PICTURE OF THE MONTH

A Multiple-Vortex Tornado in Southeastern Brazil

ERNANI DE LIMA NASCIMENTO
Grupo de Modelagem Atmosférica de Santa Maria, Departamento de Física, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brazil

GERHARD HELD AND ANA MARIA GOMES
Instituto de Pesquisas Meteorológicas, Universidade Estadual Paulista “Júlio de Mesquita Filho,” Bauru, Sao Paulo, Brazil

(Manuscript received 9 October 2013, in final form 18 April 2014)

ABSTRACT

During the late afternoon hours of 24 May 2005 a severe weather outbreak occurred in the state of São Paulo, southeastern Brazil. Severe thunderstorms were observed ahead of a surface cold front, including a (Southern Hemisphere) cyclonic left-moving supercell that produced a multiple-vortex tornado in the outskirts of the town of Indaiatuba, Brazil (23.1°S, 47.2°W). A documentation of the multivortex structure of the tornado and of the cloud-base features is performed using still images from a video that recorded the event. Characteristics of the tornadic thunderstorm and the synoptic-scale environment in which it developed are examined using Doppler radar data, geostationary satellite imagery, surface and upper-air observations, and data from the National Centers for Environmental Prediction’s Climate Forecast System Reanalysis. The cloud base of the thunderstorm displayed morphological features associated with midlatitude tornadic supercells, including a low-level mesocyclone and a “clear slot”; however, the rear-flank downdraft did not obscure the view of the tornado from the western flank of the storm. The tornadic storm developed in a moist prefrontal environment with a low-level jet. Limited mesoscale observations hampered the quantitative analysis of the local thermodynamic forcing, but the available data suggest that the supercell developed under moderate conditional instability. Strong speed and directional vertical wind shear were observed, while the local boundary layer displayed very high relative humidity and low surface-based lifting condensation level.

1. Introduction

Severe weather events associated with deep moist convection such as flash floods, damaging winds, large hail, and tornadoes are reported every year in Brazil, especially south of 20°S (e.g., Silva Dias 2000, 2011). In fact, the midlatitudes and subtropics of South America, east of the Andes mountain range, have been recognized as prone for severe convective storms for quite some time (Fujita 1973; Schwarzkopf 1982; Velasco and Fritsch 1987). More recently, Brooks et al. (2003) and Brooks (2006) identified the area enclosing Paraguay, Uruguay, northeastern Argentina, and southern Brazil as one region where atmospheric conditions favorable for severe thunderstorms and tornadoes are found. Satellite-based thunderstorm climatologies also demonstrate that subtropical South America hosts some of the strongest thunderstorms in the world (Zipser et al. 2006; Cecil and Blankenship 2012).

The propensity to severe convection in that part of the world is partially explained by the frequent establishment of a northerly low-level jet (LLJ), east of the Andes, particularly during the warm season (Marengo et al. 2002; Vera et al. 2006). This circulation has a twofold impact on midlatitude South America; transporting moisture from the Amazon basin to higher latitudes (e.g., Berbery and Barros 2002), and increasing the curvature and length of low-level hodographs (Doswell 1991; Nascimento 2005). In addition, it is not uncommon for the LLJ to become dynamically associated with geopotential height falls.
induced by migratory troughs over the La Plata basin (Salio et al. 2002; Seluchi et al. 2003); these same systems can also promote steep midlevel lapse rates by large-scale accent. All of these aspects can bring together the atmospheric ingredients necessary to the development of severe thunderstorms (Doswell and Bosart 2001).

The regular occurrence of convective ingredients highlights the need for better documentation of severe convective events in South America (Nascimento and Doswell 2006). One dramatic example of a significant severe weather episode in Brazil is described in this article. In the late afternoon hours of 24 May 2005 [mid-to late-autumn in the Southern Hemisphere (SH)], a left-moving cyclonic supercell thunderstorm developed in the countryside of the state of São Paulo (SP), southeastern Brazil. This storm produced a multiple-vortex tornado in the outskirts of the town of Indaiatuba located at 23.1°S, 47.2°W (Fig. 1), which was documented by a video surveillance camera during its mature stage.

A brief analysis of the tornado structure and cloud-base morphology is performed based on selected still images extracted from the videographic documentation; other characteristics of the parent storm are discussed through radar data analysis. In addition, the synoptic-scale conditions that prevailed around the time of the tornado event are investigated from an ingredients-based perspective (Doswell et al. 1996; Moller 2001).

2. Meteorological data

Data used in this study include hourly aviation routine weather reports (METARS) from six airports located in SP: Presidente Prudente (SBDN; 22.12°S, 51.38°W, elevation: 435 m), São José do Rio Preto (SBSR; 20.80°S, 49.40°W, 543 m), Bauru (SBBU; 22.32°S, 49.07°W, 590 m), Ribeirão Preto (SBRP; 21.12°S, 47.77°W, 549 m), São Paulo–Campinas de Marte (SBMT; 23.52°S, 46.63°W, 722 m), and Campinas (SBKP; 23.01°S, 47.13°W, 661 m), the last one being the METAR station closest to Indaiatuba (Fig. 1b). Soundings from the SBMT upper-air site (Fig. 1b) performed operationally at 0000 UTC [2100 local standard time (LST)] and 1200 UTC (0900 LST) are also examined. METARS were obtained from the Meteorological Network of Brazil’s Military Air Force (http://www.redemet.aer.mil.br), and sounding data from the Wyoming University of the Weather Web of the University of Wyoming’s Department of Atmospheric Science (http://weather.uwyo.edu/upperair/sounding.html).

