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# Analysis of the development and structure of a severe storm leading to the spawning of a tornado in Southeast Brazil

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*Abstract* — **During the early afternoon of 22 September 2013, severe storms, accompanied by large hail, damaging winds, heavy precipitation and dangerous lightning, devastated a region between 100 and 200 km south-southwest of the Bauru S-band Doppler radar. Several extremely intense storm cells moved at up to 100 km/h east-southeastward and at least one of them spawned a tornado when it reached the town of Taquarituba, in Southeastern Brazil. The synoptic pattern was very favorable for the development of severe weather conditions over southeastern Brazil, due to a cyclogenesis process that generated an MCS (Mesoscale Convective System), with a squall line inserted. The convective cells were tracked throughout their lifetime by IPMet´s Doppler radars. The cells intensified drastically, with towers overshooting into the stratosphere (10 dBZ ≤ 20 km) and shortly before reaching the town of Taquarituba, that particular cell displayed extremely strong radial shear just above the cloud base, which led to the formation of a deep meso-cyclone, from which the tornado spawned and touched down at around 14:30h LT. Before the tornado touch-down relatively few CG strokes were observed near the tornadic cell, but thereafter the frequency increased rapidly. The IC activity was extremely high at most times. WRF model proofed itself extremely efficient to forecast the severe thunderstorm.**

***Keywords — tornado, radar, meso-cyclone, WRF, numerical prediction model, lightning***

## I. INTRODUCTION

Various atmospheric phenomena in Brazil are responsible for disasters throughout the country. The severe events in the Brazil can vary from droughts to floods and severe thunderstorms (producing hail, strong gust fronts, heavy precipitation, high incidence of lightning and even occasional tornadoes) causing severe damages to the community [Hermann, 2001].

A tornado is defined as a funnel cloud that connects the base of a *Cumulunimbus* cloud to the terrestrial surface. The air rotating around the funnel cloud has sufficient force to cause severe damages [Dowswell, 2013]. When this kind of phenomena occurs over a water surface, it generates a waterspout. Tornadoes are associated with severe thunderstorms that develop in a very unstable environment.

Nunes et al. [2011] identified the occurrence of 205 events (about 167 tornadoes and 38 waterspouts) in all Brazil during the period of 1991 to 2010, and showed that the major concentration of this phenomenon occurs between the months of September to March. The month of March had the highest incidence of events (25), which could be associated with high instability during the summer. Held et al. [2010a, b] studied six events of the one or more super cells, utilizing the Doppler radars of IPMet, which cover the central and western region of the state of São Paulo (Figure 1). In some of these cases the occurrence of tornadoes had been reported. Most occurred in May, during the austral fall and, therefore in a period of transition from summer to winter, with increased baroclinity in southeastern Brazil. Nechet (2002) published a survey of information extracted from newspapers and magazines that reported the occurrence of tornadoes or waterspouts in Brazil since 1968. The described events of tornadoes were accompanied by damages and, in the major of the cases, also with the occurrence of the deaths. A preliminary survey (Held et al., 2006) showed, that tornadoes in the State of São Paulo are indeed rare events, but they are most likely to occur during the transition periods of the atmosphere, when it is more baroclinic and unstable.

According to information provided by the Civil Defense of Taquarituba (a small town of about 22.000 inhabitants – IBGE, Censo Populacional 2010 – in the southeast of the State of São Paulo), the tornado occurred during the afternoon of 22 September 2013, and caused a lot of damages like: homes destroyed, water, power and communication outages, more than 40 persons injured and 3 deaths. Witnesses said that a rotating cloud occurred over the town. Figure 1 shows the localization of Taquarituba, as well as the coverage of the Doppler radars. This figure also shows the location of airports in Curitiba/PR (SBTC) and Campo de Marte/SP (SBMT) and weather stations that had their data analyzed. The weather stations used were: Avaré (Av), Ibaiti (Ib), Itapeva (It) and Joaquim Távora (JT).

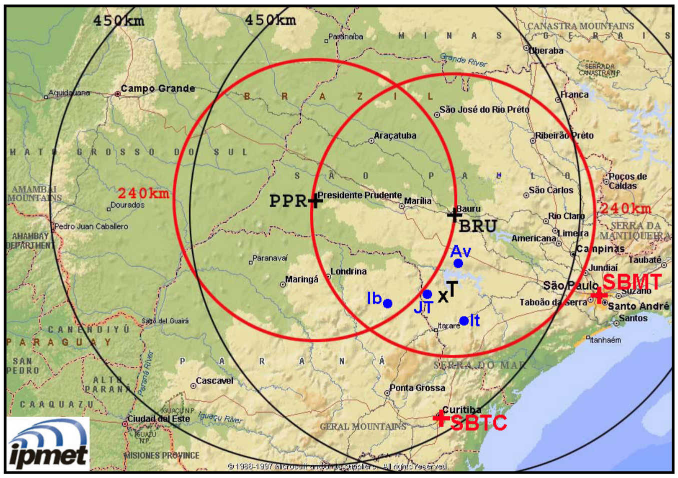



Fig. 1. IPMet's Radar Network (BRU = Bauru; PPR = Presidente Prudente), showing 240 and 450 km range rings. The town of Taquarituba is indicated with T at 135 km radar range. Also shown are the meteorological stations.

The destruction path of the tornado within the built-up area of the town extended for about 3 km from southwest to northeast, with a width of up to 1 km. The documented touch-down lasted for only 3,5 min, but no information of damage is available from outside town. Based on the damage reported, this tornado was at least an F3 according to the Fujita scale [Fujita, 1981].

The present paper aims to describe and characterize severe thunderstorms that occurred in the region of Taquarituba/SP during the early afternoon of 22 September 2013, using synoptic charts, satellite images, Doppler radar data, lightning network data, meteorological weather station data, radio soundings and simulations with the WRF (Weather Research and Forecasting) model.

## II. DATA AND METHODS

The following material was used to characterize the synoptic situation: surface and high level (250 hPa) charts of 22 September 2013 at 18h UT, as well as the medium level (500 hPa) chart of 23 September 2013 at 00h UT achieved from Centro de Previsão do Tempo e Estudos Climáticos – CPTEC / Instituto Nacional de Pesquisas Espaciais - INPE. Furthermore, data of automatic surface weather stations of INMET (Instituto Nacional de Meteorologia) were analyzed to follow the development of meteorological parameters. These are located in Avaré/SP, Ibaiti/PR, Itapeva/SP and Joaquim Távora/SP, being the closest stations to Taquarituba (Figure 1). The distances of the above weather stations from Taquarituba are 72 km, 147 km, 87 km and 85 km, respectively. Moreover, radio soundings at 12h UT of 22 September 2013 from the cities of Sao Paulo/SP and Curitiba/PR (Figure 1) were also analyzed. These soundings were chosen, because they are located forward and rearward of the meteorological system.

