A Climatology of Subtropical Cyclones in the South Atlantic

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ABSTRACT

A 50-yr climatology (1957–2007) of subtropical cyclones (STs) in the South Atlantic is developed and analyzed. A subtropical cyclone is a hybrid structure (upper-level cold core and lower-level warm core) with associated surface gale-force winds. The tendency for warm season development of North Atlantic STs has resulted in these systems being confused as tropical cyclones (TCs). In fact, North Atlantic STs are a regular source of the incipient vortices leading to North Atlantic TC genesis. In 2004, Hurricane Catarina developed in the South Atlantic and made landfall in Brazil. A TC system had been previously unobserved in the South Atlantic, so the incidence of Catarina highlighted the lack of an ST climatology for the region to provide a context for the likelihood of future systems.

Sixty-three South Atlantic STs are documented over the 50-yr period analyzed in this climatology. In contrast to the North Atlantic, South Atlantic STs occur relatively uniformly throughout the year; however, their preferred location of genesis and mechanisms for this genesis do exhibit some seasonal variability. Rossby wave breaking was identified as the mechanism for the ST vortex initiation for North Atlantic STs. A subset of South Atlantic STs forms via this mechanism, however, an additional mechanism for ST genesis is identified here: lee cyclogenesis downstream of the Andes in the Brazil Current region—an area favorable for convection. This formation mechanism is similar to development of type-2 east coast lows in the Tasman Sea off eastern Australia.

1. The South Atlantic environment in the context of subtropical storm development

This climatology of subtropical cyclones (STs) in the South Atlantic Ocean contributes to our understanding of the global distribution and mechanisms underlying these intense weather systems. It was also motivated by the formation of Hurricane Catarina in March 2004 as a ST that subsequently underwent ''tropical transition'' (e.g., Davis and Bosart 2004; McTaggart-Cowan et al. 2006; Pezza and Simmonds 2005; Pereira Filho et al. 2010). However, since no climatology of South Atlantic STs existed, there was no context for exploring the likelihood of other Catarina-type events. The first climatology of South Atlantic STs is presented here. To put it in context, we begin by describing salient aspects of the South Atlantic environment in which these STs develop.

As noted by Pezza et al. (2009), subtropical South Atlantic sea surface temperatures (SSTs) are generally cool (much less than 26.5°C across most of the basin). The poleward migration of warm SST is governed by the strength of the Brazilian Current, the South Atlantic counterpart of the Gulf Stream (Fig. 1). Yet, the striking difference between the North and South Atlantic is the strength of the cold Malvinas Current in comparison to the North Atlantic Labrador Current. The cold Malvinas Current is a northward branch of the Antarctica Circumpolar Current (Goni and Wainer 2001) and acts to suppress the poleward migration of the warm Brazilian Current, effectively capping the Southern Hemisphere (SH) subtropical SST (Fig. 1). However, the South Atlantic Ocean multidecadal cycle may have contributed to a favorable shift in these currents in recent years. The South Atlantic multidecadal cycle (roughly a 25–30-yr period; Wainer and Venegas 2002) is signaled by a change in the intensity of the westerlies associated with variability in the southward extension of the Bolivian high (a dominant feature of the upper-level warm season circulation in South America; Chen et al. 1999). This wind speed variability drives changes in the

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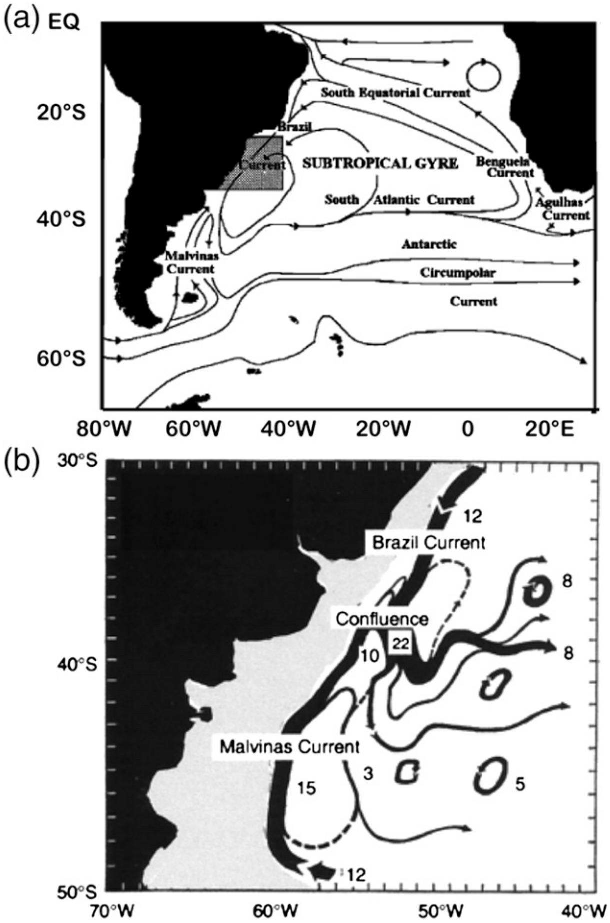

FIG. 1. Surface ocean currents for (a) the South Atlantic basin (Zavialov et al. 1999, their Fig. 1) and (b) detail of the Brazil–Malvinas confluence zone (Goni and Wainer 2001, their Fig. 1).

wind-driven ocean currents (Tokinaga et al. 2005), leading to modulation of ocean mass transport and thus to variation in the intensity of the Malvinas Current and the position of the Brazil–Malvinas confluence zone (e.g., Fig. 2).

Wainer and Venegas (2002) describe two extreme phases of the 25–30-yr South Atlantic multidecadal cycle. During the positive phase, sea level pressure increases along 40°S associated with a southward extension of the subtropical anticyclone and a weakening of the westerlies. This reduction in the westerlies leads to a weakening of the northward-flowing Malvinas Current and permits the Brazil Current to penetrate farther south, displacing the oceanic confluence region poleward. Anomalously high precipitation along an elongated (toward the southeast) South American convergence zone and a greater surface heat flux coincide with the resultant warm SST anomaly along 40°S (Wainer and Venegas 2002, see their Figs. 6c, 7a, and 6a). This environment provides for stability and moist conditions in the midtroposphere that are unusually favorable for South Atlantic ST genesis. In March 2004 the Malvinas Current was somewhat weaker than normal and warm eddies in excess of 22°C migrated poleward of 30°S (Fig. 2; see also Lumpkin and Garzoli 2011), providing a favorable oceanic environment for the formation of the ST that later transitioned into Hurricane Catarina (Vianna et al. 2010). Thus, the long-term variations of these currents may have contributed to the formation of Hurricane Catarina and could signal a climatological shift allowing for other ST formations in the South Atlantic. However, the ocean current configuration is only one component of a favorable ST environment: although the Malvinas Current was weaker in 2005 than in 2004 (Fig. 2) and four STs were observed (Fig. 3), none of these ST developed tropical characteristics, possibly due to the stronger vertical wind shear in the region (not shown).

