Analysis of Hurricane Catarina (2004)

RON MCTAGGART-COWAN AND LANCE F. BOSART

Department of Earth and Atmospheric Sciences, University at Albany, State University of New York, Albany, New York

CHRISTOPHER A. DAVIS

National Center for Atmospheric Research, Boulder, Colorado

EYAD H. ATALLAH AND JOHN R. GYAKUM

Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec, Canada

KERRY A. EMANUEL

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

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ABSTRACT

The development of Hurricane Catarina over the western South Atlantic Ocean in March 2004 marks the first time that the existence of a hurricane has been confirmed by analysis and satellite imagery in the South Atlantic basin. The storm undergoes a complex life cycle, beginning as an extratropical precursor that moves east-southeastward off the Brazilian coast and toward the midlatitudes. Its eastward progress is halted and the system is steered back westward toward the Brazilian coast as it encounters a strengthening dipole-blocking structure east of the South American continent. Entering the large region of weak vertical shear that characterizes this blocking pattern, Catarina begins a tropical transition process over anomalously cool 25°C ocean waters above which an elevated potential intensity is supported by the cold upper-level air associated with the trough component of the block. As the convective outflow from the developing tropical system reinforces the ridge component of the dipole block, the storm is accelerated westward toward the Santa Catarina province of Brazil and makes landfall there as a nominal category-1 hurricane, causing extensive damage with its heavy rains and strong winds.

The complex evolution of the system is analyzed using a suite of diagnostic tools, and a conceptual model of the tropical transition and steering processes in the presence of a dipole block is developed. Once the essential properties of the upper-level flow are established, an analog study is undertaken to investigate lower-atmospheric responses to similar blocking regimes. Persistent dipole-blocking structures are found to be rare east of South America; however, the evolution of systems occurring during these periods is shown to be complex and to exhibit various subtropical development modes.

1. Introduction

The development of Hurricane Catarina (Fig. 1) in the western South Atlantic Ocean basin in late March 2004, and the storm's eventual landfall in the Santa Catarina province of Brazil, surprised forecasters and researchers alike. Although organized deep convective clusters have infrequently been identified over the South Atlantic [e.g., April 1991 (McAdie and Rappaport 1991) and January 2004], no satellite-era confirmation of a tropical system of hurricane strength has been obtained in the region to our knowledge. As noted by Gray (1968), "tropical storm formation does not occur in these areas. . .primarily due to the large climatological vertical shear present." Indeed, long-term mean 950–200-hPa wind shear values for April off the south Brazilian coast are shown to approach 20 m s^{-1} in Gray's landmark investigation, well above the empirically derived approximately 10 m s^{-1} threshold (Zehr 1992; DeMaria et al. 2001). Such an unusual event as Hurricane Catarina is worthy of study on pragmatic

Corresponding author address: Dr. Ron McTaggart-Cowan, DEAS-ES351, University at Albany, State University of New York, Albany, NY 12222.
E-mail: rmctc@atmos.albany.edu

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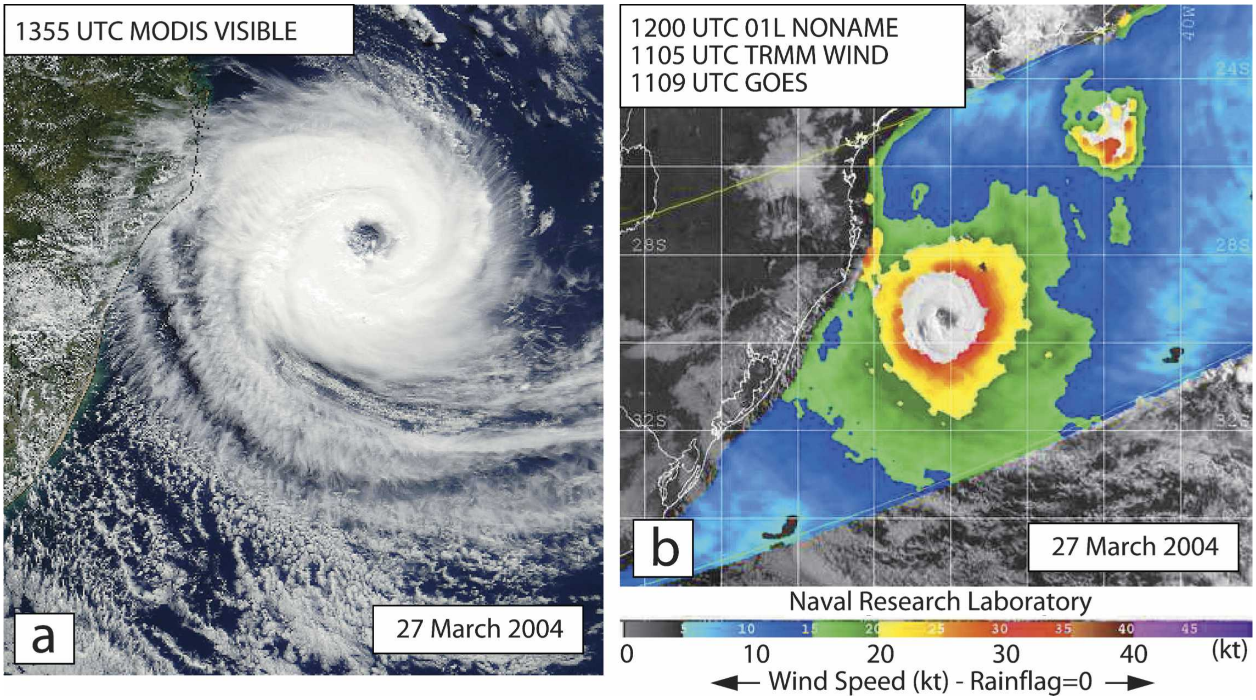

FIG. 1. (a) Visible high-resolution (1 km) image from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument mounted on the *Terra* satellite for 1355 UTC 27 Mar 2004 (courtesy of the MODIS Rapid Response Team at the NASA Goddard Space Flight Center). (b) Tropical Rainfall Measuring Mission (TRMM)-derived wind speeds for the 1105 UTC 27 Mar 2004 overpass, along with the matching *Geostationary Operational Environmental Satellite-12* visible image, with wind magnitudes as indicated (kt; 1kt ≈ 0.514 m s^{-1}) on the color bar. The TRMM instrumentation is incapable of penetrating the deep clouds near the core of the system.

grounds given the storm's large socioeconomic impact on unprepared coastal regions. A poststorm survey of residents in Santa Catarina found that over 80% of homes received damage to roof structures, almost 40% of which resulted in complete failures (Marcelino et al. 2004). This represents just a portion of Catarina's $425 million (U.S.) damage total (A. J. Pereira Filho 2005, personal communication). Furthermore, the very existence of a tropical system in the South Atlantic Ocean motivates a reanalysis of conventional wisdom as it pertains to the development of hurricanes in climatologically large shear regions. A preliminary investigation of Catarina's development from a climate change perspective is documented by Pezza and Simmonds (2005).

Unlike the Northern Hemisphere (NH), climatologies focusing on Southern Hemisphere (SH) cyclogenesis are relatively rare (Le Marshall and Kelly 1981; Trenberth 1991; Sinclair 1994, 1995, 1997). In a series of papers, Sinclair (1994, 1995, 1997) develops a vorticity-based objective technique for identifying and classifying cyclone properties. A series of climatologies is presented in the Sinclair studies with an emphasis on cyclone behaviors south of the equator. Of particular relevance to the current study, Sinclair (1995) shows maxima in cyclogenesis frequencies east of Argentina and southeast of the Cape of Good Hope, with a third weak maximum off the south Brazilian coast covering the area of Hurricane Catarina's development.

Even more rare than studies of SH cyclones are detailed investigations of anticyclones and blocking events south of the equator (van Loon 1956; Jones and Simmonds 1994; Sinclair 1996; Renwick and Revell 1999). Sinclair (1996) finds peak anticyclone frequencies in a band between 25° and 45°S with formations occurring preferentially along the eastern coasts of continents and demise events concentrated in the eastern extremities of the ocean basins. Van Loon (1956) uses a 500-hPa height gradient definition similar to that of Rex (1950a) to investigate midtropospheric blocking. The Rex (1950a) definition is modified by Wright (1974) to exclude the dominant subtropical belt of high pressure and the fast-moving systems germane to SH flow. Both the van Loon (1956) and Wright (1974) studies find that blocking events south of the equator occur with roughly the same frequency as those in the NH, but that they tend to be less intense and of shorter duration. As for anticyclone formation frequencies (Sinclair 1996), preferred blocking regions cluster on the eastern boundaries of the South American, African, and Australian continents, unlike their NH counterparts that form to the west of the North American and European landmasses.

The dynamical significance of blocking action is detailed in the seminal study by Rex (1950a). Two primary blocking modes are identified in cases analyses (Rex 1950a) and in a climatological study (Rex 1950b), one consisting of a dominant anticyclone (now known as an "Ω block") and another involving a low-latitude cutoff cyclone meridionally phase locked with a higher-latitude warm anticyclone (commonly referred to as a "dipole block" or a "Rex block"). Both Ω and dipole blocks exert similar forcings on the large-scale flow. They are characterized by the breakdown of a strong zonal jet into split streams that bound a weakly baroclinic region of horizontally cellular circulation that composes the interior of the block. Dipole blocks exhibit stronger equatorward streams in the split jet and more effectively produce anomalous easterly flow within the block because of a coherent reversal in the meridional height gradient. Pelly and Hoskins (2003) apply a potential vorticity (PV) paradigm in a study of block development and maintenance using dynamic tropopause [the 2 PV Unit (PVU)[1] surface] diagnostics. The authors show that a reversal in the meridional gradient of potential temperature on the dynamic tropopause (DT) is more representative of a blocking regime than is the traditional height gradient indicator proposed by Rex (1950a). Following the work of Tibaldi and Molenti (1990), Pelly and Hoskins (2003) find that the consideration of blocking on a 4-day time scale is more constructive than the Rex (1950a) 10-day criterion. This reduction in the temporal constraint on significant blocking events has a particular impact in the SH where blocks tend to last for shorter periods (van Loon 1956; Wright 1974).

The kinematic and thermodynamic importance of blocking in the development of Hurricane Catarina arises from the fact that weak shear regions with little baroclinicity are ideal candidates for the tropical transition (TT) of disturbances occurring within them. Two paradigms of TT are described by Davis and Bosart (2004). In a strong extratropical cyclone (SEC) TT, the passage of an intense extratropical cyclone over warm waters triggers wind-induced surface heat exchange (WISHE; Emanuel 1987). Davis and Bosart (2003) show that the diabatic heating that results from convection enhanced by the WISHE process is responsible for vertically redistributing both PV and momentum, simultaneously reducing the shear over the system and generating a protective warm DT potential temperature θ_{DT} anomaly on a subsynoptic scale over the core of the transitioning storm. Hurricane Catarina develops along the weak extratropical cyclone (WEC) pathway also described by Davis and Bosart (2004). This mode of TT is characterized by the focusing of convection by a midlevel precursor vortex or a weak baroclinic system. The constructive interaction between this precursor and an overlying upper-level cyclonic PV anomaly enhances both the circulation and the diabatic heating in the developing system as the bulk column stability is reduced by the cold perturbation aloft. Stretching of the midlevel vortex completes the positive feedback cycle in this case as vertical motions of increasing intensity begin to effectively redistribute PV and momentum as for the SEC development pathway.

Both the SEC and the WEC modes of TT require the transitioning circulation to remain over warm water for at least a day following the occlusion of the system and the development of a warm core perturbation (Davis and Bosart 2004). The requirement for warm SSTs during tropical development has been well known since the pioneering study of Palmén (1948), who set a lower SST bound of 26.5°C. Gray (1968) describes the importance of the warm, moist lower boundary through the profile of equivalent potential temperature and its influence on convective stability. Although as noted earlier Gray (1968) justifiably dismisses the western South Atlantic as a tropical genesis region because of high climatological values of vertical shear, he concedes that potential buoyancy (defined as the difference between the equivalent potential temperature at the surface and that at 500 hPa) values in the region are favorable for deep convection. An apparent paradox arises, therefore, in the development of Hurricane Catarina. As will be described in section 3, not only does Catarina undergo TT over waters cooler than the 26.5°C threshold, but also the 25°C SSTs beneath the storm's center are 0.5°C below climatological values. While potential buoyancy values near the climatological mean of 20 K cover a broad area along Catarina's track, the low-latitude trough component of the dipole block generates anomalously high potential intensity (Bister and Emanuel 1997) and provides a local thermodynamic environment conducive to tropical cyclogenesis.

The dipole-blocking structure provides an ideal environment for the WEC mode of TT as showed in the conceptual schematics in Fig. 2 from both SH [Fig. 2a(S)–c(S)] and NH [Fig. 2a(N)–c(N)] perspectives. The process begins in Fig. 2a(S,N) as a low-latitude upper-level cyclonic PV anomaly (a stationary component of a dipole block) induces quasigeostrophically forced ascent in a transient midlevel vortex over suffi-

[1] 1 PVU ≡ 1×10^{-6} m^2 K kg^{-1} s^{-1}.