To improve the identification of meteorological systems GOES–13 satellite images in the infrared channel were also deployed. The sequence of images extends from 13h UT to 18h UT at hourly intervals.

IPMet's radars are located in the central and western State of São Paulo, viz. in Bauru and Presidente Prudente, which is 240 km west of it (275° azimuth; Figure 1). Both have a 2° beam width and a range of 450 km for surveillance (0,3° PPI every 15 min), covering the entire State of São Paulo, but when operated in volume-scan mode every 7,5 minutes it is limited to 240km, with a resolution of 250 m radially and 1° in azimuth, recording reflectivities and radial velocities.

The analysis was performed with Sigmet / IRIS / Analysis, the propriety software of IPMet's radars, and NCAR's (National Center for Atmospheric Research) TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) software (Dixon and Wiener, 1993), which had been implemented at IPMet and adapted for local requirements in 2005 / 2006. Besides generating composite images, PPIs (Plan Position Indicator) and CAPPIs (Constant Altitude PPI) of the reflectivity and radial velocities, TITAN also produces a variety of important parameters for a chosen reflectivity and volume threshold throughout the lifetime of storms, such as Area, Volume, Precipitation Flux, VIL (Vertically Integrated Liquid water content), Maximum Reflectivity, Hail Metrics, speed and direction of propagation, etc, per volume scan, as well as cell tracking, including splits and mergers of cells. It also has the facility to collocate flashes with the radar echoes, including a separation into positive and negative strokes. For this analysis, TITAN was running with a resolution of 500 m in the horizontal and 500 m in the vertical. A reflectivity threshold of 40 dBZ with a volume of >16 km$^3$ was chosen for tracking the cells.

The Brazilian Lightning Detection Network (BrasilDAT) has been providing total lightning data over Southeastern Brazil (the region where the network deployment had started) since December 2010. In terms of detection efficiency (DE), the BrasilDAT presented the same values inferred for RINDAT from other studies: CG flash DE of about 88% and CG stroke DE of about 55% (Naccarato et al., 2012). In this study, total lightning data from the period 13h UT to 20h UT of 22 Sep 2013 were employed.

The fully compressible and non-hydrostatic atmospheric WRF model version 3.3.1 [Skamarock et al., 2008], coded with a terrain-following hydrostatic-pressure vertical coordinates, was implemented to process the case study simulation. During the simulation period of 24 hours, the Global Forecast System (GFS) gridded analyses fields and 3h-interval forecasts with 0.5-degree horizontal grid resolution were used to initialize the model and nudge the boundaries of the coarse domain. The model setup included a coarse 30 km grid resolution and a nest

10 km grid resolution. In the vertical direction, 31 unevenly spaced full sigma levels were selected. The Purdue Lin scheme [Lin et al., 1983] was chosen to represent the WRF microphysics, and the Kain-Fritsch scheme [Kain and Fritsch 1990; 1993; Kain, 2004] was used to simulate the convective processes. From WRF variables, it was possible to estimate the Showalter and Total Totals indices.

## III. Discussion and Results

### *A. Synoptic Description*

A frontal trough was over Southern Brazil in the 250 hPa level (Figure 2a), coupled to the jetstreams (subtropical jet and north polar jet). This synoptic pattern generated high values of divergence and cyclonic vorticity at the east of the system, over the states of SP e PR. Associated with this configuration was the Bolivian high (Alta da Bolívia), that was located over the MT state. The Bolivian high produced an anticiclonic circulation over São Paulo, with high values of divergence and intense mass losses. At the chart of 500 hPA, medium level of the atmosphere (Figure 2b), a frontal trough over southern Brazil can be observed, coupled with the trough at the high levels. There was also intense baroclinity east of this trough present, demonstrating that the states of PR an SP were in an area with high temperature advection at the low levels of the atmosphere. The surface chart (Figure 2c), shows at the time of the formation of the storm over SP, a cold front crossing over the ocean, along the coast of the state of PR, with an intense cold air mass, associated with an anticyclone of 1013 hPa at the center. The chart also shows a center of low pressure, with 1006 hPa, southwest of SP state, associated with the warm advection in this region. This favored the increase of the temperature gradient.

This situation aids the formation of mesoscale convective systems, associated with a cyclogenese. The satellite images (Figure 3) show the formation of a prefrontal squall line at 13 UTC over the east of Paraná state, because of the approaching cold air mass. This system moved in a northeasterly direction and reached the southern state of Sao Paulo, where cell tops reached temperatures of up to -80°C. The system covered a distance of nearly 500 km and lasted for about 9 hours.

The environment produced by the synoptic pattern could be observed in the following weather stations´ variables: atmospheric pressure, maximum temperature, wind directions and wind gusts (Tables 1, 2, 3). At all stations a pressure drop, predominance of northward wind and rising of the temperatures, was observed. This occurred due to the formation of South American Low-level Jets (SALLJ) and the approaching Mesoscale Convective System (MCS) associated with the process of cyclogenese over Parana state. Particularly, the Avaré station, which is closest to Taquarituba (72 km), showed the same characteristic meteorological pattern, since similar conditions are expected. At Joaquim Távora weather station the MCS affected the region of the town, observing quite a variation of the wind direction (changing first to north and afterwards veering to south/southwest), with gusts of 80 km/h (20 m/s) and a temperature drop of almost 10°C, confirming the intensity of the system, as can be seen in satellite images (Figure 3). Due to the lack of a local meteorological station in Taquarituba, it was not possible to assess the tornado wind gusts.