Tropical cyclones (TCs) routinely occur in every basin in the world except the South Atlantic. This South Atlantic TC deficit has been attributed to cool SSTs and potent vertical wind shears (Pezza and Simmonds 2005, 2008; McTaggart-Cowan et al. 2006; Veiga et al. 2008; Pereira Filho et al. 2010; Vianna et al. 2010). In both the Pacific and Indian Oceans, the monsoon environment provides the essential ingredients of dynamical organization, weak vertical wind shear, and ample convective activity needed for TC formation (Gray 1968). The South Atlantic does not have a conventional monsoon (Zhou and Lau 1998) and climatological vertical wind shears are far too strong to support development of purely tropical storms (Pezza et al. 2009). However, STs can form in environments of much cooler SSTs and stronger shear (Guishard et al. 2007, 2009) and, as noted above, North Atlantic STs have been shown to undergo tropical transition to TCs (Davis and Bosart 2003, 2004) with relative regularity (Guishard et al. 2009). Thus, a climatology of STs has the potential to provide insights on the dearth of South Atlantic TCs, as well as on the STs themselves.

Here we document the first climatology of South Atlantic STs and analyze the characteristics and formation mechanisms of the 63 STs identified over the 50-yr period August 1957 through December 2007. In the following sections, we describe the data used and modes of analysis (section 2), refine the definition developed for North Atlantic ST for application in the South Atlantic (section 3) and summarize key differences between North and South Atlantic STs and their environments (section 4). We then present the mean South Atlantic ST climatology (section 5) and explore its variability (section 6). Finally, we identify potential mechanisms for ST genesis (section 7) and conclude with a summary of our key findings (section 8).

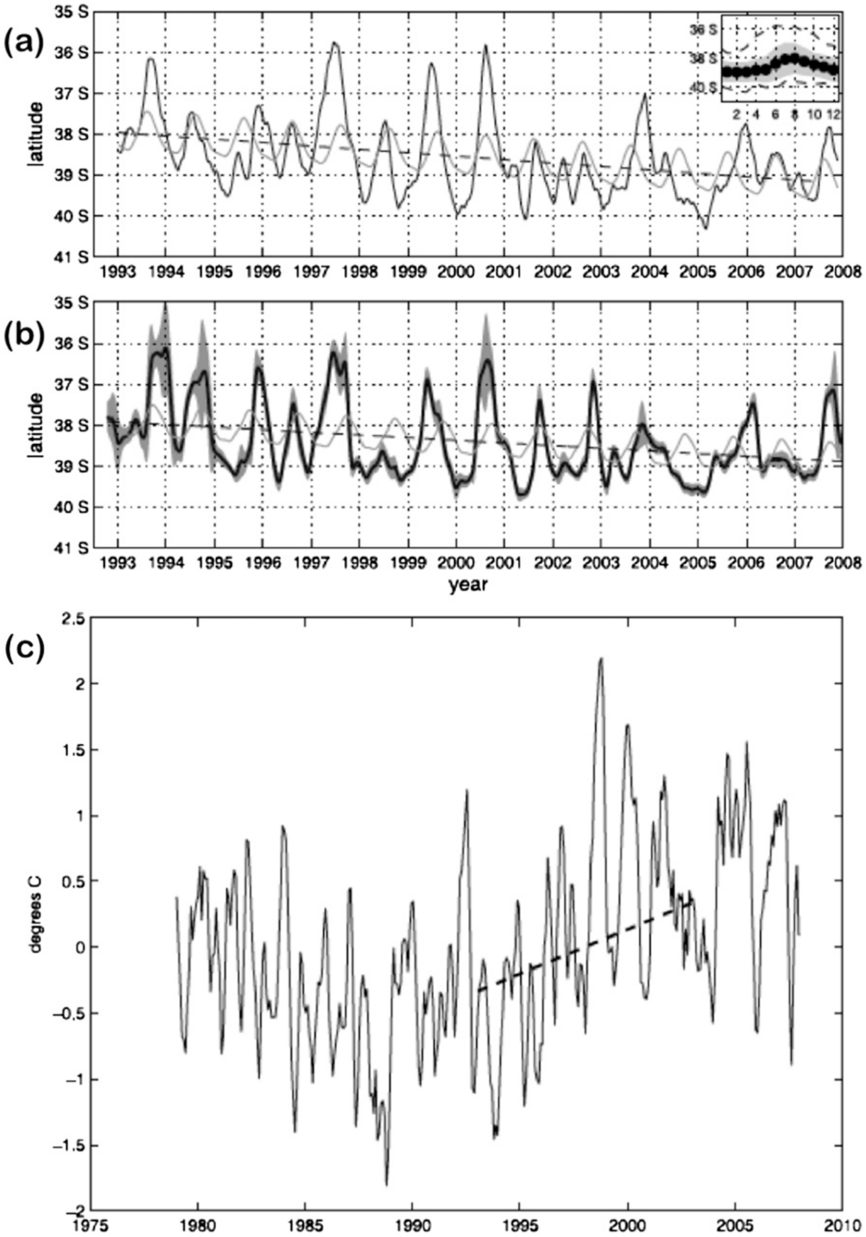

FIG. 2. Time series of metrics of the Brazil–Malvinas confluence zone from Lumpkin and Garzoli (2011). (a) Confluence latitude determined by velocity field (black line). (b) Confluence latitude determined from sea surface height (thick black line), with the error estimate given in gray shading. The linear trend (dashed line) and the combined annual and semiannual cycle (gray line) are indicated in (a) and (b). Both panels are reproduced from Fig. 3 of Lumpkin and Garzoli (2011). (c) NCEP–NCAR reanalysis SST seasonal anomaly (°C) averaged over the region 34°–38°S, 53.5°–57°W (Lumpkin and Garzoli 2011, their Fig. 4). The dashed curve is the best-fit trend over the period 1993–2002.

2. Characterization of candidate ST systems and their environment

A total of 63 STs formed in the South Atlantic basin in the period August 1957 through December 2007. The data used and methodologies applied for identifying these systems and characterizing their development environments are described here.

a. Datasets used

We employ the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis

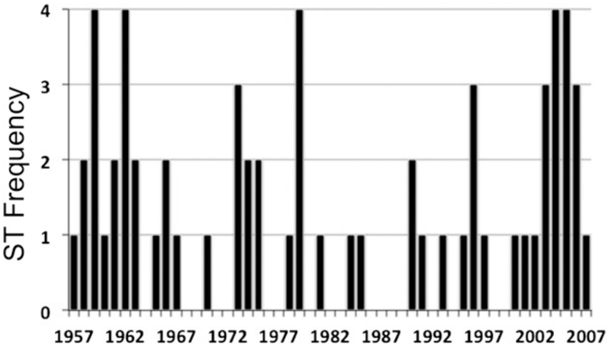

FIG. 3. Annual frequencies of ST genesis in the South Atlantic basin for 1957–2007.