Also included in the analysis are enhanced infrared imagery from the Geostationary Operational Environmental Satellite-12 (GOES-12), and composite reflectivity and Doppler velocities from the weather radar operated by the Meteorological Research Institute (IPMet, in Portuguese) of São Paulo State University. This S-band radar, hereafter referred to through its acronym BRU, is located 624 m above sea level at 22.36°S, 49.03°W in the town of Bauru, 200 km northwest of Indaiatuba. In its operational configuration in 2005 it completed a full set of plan position indicators (PPIs) at 11 elevations every 7.5 min when in volume scan mode. The beamwidth is 2°, and the range resolution is 1 km. Postprocessing of the clutter-filtered radar data was conducted using the storm tracking algorithm Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN; Dixon and Wiener 1993).

Data from the National Centers for Environmental Prediction’s Climate Forecast System Reanalysis (NCEP CFSR; Saha et al. 2010) were used in the synoptic analysis. NCEP CFSR data have 0.5° horizontal grid spacing and 37 vertical levels from the surface to 1 hPa and were obtained online (http://nomads.ncep.noaa.gov/data.php#CFSR-data). Figures of NCEP CFSR fields and skew T–log p diagrams were generated using the Center for Ocean–Land–Atmosphere Studies (COLA) Grid Analysis and Display System (GrADS).

3. Discussion

a. General overview and visual characteristics of the tornadic episode

The 24 May 2005 Indaiatuba tornado was spawned at approximately 1725 LST (2025 UTC) by a supercell thunderstorm that developed ahead of a surface cold front. During its life cycle the tornado followed a path approximately 15 km in length, from west-northwest to east-southeast, and with maximum width reaching 200 m, as found from an in situ assessment. This was conducted 48 h after the event by a damage survey team from the Natural Disasters Study Group of the Federal University of Santa Catarina (GEDN-UFSC, in Portuguese; Isabela P. V. Marcelino 2005, personal communication). Figure 2a depicts the tornado damage path according to the GEDN-UFSC survey team, who rated the tornado intensity as F3 in the Fujita scale.1

1 It is worth mentioning that prior to reaching Indaiatuba, the parent storm also produced damage in the southern sections of the town of Capivari located 32 km northwest from Indaiatuba, with one casualty due to a collapsing wall being reported. Locals attributed the damage inflicted to Capivari to a tornado. By the time the parent storm moved over Capivari it already displayed a cyclonic circulation, as indicated by IPMet’s BRU radar imagery (not shown). However, in the lack of further ground truth evidence regarding the nature and damage path of the phenomenon that hit Capivari, we limit our attention to the Indaiatuba tornado episode as documented by the video camera and damage surveyed by the GEDN-UFSC research team.
FIG. 1. (a) Geographical position of São Paulo state in the Brazilian map (bottom-right corner inset), and a detailed map of São Paulo state (larger panel); thick (thin) gray contours are topographic curves at 500 (100) m intervals; elevation of Indaiatuba: approximately 620 m MSL; (b) close-up view of the region enclosed by a dotted box in (a), locating Indaiatuba city (solid black circle) with respect to the city of São Paulo; the crisscrosses (×) indicate the position of the SBKP METAR site and SBMT upper-air site.
Just after crossing a highway (SP-075), the Indaiatuba tornado was captured in video by the operations control center of a concessionary company responsible for highway traffic surveillance and management (Rodovias das Colinas S.A.). Figure 2b is a recent high-resolution satellite image illustrating the area surrounding the documented video footage, including a warehouse (WH) and a white tower (WT) as reference points that appear between the camera and the tornado.

Figures 3a–d depict a selected time sequence of still frames from the tornado video (the full video can be found online at www.youtube.com/watch?v=8rcBZldOZBM, uploaded by the authors). The camera was located on the northwestern sector of the parent thunderstorm as schematically indicated in Fig. 4, and the storm motion was to the east-southeast at approximately 64 km h\(^{-1}\) (17.8 m s\(^{-1}\)), as determined by IPMet’s BRU radar.

Figure 3a shows the tornado and its parent low-level mesocyclone displaying a clockwise rotation (i.e., cyclonic rotation in the SH). In Fig. 3a the video camera faces the east (E)-northeast (NE) (cf. the relative positions of WT, WH, and highway SP-075 with Fig. 2b), and as the video operator followed the tornado motion, the camera gradually turned to the east (Fig. 3d). The Indaiatuba tornado produced subvortices embedded in the main tornadic circulation (Figs. 3b,c), which characterizes the first multiple-vortex tornado ever documented on video in Brazil. The bright light in Fig. 3c is one of the power flashes produced by the tornado as it downed power lines. Surprisingly, no casualties were reported with this significant tornado despite the lack of a tornado warning system in Brazil.

Figure 3d shows a wide-angle view of the tornado, with the “clear slot” being also discernible. While the low-level structure of this storm displayed morphological characteristics typical of midlatitude tornadic supercells (Moller 2001), it is interesting to note that the rear-flank downdraft (RFD) wrapping around the tornadic circulation (Fig. 4) did not obscure the tornado as seen from the vantage point of the camera, which is from the west (Fig. 3d). This indicates an absence of precipitation in that sector of the RFD despite being typically associated with the portion of the hook echo with higher reflectivity as illustrated by the conceptual model depicted in Fig. 4.