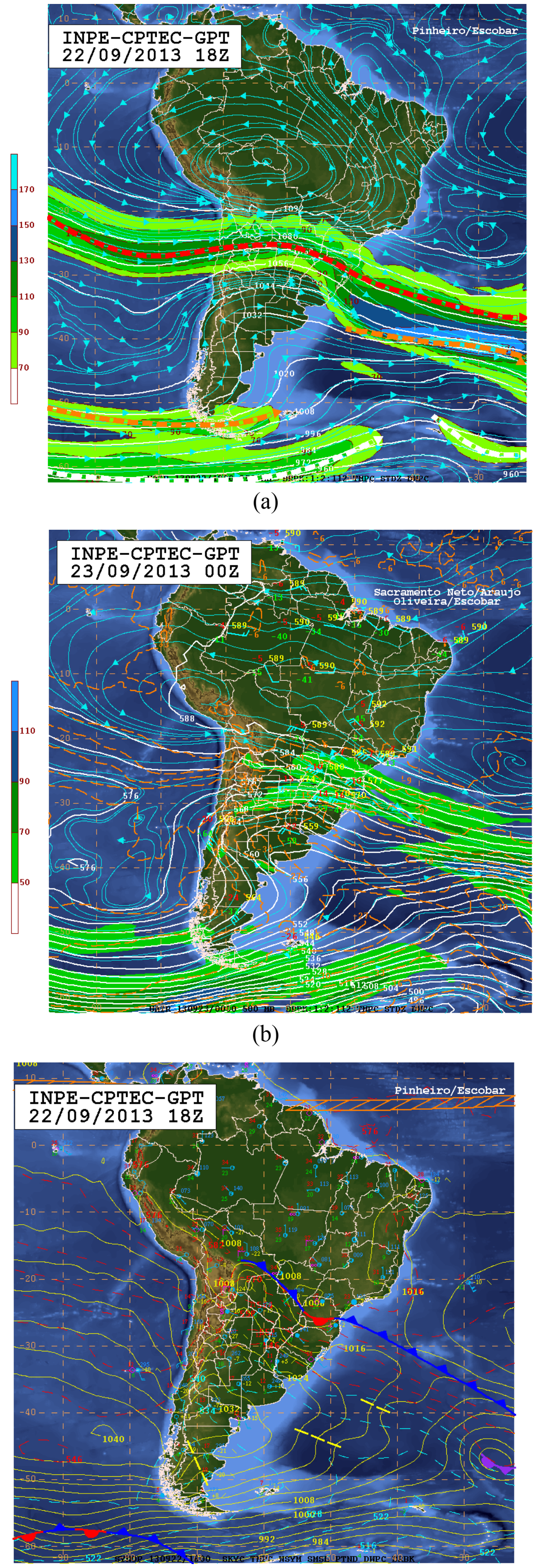



Fig. 2. Synoptic charts from CPTEC / INPE. (a) high levels (b) medium levels (500 hPa), (c) surface.

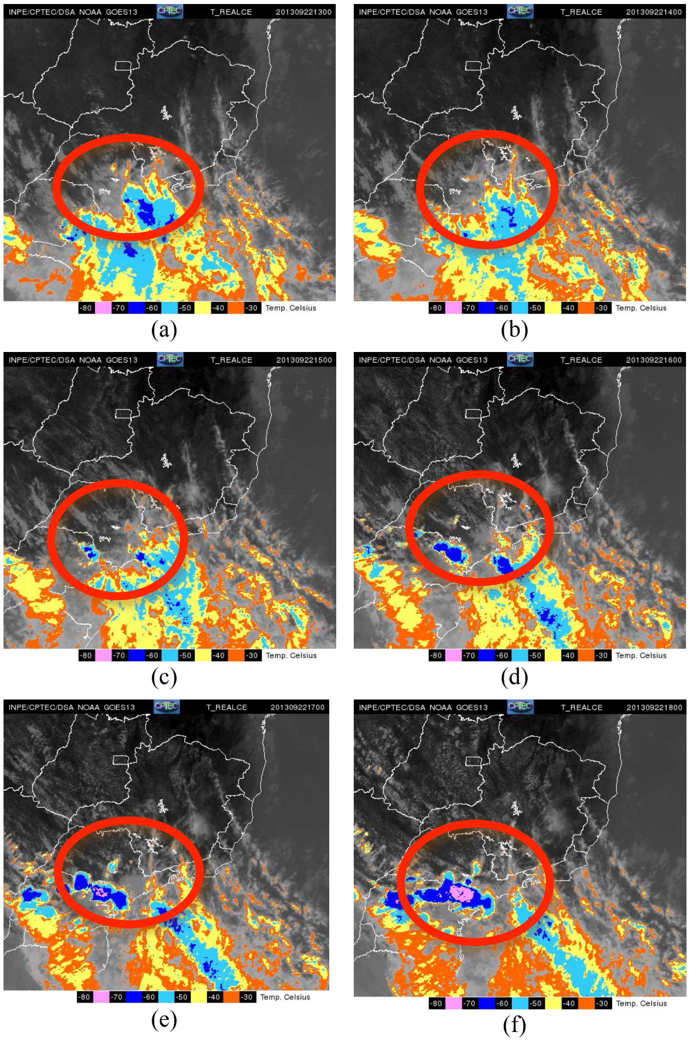




Fig. 3. GOES-13 infrared satellite images over Southeastern Brazil from CPTEC / INPE on 22 September 2013. (a) 13h UT (b) 14h UT (c) 15h UT (d) 16h UT (e) 17h UT (f) 18h UT

TABLE I. DATA FROM AVARÉ WEATHER STATION

| Time (UT) | Maximum Pressure (hPa) | Maximum Temperature (°C) | Wind Direction (°) | Wind Gust (m/s) |
|---|---|---|---|---|
| 13 | 926,4 | 23,4 | 31 | 7,3 |
| 14 | 926,3 | 25,2 | 18 | 7,6 |
| 15 | 926,2 | 26,9 | 4 | 8,9 |
| 16 | 925,5 | 28,4 | 349 | 9,0 |
| 17 | 924,5 | 30,4 | 324 | 10,7 |
| 18 | 923,0 | 30,8 | 347 | 10,5 |

TABLE II. DATA FROM IBAITI WEATHER STATION

| Time (UT) | Maximum Pressure (hPa) | Maximum Temperature (°C) | Wind Direction (°) | Wind Gust (m/s) |
|---|---|---|---|---|
| 13 | 934,2 | 21,8 | 85 | 5,9 |
| 14 | 934,2 | 25,5 | 56 | 0,0 |
| 15 | 933,7 | 26,8 | 23 | 7,9 |
| 16 | 933,4 | 25,7 | 211 | 17,1 |
| 17 | 933,4 | 20,3 | 119 | 10,9 |
| 18 | 933,9 | 20,2 | 259 | 15,9 |