(ERA-40; Uppala et al. 2005) accessed through the National Center for Atmospheric Research (NCAR); the ERA-40 reanalysis span the 45-yr period August 1957–December 2002 at 1.25° × 1.25° resolution. Vector winds, temperature, pressure and relative humidity, as well as derived variables such as vorticity, vertical wind shear, and potential temperature are analyzed on 14 pressure levels and the surface.

To extend the time period of this study, the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS)[1] operational analyses (Kanamitsu 1989) for the period 2000–07 are analyzed. These analyses were obtained in near–real time and have 1° × 1° subsampled resolution on 26 pressure levels plus the surface. The GFS operational analyses have an expanded set of 95 variables that encompasses those available from the ERA-40 used in this study. The 2-yr overlap between the NCEP and ERA-40 time periods facilitates intercomparison of results for storms occurring during 2000–02. Because of the increased variable set available in the GFS analyses, more detailed diagnostics are possible for the 17 STs identified in the 2000–07 time period (Braun 2009).

b. *Compilation of system track and structure diagnostics*

An automated detection and tracking algorithm (Hart 2003) was implemented to compile the substantial dataset of candidate ST systems assembled here. The algorithm detects and tracks minima in sea level pressure (SLP) of less than 1020 hPa, which persist for at least 24 h. Cyclones identified must have a mean sea level pressure gradient of at least 0.4 hPa per degree, in a moving 5° × 5° box within the domain of interest. The 24-h life span is used to exclude spurious SLP minima, and the SLP gradient condition is necessary to avoid locating weak minima within the tropics where the overall pressure field is generally uniform. Latitudinally dependent constraints on forward speed and direction shifts between consecutive times are enforced to avoid confusion between nearby systems (Hart 2003, see their Table 1).

The automated tracking algorithm includes a gale-force wind radius diagnostic that detects gales associated with the cyclone by inspection of wind speeds at increasing radii from the storm center. The Cyclone Phase Space (CPS) of Hart (2003) is employed to characterize the evolving three-dimensional structure of each candidate ST event and to filter storms not meeting the ST criteria developed here (section 3), which are based closely on those of Guishard et al. (2009). The CPS is spanned by three metrics quantifying structure characteristics of a synoptic system: (i) lower-tropospheric thermal wind ($-V_T^L$), (ii) upper-tropospheric thermal wind ($-V_T^U$), and (iii) lower-tropospheric thermal asymmetry (B). The STs have a hybrid structure with warm-core lower- and cold-core upper-tropospheric signatures; quantitatively, this corresponds to CPS criteria of ($-V_T^L > -10$, $-V_T^U < 10$) [taking into account the uncertainty threshold determined by Hart (2003)]. However, Manning and Hart (2007) find that the intensities of historical hurricanes are not consistently represented in the ERA-40 analyses through time (1957–2001 in their study). Further, the ERA-40 analyses may not preserve the relative differences (weaker or stronger) between hurricanes with different observed intensities. These problems were more acute for weaker systems, such as the STs studied here. Thus, we adjust our analyses in two ways to cope with these ERA-40 limitations. The ($-V_T^L$, $-V_T^U$) threshold values for detection of ST in the ERA-40 are relaxed and consistency between systems identified in the GFS–ERA-40 2-yr overlap period is required (Braun 2009). In addition, we require that the ST signature extend up to 500 hPa.

c. *Characterizing the ST environment*

Vertical wind shear and SST were used by Guishard et al. (2009) and in our study to characterize the environment of the evolving STs. Consistent with Guishard et al. (2009), environmental vertical wind shear is calculated via a storm-centered 5° × 5° area average over the 900–300-hPa layer. SST values are expected to have a more direct impact on STs via localized convection and/or warm-air advection feedbacks, so the SST averaging area is confined to a 2° × 2° box centered on the storm.

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[1] Before 2002, the GFS global model was known as the AVN. For simplicity, the model is referred to as GFS here regardless of the year under consideration.

3. A quantitative definition of a ST

Before developing a climatology for a particular class of system, it is imperative to have a clear definition of that system. The Hurricane Operation Plan used by the Bermuda Weather Service (U.S. Navy 1994) defines STs following the World Meteorological Organization as follows:

> ''a non-frontal low pressure system that has characteristics of both tropical and extratropical cyclones. The most common type is 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 centre. In comparison to tropical cyclones, such systems have a relatively broad zone of maximum winds that is located farther from the centre, and typically have a less symmetric wind field and distribution of convection.
>
> A second type of subtropical cyclone is a mesoscale low originating in or near a frontolyzing zone of horizontal wind shear, with radius of maximum sustained winds generally less than 30 miles. The entire circulation may initially have a diameter of less than 100 miles. These generally short-lived systems may be either cold core or warm core.''

While this definition describes many salient characteristics of a ST and is consistent with the definition ultimately developed here, the generality of the descriptions render them difficult to use in an objective classification.

In developing their climatology of North Atlantic STs, Guishard et al. (2009) provide a quantitative definition of STs in terms of their formation location and evolution, hybrid synoptic structure, and peak surface wind speed. They define ''hybrid'' as warm cored in the lower troposphere and cold cored aloft ($-V_T^L > 0, -V_T^U < 0$). According to Guishard et al. (2009), candidate STs must satisfy all of the following criteria:

1) Candidate STs must be located between 20° and 40° from the equator.
2) The hybrid phase of the storm must persist for at least 36 consecutive hours over the ocean. Hybrid is diagnosed using the CPS of Hart (2003) as ($-V_T^L > -10, -V_T^U < 10$).
3) The core of the ST is not vertically stacked, but tilts westward with height.
4) All STs must have surface winds of at least gale force (17 m s^{-1}, 39 mph) while they are in their hybrid state.
5) A candidate ST should not be tracked as either a purely cold- or warm-cored system with gale-force winds for greater than 24 h prior to becoming subtropical.

For this South Atlantic climatology, we place a more severe restriction on prior system history than was imposed by Guishard et al. (2009):

6) Any storm with prior tropical structures (e.g., tropical waves, depressions) is excluded from this ST climatology. If the system is embedded in the midlatitude flow, it is deemed to be a midlatitude cyclone rather than a potential ST.

As a result, only storms that developed in situ are retained as STs here.

4. Identification of the final South Atlantic ST dataset

Application of criteria 1–6 (section 3) to the set of all cyclones from the 50-yr combined ERA-40 and GFS analysis database produces a set of candidate STs. Candidate South Atlantic STs form in a relatively data-sparse region, so there is a chance that they may not be well represented in the gridded analyses (Manning and Hart 2007). To allay these concerns, we perform the following supplementary analyses for the structure and intensity of these systems.