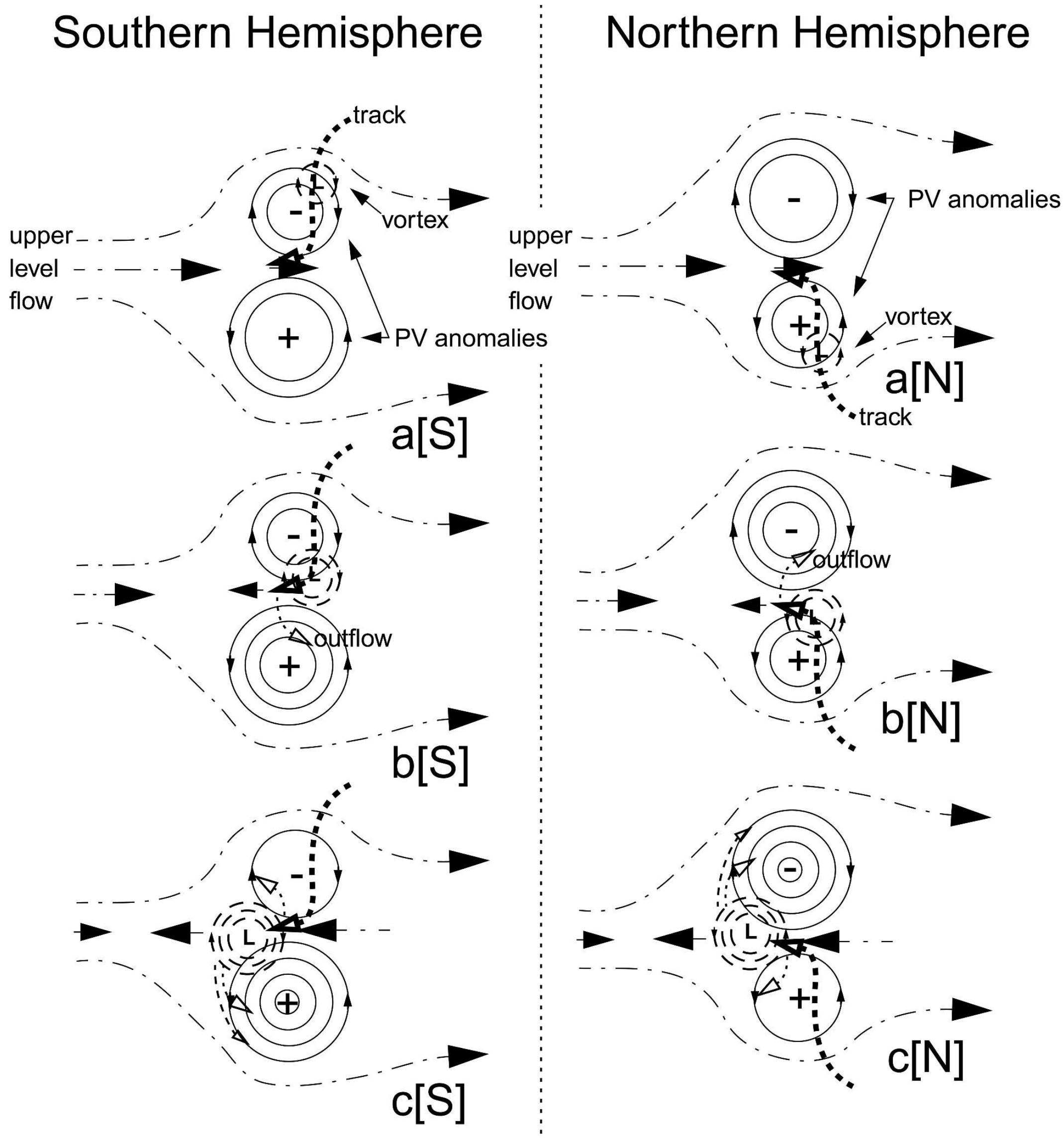

FIG. 2. Conceptual model of a TT in a dipole-blocking environment for both the (left) SH and (right) NH. The blocking component PV anomalies are signed as indicated, with relative magnitudes proportional to the number of concentric rings surrounding the feature. (a) The direction of the upper-level flow is represented by the dash–dot arrows (shown in all panels). The track of the precursor and hurricane vortex is indicated by the heavy dotted line and open arrow. The lower-level circulation itself is represented by an L and is surrounded by a number of concentric circles that increase with increasing storm intensity. (b), (c) The outflow from the system as it undergoes TT is indicated by a thin dashed line and open arrows.

ciently warm water. The destabilizing influence of this mid- and upper-tropospheric ascent profile enhances convection in the precursor circulation and leads directly to vorticity increases in the column by stretching. As the TT process continues [Fig. 2b(S,N)], the storm drifts poleward because of steering or β gyres (Holland 1983) and tracks into the reduced shear region between the oppositely signed PV anomalies that form the dipole block. Although environmental deep-layer shear enhances the organization of convection in the precursor, its suppression is a requirement for tropical cyclogenesis (DeMaria et al. 2001). The warm upper-level outflow from the storm diabatically reinforces the poleward anticyclonic component of the dipole block in Fig. 2c(S,N), leading to an enhanced anomalous easterly steering flow. These easterly winds complete the reorientation of the storm's motion vector as the diabatically enhanced ridge continues to build. In the case of Hurricane Catarina, it is these anomalous easterly winds that steer the hurricane toward the Brazilian coast.

The denotation of Catarina as a "hurricane" in this work is intentional. Many studies over the last 20 yr have investigated the development and structure of cyclones that fall between the strict classifications of tropical, extratropical, and polar. Nowhere has the debate over nomenclature been more intense than in the literature concerning Mediterranean hurricanes. These subsynoptic-scale systems that often result from the TT of weak baroclinic cyclones have alternately been called "hurricane-like storms" (Billing et al. 1983), "Mediterranean tropical storms" (Ernst and Matson 1983), and "Mediterranean hurricanes" (Emanuel 2005). Even high-latitude polar lows and Australian east coast cyclones have been referred to as "Arctic hurricanes" (Emanuel and Rotunno 1989) and "hurricane-like vortices" (Holland et al. 1987), respectively. Indeed, the "easterly dip" feature necessary for the formation of Australian east coast storms (Fig. 2 of Holland et al. 1987) bears marked resemblance to the dipole-blocking pattern present during Catarina's development (Fig. 2). [For a complete review of studies concerning Mediterranean hurricanes, the reader is referred to Reale and Atlas (2001).] In this study, we demonstrate to the fullest extent possible given available analysis and observational data, that the mature Catarina storm possesses the structures and forcings of a hurricane (Fig. 1). Furthermore, we suggest that geographical constraints and the 26.5°C SST threshold no longer accurately describe the subset of systems whose nature is now known to be undeniably tropical.

An extensive set of diagnostic tools is employed in this study of the unusual development of South Atlantic Hurricane Catarina and the conceptual model described above is shown to be representative of the system's complex life cycle. The paper begins with a description of datasets and methods in section 2. A diagnosis of Hurricane Catarina's development, TT, and intensification is presented in section 3. Section 4 describes the construction of an analog study based on long-lived western South Atlantic dipole-blocking structures and briefly analyzes the cases identified. The paper concludes with a summary and discussion of the findings in section 5.

2. Data and methodology

A number of different data sources are employed over the course of this investigation. Satellite data are obtained from the Brazilian Instituto Nacional de Meteorologia (INMET), the Space Science and Engineering Center (SSEC) at the University of Wisconsin—Madison, the Fleet Numerical Meteorology and Oceanography Center of the U.S. Navy, and the National Aeronautics and Space Administration (NASA). Gridded analysis data from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) at 1° grid spacing is used for all diagnostics of Hurricane Catarina's life cycle in section 3. The climatologies and case studies presented in section 4 are performed using gridded data with a 2.5° grid spacing from the NCEP–National Center for Atmospheric Research (NCAR) Reanalysis (NNRA) dataset. Sea surface temperature diagnostics are computed using the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature, version 2, 1° gridded weekly mean dataset (Reynolds et al. 2002) for the period 21–27 March 2004 provided by the Climate Diagnostics Center. Anomalies of the SST fields are computed relative to the linearly weighted long-term March–April means (Smith and Reynolds 1998) centered on 25 March.

Dynamic tropopause diagnostics presented in this study are generated on the 2 PVU (Ertel 1942) surface using the downward vertical interpolation method described by Morgan and Nielsen-Gammon (1998). The "deep-layer shear" referred to throughout this investigation is defined as the vector differential of the winds on the DT less the winds at 850 hPa. Dynamic tropopause winds are used instead of the traditional 200-hPa isobaric flow because the DT provides a reliable representation of upper-level dynamics that is independent of the depth of the troposphere. This is an important attribute for studies investigating the interaction of feature of tropical and extratropical origins, between which deep-layer mean temperatures can vary dramatically. The blocking index B is calculated following the method of Pelly and Hoskins (2003):

$$B(\lambda_0, \Delta\lambda) = \frac{2}{\Delta\phi}\left(\int_{\phi_0}^{\phi_0+\Delta\phi/2} \theta \, d\phi - \int_{\phi_0-\Delta\phi/2}^{\phi_0} \theta \, d\phi\right), \quad (1)$$

where B is computed along the longitude λ_0 for a strip of width $\Delta\lambda$ with a central latitude ϕ_0 and meridional dimension $\Delta\phi$. For the Catarina block $\lambda_0 = 40°$W, $\Delta\lambda = 5°$ of longitude at λ_0, $\phi = 30°$S, and $\Delta\phi = 20°$ of latitude. These values are chosen for consistency with the analog areas detailed in section 4.

The steering flow at each level is computed by averaging winds in a storm-centered annular ring between radii of 200 and 400 km, following the method of Renard (1968). The storm center is defined as the point of local maximum cyclonic relative vorticity in the 925–850-hPa mean wind field. A small error in the core location or a tilted center will not yield a large error in the steering flow computation because of its annular ring design. The depth of the steering flow is taken as the deep layer between 925 hPa and the DT. This upper bound is applied for consistency with the definition of shear used in this study. Use of a storm-dependent steering flow depth is not possible in this case because of the weak representation of the system in the analyses. The analog study in section 4 is based on 1971–2001 mean 500-hPa height fields from the NNRA. This period, and the corresponding search window for analogous cases, is chosen because of the availability of satellite observations over its entirety.

3. Hurricane Catarina

The life cycle of Hurricane Catarina is influenced by a well-defined set of features and processes throughout its 8-day period. Following a brief description of the storm's track, this section investigates the forcings that lead to the unusual TT of the South Atlantic system from a multiscale perspective, beginning with an evaluation of the environmental flow before focusing on the resolvable details of the storm itself.

a. Track and life cycle

Hurricane Catarina's precursor moves off the South Brazilian coast at 1800 UTC 19 March 2004 (Table 1 and Fig. 3). The weak system moves southeastward for 3 days with minimum mean sea level pressure (MSLP) values near 990 hPa and maximum near-surface winds below 18 m s^{-1} (35 kt). On 23 March, the storm makes an abrupt anticyclonic track reversal and begins to move northward before taking up a westward heading the next day. During this period, the center of the system is identifiable as a localized area of deep convection to the southwest of a wide convective band extending southeastward from the Brazilian coast (Figs. 4a–c). Unlike a nascent mesoscale convective system, however, extensive cyclonic inflow to the developing storm can be seen in the lower-level cloud structures in Figs. 4c,d.

Once on its westerly course toward the coast, the system begins to intensify steadily, with extensive convection developing along the inflow bands by 1200 UTC 25 March (Fig. 4e). By 0000 UTC 26 March (Fig. 4f), Catarina reaches category-1 intensity on the Saffir–Simpson hurricane scale (Simpson 1974) and develops an eye despite the loose organization of its peripheral bands. The hurricane's cloud field becomes more symmetric over the following 24 h (Figs. 4g–h) although the diameter of the cloud shield remains small (approximately 400 km) by the standards of the North Atlantic hurricanes. Asymmetries in the outer structures of the storm develop by 1200 UTC 27 March (Fig. 4i) as drier

TABLE 1. Track data for Hurricane Catarina, analyzed by R. Edson at the University of Guam. All times are in UTC. Abbreviations for the state of the system are extratropical (Ex), hybrid tropical/extratropical (Hy), tropical storm (TS), category-1 hurricane (H1; Simpson 1974), and category-2 hurricane (H2).

Day	Hour (UTC)	Lat	Lon	MSLP (hPa)	Wind speed (kt)	State
19	1800[a,b,c]	27.0°S	49.0°W		25	Ex
20	0000[a]	26.5°S	48.5°W		25	Ex
20	0600[a]	25.3°S	48.0°W		30	Ex
20	1200[a]	25.5°S	46.0°W		30	Ex
20	1800[a,b,c]	26.5°S	44.5°W		30	Ex
21	0000[a]	26.8°S	43.0°W		30	Ex
21	0600	27.5°S	42.0°W		30	Ex
21	1200[a,c]	28.7°S	40.5°W		30	Ex
21	1800[c]	29.5°S	39.5°W		30	Ex
22	0000[a]	30.9°S	38.5°W		30	Ex
22	0600	31.9°S	37.0°W		30	Ex
22	1200[a,c]	32.3°S	36.7°W		30	Ex
22	1800[b]	31.5°S	36.5°W		30	Ex
23	0000[a]	30.7°S	36.7°W		30	Ex
23	0600	29.8°S	37.0°W	1002	30	Ex
23	1200[c]	29.5°S	37.5°W	990	30	Ex
23	1800[b]	29.4°S	38.1°W	991	35	Ex
24	0000[a]	29.3°S	38.5°W	993	35	Hy
24	0600[a]	29.2°S	38.8°W	992	35	Hy
24	1200[a,c]	29.1°S	39.0°W	990	35	Hy
24	1800[a,c]	29.1°S	39.4°W	990	40	Hy
25	0000[a,b]	29.0°S	39.9°W	993	40	Hy
25	0600[b]	28.9°S	40.4°W	993	45	TS
25	1200[a,c]	28.7°S	41.2°W	994	50	TS
25	1800[b]	28.7°S	41.9°W	994	55	TS
26	0000[a,c]	28.7°S	42.6°W	989	60	TS
26	0600[d]	28.7°S	43.1°W	989	65	H1
26	1200[a,c,d]	28.8°S	43.7°W	982	70	H1
26	1800[a,c,d]	28.9°S	44.2°W	975	70	H1
27	0000[a,d]	29.1°S	44.9°W	974	70	H1
27	0600[a,d]	29.2°S	45.6°W	974	75	H1
27	1200[a,c,d]	29.5°S	46.4°W	972	75	H1
27	1800[a,c,d]	29.5°S	47.5°W	972	80	H1
28	0000[a,d]	29.3°S	48.3°W	972	80	H1
28	0600[d,e]	29.0°S	49.7°W		85	H2
28	1200[a,c]	28.5°S	50.1°W		60	TS
28	1800[a]	28.5°S	51.0°W		45	TS

[a] Infrared satellite imagery was used to estimate location and state.
[b] QuikSCAT imagery was used to estimate location and state.
[c] Visible satellite imagery was used to estimate location and state.
[d] Microwave satellite imagery was used to estimate location and state.
[e] TRMM imagery was used to estimate location and state.