TABLE III. DATA FROM JOAQUIM TÁVORA WEATHER STATION

| Time (UT) | Maximum Pression (hPa) | Maximum Temperature (°C) | Wind Direction (°) | Wind Gust (m/s) |
|---|---|---|---|---|
| 13 | 953,7 | 24,6 | 91 | 6,2 |
| 14 | 953,9 | 26,0 | 73 | 5,3 |
| 15 | 953,3 | 28,9 | 25 | 5,3 |
| 16 | 952,1 | 30,4 | 301 | 7,7 |
| 17 | 952,3 | 29,8 | 148 | 19,5 |
| 18 | 951,5 | 21,4 | 246 | 7,9 |

The atmospheric soundings in the cities São Paulo (00h UT on 22 September) and Curitiba (12h UT on 21 September) (Figure 4) show the intense advection of warm air at the low levels of the atmosphere. The temperature at the surface (780 m) was 20°C, with east wind at a speed of 5 Knots, but at the level of 1500 m it was 23°C with northwest wind at a speed of 40 Knots in Campo de Marte/SP airport. This intense wind at the low level, characterizing the South American Low-level Jet and a high value of 35 Knots of windshear. In the city of Curitiba, the wind shear was even greater, with wind speed at the level of the station (900 hPa) of 25 Knots, while at the level of 850 hPa it was 60 Knots.

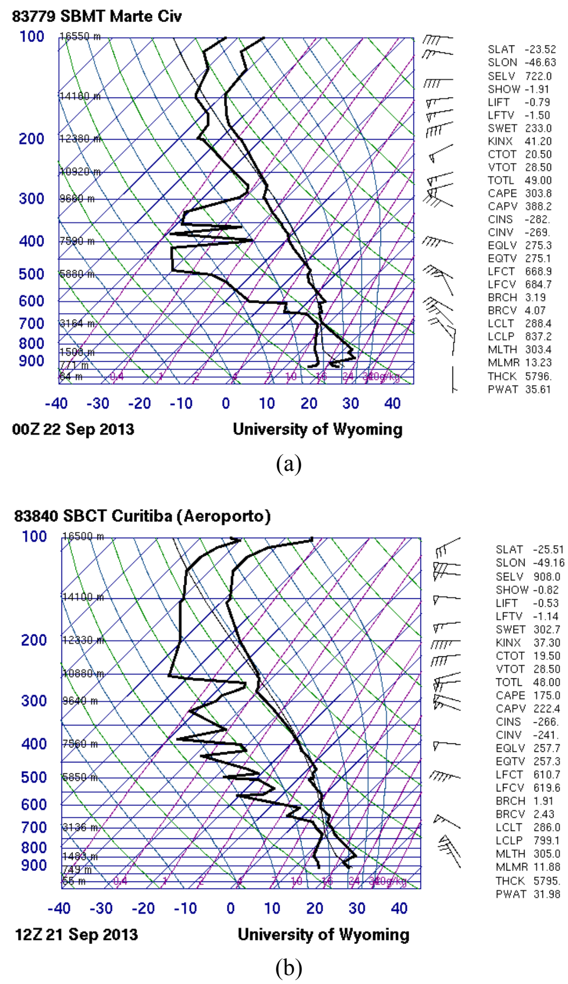




Fig. 4. Soundings at airports (a) Campo de Marte, 22 Sep 2013, 00UT and (b) Curitiba, 21 Sep 2013, 12 UT.

The soundings showed that the instability index in the region of Sao Paulo and Parana was favorable for formation of severe weather, i.e., the SW and TT index were -1.9 and 49 respectively at the sounding made at the Airport of Campo de Marte/SP. Although the times and locations of the soundings were not closer to the event, these data are fairly representative. However, the modeling provided the input data to substitute these observation data, for a WRF simulation with the data of 21 September at 18h UT.

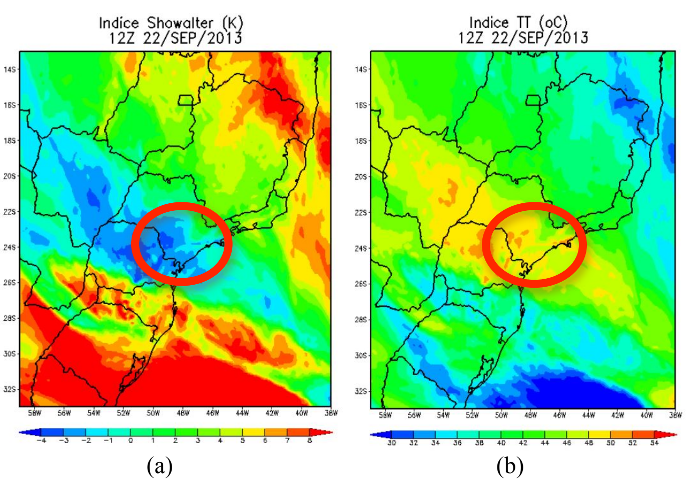
### *B. WRF Numeric Model Simulations*

According to Figure 5, the Showalter index (SW) was -3 K and Total Totals index (TT) was 48$^{o}$C at 12UT over Taquarituba city (indicated by the red circle). These values are representative of moderate instability (in the case of SW) and scattered storms (in the case of TT) [Peper, 1988]. During the occurrence of the F3 tornado (17UT to 18UT, Figures 5c to f), the WRF simulation showed an increasing instability over Taquarituba area (SW between -3 K to -4 K, and TT > 50$^{o}$ C), suggesting a higher probability of severe storm.

### *C. Radar and Lightning Observations*

The storm system, eventually spawning the tornado which hit Taquarituba during the early afternoon of 22 September 2013, developed at around 16:00UT (13:00 LT, Local Time) over northern Paraná state and was tracked by TITAN from 16:37UT onwards. The complex comprised several well-defined cells (reflectivity threshold ≥40 dBZ), which originated to the west of the Rio Jacarezinho between 16:07 and 17:22UT (indicated within the red ellipse in Figure 6), gradually merging into what was to become the "Taquarituba Cell". Some of these cells merged and later split again, as shown by the rather complex structure of the magenta arrows in Figure 6. These cells continued their life cycle until 19:30UT. However, more cells developed in the region thereafter, most of them propagating from northwest to southeast with life times of 3 to 3,5 hours, thus perpetuating the severe convective activity for several more hours.