Satellite signatures are used to confirm the hybrid structure and presence of convection in these systems. The satellite signature of the ST, revealed through the International Satellite Cloud Climatology Project (ISCCP) B1 satellite imagery [(National Climatic Data Center) NCDC 2007], has a comma-shaped structure (Evans and Guishard 2009; Hebert and Poteat 1975). At first glance, this satellite signature could be confused with that of a midlatitude storm; however, we require a relatively cloud-free center of the surface low. While satellite data are not available for the entire period back to 1950, the remaining ST criteria are first developed for the available satellite period since 1974; all remaining ST criteria are applied to candidate ST in the presatellite era and the reasonable assumption is made that the cloud signatures are consistent with those identified post-1973 (Braun 2009).

Penetration of the surface low into the upper atmosphere and isolation of the system from the midlatitude flow are confirmed using 500-hPa geopotential height and 330-K isentropic potential vorticity (PV).[2]

The complete set of physical analyses performed on candidate South Atlantic ST (combining the criteria in section 3 and these supplementary tests) is depicted in Fig. 4.

In exploring the evolution of South Atlantic ST, we *define genesis as the first time when surface gale-force*

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[2] 330 K is typically around 500 hPa in our region of interest.

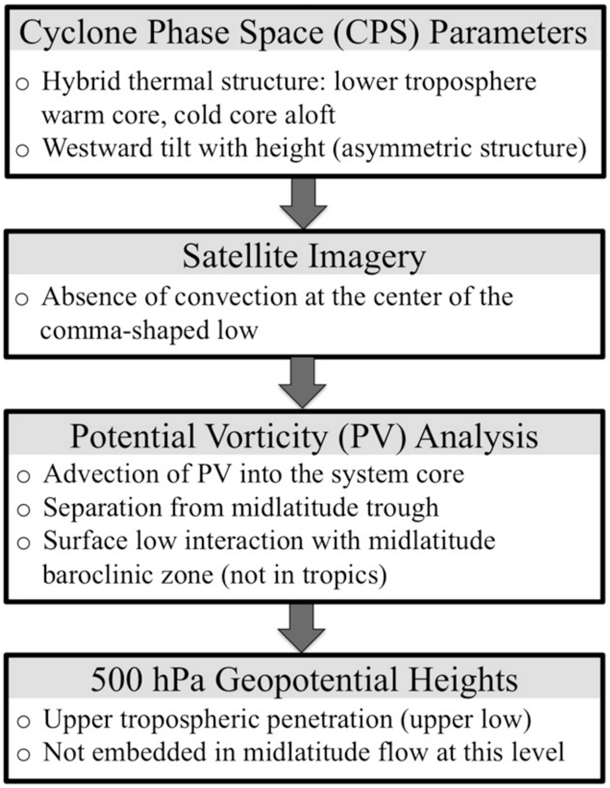

FIG. 4. System criteria employed to isolate the South Atlantic ST included in this climatology from the total set of candidate cyclones in the latitude band 20°–40°S.

winds are observed for a system with hybrid structure. This requirement for gales associated with STs is consistent with existing definitions (U.S. Navy 1994; Evans and Guishard 2009; Guishard et al. 2007, 2009; NOAA 2011). As discussed above, a low pressure center may be tracked for up to 36 h before being classified as a ST, so the formation point (first analysis of the low) and the location of genesis are often different.

Analyses of the final set of South Atlantic ST identified in this climatology reveal the following:

1) Development often occurs when a midlatitude PV reservoir intrudes into the subtropics.
2) A satellite signature consistent with the described PV pattern—convective heating forms farther out and around the center and seems to be forced into the center rather than forced outward from the center (since PV is diabatically driven, it follows that convective heating and an increase in the PV anomaly occur simultaneously).

Further, by contrasting the characteristics of North and South Atlantic STs we find that

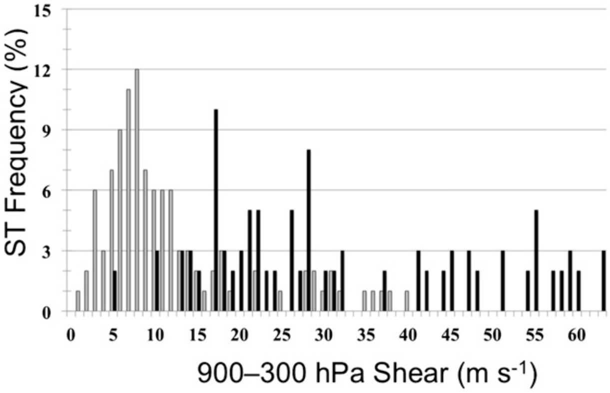

FIG. 5. Frequency distribution based on vector vertical wind shear (averaged over a 5° × 5° box centered on the system) for South Atlantic (black) and North Atlantic (gray) ST. Shear is calculated over the 900–300-hPa layer for South Atlantic ST cases and over the 900–200-hPa layer for North Atlantic ST cases (Guishard et al. 2009).

3) South Atlantic STs have a much larger gale radius than their North Atlantic counterparts.
4) A variety of system characteristics (e.g., weaker PV at the center) and climatological factors (e.g., seasonal distribution and shear) of these SH STs contribute to a decreased likelihood (cf. North Atlantic STs) of their transitioning into TCs.
5) The SH STs seem to have more extratropical storm characteristics; however, they are distinguished from midlatitude cyclones by their hybrid thermal structure.

Consistent with all of these features, typical SH STs are more asymmetric than their NH counterparts. Further analysis suggests that this greater asymmetry is due to the difference in mean baroclinicity between the two hemispheres. This distinct difference between North and South Atlantic shear structures (Fig. 5; Peixoto and Oort 1992) raises the possibility of additional formation mechanisms for SH STs (section 7).

5. Climatology

A total of 63 STs were identified in the South Atlantic latitude band 20°–40°S through the period August 1957–December 2007. Their mean climatology is presented here, followed by discussion of their temporal variability (section 6). Typical formation environments and possible genesis mechanisms are explored in section 7.

South Atlantic STs typically formed in median vertical wind shear of 28 m s^{-1} (Fig. 5), with the weakest (strongest) shear diagnosed to be 4 m s^{-1} (63 m s^{-1}). As with North Atlantic STs, the genesis environment for STs in the South Atlantic is the strongest vertical wind

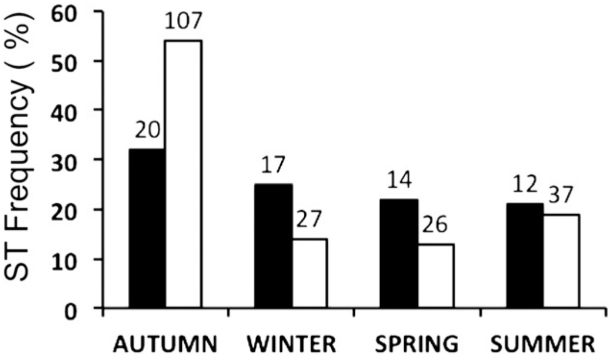

FIG. 6. Seasonal distribution of ST occurrences in the South Atlantic (black) and North Atlantic (white). Each season is defined as a three calendar month period [e.g., austral summer (boreal winter) is December–February].

shear experienced by the system throughout its life cycle (Braun 2009).