b. Radar data analysis

The first echo of the storm that would eventually evolve into Indaiatuba’s tornadic supercell was detected approximately 30 km southeast of BRU radar at 1737 UTC. TITAN’s identification algorithm, with a reflectivity threshold of 40 dB\(Z\) over 16 km\(^3\), detected this cell in the subsequent volume scan at 1744 UTC and tracked it until 2059 UTC (i.e., including the tornadic stage) when it reached the limit of the quantitative 240-km volume scan range. Figure 5 shows TITAN’s full tracking sequence of the 40-dB\(Z\) composite reflectivity area at 7.5-min intervals depicting the storm movement that was at an average speed of 64 km h\(^{-1}\) toward the southeast in the first half of the trajectory and then to the east-southeast after a slight deviation to the left. In this later stage the storm moved approximately 10° to the left of the prevailing 0-6-km mass-weighted mean wind vector (\(u_6 = 12.3\), \(v_6 = -9.9\) m s\(^{-1}\)) as computed from the NCEP CFSR data valid at 1800 UTC for a 2° × 2° grid-sized box centered over Indaiatuba. The cell was discrete during its entire life cycle.

After a rapid development in both intensity and size during its early stages, the storm maintained a rather steady behavior with maximum reflectivity of 55 dBZ during the first 2 h of its life cycle. However, from 1944 to 1952 UTC, at approximately 35 km west of Indaiatuba
The storm experienced a growth in the 40-dBZ area and an intensification in reflectivity, reaching 57.5 dBZ. It is not clear what caused the storm intensification in that stage, but interaction with local mesoscale boundaries is one possibility (Markowski et al. 1998a; Atkins et al. 1999). The discrete storm trailed behind previous convective activity in the form of multicells (not shown) that may have produced outflow boundaries not detected by the available low-resolution surface data and satellite imagery. In addition, the Tietê River valley, along which the storm moved during most of its life cycle (Fig. 5), may also have been a source for local circulations (Acevedo et al. 2007) that could have influenced the storm evolution. Interestingly, the storm maintained or even increased its strength while following the Tietê River valley, a similar behavior also described in Held et al. (2010) for other supercell storms that occurred in the state of SP.

The storm remained strong and displayed a cyclonic circulation in the radial velocity field (not shown) as it caused damage and one casualty in the southern suburbs of Capivari (Fig. 5). Figure 6 shows composite reflectivity (left column) and constant altitude plan position indicators (CAPPIs) of ground-relative radial velocities (right column) from volume scans completed at 2022, 2029, and 2037 UTC (i.e., just before and around the time of the tornado video). For convenience, the tornado damage path and video camera position are also indicated in the images. Figures 6a and 6c show the high reflectivity core of the storm passing south of Indaiatuba with maximum values reaching 55 dBZ, which are not particularly high values for supercells (e.g., Kumjian and Ryzhkov 2008); at 2029 UTC (Fig. 6c) the relative position of the video camera with respect to the reflectivity field is in general agreement with the conceptual model sketched in Fig. 4. It should be noticed that at this stage the cell was 200 km away from BRU and thus, the low-levels of the storm were not effectively sampled; in addition, at such a distance from the radar, the spatial resolution of the 2°-wide radar beam is low. These combined aspects may account for the lack of a clear-cut hook echo in the images; a closer look in Fig. 6c, however, shows a hint of a weak echo region just to the east of the label CAM. At 2037 UTC (Fig. 6c) the storm showed signs of weakening; a trend that would continue until the last volume scan tracked by TITAN.
The large volume of the radar pulse 200 km away from BRU and thus, the scarcity of scatterers filling it, preclude a precise analysis of the radial velocity fields. The best depiction for the midlevel circulation within the storm is provided by CAPPIs of the ground-relative radial velocities interpolated at 6.5 km (for the 2022 and 2037 UTC volume scans; Figs. 6b and 6f, respectively) and 8.0 km for the 2029 UTC volume scan (Fig. 6d). At 2022 UTC the radial velocities display a broad area of (SH) cyclonic circulation to the southwest of Indaiatuba (Fig. 6b). Inbound and outbound velocities above 11 m s$^{-1}$ are found and TITAN analysis indicates shear of 4.5 $\pm$ 10$^{-1}$ s$^{-1}$ with this structure. Similar quantitative results are obtained when individual PPIs are evaluated, especially for the lower elevation scans such as the one illustrated in Fig. 7 for the 0.8$^\circ$ elevation scan (approximately 6 km above ground level) at 2022 UTC. At 2029 UTC (Fig. 6d) the general structure of the cyclonic circulation is still discernible south of Indaiatuba, while at 2037 UTC (Fig. 6f) paucity of data hampers a meaningful inference about the velocity field.

Nearly all of the objective criteria described in Stumpf et al. (1998) for the detection of velocity couplets using Weather Surveillance Radar-1988 Doppler (WSR-88D) systems, for a storm approximately 200 km away from the radar, are satisfied for the Indaiatuba storm at 2022 UTC for the lower elevation PPIs. Although BRU radar is not a WSR-88D, this result is meaningful given that the actual cyclonic circulation, poorly resolved by BRU’s 2$^\circ$ beamwidth, was likely stronger than the one indicated in Fig. 6b. However, the assessment of Stumpf et al.’s criteria regarding the depth and longevity of the cyclonic circulation for a rigorous characterization of mesocyclones was not possible because of numerous missing data in the higher elevation PPIs at 2022 UTC and in PPIs from the precedent 2015 UTC scan and subsequent 2029 and 2037 UTC scans.