The TITAN analysis yielded some unusually high severe storm signatures for the period 14:45-23:52UT: the majority of the cells moved at speeds of 60–100 km.h$^{-1}$ with directions varying from west – east in the south to northwest – southeast in the northeastern corner of the area shown in Figure 6.



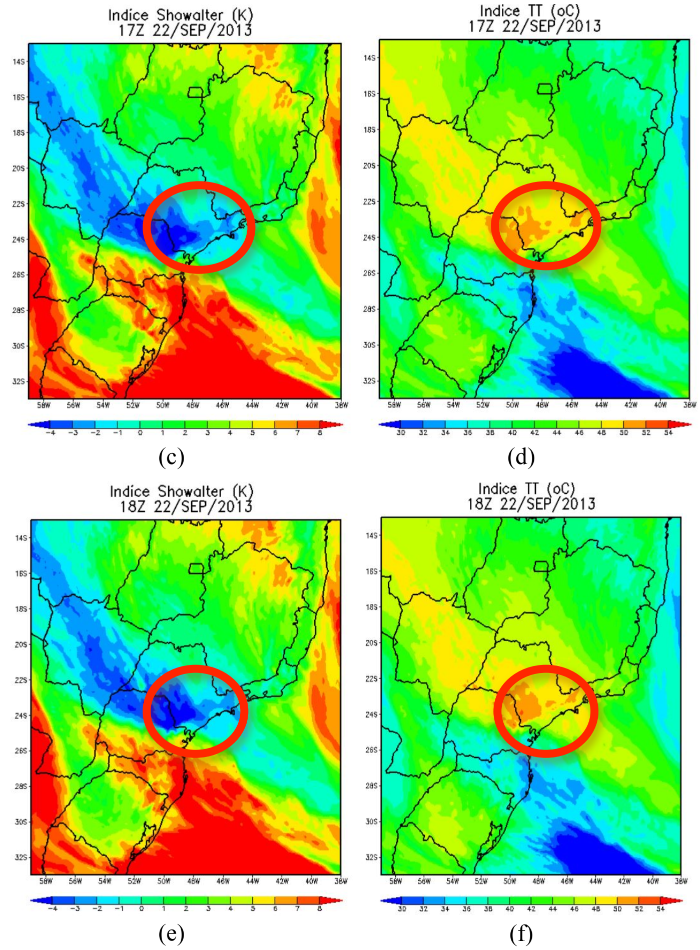




Fig. 5. WRF model outputs (22 Sep 2013) of SW index at (a) 12h UT, (c) 17h UT, (e) 18h UT, and TT index at (b) 12h UT, (d) 17h UT and (f) 18h UT.

Maximum reflectivities were generally between 45 and 60 dBZ, with the 40 dBZ contour varying between 10–14 km, except for the tornadic cell where it exceeded 16 km. The VIL (Vertical Integrated Liquid water content) reached values of 20-50 kg.m$^{-2}$ during the peak activity of the various cells.

As the storm complex traversed the Chavantes Dam of the Rio Itararé, which forms the border between Paraná and São Paulo states, its cells intensified drastically and shortly before reaching the town of Taquarituba, that particular cell displayed extremely strong radial shear just above the cloud base (about -25 to +15 m.s$^{-1}$), which led to the formation of a deep mesocyclone up to 9 km, from which the tornado spawned and touched down at around 14:30 LT. Figure 7 shows the storm complex approaching the town of Taquarituba at 17:29UT, which is about the time reported for the tornado touch-down.

Cell properties calculated by TITAN showed a drastic increase of VIL from 16:14UT (7,2 kg.m$^{-2}$) to a max of 75,2 kg.m$^{-2}$ at 17:22UT, indicative of destructive winds reaching the ground, coincident with the tornado touch-down. Thereafter the VIL dropped gradually to 13,7 kg.m$^{-2}$ at 18:00UT. Simultaneously, the accumulated hail mass aloft increased from 0 to 1120 ktons at 17:30UT, which subsequently dropped to the ground, also confirmed by the likewise decrease of VIL. The fact that the 40 dBZ radar reflectivity reached up to 16,6 km just before the time of the tornado occurrence was also outstanding, while maximum reflectivities varied between 51 and 59 dBZ during 75 min. The maximum values of these variables were all reached just before the tornado was reported (17:22UT), except for the accumulated hail mass aloft.

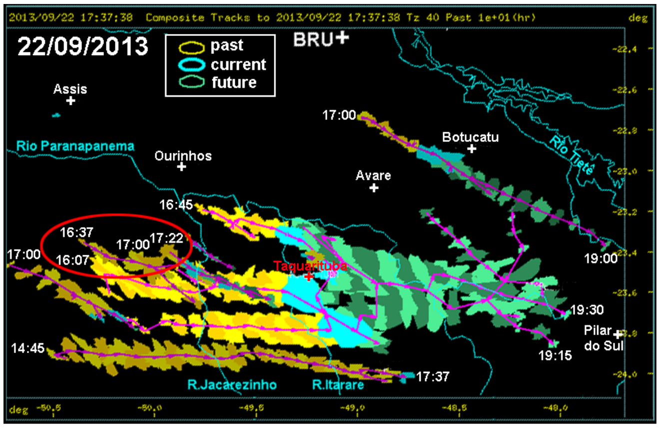
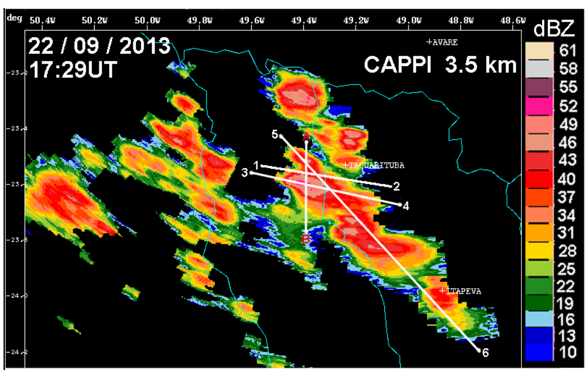
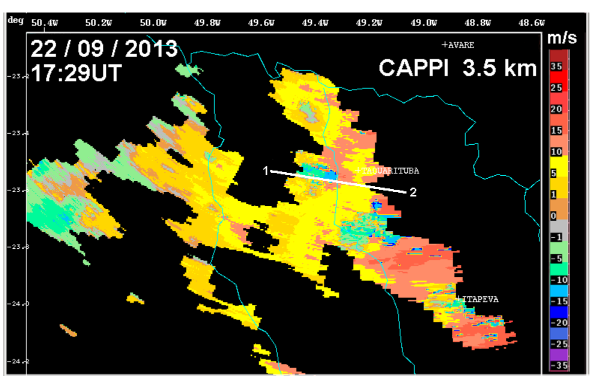



Fig. 6. TITAN tracks of the storm complex spawning a tornado over Taquarituba on 22 September 2013; reference time of 17:37UT (14:37 LT, closest to the tornado occurrence) is shown in blue. Cells (≥40 dBZ) are shown every 7,5 min before (yellow) and after (green) 17:37UT. BRU indicates the location of the Bauru radar.