Maximum shear values associated with South Atlantic STs compared to North Atlantic STs are noticeably different: of the 197 North Atlantic STs identified by Guishard et al. (2009), only one encountered environmental wind shear values of 40 m s^{-1}. This disparity is largely explained by a combination of the ST seasonality (Fig. 6) and differences in the climatological vertical wind shear in each basin (e.g., Peixoto and Oort 1992).

The maximum in North Atlantic ST activity occurs in the summer and autumn months, seasons with climatologically low shear. South Atlantic ST genesis is distributed more uniformly through the year (Fig. 6) and proximity of the South Atlantic ST region to the Antarctic Circumpolar Current and the Antarctic continent leads to a stronger regional temperature gradient (cf. the North Atlantic) and larger environmental wind shear values across the basin (Gnanadesikan and Hallberg 2000). In fact, both North and South Atlantic STs develop in environments close to the local mean climatological shear: 27 m s^{-1} in the South Atlantic (Pezza and Simmonds 2005) compared to 15 m s^{-1} in the North Atlantic (Guishard et al. 2009). While the differences in shear ranges between the North and South Atlantic basins are large, two-thirds of South Atlantic STs develop in the range of shear observed for the North Atlantic systems (Fig. 5).

Differences in the observed SSTs at the time of genesis for North and South Atlantic STs are consistent with the differences in climatological SSTs between the hemispheres: the median SST coincident with South Atlantic ST genesis is 18°C (interquartile range 15°–20°C; Fig. 7a), while the median North Atlantic SST is 26°C (interquartile range 23°–28°C; Fig. 7b).

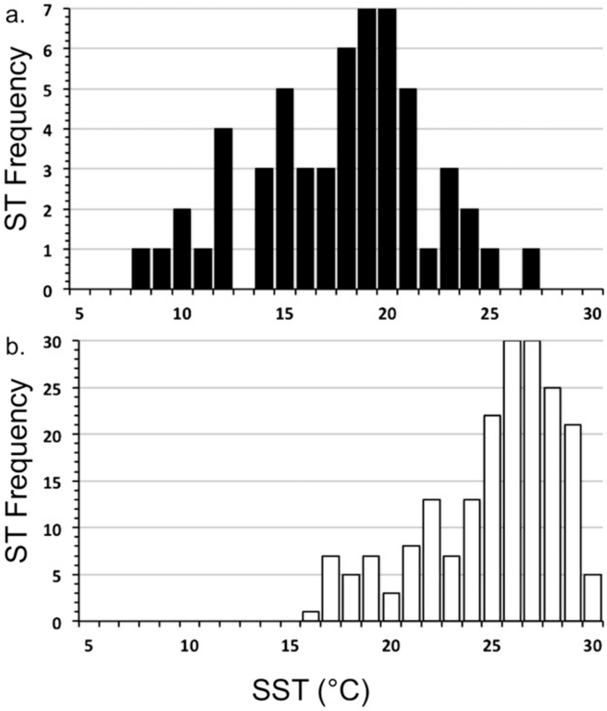

FIG. 7. Frequency distributions of SST (°C) at the time of ST genesis for (a) South Atlantic and (b) North Atlantic basins. SST values are averaged over a 2° × 2° box centered on the ST.

In their exploration of genesis mechanisms for North Atlantic STs, Evans and Guishard (2009) partitioned the North Atlantic STs in their climatology into four subsets based on vertical wind shear and SST. The majority of North Atlantic ST events occur in regions with SST exceeding 25°C and are evenly split between regions of shear above and below 10 m s^{-1} (in the 900–200-hPa layer; Evans and Guishard 2009, their Fig. 9). We repeat that analysis here (Fig. 8) and find different distributions of ST genesis environments between the two basins with the majority of South Atlantic STs occurring over cooler SST (below 25°C, Fig. 7) and higher shears (Fig. 5). This difference in the distribution between genesis environments is reasonable given the seasonality between the two basins (Fig. 9) and may also suggest differing degrees of environmental support for alternative paths to genesis (section 7).

6. Variability within the ST climatology

Variability in the 50-yr climatology (Fig. 3) provides a context for genesis environment variation and formation mechanisms in the South Atlantic basin. An average of just over one storm developed per year in the South Atlantic with higher ST activity early and late in the 50-yr period presented here (Fig. 3).

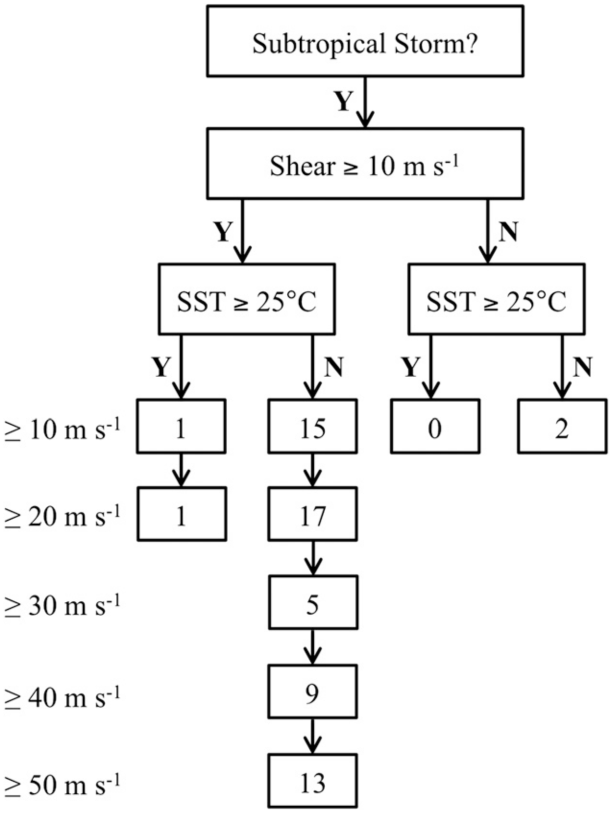

FIG. 8. Characterization of the 63 South Atlantic STs in the 50-yr period based on synoptic diagnostics at the time of genesis (hybrid thermal structure and surface gales). Shear is calculated as the vector wind difference over 900–300 hPa (values to the left in units of m s^{-1}).