Regarding the longevity of the circulation, it should be stated that radial velocity patterns similar to that shown in Fig. 7 were found in PPIs from volume scans preceding 2015 UTC (not shown). In addition, the in situ confirmation of a strong tornado and of its parent low-level mesocyclone (Fig. 3) points to the existence of a mesocyclone aloft around the time of volume scans shown in Fig. 6 (Trapp et al. 2005). Hence, the rather diffuse cyclonic circulation pattern shown in Figs. 6b,d and 7 most likely results from a midlevel mesocyclone sampled by a low-resolution radar beam (Wood and Brown 1997). In line with a discussion conducted by Brotzge and Donner (2013) for the United States, the difficulties found in this work regarding the quantitative analysis of the radial velocity fields have important operational implications to the nowcasting of tornadic storms in regions where radar data coverage is poor.

Reflectivity cross sections along the A–B segments indicated in Fig. 6 are shown in Fig. 8. An interesting feature seen at 2022 UTC (Fig. 8a) is the downshear leaning of the high reflectivity core. At 2029 UTC (Fig. 8b) such
a structure is no longer seen along the same A–B segment and the depth of the high reflectivity core is lower since this cross section is now placed closer to the edge of the 40-dBZ polygon, which has reduced in size (Fig. 6c). Compared to supercells documented in other parts of the world (e.g., Kumjian and Ryzhkov 2008) the height of the 40-dBZ reflectivity threshold shown in Figs. 8b and 8d is rather modest, the same being found for cross sections through the central portion of the storm (not shown). It is our experience that severe storms observed in central SP during austral autumn are relatively low topped (Held et al. 2010).
c. The synoptic-scale environment

1) SATELLITE IMAGERY

To describe the synoptic-scale environment in which the tornadic thunderstorm evolved, it is useful to start with the enhanced thermal infrared images from GOES-12 satellite shown in Fig. 9, valid a few hours around the tornado event (no sectorized geostationary satellite image was found for the time of the tornado).

At 1730 UTC (Fig. 9a) deep convection was already under way ahead of an advancing surface cold front positioned in between Santa Catarina and Paraná states, south of SP, as determined by subjective analysis. A gradient in brightness temperature is discernible across SP, with southern and eastern sections displaying cloudy conditions, and even fully developed thunderstorms, while western and northern areas of the state displayed fewer clouds and patches of clear skies. Combining this information with the radar analysis described above, it appears that storm initiation occurred at the transition region between partially cloudy skies to the west and north of SP and cloudy skies to the east and south of the state.

The conditions a few hours after the demise of the tornado (Fig. 9b) showed widespread convective activity over the totality of southern and eastern SP, with new discrete cells developing to the north-northwest. By this time, the city of São Paulo was under very heavy rainfall, leading to a significant flash flood event (Vasconcelos and Cavalcanti 2010).

2) MAP ANALYSIS AND ATMOSPHERIC PROFILES

Figures 10 and 11 show atmospheric fields extracted from NCEP CFSR valid at 1800 UTC 24 May 2005 (i.e., just around the time of the thunderstorm initiation and a couple of hours before the tornado) for the entire La Plata basin (Fig. 10a, only) and for south-southeastern Brazil (Figs. 10b–e and 11a–d). Figure 10a shows 500-hPa geopotential heights and areas with negative omega velocity, and indicates that SP was located just downstream of a broad migratory SH trough. As expected, a large area of upward motion was induced east of the moving trough, where 500-hPa heights were falling. At higher levels (not shown), the westerly jet stream displayed a strong cyclonic curvature just east of the Andes around 25°S, while over the southern Brazilian coast, around 30°S, a change to anticyclonic curvature was evident on the jet, as a response to an upper-level anticyclone positioned just south of the equator over Brazil. No important feature of the jet stream structure...
was positioned over SP at that time, except for some indication of a weakly diffuent flow.

Surface variables over southeastern Brazil showed two low pressure centers in the mean sea level pressure field (Fig. 10b): one to the west and another one to the south of SP. The latter was a developing extratropical cyclone associated with the migratory upper-level trough; the former characterized a baroclinic trough the genesis of which occurred several hours before just east of the Andes mountain range before drifting eastward also in association with the upper-level forcing. This was a manifestation of the so-called northwestern Argentinean low (NAL; Seluchi et al. 2003). The combination of the displaced NAL and the developing extratropical cyclone produced a frontogenetical configuration as confirmed by the positive values of the frontogenetic function (computed following Satyamurty and Mattos 1989) within the elongated dot-shaded areas with northwest-southeast orientation shown in Fig. 10b.

Figure 10c depicts air temperature at 2 m, which displayed both a synoptic-scale gradient across the south of Brazil and extreme northern Paraguay and an important smaller-scale temperature gradient across SP with lower (higher) temperatures to the east (north and west) of the
state. This pattern is consistent with the prevailing cloud cover (Fig. 9a). The city of Indaiatuba was located within the cloudy sector with lower temperatures, while the tornadic thunderstorm initiation occurred farther to the northwest where less cloud cover contributed to warmer surface temperatures. NCEP CFSR fields show SP under northwesterly surface winds (barbs in Fig. 10c) except for the eastern section that includes Indaiatuba, where surface winds are indicated from the northeast. Albeit weak, these northeasterlies may have played some role in producing a mesoscale environment conducive to the tornadic event.

To assess how well the NCEP CFSR is representing the local surface conditions we examine Fig. 12a, which indicates plots of the METAR hourly reports conducted from 1600 to 2000 UTC (i.e., just prior to the tornadic event) at the Viracopos International Airport in the nearby city of Campinas (SPKP), approximately 20 km northeast of the tornado touchdown location (see Fig. 1b). Surface winds were continuously reported from the northeast, with cloudy skies and relatively low temperatures for midafternoon hours.