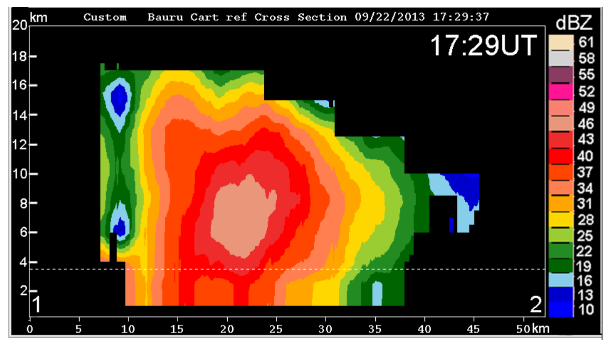

(a)



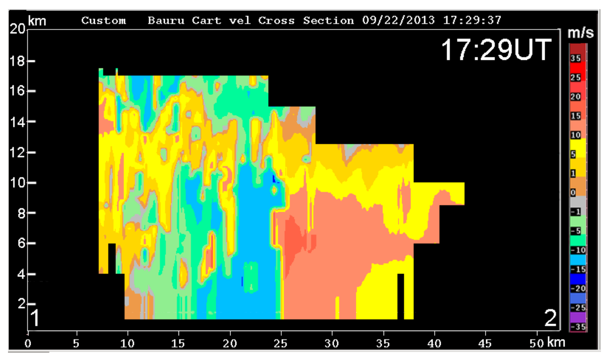

(b)

Fig. 7. CAPPI at 3.5 km amsl, 22 September 2013, 17:29UT: a) Reflectivity in dBZ; b) Radial velocities in m.s$^{-1}$, negative velocities towards and positive away from the radar. The white lines correspond to the baselines of the vertical cross-sections in Figure 8.

Figures 8a, b show vertical cross-sections along the base line 1-2 indicated in Figure 7, which cuts perpendicular through the mesocyclone, clearly indicating the strong cyclonic rotational shear (Figure 8b) of the "Southern Hemisphere cyclonic velocity couplet" reaching up to 9 km above mean sea level (amsl). It should be noted, that this feature marks the position of the updraft maximum and is characteristically located to the left of the echo core (reflectivity maximum). Cross-section 3-4 (Figure 8c) transects through the reflectivity maximum and is also orientated in direction of the cell movement, which was 74 km.h$^{-1}$ at that time, but had reached a maximum of 85 km.h$^{-1}$ at 17:00UT. Figure 8d shows a longitudinal cross-section through the three cells, starting at the hook echo in the north. A Bounded Weak Echo Region (BWER), indicated by a drop in reflectivity of 8-9 dB, can be seen reaching up to 3-4 km amsl. The horizontal white lines mark the height of the CAPPI at 3,5 km amsl (Figure 8a) and the reflectivity maximum at 6 km amsl (Figure 8c).




(a)

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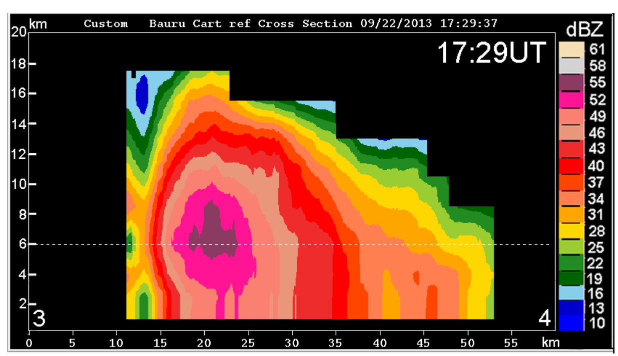


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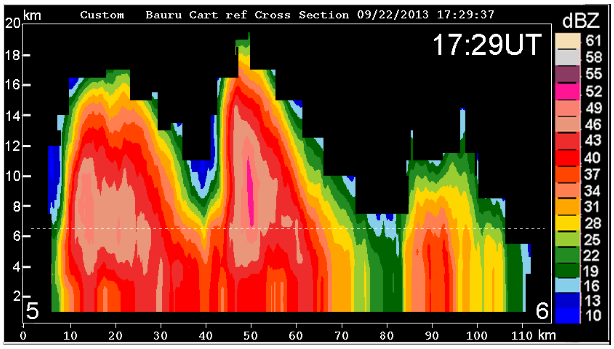
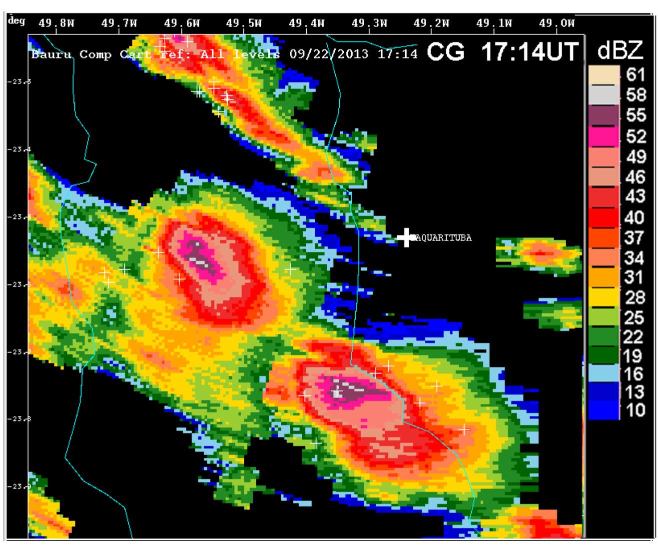


