for a variety of reasons, including the following: no gales associated with the system in the ERA-40 analyses, formation over land, hybrid characteristics were not in evidence for the required 36 h, or the system persisted as a purely tropical or extratropical storm prior to obtaining ST (hybrid) structure. Another 26 storms in HURDAT were not labeled subtropical but did meet our ST criteria, making a total of 53 cyclones overlapping between the HURDAT and ERA-40 sets. Therefore, according to the current climatology, 11.7% of all tropical cyclones had origins as an ST in the 45-yr period of this study (there were 453 tropical cyclones in HURDAT for this period).

Roth's (2002) dataset was made up of a total of 212 cyclones of ambiguous origin, some of which never attained gales. Thirty-six ST were in both the Roth and ERA-40 databases but did not exist in HURDAT. Of the 212 systems in Roth's dataset, 85 cyclones (40%) met neither the criteria of the ERA-40 climatology nor

TABLE 2. Comparison of the necessary conditions for subtropical cyclogenesis determined in this study against those required for tropical cyclogenesis.

Subtropical cyclone (ST)	Tropical cyclone (TC)
Dynamic conditions	
Upper trough (nontrivial deep layer shear)	Weak deep layer shear
Positive low-level relative vorticity	Positive low-level relative vorticity
Latitudes 20°–40°N (Coriolis parameter is large compared with tropical genesis)	Latitudes 10°–20°N (Goldenberg and Shapiro 1996)
Thermodynamic conditions	
Near-neutral stability in the free troposphere. Facilitated by warm SST and cold upper temperatures. Deep convection possible with forced ascent.	Ability to sustain deep convection. Facilitated by warm SST and saturation in the boundary layer.
Anomalously high lower-tropospheric moisture (cf. long-term monthly average).	Anomalously high lower-tropospheric moisture (cf. long-term monthly average).

the criteria of the HURDAT. Considering that Roth's list includes some cyclones gleaned from the surface analyses in the absence of satellite imagery (in the presatellite era), some classified from satellite imagery in areas of sparse surface or upper-air observations, and all HURDAT ST, it is unsurprising that a largely automated and consistent method should filter out such a high proportion of the cyclones in that dataset. The overlap for all three datasets was only 27 storms (Fig. 15).

In the context of the historical ST record, the objective ERA-40 climatology presented here leads to several conclusions. The HURDAT records include 118 systems that were acknowledged as ST of the 453 total storms recorded for this 45-yr period; however, the analyses presented here imply that 65 of these ST are not identified in the ERA-40 ST dataset (mainly because of the lack of a hybrid structure), leaving only 53/453, or 12%, of the ST identified in both the HURDAT and the current ERA-40 study. Inclusion of the 144 newly identified ST in the ERA-40 climatology changes this statistic dramatically: now 197 ST are recorded in a total storm set of 597 (the original 453 best-track storms and the additional 144 ST newly identified here). This amounts to 33% of the revised (HURDAT plus independent ERA-40 cases) storm set being classified as ST—certainly a nonnegligible fraction of the warm-season storms in the Atlantic basin!

6. Subtropical cyclones as a tropical cyclogenesis source

The necessary (but not sufficient) environmental features for subtropical and tropical cyclogenesis are contrasted in Table 2. Although subtropical and tropical cyclogenesis have some environmental characteristics in common, even some of these similar conditions are associated with different large-scale features and forcings. For example, although deep convection appears necessary for ST development, the mean environment is nearly moist neutral and requires deep, forced ascent (e.g., ahead of an approaching trough) for convection to be sustained.

The most significant difference between the environmental conditions for ST and TC is the shear regime necessary. Numerous studies have concluded that weak shear is optimal for TC genesis because strong environmental shear will disrupt the warming provided by convection in a developing TC (e.g., Gray 1968; De Maria et al. 2001). In contrast, ST are observed to form in the baroclinic zone ahead of an approaching upper trough. Bracken and Bosart (2000) found that the surface lows of incipient ST in the northern Caribbean were present under the point of inflection between an upshear upper trough and a downshear upper ridge, the region of strongest deep layer shear in a trough–ridge couplet. The predominance (121/197 or 61%) of ST in the ERA-40 climatology that formed in a moderate to high shear environment ($U_{200\ \mathrm{hPa}} - U_{900\ \mathrm{hPa}} > 7.5\ \mathrm{m\ s^{-1}}$) further supports the role of shear in ST genesis. Finally, ST case studies indicate that $U_{200\ \mathrm{hPa}} - U_{900\ \mathrm{hPa}} > 10\ \mathrm{m\ s^{-1}}$ is characteristic in the initial stages of subtropical cyclogenesis (Guishard 2006; Part I).