A broader view of METAR reports at 1800 UTC is provided in Fig. 12b, with temperature and dewpoint temperature being compared to the respective NCEP CFSR values. A temperature gradient was evident toward the north and west portions of the state. Dewpoint temperatures were more variable, but with some indication of moister conditions to the west. With the exception of station SBRP, METAR sites from the north and west reported winds from the northwest or northwest (SBBU), while to the east SBKP and SBMT reported northeasterly winds. Thus, qualitatively speaking, there is a good agreement between NCEP CFSR surface fields at 1800 UTC (Fig. 10c) and the actual local observations. A more quantitative examination, however, indicates important differences in terms of temperature and moisture. For most sites, especially those in central and western SP, NCEP CFSR underestimated both temperature and dewpoint by as much as 5°C. In eastern SP the differences are less but still with potential implications regarding the assessment of the prevailing thermodynamic conditions just preceding the tornado.

Moisture availability in a deeper layer is inspected by examining the NCEP CFSR average dewpoint temperature in the lowest 30 hPa and the 1000–800 hPa vertically integrated moisture convergence (MCONV; Fig. 10d). Most of SP, including Indaiatuba and the genesis area of the tornadic storm, was within a northwest–southeast-oriented sector with average dewpoints above 16°C, characterizing a moist environment. In fact, given that NCEP CFSR underestimated surface dewpoints, it is likely that the 30-hPa-averaged dewpoints shown in Fig. 10d are also underestimated. The MCONV field in Fig. 10d highlights the linearly oriented convergent patterns to the south and west of SP associated with the ongoing frontogenesis; in contrast, over central SP the MCONV field was more diffuse, indicating less linearly organized forcing for convective initiation, which may have been a factor supporting a more discrete mode of convection. This further contributes to the evidence that the Indaiatuba tornadic storm developed as a part of a prefrontal convective activity.

Given that the east-central portion of SP was under a thick layer of cloud around 1800 UTC, the impact of cloud shading upon the magnitude of the conditional instability for a surface air parcel should also be clear. The shaded field in Fig. 10e is the surface-based CAPE valid at that time. Values above 1000 J kg⁻¹ are indicated to the north and south of Indaiatuba, while a narrow stretch of low CAPE is discernible in east-central SP. Midlevel lapse rates, also depicted in Fig. 10e, display no high values over SP, becoming significant only over extreme southern Brazil.

To perform an evaluation of the NCEP CFSR’s conditional instability fields valid at 1800 UTC 24 May 2005

---

Fig. 10. Meteorological fields from NCEP CFSR valid at 1800 UTC 24 May 2005 over (a) the La Plata basin and over (b)–(e) south-southeastern Brazil. (a) 500-hPa: geopotential heights (thick solid contours, in dam), upward vertical motion (gray shading, in Pa s⁻¹), and winds (barbs, in m s⁻¹); (b) mean sea level pressure (thick solid contours, in hPa), and the surface frontogenetic function, only where is equal to or greater than 4 × 10⁻⁸ K (m s⁻¹) (densely dotted shading); (c) winds at 10 m (barbs, in m s⁻¹) and air temperature at 2 m (gray shading, in °C); (d) mean dewpoint temperature in the first 30 hPa, only where is equal to or greater than 16°C (thick solid contours, in °C) and moisture divergence (only where is negative) integrated over the 1000-800-hPa layer (gray shading, in 10⁻³ m s⁻¹ kg kg⁻¹); and (e) surface-based CAPE (gray shading, in J kg⁻¹) and lapse rates for the 700–500-hPa layer, only where is equal to or greater than 6.5°C km⁻¹ (thick solid contours, in (−1 × 10⁻³)°C km⁻¹). In all figures the state of São Paulo is outlined by a thick dotted contour and the location of Indaiatuba is depicted by a solid black circle. The box in (a) shows the close-up area for (b)–(e).
FIG. 11. As in Figs. 10b–e, but for (a) 850-hPa: geopotential heights (thick solid contours at every 1 dam, and labeled at every 6 dam), winds (barbs, in m s$^{-1}$), and wind speed (gray shading, in m s$^{-1}$); (b) 0–6-km (bulk) vertical wind shear, only where is equal to or greater than 20 m s$^{-1}$ (thick solid contours, in m s$^{-1}$), and 0–1-km (bulk) vertical wind shear (gray shading, in m s$^{-1}$); (c) 0–3-km storm-relative helicity (gray shading, in m$^2$ s$^{-2}$), with the white dashed lines enclosing regions where the 0–1-km storm-relative helicity is less than $-200$ m$^2$ s$^{-2}$, and with barbs indicating the estimated storm motion in m s$^{-1}$; and (d) dewpoint depression at 2 m, only where is equal to or less than 3$^\circ$C (thick solid contours, for 1$^\circ$ and 3$^\circ$C) and height of the lifting condensation level (for a surface air parcel) (gray shading, in m).
we first examine the 1200 UTC 24 May 2005 and 0000 UTC 25 May 2005 soundings of São Paulo city (SBMT; Figs. 13a,b) located approximately 75 km southeast of Indaiatuba (see Fig. 1b for location) and compare them with the respective profiles from NCEP CFSR. Overall, the actual soundings (dashed lines) display a moist tropical-like troposphere devoid of deep layers of strong lapse rates. Nevertheless, an increase in the 975–700-hPa lapse rate is discernible for the 0000 UTC 25 May profile, which displays some CAPE \[309 \text{ J kg}^{-1} \times (363 \text{ J kg}^{-1}) \] for the surface (most unstable) air parcel along a rather shallow layer. It can be argued that none of these represents a true proximity sounding (Potvin et al. 2010) of the Indaiatuba tornado; and that the 0000 UTC 25 May 2005 is, at least partially, contaminated by ongoing convection over São Paulo (Fig. 9b). However, some relevant assessment of the NCEP CFSR profiles can be carried out.