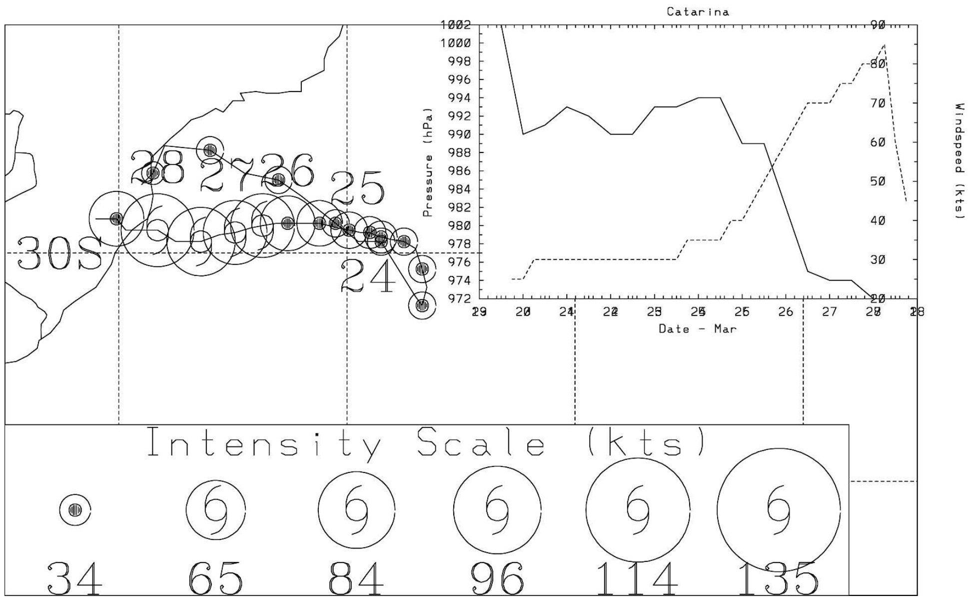

FIG. 3. Estimated track data for Hurricane Catarina (analyzed by R. Edson) and plotted from Table 1.

coastal air appears to be wrapping around the system from the north and east. However, the strength of the hurricane continues to increase, and Catarina reaches its peak intensity at 0000 UTC 28 March with maximum winds estimated at 44 m s^{-1} (85 kt; see Table 1; satellite winds shown at 1200 UTC 27 March in Fig. 1b) and a minimum MSLP of 972 hPa (Table 1; Fig. 4j). The 0000 UTC 28 March Brazilian significant weather analysis (Fig. 5) shows a tropical storm (an underrepresentation of the vortex's intensity compared with the satellite imagery of Fig. 1b) off the Santa Catarina coast surrounded by deep convective features. The hurricane weakens slightly before landfall at 0900 UTC 28 March and fills rapidly thereafter. By 1200 UTC 28 March, the decaying system is barely identifiable on satellite imagery (Fig. 4k).

b. Environmental conditioning

The evolution of the environmental conditions over Hurricane Catarina's lifetime are summarized using traditional synoptic fields in Fig. 6. The low pressure center representing the weak initial system lies 200 km off the Brazilian coast at 0000 UTC 21 March (Fig. 6a) This precursor disturbance tracks southeastward on 21 and 22 March (Figs. 6a,b) along the leading edge of a thickness trough and under the influence of the equatorward branch of a split jet. The axis of the jet shifts approximately 5° eastward between 0000 UTC 22 March and 0000 UTC 23 March (Figs. 6b,c), positioning the storm in its favorable poleward exit region at 40°W, which is also characterized in this case by an area of reduced westerly flow at 500 hPa.

Weak ridging in the thickness field downshear of the system (indicated with arrows in Figs. 6c,d), suggests that the convective processes noted in Figs. 4a,b are beginning to warm the troposphere (Fig. 7). The reversal of the 500-hPa flow west of the system to the Brazilian coast is indicative of a large area of reduced vertical shear below this level and implies an easterly steering current for the embedded system. Moving into this region by 0000 UTC 25 March (Fig. 6e), the TT of the storm—initially signaled by the increasing thickness values over the low (Fig. 7)—continues as the midlevel flow contracts and becomes increasingly symmetric. By 0000 UTC 26 March (Fig. 6f), although a large thickness trough surrounds the hurricane, a local thickness maximum is present at its center.[2] Calculations based on analyzed 500-hPa heights and estimated MSLP values suggest that thicknesses in excess of 592 dam exist near the core of the hurricane between 1200 UTC 26 March and 0000 UTC 28 March (not shown). Although this value is likely an overestimate because of the lack of a sufficient 500-hPa height depression in the analysis,

[2] The decreasing near-core thickness indicated following 0000 UTC 26 March 2004 in Fig. 7 is caused by a poor representation of the lower-level vortex in the analysis. The failure of the analysis cycle to resolve low MSLP values near Catarina's center results in an underestimate of the near-core thickness that becomes more acute as the vortex intensifies.

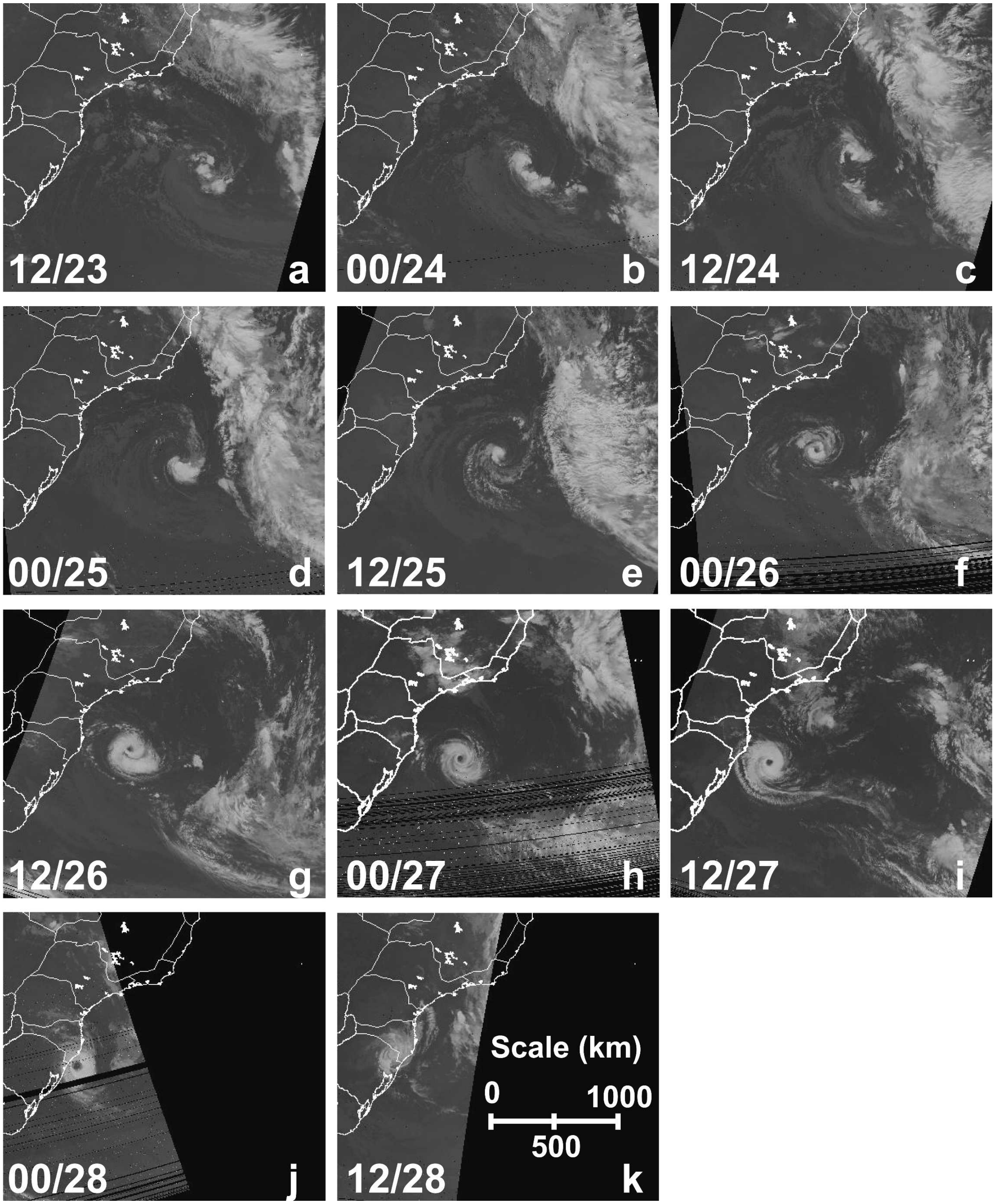

FIG. 4. Infrared satellite imagery from INMET at approximately 12-h intervals during Catarina's TT and intensification. The nearest synoptic times are indicated in each panel with the hour followed by the day number in March 2004. (h) and (i) Satellite imagery taken from different satellite platforms because of image corruption on 27 March 2004; however, all images are comparable. A length scale is provided for reference in (k).

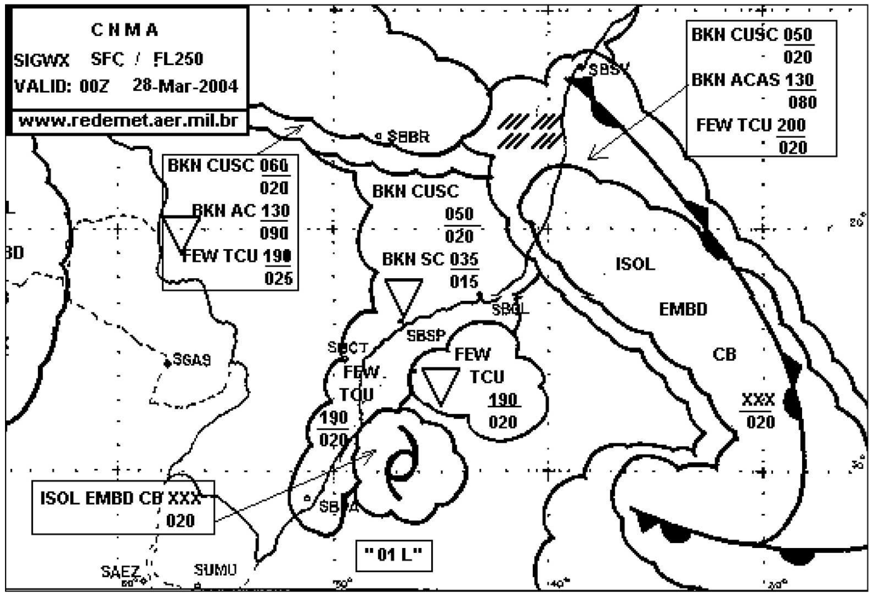

FIG. 5. Surface and flight level 250 significant weather analysis from Conforência Nacional do Meio Ambiente for 0000 UTC 28 Mar 2004. Hurricane Catarina is labeled as a tropical storm with the identifier "01 L."

it is suggestive of a strong warm core feature embedded in the near-uniform 570-dam thickness environment. The development of outflow to the east of the tropical system isolates the storm from the equatorward branch of the jet, thus releasing Catarina from the influence of its baroclinic precursors. As described in section 1 and shown in Fig. 2, Catarina's outflow (to be described from a PV perspective later in this section) also reinforces the anomalous easterly component of the upper-level winds surrounding the storm, further isolating the system from the strong poleward branch of the jet. Although the hurricane continues to intensify on 27 and 28 March (Figs. 6g,h), the processes responsible for this development appear to be contained in the system's internal structures because synoptic-scale forcings over this period are weak. As soon as the hurricane makes landfall and weakens, however, the deep westerly flow over the South American continent becomes rapidly progressive and shears out the remnants of the hurricane (Fig. 4k).

The features in the background flow that are of particular importance to the development of Hurricane Catarina are the split jet and the low shear region between the jet branches. An analysis of θ_{DT} and DT winds (Fig. 8; see Table 2 for description of feature labels) shows that these essential ingredients are the direct result of a dipole block established and reinforced by repeated injections of high (low) θ_{DT} air into the quasi-stationary ridge (trough) blocking component east of Brazil over the period of interest. At 0000 UTC 20 March, the precursor disturbance for Hurricane Catarina is represented by a small vorticity maximum to the right of the X in Fig. 8a.

At 0000 UTC 20 March 2004 (Fig. 8a), two transient troughs (A and B) and a transient ridge (1 in Fig. 8) are noted on the domain. Trough A interacts almost immediately with the blocking trough X, injecting cool (<330 K) air parcels into the trough's circulation (Fig. 8b). As transient ridge 1 moves rapidly along the leading edge of a broad trough west of Brazil, trough B intensifies and shares an axis with the blocking trough by 0000 UTC 22 March (Fig. 8e). Almost simultaneously, transient ridge 1 reinforces the decaying blocking ridge (0 in Fig. 8) with warm θ_{DT} air (>350 K), triggering a reversal of the westerly flow on the DT beginning 0000 UTC 23 March 2004 (Fig. 8g) and signaling the onset of the more restrictive Pelly and Hoskins (2003) defined blocking episode (Fig. 9). This time corresponds with the initiation of the lower-level system's anticyclonic track reversal noted in section 3a. The reinforcement of both components of the dipole block on 22 March is therefore crucial to Catarina's development because it leads to an initial sharp reduction in the westerly steering flow above the system. This prevents the storm from being enveloped by the midlatitude flow as was the case with the predecessor disturbance described at the beginning of this section.

The third and final transient trough (C) to interact with the blocking trough (X) appears east of South America at 0000 UTC 24 March (Fig. 8i). Meanwhile, a

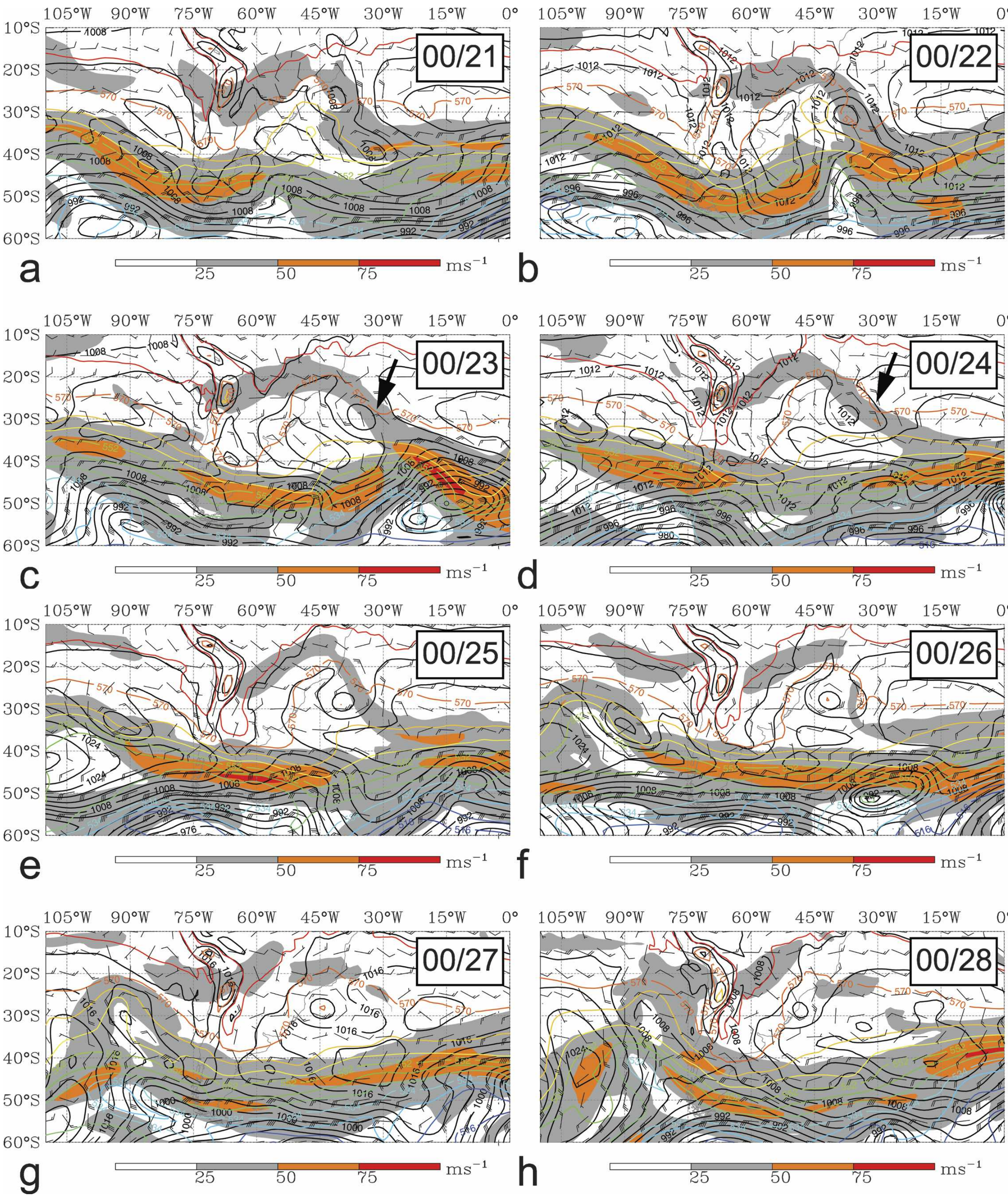

FIG. 6. MSLP (heavy black contours at 4-hPa intervals), 1000–500-hPa thickness (solid contours at 6-dam intervals with warmer colors for larger thicknesses), 500-hPa winds (black barbs with short, long, and flag pennants indicating 2.5, 5, and 25 m s^{-1} of wind, respectively), and 200-hPa wind speeds (shaded with magnitudes in m s^{-1} as indicated on the color bar beneath each panel). Analyses are at 24-h intervals in hour/day format for March 2004. Annotations as noted in text.