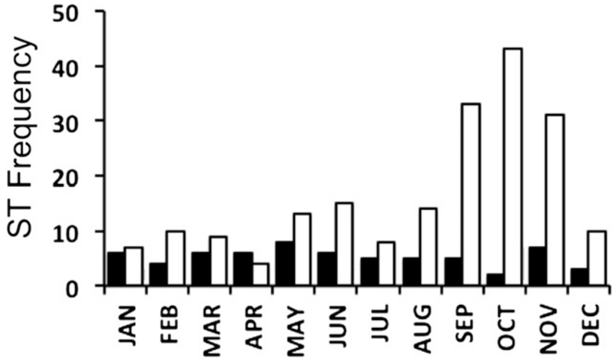

FIG. 9. Monthly distribution of ST occurrences in the South Atlantic (black; 63 ST events) and the North Atlantic (white; 197 ST events).

The relative increase in ST activity between the 1980s and 1990s (Fig. 3) is consistent with variability in the confluence zone between the Brazil and Malvinas Currents in that period (Fig. 2). Lumpkin and Garzoli (2011) document a warming trend in the SST averaged over the region 34°–38°S, 53.5°–57.5°W since the early 1990s. They demonstrate that this warming in the SST results from a poleward progression of the latitude of the confluence zone (Fig. 2). Their data extends back to 1980 and no SST trend is evident in the earlier part of this record. While these analyses say nothing about long-term climate changes, warmer SSTs are observed in the preferred South Atlantic ST genesis region in the 1990s compared to the 1980s, coincident with a concomitant increase in ST frequency.

Almost 75% of genesis events (45/63) detected are in the region 20°–40°S, 60°–30°W, with over 60% of all ST genesis events (38/63) occurring in warmer SST region of the Brazil Current. Evans and Guishard (2009) note that the convection necessary for ST intensification could be forced either by development over warm SST or warm-air advection. This tendency for ST formation in or near the warm Brazil Current (strong SST gradients) is consistent with either local surface fluxes or warm-air advection acting to enhance convective forcing and ultimately to induce a hybrid ST structure. In their analyses of wintertime cyclogenesis in the South Atlantic, Vera et al. (2002) also conclude that the Brazil Current provides support for convection in this region. Further, within-season (spring, summer, etc.) temperature difference ($SST - T_{300\ \mathrm{hPa}}$) at the seasonal centroid of genesis locations in the North and South Atlantic (not shown) provide evidence of environmental support for convection in both basins.

7. Proposed mechanisms for ST formation

Based on the South Atlantic ST climatology just described, two mechanisms of ST formation are proposed: ST genesis related to Rossby wave breaking (similar to the North Atlantic genesis mechanism described by Evans and Guishard 2009) and a mechanism of ST formation through lee cyclogenesis due to interactions between the subtropical jet and the Andes.

To explore these potential genesis mechanisms, we concentrate on features of the ST genesis environment in June–August (JJA; Figs. 10 and 11) and December–February (DJF; Fig. 12). Since 75% (9/12) of DJF STs and almost 70% (11/16) of JJA STs form in the near-coastal region,[3] we discuss near-coastal developments in both DJF and JJA. We also present results for JJA open-ocean ST cases.

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[3] The coastal zone is taken here as 20°–30°S, 50°–35°W and 30°–40°S, 60°–40°W, a region extending from the South American coast across the typical longitudes of the warm Brazilian Current (Fig. 1).

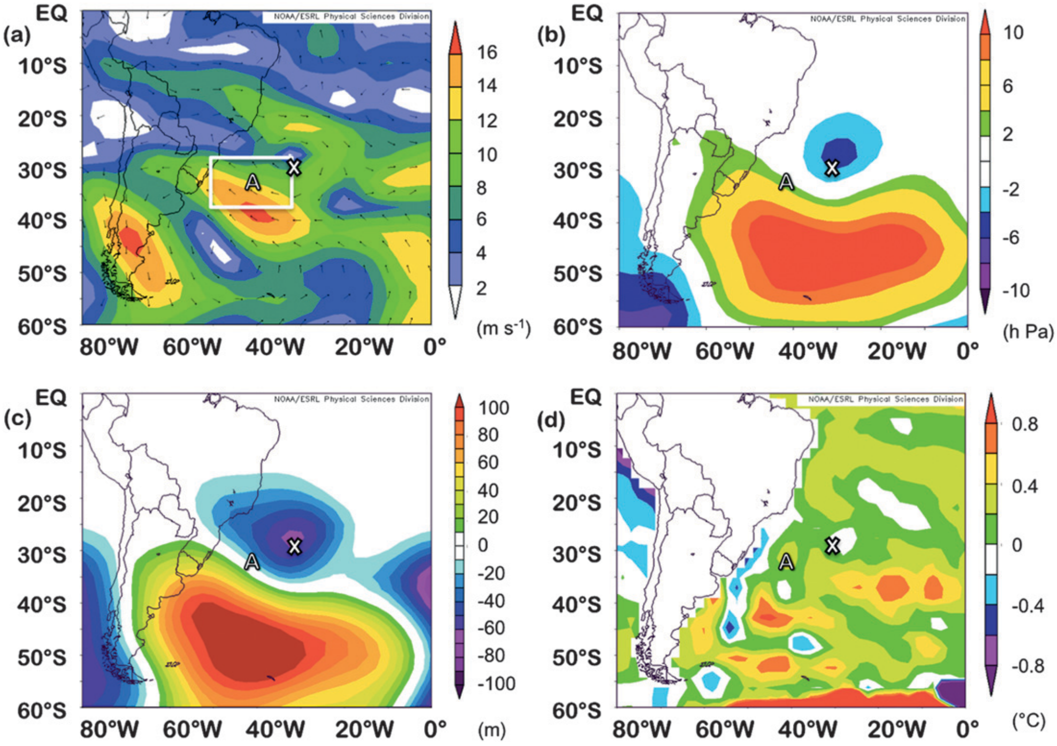

FIG. 10. Anomalies of winter (JJA) genesis conditions for ST forming in the open ocean of the South Atlantic: (a) 300-hPa winds, (b) MSLP, (c) 500-hPa geopotential height, and (d) SST. Anomalies are calculated as the difference between a composite of the NCEP–NCAR reanalyses for genesis days and the 1981–2010 climatology. The mean location for all JJA STs (33.0°S, 40.7°W) is indicated by an "A" and the mean location for JJA open-ocean STs (28.5°S, 31.3°W) is indicated with a cross. The rectangle in (a) encloses the region bounding 75% of JJA ST genesis events. (Plots were created on the NOAA/ESRL Physical Sciences Division, Boulder, CO, website at http://www.esrl.noaa.gov/psd/.)