The reanalysis-derived sounding valid at 1200 UTC (solid lines in Fig. 13a) shows a profile that is saturated or nearly saturated for most of the troposphere. While the temperature profile shows a good agreement with the observations above 800 hPa, the presence of cloudiness in the NCEP CFSR “sounding,” not present in the real sounding, may explain the underestimated temperature at the surface. At 0000 UTC 25 May (Fig. 13b), one particularly relevant feature is the weaker lower-tropospheric lapse rate in the NCEP CFSR profile as compared to observations. The important distinctions described above highlight some difficulties in relying solely in reanalysis data to assess the conditional instability observed around 1800 UTC, when no operational sounding was available. The finding that NCEP CFSR underestimated surface temperatures and dewpoints at 1800 UTC (Fig. 12b) also raises questions about the interpretation of the surface-based CAPE values (Fig. 10e).
However, as illustrated for other reanalyses (e.g., Allen and Karoly 2014; Gensini et al. 2014), surface modified profiles from the NCEP CFSR can provide valuable information where observations are limited. To illustrate that we analyze NCEP CFSR profiles valid at 1800 UTC 24 May 2005 for the six METAR sites depicted in Fig. 12b and compare the adiabatic ascent of a surface air parcel using NCEP CFSR data (labeled 1) and the METAR reports (labeled 2). The results are indicated in Fig. 14. Since the real profiles are unknown it is not possible to perform a complete quantitative evaluation of NCEP CFSR, but in all six locations the METAR-based surface air parcel is more unstable than the NCEP CFSR counterpart. This is particularly true for SBDN site (Fig. 14a) in far west SP (Fig. 12b) where the 5°C difference in both temperature and dewpoint was found. Perhaps more importantly is Fig. 14c for the SBBU site in the central part of SP within the stretch of low CAPE values shown in Fig. 10e. This site is close to the storm initiation point around 1744 UTC (Fig. 12b). Figure 14c displays a potentially significant destabilization of the surface air parcel when observations are used. For the eastern section of the state (SBKP and SBMT) where lower temperatures were observed, the distinctions are less but still present and always suggesting a CAPE underestimation (Figs. 14e,f).

Given the points above, the highly detailed CAPE features shown in Fig. 10e may not be realistic. Based on the mismatch with the surface observations, it is reasonable to state that at least moderate instability was in place in the sector where NCEP CFSR shows low CAPE values in between SBBU and SBKP (see Fig. 12b). It should also be mentioned that tornadic environments in some parts of the world and times of the year do not display extreme values of instability, but rather strong low-level wind shear (Hanstrum et al. 2002). In this context, we shall now turn our attention to the analysis of the kinematic fields.

Figure 11a illustrates 850-hPa geopotential height and wind fields. The developing extratropical cyclone over the southern coast of Brazil is evident, with strong northwesterly and northerly flow over the warm sector.
to the north and east of the cyclone. This wind pattern was entirely within the region of high moisture content (Fig. 10d), highlighting the relevant role played by the lower-tropospheric flow in transporting moisture poleward. The 850-hPa winds on the western part of the domain were particularly strong reaching more than 24 m s$^{-1}$, with a LLJ structure (Vera et al. 2006). The LLJ over southern Brazil was a response to height falls (as strong as $-40$ gpm just off the Brazilian coast from 1200 to 1800 UTC) induced by the approaching migratory system seen in Fig. 10a. Comparatively speaking, over SP the 850-hPa northwesterly flow was not as strong at this time (Fig. 11a), despite some indication of a local wind speed maximum over central SP.

The magnitude of the bulk vertical wind shear is shown in Fig. 11b for both 0–6-km (contours) and 0–1-km (shaded areas) layers. It is interesting that, while most of southern Brazil displayed strong deep-layer bulk shear (DLS), above 20 m s$^{-1}$, over SP the DLS field displayed a horizontal gradient, becoming stronger on the eastern half of the state. A similar pattern is discernible in the low-level bulk shear field (LLS), reaching values above 16 m s$^{-1}$ only over east central SP, including the Indaiatuba region. Under a moderately strong 850-hPa northwesterly flow, the higher elevation of the eastern half of the state may have had an influence in the increase in LLS from western SP to east-central SP.

Given the combination of strong DLS and LLS associated with a northwesterly flow aloft (see also Fig. 10a) and the northeasterly surface winds in that same area (Figs. 10c and 12b), strong speed and directional vertical shear appeared to be in place over east-central SP. To analyze this, 0–3- and 0–1-km storm-relative helicity (SRH) are the ones relevant for evaluating severe storm potential associated with left-moving cells. The ESM field was determined using the Davies and Johns (1993) algorithm (adapted to the SH), which could be regarded as inappropriate for South American supercell storms. Nevertheless, a comparison of the ESM over east-central SP ($u = 12.8; v = -4.3$ m s$^{-1}$) with the radar-determined storm motion discussed earlier ($u = 15.9; v = -8.1$ m s$^{-1}$), shows, perhaps surprisingly, a fairly good agreement between them. In fact, if one employs the observed storm motion for the computation of SRH the change will be less than 10% (magnitude) decrease in SRH3, from $-321$ to $-293$ m$^2$ s$^{-2}$, and a 6% (magnitude) increase in SRH1, from $-202$ to $-214$ m$^2$ s$^{-2}$, for the grid point closest to Indaiatuba.