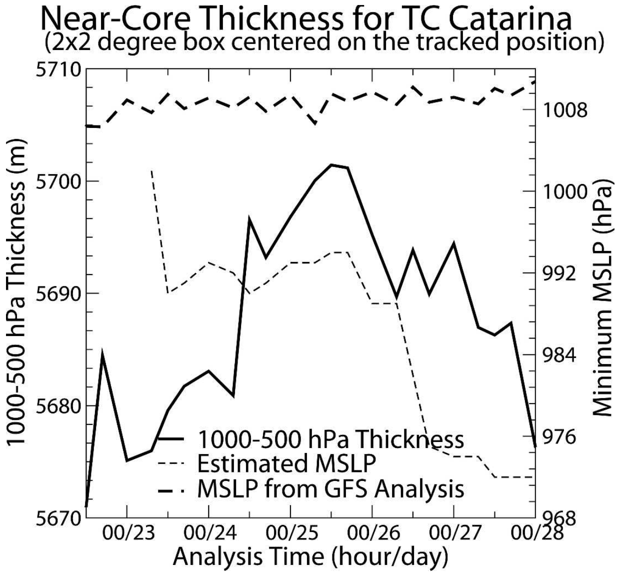

FIG. 7. Near-core time series of 1000–500-hPa thickness (heavy solid line), estimated MSLP (from Table 1, thin dashed line) and MSLP from the 1° GFS analysis (heavy dashed line) from 1200 UTC 22 Mar 2004 to 0000 UTC 28 Mar 2004.

second transient ridge (2 in Fig. 8) is moving along the leading edge of the longwave trough still anchored over the eastern South Pacific Ocean. Trough C interacts only briefly and weakly with the blocking trough at 0000 UTC 25 March (Fig. 8k), the latter being now virtually isolated from the midlatitude flow by the reinforced ridge component of the dipole block (0 in Fig. 8). The large scale of transient ridge 2 results in an apparent southward shift of quasi-stationary ridge 0 on 25 March (Figs. 8k,1). This leads to an expansion of the weak-wind region on the DT and an implied reduction in the deep-layer shear (Fig. 9) over a broad area within the diffluent flow during the TT of the storm. This pattern persists on 26 March (Figs. 8m,n) as Hurricane Catarina intensifies and moves westward toward the Brazilian coast. Although the advectively created ridge component of the dipole block appears to weaken on 27 March (Figs. 8o,p), the fully developed storm is capable of assisting synoptic-scale eddies with the maintenance of the blocking pattern through the production of warm θ_{DT} in its own convective outflow region (Fig. 8p). A quantification of the influence of Catarina's outflow on the blocking environment requires numerical simulation and will form the basis of a future study. The maintenance of the dipole block through the bulk upscale effects of the cumulus outflow and advection of high θ_{DT} values is important because of Catarina's high formation latitude and its proximity to the strong midlatitude flow that rapidly destroys the system after landfall.

The nature of the deep-layer flow that composes Hurricane Catarina's environment is of particular importance for two reasons throughout the storm's life cycle. First, it is responsible for initiating the anomalous easterly steering flow that prevents Catarina from tracking directly into the midlatitudes. Second, its reduction of the deep-layer shear permits the onset of the WEC pathway of the TT process and allows for a tropical mode of intensification thereafter.

A diagnosis of Catarina's steering flow is presented in Fig. 10. The decomposition of the full steering vector into "trough" and "ridge" components is achieved using the piecewise PV inversion framework of Davis and Emanuel (1991). The trough PV anomaly [relative to the NNRA long-term mean (Smith and Reynolds 1998) and shown in Fig. 11] is defined as all anomalous PV within the box bounded by 27.5°S, 55°W and 10°S, 25°W. Similarly, the ridge PV anomaly is taken over an area from 60°S, 70°W to 32.5°S, 10°W, also shown in Fig. 11. These regions are chosen to encompass the dipole block over Catarina's full lifetime and are consistent with the analog boundaries described in section 4. The difference in the sizes of the boxes—exaggerated by the cylindrical projection in Fig. 11—is a reflection of the relative sizes of the dipole-blocking components. Inversion of the anomalous PV fields yields balanced (Charney 1955) heights and winds that are used to compute the component steering vectors shown in Fig. 10. These vectors show the anomalous steering flow associated with the trough- and ridge-blocking components, and should not be expected to sum to the total steering flow because of the westerly mean wind over the steering domain. Discrepancies between the analyzed track (Table 1) and the steering flow are likely a result of mesoscale structures that are unresolved in the analysis grids. The weak representation of the storm throughout its life cycle has a negative impact on the local analysis quality as the upscale effects of the hurricane's dynamics and thermodynamics are not incorporated into the analysis cycle.

The full steering flow (directly from the analysis grids) is initially westerly, but drops to low values (below the 2 m s^{-1} plotting threshold) after Catarina turns northwestward at 0000 UTC 23 March (Fig. 10). By 0600 UTC 24 March, the full steering is driving the system slowly to the west, and it continues to do so for the remainder of Catarina's life cycle. The reinforcement of the ridge component of the dipole block between 1200 UTC 22 March and 0000 UTC 24 March (Figs. 8f,i) is reflected in the enhancement (prior to 0600 UTC 23 March) and backing of the anomalous steering vector over this early period. The rapidly increasing southerly component of the anomalous ridge

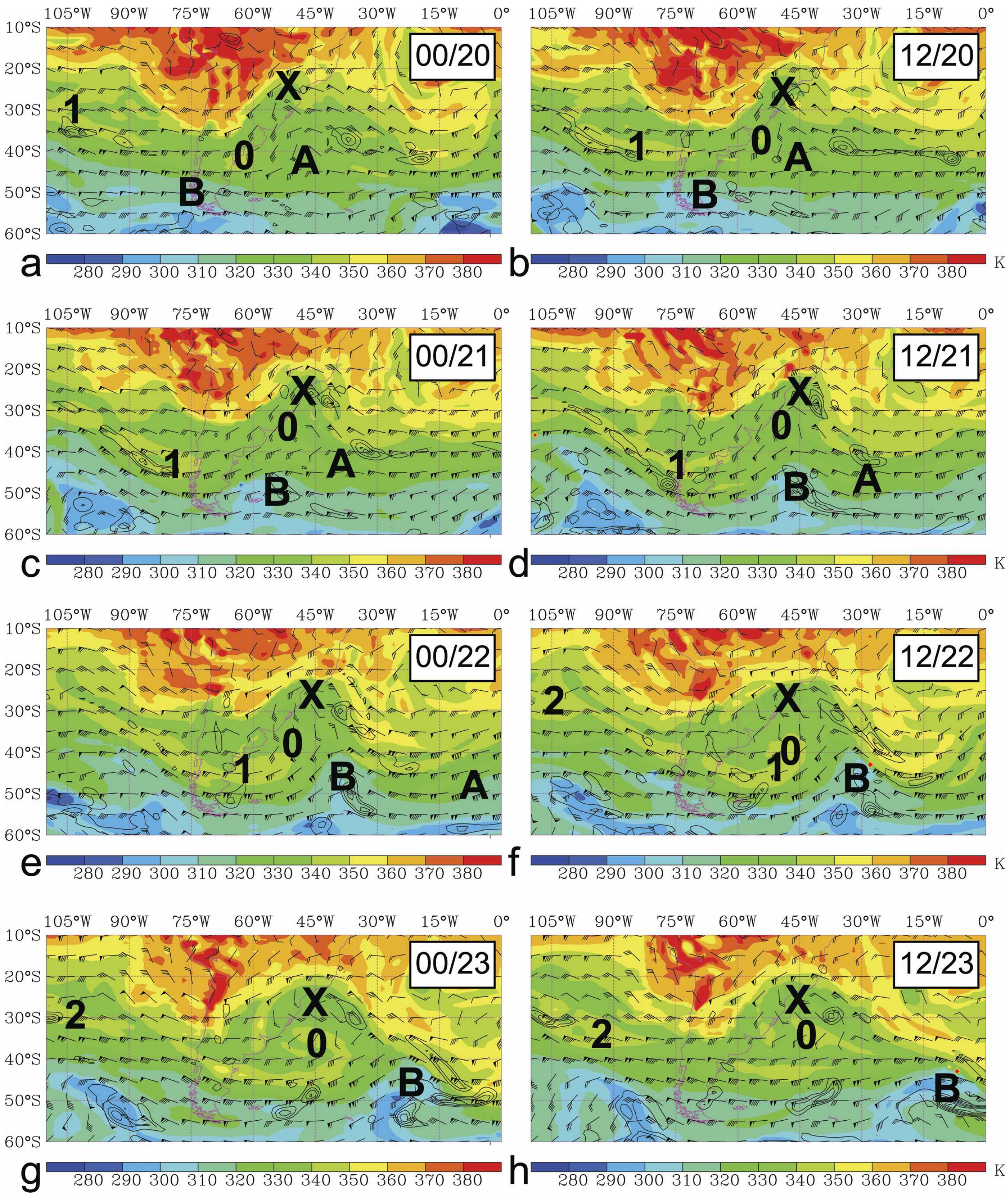

FIG. 8. Dynamic tropopause potential temperature (shaded at 10-K intervals as indicated on the color bar beneath each panel) and winds (black barbs with short, long and flag pennants indicating 2.5, 5, and 25 m s^{-1} of wind, respectively). The cyclonic relative vorticity of the 925–850-hPa mean flow is shown with black contours at intervals of 5×10^{-5} s^{-1} beginning at 5×10^{-5} s^{-1}. Analyses are at 12-h intervals in hour/day format for March 2004. Feature labeling is summarized in Table 2 and is described in detail in the text.

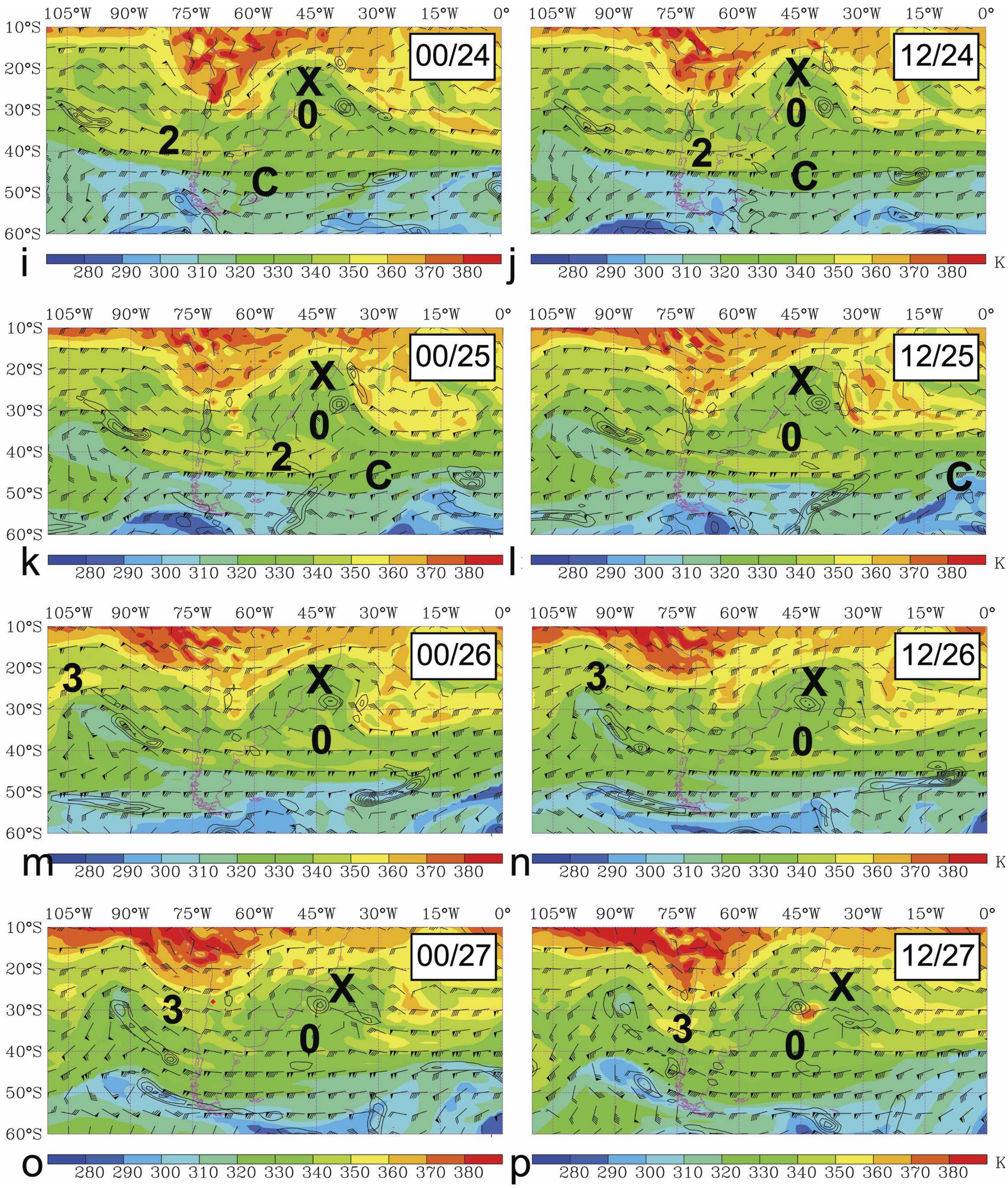

FIG. 8. (*Continued*)

steering flow appears to be responsible for halting and reversing Catarina's initial southeasterly progression. After 1200 UTC 23 March, the anomalous ridge steering vector acquires an easterly component that assists the weaker anomalous trough steering flow in guiding Catarina toward the coast. This portion of Catarina's life cycle is characterized by the completion of TT and the intensification of the tropical vortex as it is steered

TABLE 2. Lookup table for feature identification. Details concerning each entry are contained in the text.