As described by Evans and Guishard (2009), North Atlantic ST formation is preceded by a Rossby wave break, either in a region of warm SST or accompanied by strong warm-air advection, both of which act to enhance the local convective forcing. The Rossby wave break results in the development of a cutoff low of similar scale to the developing ST, while the subsequent convective heating intensifies the low-level ST vortex, maintaining the lower warm core (see also Vera et al. 2002). The superposition of these baroclinic and convective forcings results in a hybrid subsynoptic low pressure center with surface gale-force winds. We find that this ST genesis mechanism also operates in South Atlantic ST genesis events. Anomaly composites of JJA days with ST formations in the open ocean reveals an anticyclonic wave breaking signature with the northernmost extent of the trough corresponding to the mean genesis location 28.5°S, 31.3°W for these events (Fig. 10). Open JJA ocean STs form equatorward of the JJA near-coastal STs. In all five cases, (SST $-$ $T_{300\ \mathrm{hPa}}$) is positive, because of a combination of anomalously low $T_{300\ \mathrm{hPa}}$ and warm open-ocean SST (around 24°C). The anomalously warm SST and cool $T_{300\ \mathrm{hPa}}$ enhances local environmental support for the convection necessary to develop the strong surface circulation and gale-force winds (Evans and Guishard 2009).

An anticyclonic wave breaking event and anomalously low shear environment provide the precursors to JJA near-coastal ST genesis (Fig. 11). The mean genesis location for these STs is 35°S, 45°W, in the lee of the Andes Mountains and associated with a coastal trough (Fig. 11; Hoskins and Hodges 2005). This near-coastal environment is favorable for cyclogenesis and conducive to convection (Vera et al. 2002). These results are in agreement with the Southern Hemisphere storm-track analyses of Hoskins and Hodges (2005), who find a dual wintertime South Atlantic storm track, with branches associated with the subtropical jet and the polar jet; they identify a preferred region for genesis of lower-tropospheric cyclonic storms near the Atlantic coast of South America around 30°S. GCM simulations (Inatsu and Hoskins 2004) demonstrate that the current wintertime intensities of cyclones in either branch of the South Atlantic storm track cannot be replicated without the

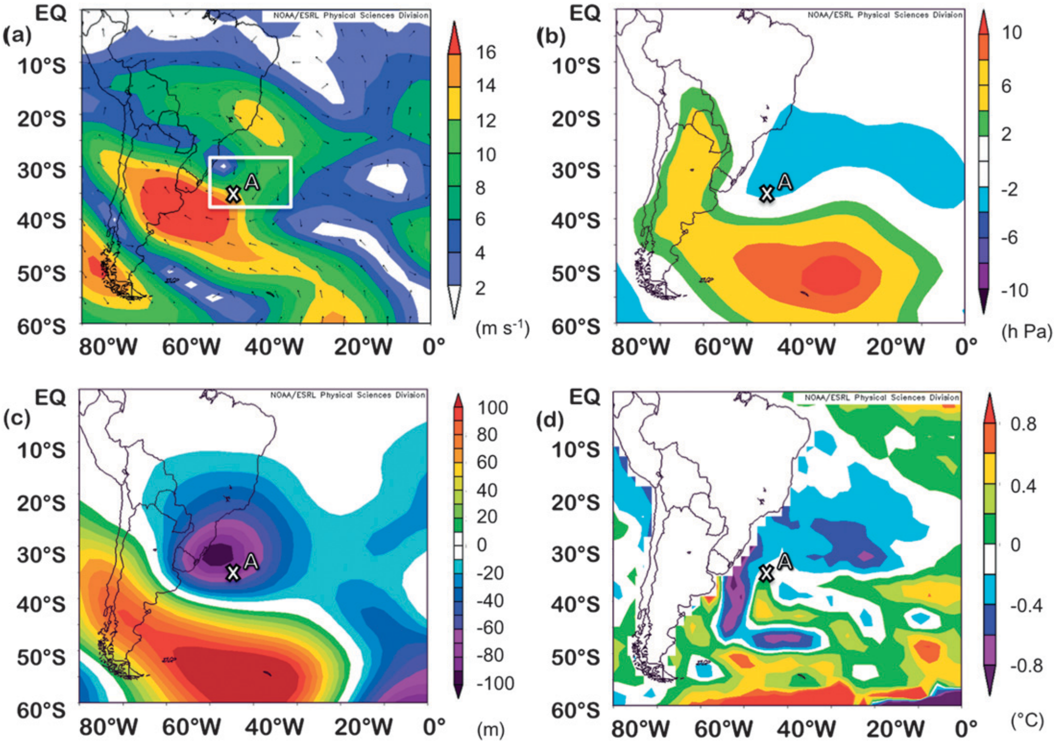

FIG. 11. As in Fig. 10, but for ST forming in the region of the Brazil Current: The mean location for JJA ST in the region of the current (35.0°S, 45.0°W) is indicated with a cross. Locations A and the rectangle in (a) are the same as in Fig. 10.

topography of South America. These results support the hypothesis that lee cyclogenesis plays a role in ST genesis in this region. Lee cyclogenesis downstream of the Great Dividing Range also contributes to the formation of type-2 mesosynoptic east coast lows in the Tasman Sea off the east coast of Australia (Holland et al. 1987). Braun (2009) demonstrated that a substantial fraction of east coast lows satisfy all of the criteria used here for classification as STs.

Only three summer (DJF) systems formed in the open ocean in the 50-yr period. Because of the dearth of open-ocean STs, we focus here on coastal formations.

In their analyses of the characteristics of the SH storm tracks, Hoskins and Hodges (2005) identify a preferred region for DJF cyclogenesis in the subtropics near the coast of South America (around 32°S). Nakamura and Shimpo (2004) also identified this preferred region for cyclone development. The mean genesis location for these DJF coastal ST formations is 30.6°S, 47°W (“X” in Fig. 12), over Brazil Current waters warmer than 20°C (Figs. 2 and 12). A time-mean trough along the South American coast is associated with a lower shear environment than farther east and is stronger in a composite of coastal ST genesis days only (Fig. 12). As with the coastal developments in austral winter, this configuration is consistent with lee cyclogenesis playing a role in the ST evolution.

8. Discussion and conclusions

The first climatology of South Atlantic STs is presented here. The STs are lower-tropospheric warm-cored and upper-tropospheric cold-cored cyclones. Guishard and collaborators (Guishard et al. 2009; Evans and Guishard 2009) developed a set of criteria for identification of STs in the North Atlantic. We introduce a parallel set of criteria for ST identification in the South Atlantic (Fig. 4); while these criteria are consistent with previous research (e.g., Guishard et al. 2009; U.S. Navy 1994), they are modified to account for interbasin differences in the North and South Atlantic environments. Based on this climatology, we now know that STs develop regularly in the strong vertical wind shear and relatively cool SST environment of the South Atlantic (Figs. 5 and 7).