Two dynamic conditions necessary for both tropical and subtropical cyclogenesis are positive low-level relative vorticity and a ''sufficiently large'' Coriolis parameter (i.e., off-equator location). In light of the latitude range in which ST genesis occurs, the sufficiency of the Coriolis parameter is a trivial result when compared with that for TC genesis. Preexisting low-level vorticity is necessary for both cyclogenesis types, but the source of vorticity is likely to be different for each: a TC may develop from an African easterly wave, an equatorial Rossby or mixed Rossby–gravity wave, or a monsoon disturbance in the trough. ST genesis is more likely to occur on a shear zone associated with an old frontal boundary linked to the upper trough, which is forcing the cyclogenesis. Combined with the higher levels of planetary vorticity (f is on the order of 10^{-4} s^{-1} in the subtropics), this represents an increase of up to an order in magnitude in preexisting absolute vorticity in ST versus TC genesis environments. Further, the incipient vortex in the ST genesis is larger in scale than the incipient TC (Guishard 2006).

In their study, Hendricks et al. (2004) investigate the role of ''vortical'' hot towers during the development of Hurricane Diana in 1984, a well-documented storm of baroclinic origin (Davis and Bosart 2001, 2002; Bosart and Bartlo 1991). They conclude that the vortical hot towers associated with cumulonimbus convection play dual roles in the genesis of Diana: 1) preconditioning of the environment by generating positive low-level PV as they pulse and 2) direct contribution to the mean vorticity of the incipient cyclone through vortex merger. This view of cyclogenesis is appropriate for both TC and ST; as foreshadowed above, the difference is the forcing for the convection. In the case of TC, warm SST allow enough convection through the generation of localized CAPE by near-surface parcel heating and moistening and the absence of disrupting deep layer vertical shear. In the case of ST genesis, large-scale mass ascent of the moist boundary layer air is induced through quasigeostrophic dynamic processes in the moderate vertical shear ahead of an upper trough in the genesis region. The associated forced ascent over relatively warm water is associated with a region of weak static stability (and large Rossby penetration depth), facilitating the development of deep convection.

7. Summary

Application of a consistent set of criteria for ST in the ERA-40 reanalyses has resulted in the identification of 197 North Atlantic ST in the 45-yr climatology. Sixty-two percent of these ST were documented to form over SST in excess of 25°C. It is proposed that warm SSTs contribute to the potential for ST cyclogenesis but the associated SST threshold is lower than that for tropical cyclogenesis (Gray 1968; Evans 1993). Warm SST is used here as a proxy for the ability to sustain deep convection. The convection is not only a source of warming, as it is in TC, but also a means of reducing the vertical shear (Davis and Bosart 2003) and increasing the Rossby penetration depth so that the low-level warm core of the system may be intensified. The mechanism for this reduction of shear is described later in this section, from a PV perspective, and further explanation is available in Davis and Bosart (2003), who use absolute momentum arguments.

It is helpful to view ST in the context of the storm continuum implied by the CPS. ST, when compared to TC, generally have weaker surface circulations and are typically warm cored and barotropic from the near-surface levels up to approximately 500 hPa, whereas TC may have very deep warm cores, extending upward from the surface into the upper troposphere. Lacking this deep warm core, an ST cannot fully develop and maintain its circulation solely via surface fluxes as a TC might (Emanuel 1986, 1995). However, an ST has an additional source of dynamic support: the upper-level PV anomaly (trough or cutoff low), which forces large-scale ascent via geostrophic adjustment in a weakly stable large-scale environment. This deep vertical ascent in a region of near-neutral stability forces convection and resulting cyclonic development through WISHE, even with only weak (relative to tropical cyclogenesis processes) thermodynamic support from the sea surface fluxes. In the absence of the upper trough or cutoff low, an ST is unlikely to form. Hence, the presence of a cold upper feature facilitating near-neutral stability constitutes a necessary condition for subtropical cyclogenesis. If an ST attains enough convection that the warm lower core begins to extend upward past the midlevels and the upper cyclone begins to erode, the system may become self-sustaining through convection and transition into a fully tropical cyclone. This is a mode of tropical cyclogenesis (which may be defined as the production of a deeply warm-cored, self-sustaining cyclone) that has only recently begun to be explored in the literature (e.g., Davis and Bosart 2003).