Symbol	Fig.	Description
0	8	Ridge component of dipole block
1	8	Transient ridge interacting with 0 at 0000 UTC 23 Mar 2004
2	8	Transient ridge interacting with 0 at 0000 UTC 25 Mar 2004
3	8	Transient ridge that remains west of South America
A	8	Transient trough interacting with X at 0000 UTC 20 Mar 2004
B	8	Transient trough interacting with X at 0000 UTC 22 Mar 2004
C	8	Transient trough interacting with X at 0000 UTC 25 Mar 2004
L	2	Lower-level circulation center in the conceptual model
S	20	Subtropical system in 1974 blocking case
X	8	Trough component of dipole block

westward under the return flow on the dynamic tropopause (Fig. 8), a kinematic necessity of the upstream diffluent pattern established by the long-lived dipole block.

The flow around, and most importantly within, the dipole block is simultaneously responsible for the steering and the evolution of the precursor vortex. Before the abrupt anticyclonic track change on 23 March (Fig. 10), the system lies beneath an area of strong deep-layer shear (Figs. 12a,b) with magnitudes in excess of 25 m s^{-1} (Fig. 13). Following the ridge component enhancement and resulting steering flow reversal, however, the storm is guided directly into a broad region of weak shear (Fig. 12c) between the strengthened components of the dipole block (Fig. 9). The shear magnitude in Fig. 9 leads the blocking index prior to block onset (0000 UTC 23 March) because of the approach of the anticyclonic reinforcement (1 in Fig. 8) from the west of the blocking domain (section 2). Once the anticyclonic component of the dipole block is established within the blocking region, shear and blocking index values are strongly linked (Fig. 9). By 1200 UTC 23 March (Fig. 12d), the system is under the influence of weak shear [<10 m s^{-1}; Zehr (1992)] and remains in such a state throughout the TT and intensification stages of its life cycle (Figs. 12e–h and 13). Although Davis and Bosart (2004) note that TT can occur in regions whose vertical shear values generally preclude tropical development, Gray (1968) argues that reduced deep-layer shear such as that experienced by Catarina prevents the ventilation of cumulus towers, thereby promoting the growth of a upright warm core.

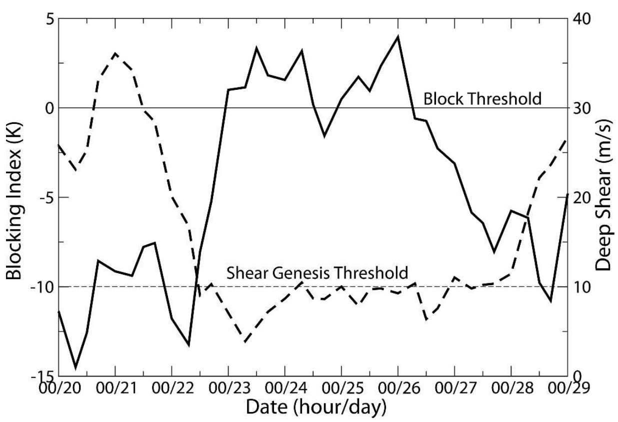

FIG. 9. Time series of the (Pelly and Hoskins 2003) blocking index B (solid line). Values greater than zero represents a reversal in the meridional gradients of θ_{DT} and characterize a blocking pattern. Mean deep-layer shear over the 5° × 5° box centered on the block 30°S, 40°W is plotted with a dashed line. The 10 m s^{-1} tropical cyclogenesis critical shear (Zehr 1992) is shown for reference.

c. Thermodynamic development

The importance of the trough component of the dipole block extends well beyond its relatively weak direct influence on Catarina's steering flow (Fig. 10). From both dynamical and thermodynamical perspectives, the upper-level cold low plays an important role in the TT and development of the storm. Similar impacts of trough features and cutoff circulations have been documented by Holland et al. (1987), Emanuel (2005), and others for tropical systems developing over relatively cool SSTs (Reale and Atlas 2001). An investigation of the role of the trough component of the dipole block during Catarina's life cycle in the context of these previous studies highlights structures and processes germane to TT and tropical development irrespective of geographic region.

The thermodynamic influence of a cold oceanic upper trough during the development of a troposphere deep tropical system has been investigated by Emanuel (2005) for Mediterranean hurricanes. The cool air aloft reduces the bulk column stability as indicated by a minimum in mean coupling index values east of Brazil (Fig. 14). The coupling index is defined as the difference between θ_{DT} and the maximum equivalent potential temperature at or below 850 hPa (Bosart and Lackmann 1995) and acts as an estimate of bulk column convective stability and coupling between the upper- and lower-level flows. Air parcels approaching the trough are forced to ascend in accordance with traditional quasigeostrophic theory, leading to further destabilization of the column. In addition, the upgliding

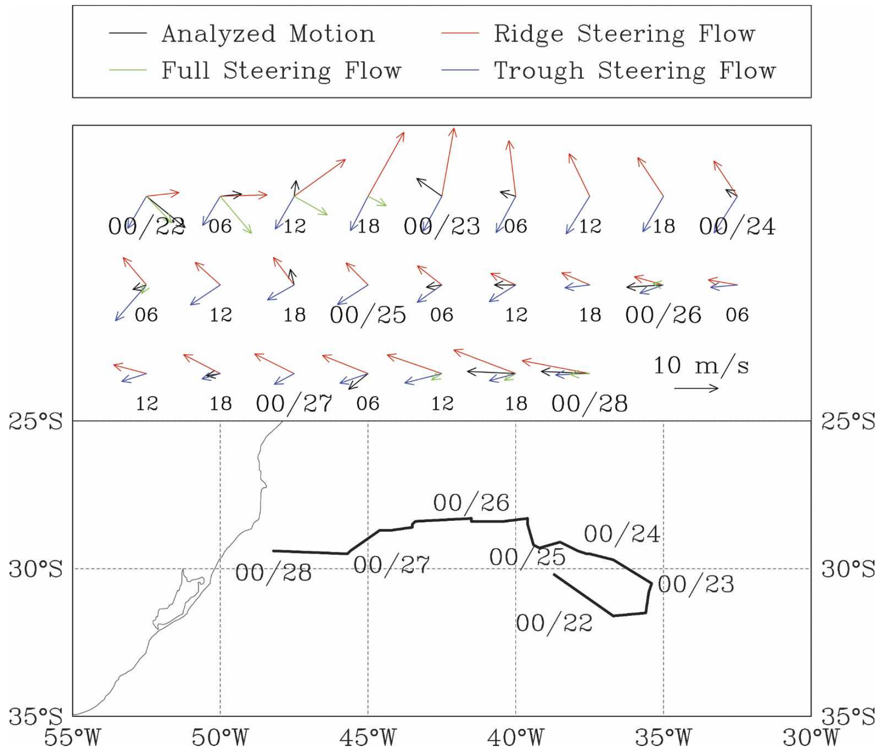

FIG. 10. Steering flow diagnosis for Hurricane Catarina's full life cycle. Catarina's track is shown in the bottom half of the plot, with instantaneous storm locations indicated by the date stamps. The vectors in the top half of the plot are color coded as indicated in the legend and represent the analyzed storm motion vector (black), the full steering flow (green), the steering flow contribution from the ridge component of the dipole block (red), and the steering flow contribution from the trough component of the block (blue). Steering and motion vectors are plotted at 6-h intervals as indicated by their associated date stamps and represent both the magnitude (scaled against the reference vector in the lower-right corner of the panel) and the direction of the component forcing.

air approaches saturation [as in Fig. 3 of Holland et al. (1987)], thereby reducing the deleterious effects of downdrafts during moist convection. Emanuel (2005) shows that SSTs well below the traditional 26.5°C tropical genesis threshold can produce large values of potential intensity [PI; Bister and Emanuel (1997)] when coupled with a cold anomaly aloft. This result is supported by Holland et al. (1987) whose study of type-1 and -3 Australian east coast cyclones finds that these subsynoptic-scale hurricane-like vortices develop under the influence of the trough component of an easterly dip (dipole block) over SSTs of 20°–24°C.

The PI of the environment in which Catarina developed is shown in Fig. 15a. Despite SSTs between 22° and 25°C (Figs. 13 and 15b), the cold trough aloft results in 40–50 m s^{-1} PI values over a broad area equatorward of 30°S east of South America. As shown in Fig. 15, these SST values are below climatological norms, a further indication of the importance of the trough component of the dipole block to Catarina's TT and development. The climatological PI along the track of the storm is compared with analyzed values in Fig. 16. At all times during Catarina's life cycle, the PI remains above climatology, with differences of up to 15 m s^{-1} (35%) developing during the TT of the system. A pair of Coupled Hurricane Intensity Prediction System (CHIPS; Schade and Emanuel 1999) hindcasts demonstrate the sensitivity of Catarina's development to the anomalously high PI values (Fig. 17). The CHIPS hindcast run under climatological conditions yields maximum wind speeds of less than 28 m s^{-1} while the hindcast initialized with analyzed PI values results in a storm with peak wind speeds of 40 m s^{-1}, which is in good agreement with tracking estimates (Table 1).

Recent advances in our understanding of TT and tropical development appear to call into question the wisdom of strict adherence to the 26.5°C SST threshold for tropical genesis. The hurricane-like storms documented by numerous authors (see review by Reale and Atlas 2001) and this study can occur over SSTs below

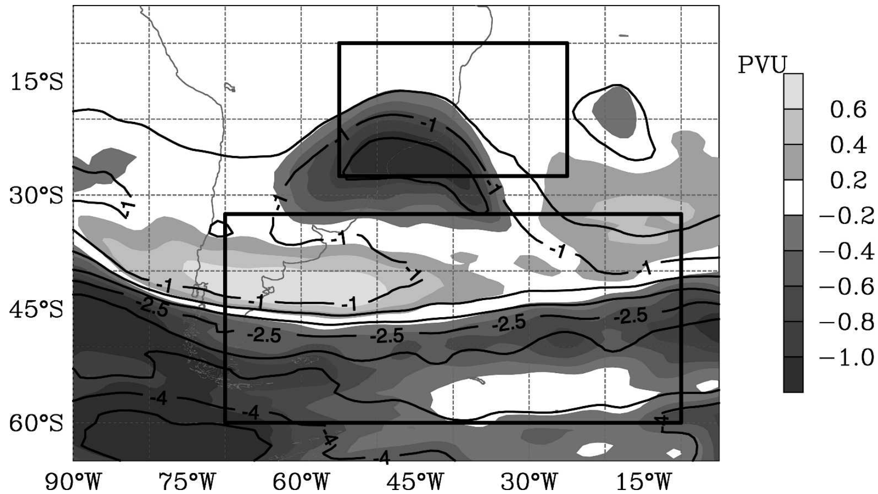

FIG. 11. Mean 500–200-hPa PV over Catarina's lifetime, taken as 0000 UTC 20 Mar 2004 to 0000 UTC 28 Mar 2004 (solid lines 0.5-PVU intervals), and mean anomaly over the same period (shading with values as indicated on the grayscale bar). The boundaries of the equatorward (trough) and poleward (ridge) regions for the partitioned steering flow analysis are shown by heavy solid boxes.

this empirical threshold. However, they posses all the hallmarks of tropical cyclones including hurricane-force winds, warm core structures, banding features, and eye development (e.g., Fig. 1). Sustained by the WISHE process (Emanuel 1987) through the interaction between the deep layer of cool air associated with the low-latitude trough and the relatively warm lower boundary SSTs, these systems are indeed isomorphic with traditional hurricanes (Emanuel 2005). A relaxation of the artificial geographical and SST constraints will result in a necessary expansion of tropical cyclone, hurricane, and typhoon terminology that will yield a structurally based categorization for tropical systems developing anywhere on the globe. Under such a scheme, this study suggests that Catarina has certainly earned its place in history as a South Atlantic hurricane.

4. Blocking analogs

The importance of the upper-level flow in developing conditions favorable for the TT and intensification of Hurricane Catarina has been described in detail in the previous sections. In particular, the long-lived dipole-blocking structure established and maintained east of Brazil plays two important roles in modifying the environmental flow around the storm. First, it steers the developing system westward instead of southeastward into the midlatitudes as is common for cyclones in this area (Sinclair 1997). Second, it reduces the deep-layer shear above the storm to below the 10 m s^{-1} theoretical limit proposed by Zehr (1992). As noted by Sinclair (1996), there is a weak maximum in anticyclone frequencies off the southeast Brazilian coast in the austral summer; however, these features tend to be short lived and there is no indication of a favorable "persistent anomaly" region in the western South Atlantic equatorward of 40°S. The lack of anomalously favorable SSTs leads directly to the hypothesis that the key to this rare tropical development in the western South Atlantic lies in the intensity and the longevity of the upper-level blocking pattern.