The qualitative agreement between NCEP CFSR wind profiles and observations at SBMT at 1200 UTC 24 May and 0000 UTC 25 May, especially at low levels, provides confidence that the substantially negative values of SRH3 and SRH1 shown over Indaiatuba in

The wind profile for the SBMT upper air site is depicted in Fig. 15 by environmental hodographs from the surface to the mid- to the upper troposphere. First, Fig. 15a superimposes two observed hodographs; the thin (thick) line refers to the 1200 UTC 24 May (0000 UTC 25 May) sounding. As expected, both show a counterclockwise turning of the wind with height in the lower troposphere, indicative of warm advection at low levels (SH). Some striking features when comparing the two hodographs are the remarkable strengthening of the northwesterly flow around 2900 m AGL leading to a much longer and more curved hodograph, and the hodograph lengthening in the first 950 m for the later sounding. Computing SRH using such profile and the observed storm motion leads to high magnitudes of both SRH3 ($-397$ m$^2$ s$^{-2}$) and SRH1 ($-347$ m$^2$ s$^{-2}$) for SRH1. The pattern shown in Fig. 15a confirms that a strong increase in LLS was observed over eastern SP from morning to evening hours on 24 May 2005.

Figures 15b and 15d compare the observed hodographs with the NCEP CFSR counterparts, while Fig. 15c depicts the 1800 UTC NCEP CFSR hodograph alone. The lower-tropospheric portion of the CFSR NCEP 1200 UTC hodograph (Fig. 15b) agreed with the observations in terms of the maximum wind speed within the 0–1-km layer, although this maximum occurred 200 m lower than in the actual hodograph. Surface winds were stronger in the reanalysis, and above 2000-m deviations from the observations became more evident. The 0000 UTC 25 May hodograph (Fig. 15d) showed that NCEP CFSR replicated the significant enhancement of the LLS as well as the curvature of the hodograph associated with the northwesterly LLJ. Despite differences in the surface winds and above 4000 m, the principal aspects associated with the lower-tropospheric wind profiles, namely, shape and length of the hodograph, were relatively well represented by NCEP CFSR.

An evident trend in increasing speed and directional LLS is discernible in the NCEP CFSR wind profiles (Figs. 15b–d), depicting an evolution that is in accordance with the establishment of a synoptic-scale LLJ (Doswell 1991). This represents one relevant aspect because, while the role played by the LLJ in conditioning environments conducive to severe thunderstorms is widely documented for North America (e.g., Johns 1993; Doswell and Bosart 2001), in Brazil this documentation is still poor (Silva Dias 2001), particularly when it comes to tornadic supercells.
FIG. 14. Skew $T$–log$p$ diagrams displaying vertical profiles of $T$ and $Td$ (thick solid lines) valid at 1800 UTC 24 May 2005 extracted from NCEP CFSR grid points nearest to each of the six METAR stations indicated in Fig. 12b. In each panel the thick dotted lines depict adiabatic ascents for two surface air parcels: using $T$ and $Td$ at 2 m from CFSR (air parcel 1), and $T$ and $Td$ from the respective METAR report (air parcel 2). METAR station identifiers are indicated on the top of each panel.
Fig. 11c are realistic. This, combined with high values of DLS and LLS, indicates a kinematic profile consistent with a significant tornadic environment (Rasmussen and Blanchard 1998; Rasmussen 2003; Thompson et al. 2003; Markowski et al. 2003).

Studies have shown that the tornadic mode in supercell environments tends to be favored in regions with strong LLS and low lifting condensation level (LCL) (or, equivalently, boundary layers with high relative humidity; Markowski et al. 2002; Thompson et al. 2003; Craven and Brooks 2004; among others). In that sense, it is interesting to note that the METAR observations at SBKP (Fig. 12a) did report near-saturated conditions continuously during several hours prior to the tornado event. Similarly, Fig. 11d shows that LCL heights were lowest over central SP and associated with a very narrow dewpoint depression of less than 1°C.

Regarding the synoptic-scale conditions that favored the development of a significant tornado, our analysis shows that intense speed and directional wind shear combined with low LCLs over the Indaiatuba region have contributed to the conditioning of the pretornadic environment.

4. Summary and final remarks

This study described a rare significant tornado over southeastern Brazil. The video documentation of the episode showed that the base-level of the parent storm displayed morphological characteristics commonly associated with midlatitude tornadic supercells. The multiple-vortex structure of the tornado is also evident in the images, which adds scientific value to the video given the scarce visual documentation of significant tornadoes in South America. An interesting feature present in the video is the absence of precipitation within the RFD wrapping around the tornadic circulation on the western flank (i.e., rear) of the low-level mesocyclone. Given the absence of finescale observations sampling the environment near and within the storm (e.g., Kosiba et al. 2013), the cause(s) for the precipitation-free RFD and its (their) possible relation to the genesis and strength of the Indaiatuba tornado are unclear. It is worth mentioning, though, that the study by Wakimoto and Cai (2000), comparing observed storm-scale structures between a nontornadic supercell and a tornado-producing counterpart in the United States, found “more extensive precipitation echoes behind the rear-flank gust front” in the
nontornadic storm. Future studies on the Indaiatuba tornadic cell should include a realistically configured high-resolution numerical simulation of the parent storm and surrounding environment, which may provide important insight regarding the mechanisms that led to tornadogenesis.