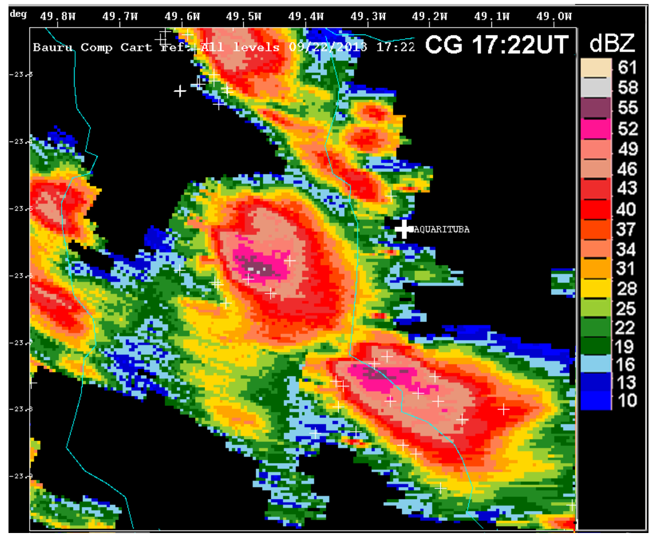

(d)

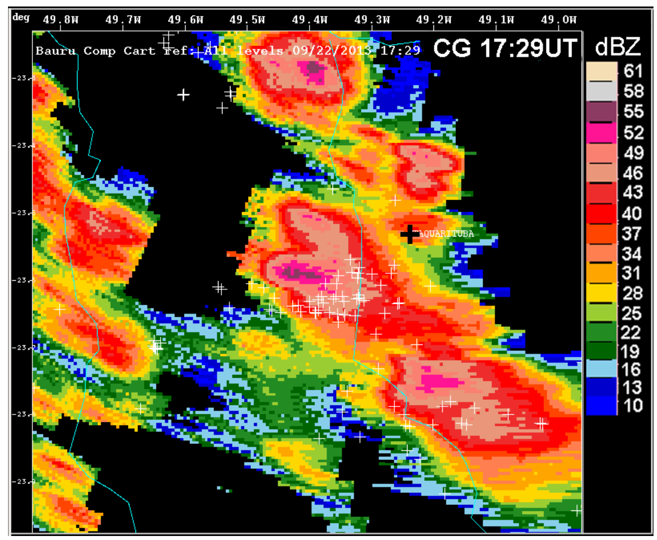
Fig. 8. Vertical cross-sections at 17:29UT along the base lines shown in Fig. 7: (a) Reflectivity along line 1-2; (b) Radial velocities along line 1-2; (c) Reflectivity along line 3-4; (d) Reflectivity along line 5-6.

The hook echo is a low-level feature and characteristic of tornadic cells. Due to the distance of the storm from the radar, it was best visible at the 1,7º PPI (Figure 7a), similar to the reflectivity field reproduced in the 6,0 km CAPPI. The vertical section through it can be seen in Figures 8a and 8c. The BWER, indicated by a drop in the reflectivity levels (8-9 dB), is even more pronounced in the latter figures.

According to BrasilDAT network, during the occurrence of F3 tornado (from 17h UT to 18h UT) it was detected 436 total lightning events (from those 391 were IC discharges) within the Taquarituba town area. Approximately 55% of all lightning events occurred between 17:30h UT and 17:40h UT. Figure 9 shows the occurrence of CG lightning and Figure 10 the occurrence of IC lightning during the period from 17:14h UT to 17:37h UT relative to the cell structure. In this figure the lightning strokes (white +) are superimposed on TITAN-generated Composite CAPPIs. The strokes shown in each CAPPI are within a 7.5 min interval ending at the time indicated in the image. Analysis of these figures revealed, that before the tornado touch-down relatively few CG strokes were observed near the tornadic cell (Figure 9, 17:14 and 17:22UT), but thereafter the frequency increased rapidly (17:29 and 17:37UT). It is also noteworthy, that the IC activity was absolutely phenomenal at most times (Figure 10).



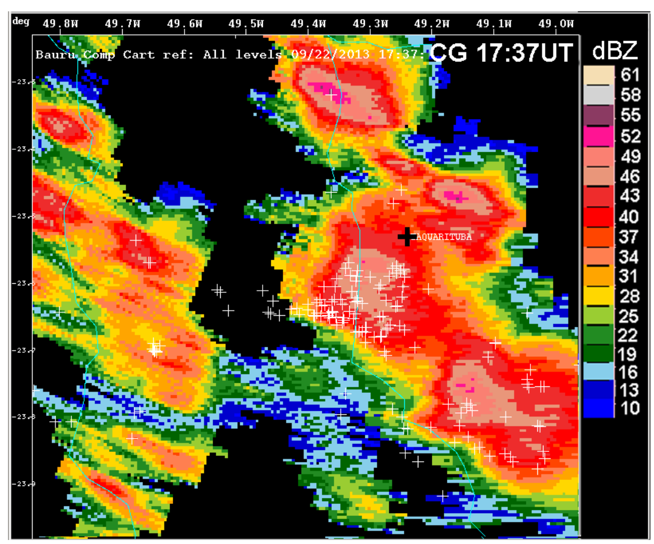
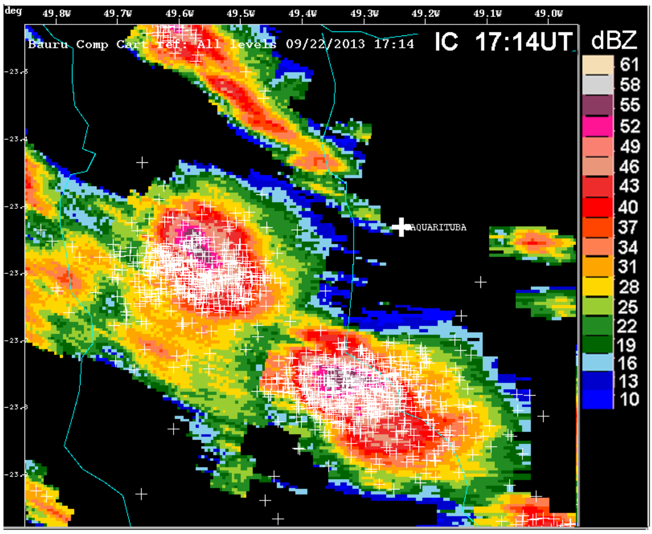
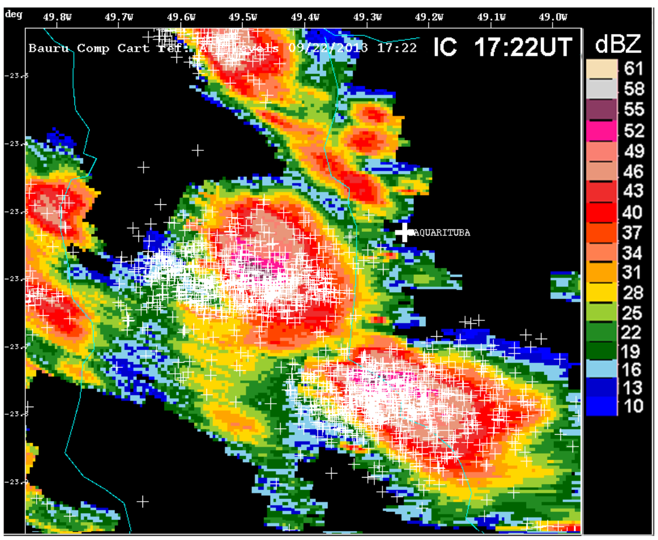
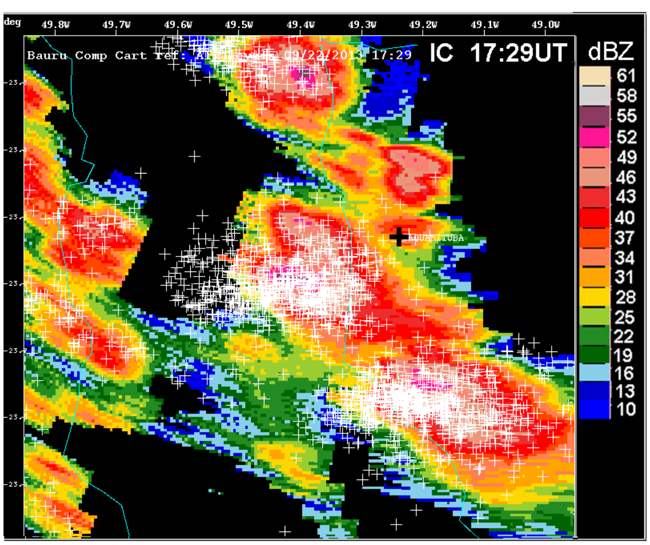