Despite the differences in identification techniques between the ERA-40 and HURDAT datasets, it is interesting to note the similarities between the ST climatology compiled in this study and that of TC derived from the NHC HURDAT best-track data. The daily frequency of storm genesis from the NHC HURDAT dataset is plotted in Fig. 16: the solid line is the total number of storms (TC and ST) and the bars are the TC only (i.e., ST from this climatology are excluded)—the difference represents the ST in this climatology. ST make a major contribution (12%) to the number of TC developments in HURDAT, equivalent to one in eight genesis events from an incipient ST disturbance. However, with the addition of 144 ST newly identified in this climatology (i.e., not presently in HURDAT) and the reclassification (as NOT ST) of 65 existing storms in HURDAT, 197/597 storms in the newly combined database are ST.

The number of ST is influenced each year by the relative positions of the baroclinic zone and the thermodynamic forcing [characterized here using SST as a proxy for Emanuel's potential intensity (PI) The

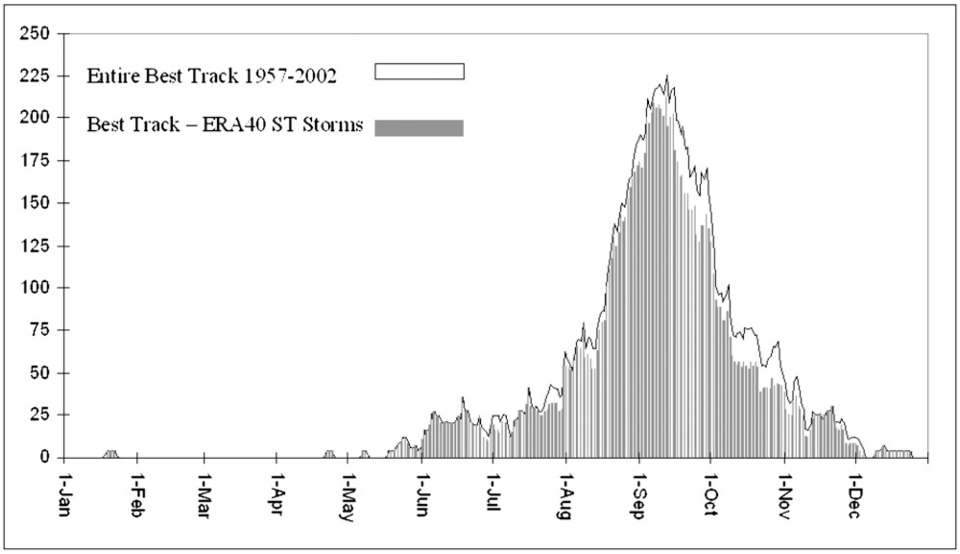

FIG. 16. Annual cycle of HURDAT daily tropical cyclone activity (black line) overlaid with removed ERA-40 ST (histogram). Thus, the white space between the histogram and the line indicates the annual distribution of ERA-40 derived ST.

baroclinic zone is characterized here by Eady baroclinic wave growth rate (σ), a crude proxy of which is vertical shear of the horizontal wind.

At the beginning of the Atlantic tropical season in June, the baroclinic forcing zone (using a threshold of $\sigma \geq 0.1$) is far enough south in the North Atlantic to be in close proximity to or to overlap the 25°C SST isotherm, allowing for occasional ST genesis and, potentially, tropical transition. In July, this baroclinic zone retreats north, away from the region of warm SST, weakening or removing one mechanism for ST genesis and thus also for TC genesis. As warm SST advance northward in August, the baroclinic zone may once again overlay regions of sufficient thermodynamic forcing for ST genesis to occur. As the transition season approaches, the baroclinic zone begins to extend farther south and the warm SST remain, further increasing the chance of ST genesis. Results from the ET climatology of Hart and Evans (2001) indicate that when this superposition of baroclinic and thermodynamic forcing occurred, extratropical transition events were more likely because transitioning TC also become hybrid cyclones. It should be unsurprising then that the seasonality of North Atlantic ST genesis identified in this paper has a similar temporal distribution to the ET seasonal cycle identified by Hart and Evans (2001).

The importance of ST is significant in the context of warm-season storms in the North Atlantic. ST pose a forecasting problem for subtropical locations such as Bermuda because of potentially rapid cyclogenesis close to land (Guishard et al. 2007), which was evident during the evolution of Karen. ST were identified in the ERA-40 climatology in 43/45 yr and represent a potential TC genesis mechanism.

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