The 63 South Atlantic STs analyzed here develop in a wide variety of vertical wind shear and SST environments (Fig. 8). In contrast to the tendency for North Atlantic STs to occur in the late summer through early autumn, South Atlantic STs occur relatively uniformly

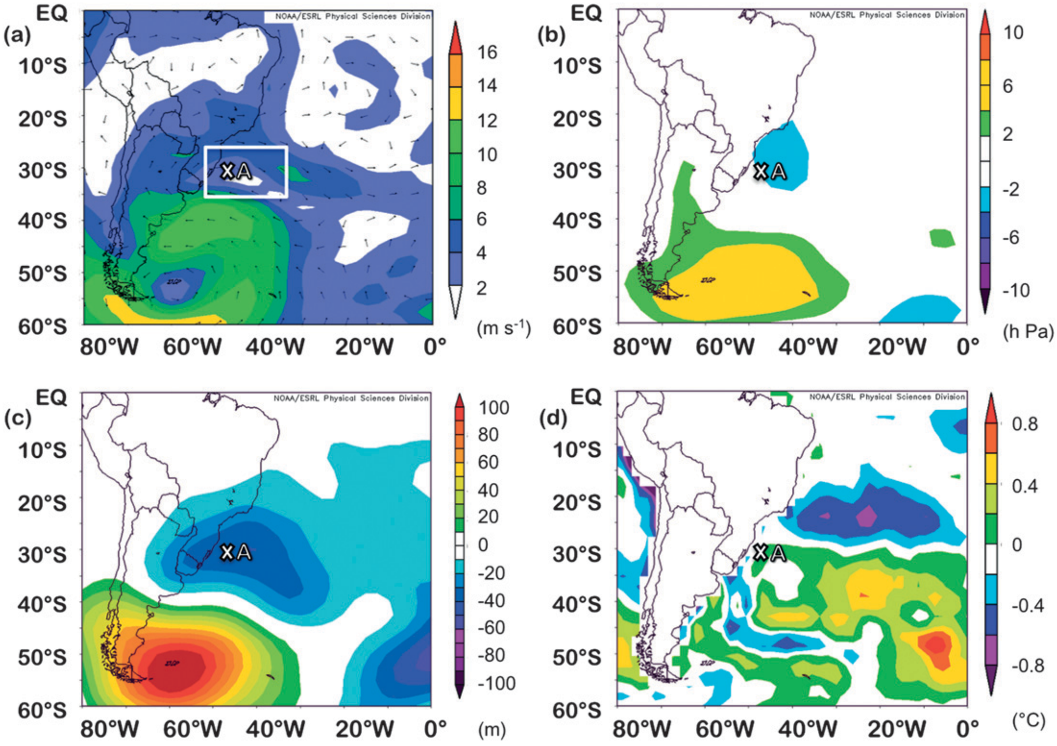

FIG. 12. As in Fig. 11, but for summer (DJF). The mean location for all DJF STs (30.6°S, 43.1°W) is indicated by an "A" and the mean location for DJF STs in the region of the current (30.6°S, 46.8°W) is indicated with a cross. The rectangle in (a) encloses the region bounding 75% of DJF ST genesis events.

throughout the year (Fig. 6). This difference in seasonality leads to the distinctly different mean genesis environments between the two basins: there is a clear seasonal minimum in vertical wind shear in the subtropical North Atlantic, while shear magnitudes in the South Atlantic ST genesis zone are relatively consistent throughout the year (Figs. 10–12; Peixoto and Oort 1992; Hoskins and Hodges 2005). All STs interact with the midlatitude baroclinic zone, although the patterns are distinct between hemispheres.

The majority of South Atlantic STs form in the coastal zone impacted by the Brazil Current and downstream of the Andes (Figs. 10 and 12). Compositing of the genesis environments of these coastal zone STs in austral winter and summer reveals alternate genesis pathways involving Rossby wave breaking (as in the North Atlantic) and lee cyclogenesis. While comparisons of the genesis and evolution of North and South Atlantic STs reveal many aspects in common, the lee cyclogenesis mechanism identified here for South Atlantic ST formation has no equivalent in the North Atlantic. Mechanisms leading to ST genesis in the central South Atlantic parallel the North Atlantic ST genesis pathway documented by Evans and Guishard (2009).

Substantial variation in ST activity is observed between the decades: in only three years at the end of the 1950s we analyze 7 STs, while 13 STs are recorded over each of the decades of the 1960s and 1970s. The ST activity decreases substantially in the 1980s (only 3 STs), recovering somewhat in the 1990s (9 STs). We identify 18 STs in the years 2000–07. The variations in South Atlantic ST activity over the past 20–30 years are consistent with changes in the location of the confluence zone between the Malvinas and Brazil Currents (Figs. 1–3). Southward progression of the Brazil–Malvinas confluence and concomitant near-coastal SST increases are diagnosed from the mid-1980s into the twenty-first century. These changes enhance support for convection and ST development in the near-coastal region, all else equal. However, while the agreement between the SST and ST activity is tantalizing, the period of less than 30 years is insufficient for drawing any conclusions on causality.

The lee cyclogenesis path to ST genesis identified here is fundamentally different than the favorable baroclinic environment attributed to North Atlantic ST development (Evans and Guishard 2009). Lee cyclogenesis is not observed to play a role in North Atlantic ST formation.

In the lee cyclogenesis scenario, the combined effects of the Andes mountains and the warm Brazil Current provide a region already conducive to cyclogenesis (e.g., Vera et al. 2002; Hoskins and Hodges 2005). The region of most frequent ST genesis off the South American coast has climatologically lower shear than the basin as a whole (e.g., Pezza et al. 2009). Further, Vera et al. (2002) note a decoupling of the lower- and upper-tropospheric vortex for cool season cyclones transiting the Andes, leading to a tendency for lower-tropospheric warm-cored systems in the lee of the Andes in the latitude range studied here.

Whether the incipient vortex for the ST initiates from a midlatitude Rossby wave break (Evans and Guishard 2009), an instability on the subtropical jet (Hoskins and Hodges 2005) or from an existing cyclone transiting the Andes (Vera et al. 2002), the cyclogenetically favorable environment downstream of the Andes facilitates the further development of near-coastal STs. Locally warm SST or poleward advection of warm, moist air provides convective forcing in the genesis region (e.g., Vera et al. 2002). This convective forcing is necessary for the ST to develop a hybrid, rather than baroclinic structure.

Significant weather associated with STs includes gale-force winds and intense rainfall, so these systems can have major societal impacts in their own right. In addition, a subset of warm season North Atlantic STs has been observed to develop into TCs. Until the evolution of Hurricane Catarina (2004) from a ST, a TC had not been observed in the South Atlantic, but now that this pathway from ST to TC has been documented, the potential for further TC developments in the South Atlantic has been raised. Possible impacts of climate change on subtropical, and even tropical, cyclogenesis in the South Atlantic remain an open question.

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