Fig. 9. Cloud-to-groung lightning strokes observed by the BrasilDAT network on 22 September 2013, 17:14-17:37UT.



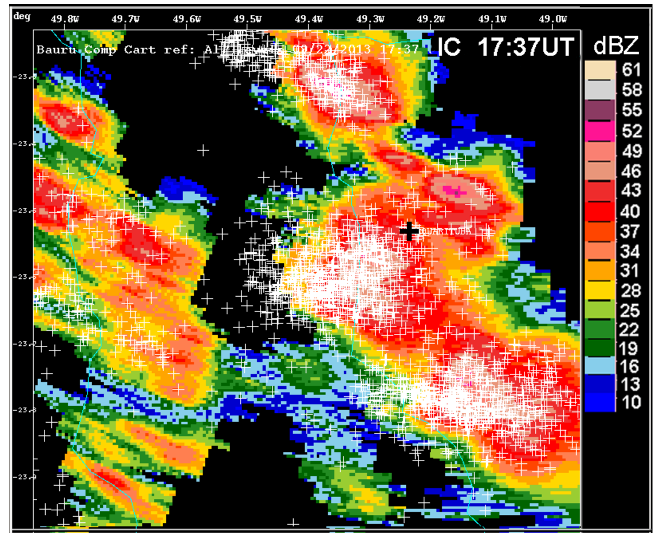




Fig. 10. Intracloud lightning discharges observed by the BrasilDAT network on 22 September 2013, 17:14-17:37UT.

## IV. Conclusions

The synoptic pattern was very favorable for the development of severe weather conditions over southeastern Brazil, due to a strong cold front approaching through Paraná and reaching the southeastern part of the State São Paulo, creating extremely unstable conditions that led to deep convection and overshooting towers of up to 20 km. This deep convection was further facilitated by a cyclogenesis process over the state of Paraná, which a caused the formation of a South American Low-Level Jet (SALLJ), with winds up to 20 m/s in the region up to 850 mb. This SALLJ contributed to the advection of humidity and high values of dew point temperatures, up to 17°C at the surface, and also supporting strong vertical wind shear. The SALLJ, associated with the intense flux divergence at the 250 mb level, produced by the interaction between the short-wave trough and the anticiclonic circulation from the Bolivian high, generated the total coupling of the synoptic variables for the explosion of the clusters of severe thunderstorms. The clusters of thunderstorms had characteristics of mesoscale convective systems (MCS). Due to the flux of the SALLJ, the thunderstorms in the MCS were organized in line, featuring a well-defined squall line. The MCS could also be observed well-define in the satellite images, with an area of *cirrus*, *Nimbostratus* and a smaller area where was the deep convection was located, with enhancement temperatures of up to -80°C.

The pre-frontal and frontal convective cells were tracked throughout their lifetime by IPMet´s Doppler radars, which cover the western and central regions of the State of São Paulo, as well as northern Paraná State. Radar volume scans, generated every 7,5 min, were processed with the TITAN software, yielding the following results: extremely strong radial shear just above the cloud base (about -25 to +15 $m.s^{-1}$), which led to the formation of a deep meso-cyclone up to 9 km, from which the tornado spawned and touched down at around 17:30h UT. Cell properties calculated by TITAN showed maximum values of VIL up to 75,2 $kg.m^{-2}$, indicative of destructive winds reaching the ground, coincident with the tornado touch-down. Simultaneously, the accumulated hail mass aloft was 1120 ktons. Also outstanding was the fact that the 40 dBZ radar reflectivity reached up to 16,6 km, with the 10 dBZ tops up to 20 km at the time of the tornado occurrence, while maximum reflectivities varied between 51 and 59 dBZ during 75 min.

Before the tornado touch-down relatively few CG strokes were observed near the tornadic cell, but thereafter the frequency increased rapidly. By the other hand, the IC activity was extremely high at all times.

Finally it was noted that the WRF model proofed itself extremely efficient to forecast the severe thunderstorm in the town of Taquarituba, based on instability index (Showalter and Total Totals) data for the period of the occurrence of the tornado. This highlights the importance of this tool for forecasting events of severe weather.

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