To investigate this hypothesis, an analog study is performed using January–March 500-hPa geopotential heights from the NNRA for the period 1971–2001. Because the dipole blocking described by Rex (1950a) is

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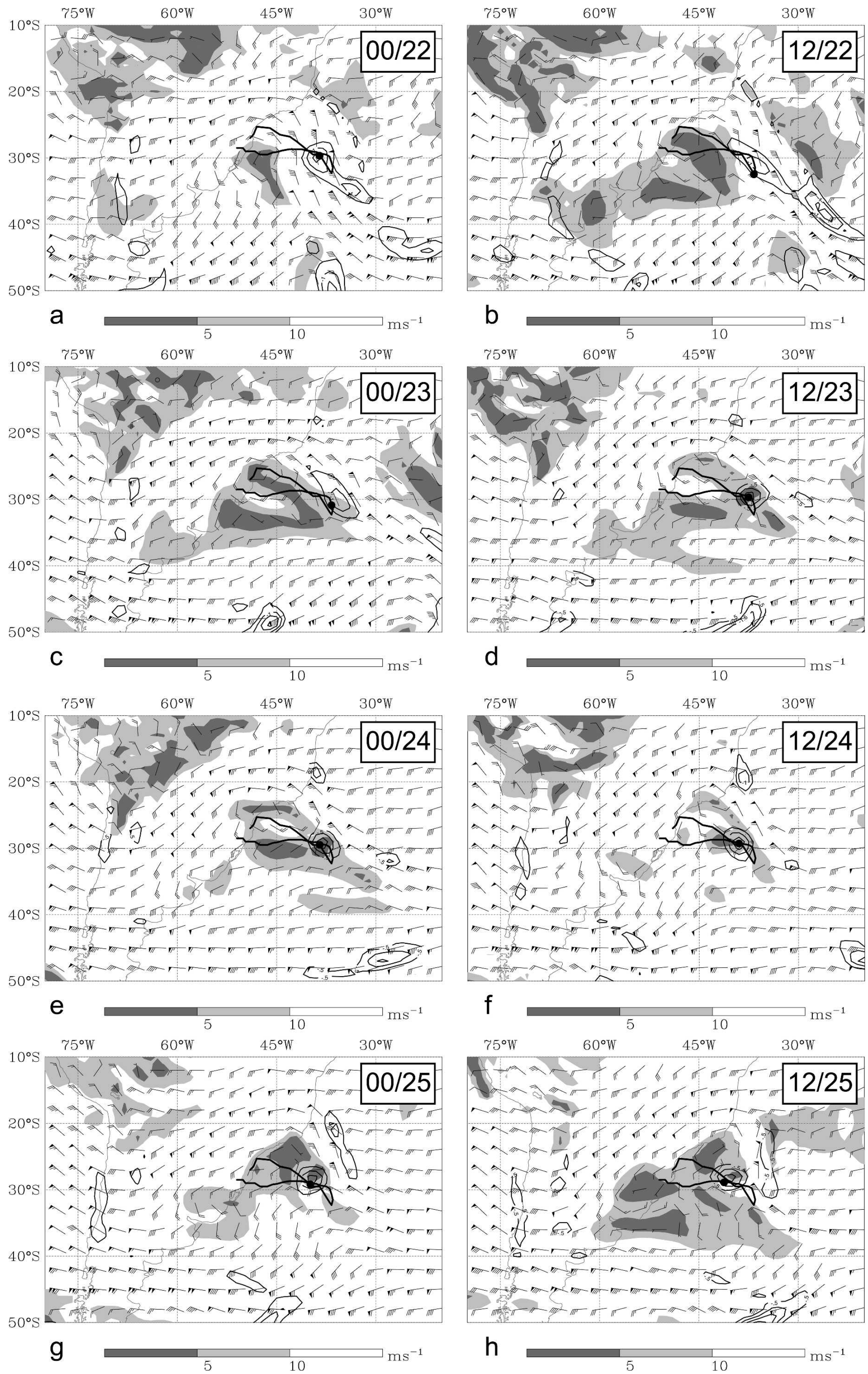
FIG. 12. Deep-layer shear (DT–850-hPa winds) is plotted with black barbs where short, long and flag pennants indicate 2.5, 5, and 25 m s^{-1} of shear, respectively. The shear magnitude is shaded in m s^{-1} as indicated on the grayscale bars beneath the panels. The cyclonic relative vorticity of the 925–850-hPa mean flow is shown with dark contours at intervals of 5×10^{-5} s^{-1} beginning at 5×10^{-5} s^{-1}. Analyses are at 12-h intervals over Catarina's TT stage in hour/day format for March 2004. The storm's track is shown with a heavy solid line with the instantaneous observed location denoted by a dot.


75°W
60°W
45°W
30°W
10°S
20°S
30°S
40°S
50°S
00/22
12/22
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b
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ms^{-1}

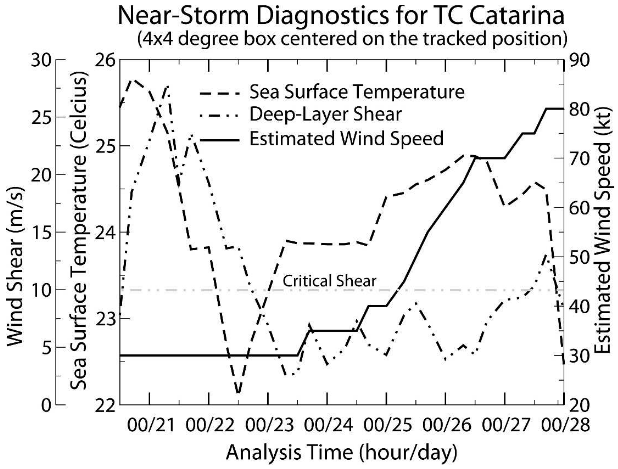

FIG. 13. Near-storm time series of SST (dashed line), deep-layer shear (DT–850 hPa, dash–dotted line) and estimated wind speed (from Table 1; solid line). The approximate threshold shear value of 10 m s^{-1} (Zehr 1992) is shown with a gray dash–dotted line. The 4° × 4° box follows the storm center at 6-h intervals.

characterized by a lower-latitude trough beneath a higher-latitude ridge, the dataset is searched for cases in which anomalous 500-hPa troughing is present in the box bounded by 27.5°S, 55°W and 10°S, 25°W and anomalous ridging is present in two of the three boxes along the latitude band 60°–32.5°S bounded by 70°–40°W, 55°–25°W, and 40°–10°W as shown in Fig. 18. The definition of the three boxes for the ridge anomaly allows for small tilts in the dipole-blocking axis and for the varying scales of trough and ridge anomalies at different latitudes. This height anomaly structure implies only an easterly geostrophic anomaly, rather than a reversal of the midlevel flow as observed for Catarina. This easing of the easterly wind restriction places the analog search in the context of previous studies and has the advantage of identifying cases that represent a spectrum of blocking strengths. Because the longevity of the blocking pattern is important for the development of an environmental flow that allows for TT and development over a period of several days to a week, only those events lasting 9.5 or more days [twenty 12-hourly periods, chosen to match the Rex (1950a) 10-day criterion with a 0.5-day buffer to account for the coarse 12-h temporal resolution of the analog search] are considered. This longevity condition is particularly restrictive in the SH, where van Loon (1956) and Wright (1974) find blocking periods to be generally shorter than those north of the equator. However, as shown in Fig. 18, the dipole block that aids in the development of Hurricane Catarina lasts for a total of 26 periods (12.5 days).

In the 30-yr dataset examined, only six cases of long-lived summertime western South Atlantic dipole blocks are found (Table 3). Only two of these events last longer than the Catarina block, both extending for 29 periods (14 days). A grouping of the events is also noted, with all six events occurring in only three separate years (breaks of at least 3 days between blocking episodes within each year ensure at least minimal synoptic-scale independence of the events). This result suggests that planetary-scale flow regimes may be responsible for establishing conditions favorable for dipole-blocking episodes in the western South Atlantic. Investigation of this possibility will be the subject of a future study. The mean 500-hPa height anomaly patterns for the full period of the Catarina block is shown as the inset in Fig. 18. Similar diagnostics for the six cases identified in the analog study are shown in Fig. 19.

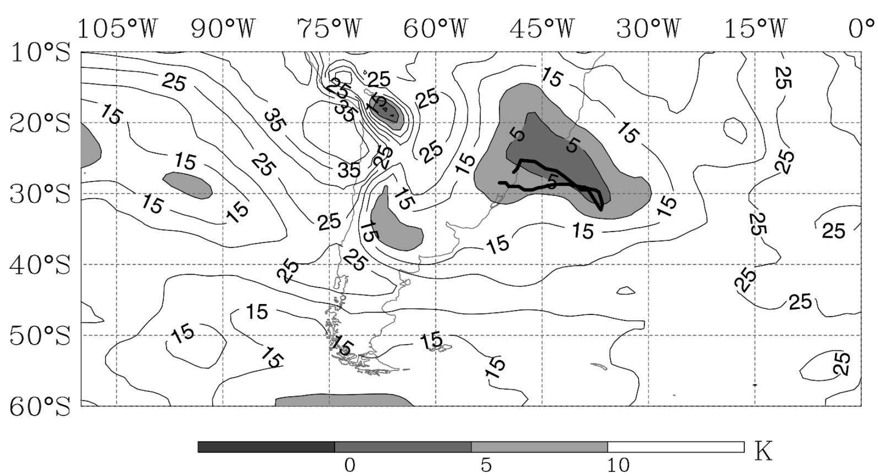

FIG. 14. Mean coupling index during Catarina's life span (0000 UTC 20 Mar–0000 UTC 28 Mar 2004) plotted at 5-K intervals with shading as indicated on the grayscale bar for regions of lowered bulk stability. Hurricane Catarina's track is indicated by the heavy black line.

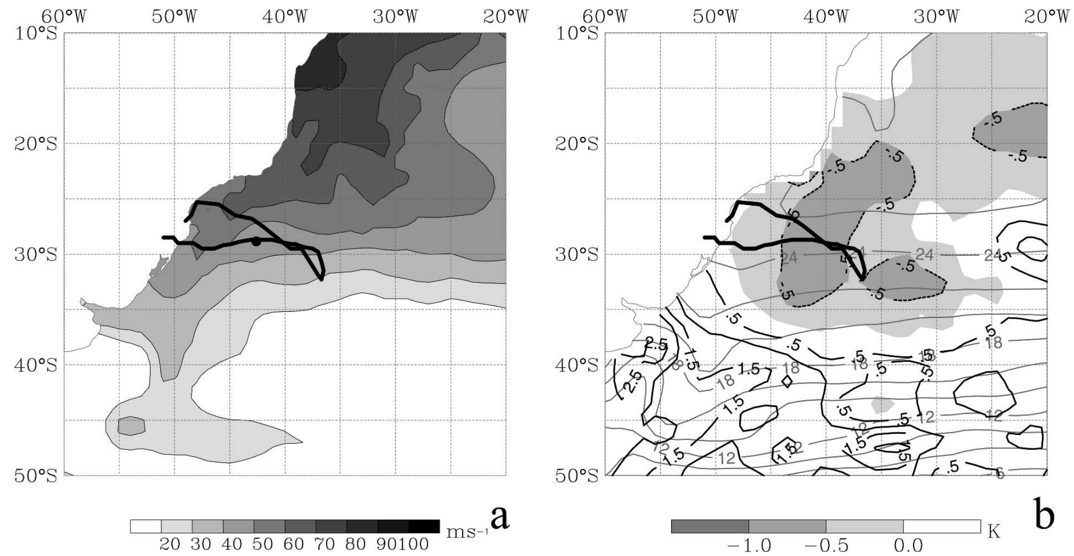

FIG. 15. (a) Potential intensity (Bister and Emanuel 1997) at 0000 UTC 26 Mar 2004 with shading in m s^{-1} as indicated on the grayscale bar. (b) SST (light gray contours at 2°C intervals) and SST anomalies from the long-term mean described in section 2 (heavy contours at 0.5-K intervals with no 0-K contour and dashed lines for negative values—shading emphasizes regions of below-normal SSTs with magnitudes as indicated on the grayscale bar). The SST contour near 10°S off the Brazilian coast in (b) is 28°C. Hurricane Catarina's track is denoted by a heavy black line in both panels and the instantaneous location of the storm at 0000 UTC 26 Mar 2004 is marked with a dot in (a).

a. January–February 1974

The mean and anomalous 500-hPa heights for the period 23 January–3 February 1974 are shown in Fig. 19a. While the signature of the dipole block is present in the mean field—note the geostrophic diffluence east of South America—the magnitude of the trough anomaly is less than 25 m and the feature does not show up with the shading increments used on the anomaly plots. This weakness in the trough component of the dipole block suggests that the anomalous easterly wind in the blocking area is minimal and that systems steered by the deep-layer flow will be more progressive than in the Catarina case. This hypothesis is borne out midway through the blocking episode as a system on a track initially very similar to that of Catarina is swept into the

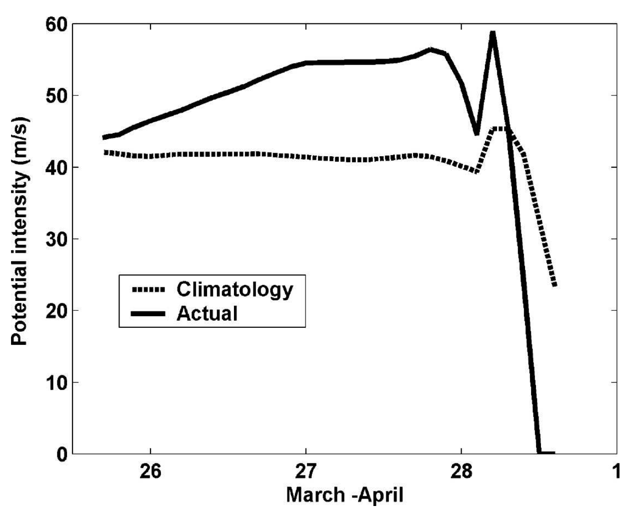

FIG. 16. Evolution of analyzed ("Actual"; solid curve) and climatological (dashed curve) PI along the track of Hurricane Catarina.

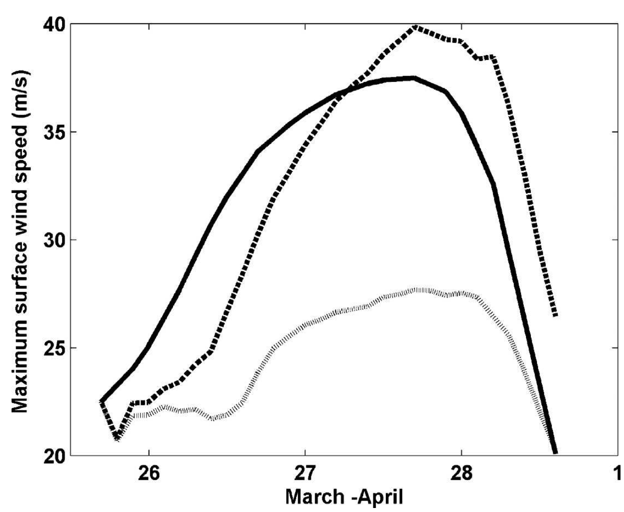

FIG. 17. Storm intensity in CHIPS hindcasts initialized with analyzed PI values (dashed curve) and climatological PI values (dotted curve) compared with track (solid curve) wind speeds for Catarina (Table 1).