Weather radar analysis confirmed that the parent storm was a left-moving cell. Reflectivity values were not particularly high and the storm was rather low topped as compared to “classic” supercells documented in other parts of the world (e.g., Kumjian and Ryzhkov 2008). Interestingly, the study by Held et al. (2010) reports further examples of supercells with relatively low tops over SP during the cold seasons (austral autumn and winter). Despite the strong tornado confirmed on the ground, no evident hook echo was observed; its detection may have been hampered by a combination of the long distance between the storm and the radar and the 2° width of the radar beam. Nevertheless, some indication of a weak echo region on the northwestern flank of the storm was found in the reflectivity field. As the storm approached Indaiatuba, its midlevel cyclonic circulation was also detected, although a typical mesocyclone detection algorithm (Stumpf et al. 1998) would most likely not have flagged the structure as a mesocyclone, given the poorly resolved radial velocity field. As for operational implications (Brotzge and Donner 2013), forecasters working in tornado-prone areas around the world, some of them not densely covered by radars, must be reminded that features such as mesocyclones and hook echoes may be difficult to detect when tornadic storms are distant from the radar and/or when the radar beamwidth is greater than 1°. Thus, knowing the configuration of the specific radar system is important.
Assessment of the synoptic-scale atmospheric conditions prevailing around the time of the event found that the tornadic thunderstorm developed under moderately strong synoptic forcing, in a moist prefrontal environment and under a developing synoptic-scale LLJ. Evaluation of the thermodynamic forcing based on the combination of NCEP CFSR data and observations suggests that the severe thunderstorm initiation occurred in warm and moist conditions in central SP under moderate conditional instability. This quantitative analysis, however, was limited by the lack of observations on the mesoscale.

Farther downstream, over central-eastern SP, where the tornado was observed, surface temperatures were lower but the combination of a northwesterly LLJ and northeasterly surface winds promoted strong speed and directional vertical wind shear, especially at low levels. In addition, the local boundary layer displayed very high relative humidity leading to low surface-based LCL heights. These findings agree with previous studies that showed that substantial lower-tropospheric vertical wind shear and near-saturated boundary layer conditions are among the best atmospheric discriminators of tornadic environments once a severe storm is formed (Craven and Brooks 2004). It is also interesting to mention Parker (2014) who examined several soundings that sampled the near-storm conditions of tornadic and nontornadic supercells at different stages of their life cycles during the Verification of the Origins of Rotation in Tornadoes Experiment 2. For the later stages of the supercells’ development Parker (2014) described the intensification of the low-level wind shear and SRH concomitant with the drop (increase) in surface temperature (relative humidity) as the boundary layer underwent the evening transition toward nocturnal stable conditions. This trend in turn led to enhanced values of parameters indicative of severe weather potential. It is tempting to trace a parallel between this time-dependent transition in the near-storm atmospheric conditions with the very similar (but mostly space dependent) environmental transition that the Indaiatuba storm experienced when moving from central SP to the eastern portions of the state, described above. At this stage, however, the parallel traced with the work by Parker (2014) is just speculative.

In summarizing the synoptic-scale analysis, it appears that the magnitude of the kinematic parameters played a more prominent role than the instability parameters in creating conditions conducive to this tornadic supercell, similar to what is found for other regions in the world (Hanstrum et al. 2002; Grams et al. 2012). However, this investigation does not provide a complete picture of the near-storm atmospheric conditions. Possible storm interaction with low-level boundaries or convergence lines (e.g., Rasmussen et al. 2000), as well as the mesoscale and storm-scale variability of weather parameters within the inflow layer of the storm (e.g., Markowski et al. 1998b; Parker 2014) should be assessed in future studies in order to fine-tune the characterization of the processes that favored the tornado formation. Of particular interest is the fact that convective activity was observed ahead of the tornadic cell, which may have produced surface boundaries and modified the air mass effectively ingested by the severe storm; in addition, the storm followed a path that coincided quite well with a river valley, which is a topographic feature also capable of locally modifying an air mass (Acevedo et al. 2007).

Our results stress the value of the ingredients-based approach and of a judicious choice of weather parameters to characterize the South American severe weather environment (Nascimento 2005). Moreover, it is important to point out a few distinctions in the synoptic patterns conducive to severe storms and tornadoes between South and North America. The Indaiatuba tornado occurred in a prefrontal environment far northwest from the low center of an extratropical cyclone at the surface (i.e., very far from the surface warm front; Fig. 10b). This synoptic pattern, also found in other studies (Nascimento and Foss 2010), is somewhat distinct from the classic conceptual model that describes a weather pattern favorable for severe thunderstorms in North America under strong synoptic forcing (Fig. 5 of Johns 1993), where the most favorable region usually is much closer to the center of the surface cyclone and to the warm front. Additional investigations focusing on South American supercells are encouraged, ranging from the preconvective environment to their internal structure.

Acknowledgments. This study was concluded while the first author was in a postdoctoral sabbatical year at the Center for the Forecast of Severe Weather by Remote Sensing and Numerical Modeling, University of L’Aquila, Italy, funded by Brazil’s Centro Nacional de Desenvolvimento Científico e Tecnológico (National Center for Scientific and Technological Development; CNPq) under Grant 245576/2012-6. The authors are grateful to the three anonymous reviewers for their constructive comments that led to the improvement of the manuscript. The authors also wish to thank the following: the Operations Center from Rodovia das Colinas S. A. for authorizing the publication of the still frames from the tornado video, National Center for Atmospheric Research for making available the latest version of TITAN and assisting with its implementation at IPMet, Mrs. Isabela Pena Viana de Oliveira Marcelino for sharing detailed information of the tornado damage.
assessment, and Mr. Eduardo de Paula from Instituto Tecnológico SIMEPAR for preparing some of the map figures.

REFERENCES