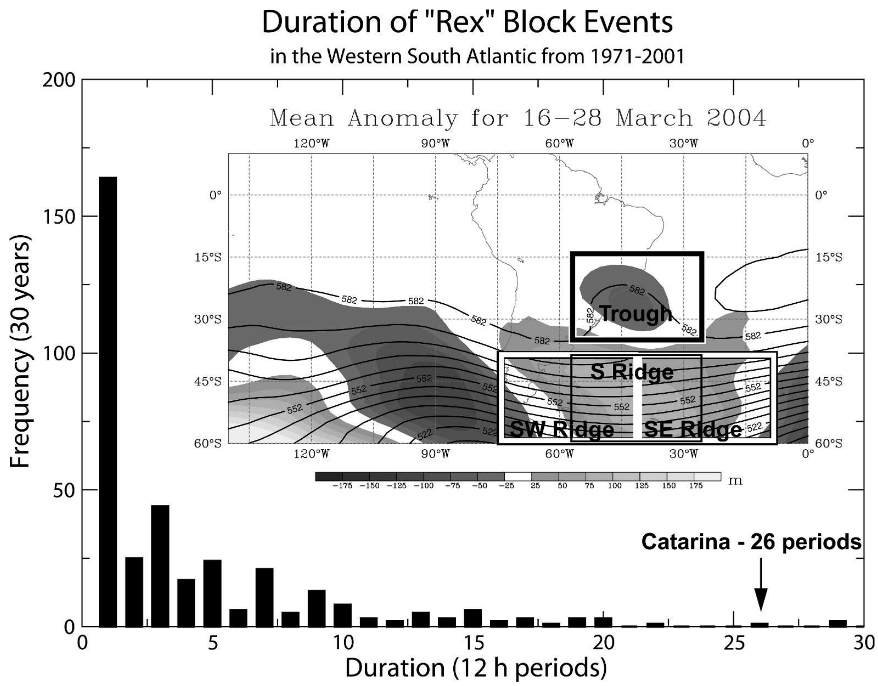

FIG. 18. Histogram of dipole-blocking persistence in the western South Atlantic over the period 1971–2001. Dipole blocking is identified by anomalously low 500-hPa heights in the equatorward box of the inset (labeled "Trough") and anomalous high heights in two of the three poleward boxes (labeled "Ridge"). The mean 500-hPa height (black contours at 6-dam intervals) and mean height anomaly pattern (shading in m as indicated by the grayscale bar) for 16–28 Mar 2004 is shown in the inset.

midlatitude baroclinic westerlies instead of curving back toward the South American coast (not shown).

b. Early March 1974

Figure 19b shows mean and anomalous 500-hPa heights for the period 6–15 March 1974. A quick comparison of Figs. 19b and 18 shows a clear difference in the structure of the midlevel flow. In this case, an anomalous trough axis tilts northwestward from the central South Atlantic beneath a well-established ridge. Although this pattern meets the criteria of the analog search, the dynamics of the implied flow is different since a tilted wave pattern does not necessarily support weakened midlevel wind speeds. The two key properties of the dipole block for TT and tropical development (shear reduction and easterly steering) are thus not present in this case.

c. Late March 1974

The second long-lived dipole-blocking episode in March 1974 occurs from 18 to 28 March. Mean and anomalous 500-hPa heights for this period are shown in Fig. 19c. The negatively tilted trough responsible for the false positive dipole block in early March 1974

TABLE 3. Summary of western South Atlantic blocking periods. See the text for a description of the blocking criteria used to create this table.

Onset	Decay	Duration (days)	Section
1200 UTC 23 Jan 1974	0000 UTC 3 Feb 1974	10.5	4a
0000 UTC 6 Mar 1974	1200 UTC 15 Mar 1974	9.5	4b
1200 UTC 18 Mar 1974	0000 UTC 28 Mar 1974	9.5	4c
0000 UTC 6 Jan 1979	0000 UTC 20 Jan 1979	14	4d
1200 UTC 5 Jan 1992	0000 UTC 15 Jan 1992	9.5	4e
0000 UTC 22 Jan 1992	0000 UTC 5 Feb 1992	14	4f
0000 UTC 16 Mar 2004	1200 UTC 28 Mar 2004	12.5	3

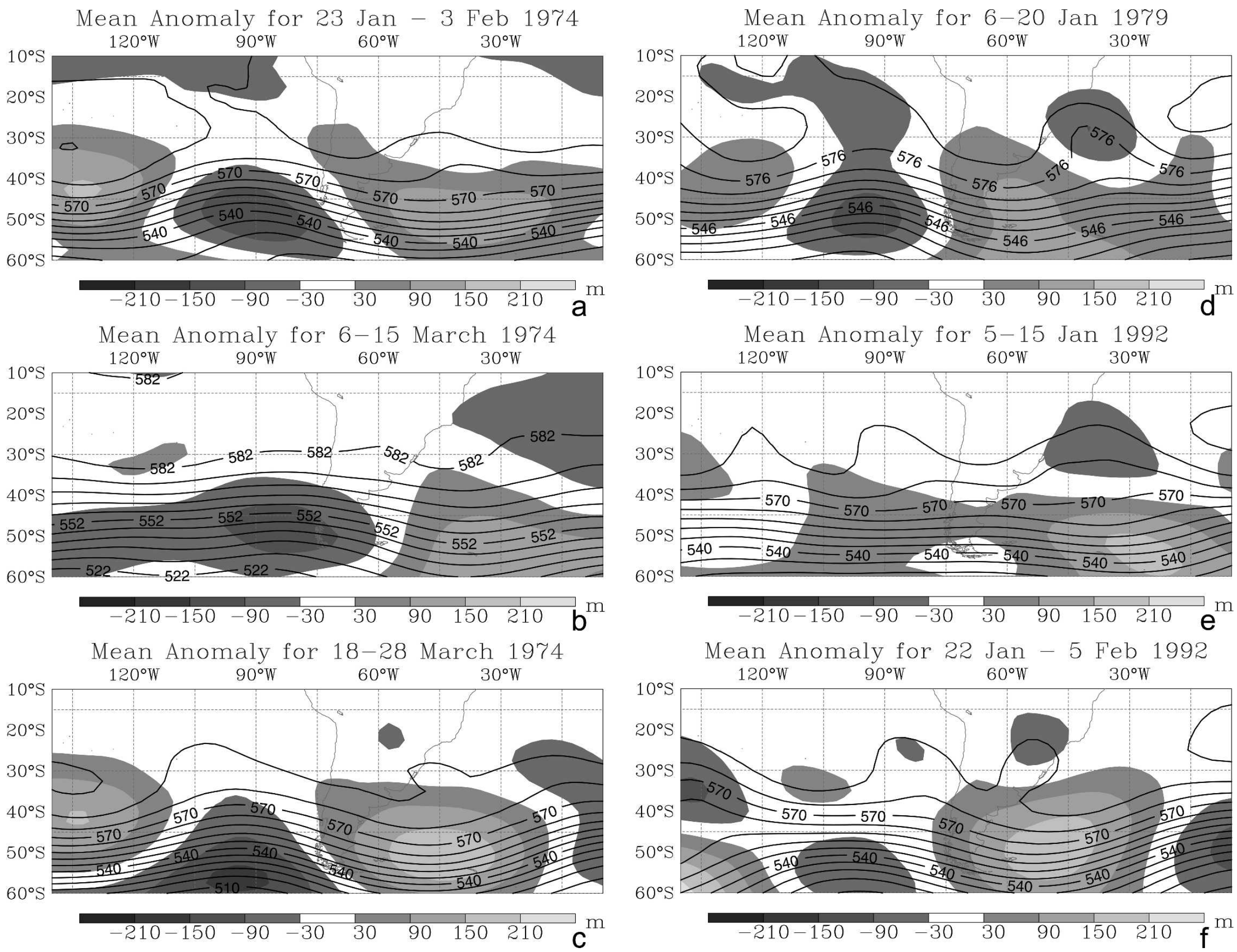

FIG. 19. Mean 500-hPa heights (black contours at 6-dam intervals) and mean height anomalies (shading in m as indicated by the grayscale bar beneath each panel) for the blocking periods indicated in the title of each panel. Blocking periods are summarized in Table 3 and are described in detail in the text.

leaves a cutoff trough anomaly over the Brazilian continent as it progresses eastward. A small perturbation in the mean geostrophic wind is present near 30°S east of the South American coast. It is here that a weak area of low pressure originating over the Amazon (S in Fig. 20a) begins to intensify on 27 March, near the end of the blocking period. The system develops quickly over the next 48 h (Figs. 20b,c) and results in a broad circulation over the western South Atlantic with banding structures and deep convection near its core. In the NNRA, the system develops a troposphere deep (850 hPa to DT) warm core anomaly of 5 K from the local latitudinal mean and a central MSLP of 988 hPa (Fig. 21). By the time this subtropical system begins its intensification, however, the dipole block is weakening and the westerly flow is encroaching on the storm's environment, steering it into the midlatitudes after 29 March. This poleward displacement relative to Hurricane Catarina places the storm over cooler SSTs throughout its life cycle and the increasing northwesterly steering flow causes it to track rapidly toward the cold South Atlantic waters south of 40°S (not shown). It is unknown whether this system would have undergone an SEC mode TT (Davis and Bosart 2004) if it had been supported by a more favorable dipole block of the kind responsible for Catarina.

d. January 1979

Figure 19d shows the mean and anomalous 500-hPa heights for the period 5–15 January 1979. The mean heights in this case imply a wavelike flow rather than a dipole-blocking structure. A ridge is dominant over South America and a strong trough lies off the Brazilian coast. As noted is section 4b, this stationary wave pattern lacks the key ingredients (shear reduction and easterly steering) of Hurricane Catarina's development.

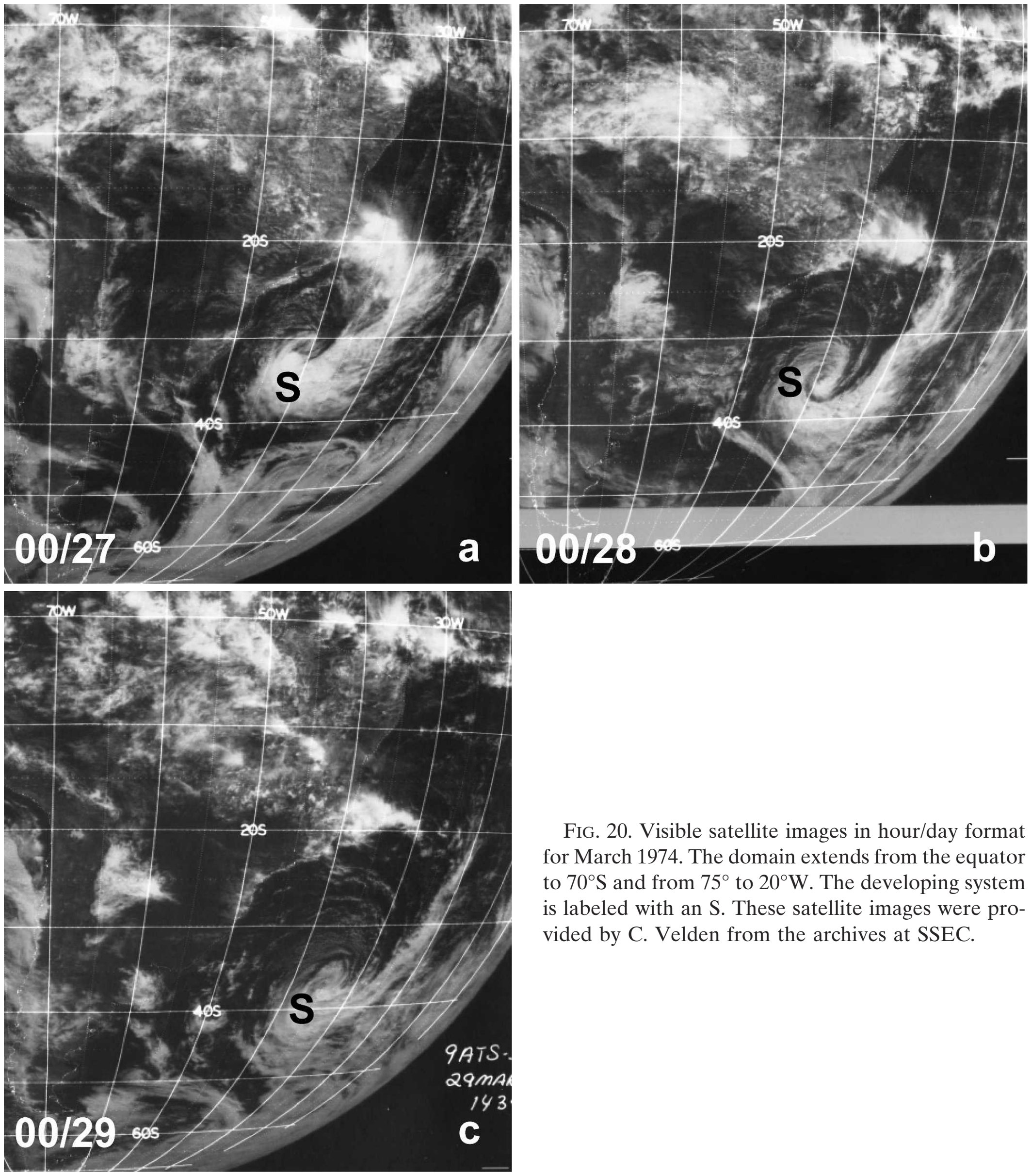

FIG. 20. Visible satellite images in hour/day format for March 1974. The domain extends from the equator to 70°S and from 75° to 20°W. The developing system is labeled with an S. These satellite images were provided by C. Velden from the archives at SSEC.

e. January 1992

The mean and anomalous 500-hPa heights between 5 and 15 January 1992 are shown in Fig. 19e. A strong dipole blocking structure is observed in both the mean heights and the anomaly patterns. Just prior to the onset of the block, an area of low pressure moves off the Brazilian coast and intensifies between 5 and 10 January (Fig. 22) under the trough component of a dipole block and in the entrance region of a split jet that is unusually far north for the austral summer (Koch 2004). Because of this jet interaction, the system remains progressive through its life cycle and moves directly into the midlatitudes. Although lower-level ridging dominates for the remainder of the blocking period, another system moves off the Brazilian coast on 14 January, only to be swept eastward by the block-ending trough passage early on 16 January. The lack of a consistently strong dipole block in this January 1992 case results in a pair of weak, progressive features despite dominant lower-level ridging.

f. January–February 1992

The second long-lived dipole-blocking event of 1992 occurred between 22 January and 5 February. Mean and anomalous 500-hPa fields for this period are shown in Fig. 19f. The dominant feature in this case is the

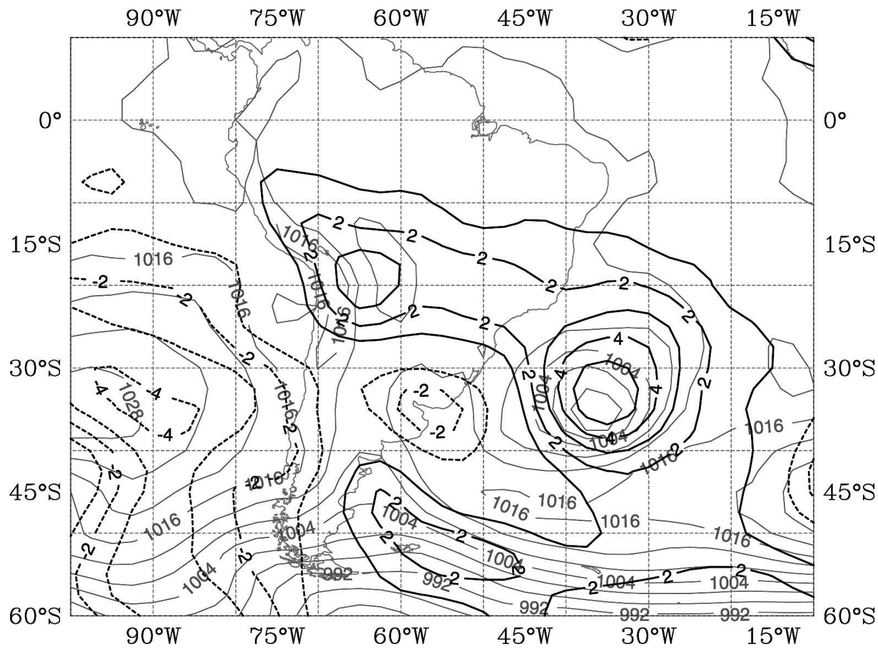

FIG. 21. Troposphere deep (surface–DT) thermal anomaly from the latitudinal mean (dark lines at 1-K intervals with negative values dashed and the 0-K contour not plotted) and MSLP field (light solid line at 4-hPa intervals) at 0000 UTC 29 Mar 1974.

strong ridging east of Argentina. A near-cutoff low is present in the mean field over southeastern Brazil. The persistent equivalent barotropic structure of the Brazilian cutoff leads to a stationary lower-level center (not shown). Although this system evolves in a low shear environment, it remains over land for its entire life cycle and does not intensify.

5. Summary and discussion

Hurricane Catarina (2004) has the distinction of being the first documented hurricane in the South Atlantic. Although other systems have been observed to undergo brief periods of tropical development (western South Atlantic in January 2004, eastern South Atlantic

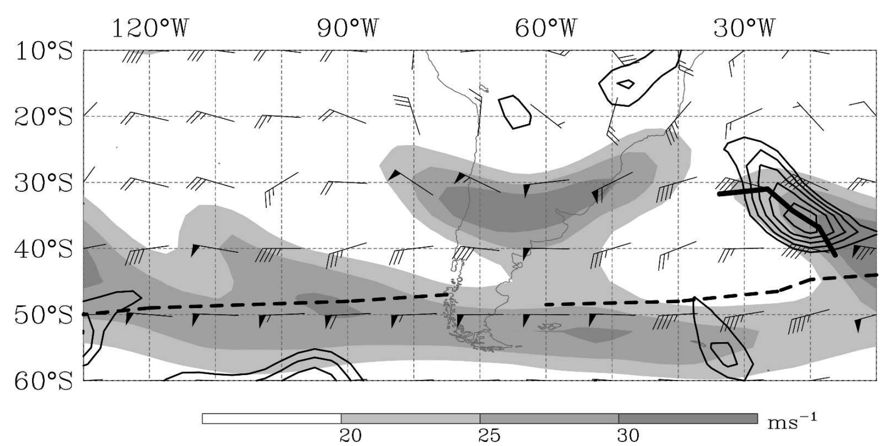

FIG. 22. Mean winds on the DT for the blocking period 5–15 Jan 1992 (black barbs with short, long, and flag pennants indicating 2.5, 5, and 25 m s^{-1} of wind, respectively, shading for wind speed emphasis as indicated by the grayscale bar) and cyclonic relative vorticity of the mean 925–850-hPa flow at 0000 UTC 8 Jan 1992 (dark contours at 1×10^{-5} s^{-1} contours beginning at 2×10^{-5} s^{-1}). The heavy solid line shows the track of the system between 1200 UTC 6 Jan 1992 and 1200 UTC 9 Jan 1992. Heavy dashed lines indicate the mean location of the upper-level jet for December–Februrary (Koch 2004).

in April 1991), none has displayed the clear hurricane characteristics of Catarina (Figs. 1 and 4). The storm begins on 1800 UTC 19 March 2004 as a weak low pressure center off the southeastern coast of Brazil (Table 1; Fig. 3) and moves southeastward for 2 days before turning anticyclonically to track northward and then westward under the influence of anomalous easterly steering flow (Fig. 10). As the system encounters a broad region of reduced vertical shear between the streams of a split flow around a long-lived dipole block (Fig. 12) it undergoes TT under the WEC paradigm of Davis and Bosart (2004). Moving slowly over slightly warmer waters (though still anomalously cool and below 25°C), the developing tropical system begins to intensify on 25 March under continued weak shear (<10 m s^{-1}) conditions. Catarina reaches category-1 hurricane status (Simpson 1974) at 0600 UTC 26 March and continues to intensify until 0600 UTC 28 March, when the track data (Table 1) indicates surface wind speeds of 44 m s^{-1} (85 kt) based predominantly on satellite imagery (Fig. 1b). Hurricane Catarina makes landfall soon thereafter and weakens rapidly once ashore.

A dipole-blocking structure is found to play a dual role in aiding the tropical development of the system as shown in the conceptual diagram of Fig. 2. An anomalous easterly steering flow results from the low-latitude troughing and higher-latitude ridging that characterizes the dipole block (Rex 1950a). The reinforcement of the block at 0000 UTC 23 March by transient features on the DT (Fig. 8g) is shown to lead directly to the rapid backing of the steering vector over the storm center (Fig. 10). The resulting reversal of the system's track directs it into a broad area of reduced deep-layer shear (Fig. 12), the second ingredient for Catarina's TT associated with the long-lived dipole block. By the time that the large-scale ridge component of the dipole block begins to break down on 27 March (Fig. 8o), the hurricane has established an outflow channel and is able to assist with the maintenance of the block locally through diabatic ridging.

The trough component of the dipole block is found to provide an ideal environment for the TT and development of the Catarina precursor. The deep column of cold air associated with the trough raises the PI for the system well above climatological values despite anomalously cool SSTs. With stability decreased and relative humidity increased in the ascending flow approaching the trough, the environment is primed for a tropical mode of development.

To further investigate the role of long-lived dipole blocking in western South Atlantic cyclogenesis, the results of an analog study are presented. In the 1971–2001 January–March period, only six similar dipole-blocking episodes have persisted for a period of 9.5 days or more (Table 3). Of the six blocking cases identified in the analog study, two are rejected because of wavelike patterns in the mean field (sections 4b,d), two have trough anomalies that are too weak or variable to halt the progression of systems under the block (sections 4a,e), one contains an equivalent barotropic cutoff (section 4f), and one leads to the development of a system with subtropical characteristics (section 4c). The long-lived dipole block is thus shown to be an infrequent, yet potentially potent, feature in the western South Atlantic during the austral summer and early autumn.

Although the TT and intensification of Hurricane Catarina off the coast of Brazil represents an unusual event, the establishment of synoptic-scale patterns leading up to the storm's development take place over an extended period of time. Until the diabatically warmed outflow from Hurricane Catarina strengthens the ridge component of the dipole block, repeated injections of transient trough (ridge) anomalies from the central Pacific Ocean into the quasi-stationary trough (ridge) components of the block are required to maintain the weak shear region and to generate a steering flow directed toward the Brazilian coast. The forecasting for this event was complicated by the fact that SSTs east of Brazil were below climatological normals—though PI values were anomalously large—and that a hurricane had never before been recorded in the South Atlantic Ocean. However, an understanding of the development mechanisms for Hurricane Catarina and a relaxation of artificial geographical and SST-based constraints on tropical cyclone terminology should facilitate the prediction of future analogous events.

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REFERENCES

Billing, H., I. Haupt, and W. Tonn, 1983: Evolution of a hurricane-like cyclone in the Mediterranean Sea. *Beitr. Phys. Atmos.,* **56,** 508–510.

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev.,* **125,** 2662–2682.

Bosart, L. F., and G. M. Lackmann, 1995: Postlandfall tropical cyclone reintensification in a weakly baroclinic environment: A case study of Hurricane David (September 1979). *Mon. Wea. Rev.,* **123,** 3268–3291.

Charney, J., 1955: The use of the primitive equations of motion in numerical prediction. *Tellus,* **7,** 22–26.

Davis, C., and K. Emanuel, 1991: Potential vorticity diagnosis of cyclogenesis. *Mon. Wea. Rev.,* **119,** 1929–1953.

——, and L. F. Bosart, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.,* **131,** 2730–2747.

——, and ——, 2004: The TT problem. *Bull. Amer. Meteor. Soc.,* **85,** 1657–1662.

DeMaria, M., J. A. Knaff, and B. H. Connell, 2001: A tropical cyclone genesis parameter for the tropical Atlantic. *Wea. Forecasting,* **16,** 219–233.

Emanuel, K. A., 1987: An air-sea interaction model of intraseasonal oscillations in the Tropics. *J. Atmos. Sci.,* **44,** 2324–2340.

——, 2005: Genesis and maintenance of "Mediterranean hurricanes." *Adv. Geosci.,* **2,** 1–4.

——, and R. Rotunno, 1989: Polar lows as arctic hurricanes. *Tellus,* **41,** 1–17.

Ernst, J. A., and M. Matson, 1983: A Mediterranean tropical storm? *Weather,* **38,** 332–337.

Ertel, H., 1942: Ein Neuer hydrodynamischer Wirbelsatz. *Meteor. Z.,* **59,** 271–281.

Gray, W., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700.

Holland, G. J., 1983: *Tropical Cyclones in the Australian/Southwest Pacific Region.* Colorado State University, 264 pp.

——, A. H. Lynch, and L. M. Leslie, 1987: Australian east-coast cyclones. Part I: Synoptic overview and case study. *Mon. Wea. Rev.,* **115,** 3024–3036.

Jones, D. A., and I. Simmonds, 1994: A climatology of Southern Hemisphere anticyclones. *Climate Dyn.,* **10,** 333–348.

Koch, P., 2004: Novel perspectives of jet-stream climatologies and events of heavy precipitation on the alpine southside. Ph.D. thesis, Swiss Federal Institute of Technology, Zürich, Switzerland, 217 pp.

Le Marshall, J. F., and G. A. M. Kelly, 1981: A January and July climatology of the Southern Hemisphere based on daily numerical analyses 1973–1977. *Aust. Meteor. Mag.,* **29,** 115–123.

Marcelino, I. P. V. O., S. M. Saito, E. V. Marcelino, R. F. Goerl, and G. S. F. Molleri, 2004: Análise dos quesionários aplicados nas comunidades catarinenses mais atingidas pelo Ciclone Catarina. *Simpósio Brasileiro de Desastres Naturais,* Vol. 1, Florianópolis, Santa Catarina, Brasil, Universidad Federal de Santa Catarina, 719–733.

McAdie, C. J., and E. N. Rappaport, 1991: Diagnostic report of the National Hurricane Center. NOAA Tech. Rep. 4 (1), National Hurricane Center, Coral Gables, FL, 45 pp.

Morgan, M. C., and J. W. Nielsen-Gammon, 1998: Using tropopause maps to diagnose midlatitude weather systems. *Mon. Wea. Rev.,* **126,** 2555–2579.

Palmén, E. H., 1948: On the formation and structure of tropical cyclones. *Geophysica,* **3,** 26–38.

Pelly, J. L., and B. J. Hoskins, 2003: A new perspective on blocking. *J. Atmos. Sci.,* **60,** 743–755.

Pezza, A. B., and I. Simmonds, 2005: The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change. *Geophys. Res. Lett.,* **32,** L15712, doi:10.1029/2005GL023390.

Reale, O., and R. Atlas, 2001: Tropical cyclone-like vortices in the extratropics: Observational evidence and synoptic analysis. *Wea. Forecasting,* **16,** 7–34.

Renard, R. J., 1968: Forecasting the motion of tropical cyclones using numerically derived steering current and its bias. *Mon. Wea. Rev.,* **96,** 453–469.

Renwick, J. A., and M. J. Revell, 1999: Blocking over the South Pacific and Rossby wave propagation. *Mon. Wea. Rev.,* **127,** 2233–2247.

Rex, D. F., 1950a: Blocking action in the middle troposphere and its effect upon regional climate. I. An aerological study of blocking action. *Tellus,* **2,** 196–211.

——, 1950b: Blocking action in the middle troposphere and its effect upon regional climate. II. The climatology of blocking action. *Tellus,* **2,** 275–301.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate,* **15,** 1609–1625.

Schade, L. R., and K. A. Emanuel, 1999: The ocean's effect on the intensity of tropical cyclones: Results from a simple coupled atmosphere-ocean model. *J. Atmos. Sci.,* **56,** 642–651.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise,* **27,** 169–186.

Sinclair, M. R., 1994: An objective cyclone climatology for the Southern Hemisphere. *Mon. Wea. Rev.,* **122,** 2239–2256.

——, 1995: A climatology of cyclogenesis for the Southern Hemisphere. *Mon. Wea. Rev.,* **123,** 1601–1619.

——, 1996: A climatology of anticyclones and blocking for the Southern Hemisphere. *Mon. Wea. Rev.,* **124,** 245–263.

——, 1997: Objective identification of cyclones and their circulation intensity, and climatology. *Wea. Forecasting,* **12,** 595–612.

Smith, T. M., and R. W. Reynolds, 1998: A high-resolution global sea surface temperature climatology for the 1961–90 base period. *J. Climate,* **11,** 3320–3323.

Tibaldi, S., and F. Molenti, 1990: On the operational predictability of blocking. *Tellus,* **42A,** 343–365.

Trenberth, K. E., 1991: Storm tracks in the Southern Hemisphere. *J. Atmos. Sci.,* **48,** 1481–1490.

van Loon, H., 1956: Blocking action in the Southern Hemisphere. *Notos,* **5,** 171–177.

Wright, A. D. F., 1974: Blocking action in the Australian region. Australian Bureau of Meteorology Tech. Rep. 10, 29 pp. [Available from the Bureau of Meteorology, G.P.O. Box 1289K, Melbourne, Victoria 3001, Australia.]

Zehr, R. M., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, NOAA/NESDIS, 181 pp.