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THE STRUCTURE OF THREE TORNADO-GENERATING STORMS BASED ON DOPPLER RADAR AND LIGHTNING OBSERVATIONS IN THE STATE OF SÃO PAULO, BRAZIL

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1. INTRODUCTION

The three-dimensional structure of radar reflectivities and radial velocities of severe storms in the State of São Paulo, Brazil, which cause enormous damage to agriculture, urban areas, industries, as well as loss of many lives, due to strong winds, hailstones, intense lightning and flash floods, have been studied for many years (Gomes *et al*., 2000, Held *et al*., 2001; Held and Gomes, 2003). Efforts had been concentrated on identifying specific signatures during severe storm events, which could be used by the forecaster as indicators of storm severity, as well as to develop algorithms for an automated alert system.

Until recently, it was believed, that tornadoes were rather rare events in Brazil, and very few of those reported had been observed within radar range (Gomes *et al*., 2000). However, two tornadoes (F2-F3 and F2, respectively, Fujita scale) occurred during the afternoon of 25 May 2004 in the west of the State of São Paulo (Held *et al*., 2004, 2005). Their tornado-vortex signatures had been observed by the S-band Doppler radars located in Bauru and Presidente Prudente, respectively (Figure 1). Another significant tornadic storm was recorded by the Bauru radar on 24 May 2005, almost exactly one year later, in Indaiatuba, near Campinas (F3). These well-documented occurrences prompted a detailed investigation, in an attempt to find relevant signatures in radar and lightning observations, which could be used for nowcasting and an early alert system. This is vitally important for the SIHESP (Portuguese acronym for "Hydro-meteorological System of the State of São Paulo") Project, which is currently being implemented, to provide early warnings of severe storms to local authorities, Civil Defense Organizations, industry and the general public.

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The radars are located in Bauru (Lat: 22°21'28" S, Lon: 49°01'36" W, 624 m amsl) and in Presidente Prudente, 240 km west of Bauru (Lat: 22°10'30" S, Lon: 51°22'22" W, 460 m amsl). Both have a 2° beam width and a range of 450 km for surveillance, but when operated in volume-scan mode every 7.5 minutes it is limited to 240 km, with a resolution of 1 km radially and 1° in azimuth, recording reflectivities and radial velocities. The reflectivity threshold for this study was set at 10 dBZ. Both radars have Sigmet processors and run under the IRIS Operating System.

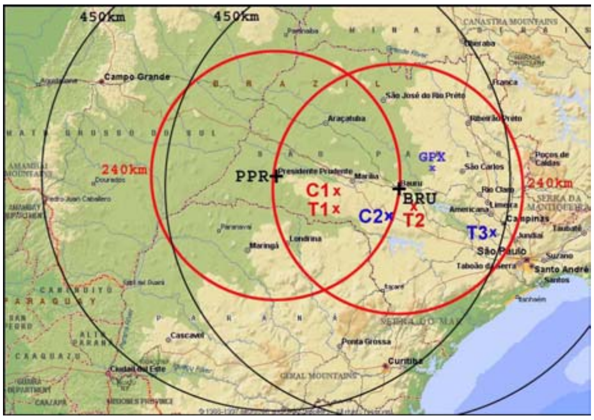

Figure 1. IPMet's Radar Network (BRU = Bauru; PPR = Presidente Prudente), showing 240 and 450 km range rings. The areas where the tornadoes occurred are marked T1 (Palmital), T2 (Lençois) and T3 (Indaiatuba). C1 and C2 are severe storm cells moving on parallel tracks of T1 and T3, respectively.

2. SYNOPTIC SITUATIONS

The synoptic situation on 25 May 2004 was dominated by an extra-tropical cyclone over the South Atlantic Ocean, off the coast of Southeast Brazil, from which a cold front extended far into the interior, sweeping across the western part of the State of São Paulo. The frontal movement was accompanied by relatively strong convective activity in the western part of the State during the morning (Figure 2), due to a strong low-level convergence, overlaid by divergence above 500 hPa, which created very unstable conditions (Held *et al.*, 2004). While traversing the farming region of Palmital, one of the storm complexes spawned a tornado (T1, Figure 1) at around 14:00 (all times in local time; LT = UT-3h), causing enormous damage to the sugar plantations and overturning a large stationary bus, filled with 53 agricultural workers, along its longitudinal axis, leaving it on its roof about 30 m from its original position (F2-F3 damage on the Fujita scale). Two passengers were killed and many others injured. The destruction path was up to 100 m wide and extended for approximately 15 km towards east-south-east. The second tornado (T2, Figure 1), which occurred at around 17:00 about 140 km east of the first one, only caused significant damage to sugar plantations along its 100 m wide and 8 km long path, but fortunately no harm was done to persons (F2 damage).

Similarily, on 24 May 2005, the synoptic situation showed a true severe weather outbreak, dominated by a cold front, which moved rapidly in a north-easterly direction from southern Paraná to the central State of São Paulo. This intensified the already strong divergence at 200 hPa over the State, and together with the embedded jet stream, created areas of extreme instability, resulting in widespread pre-frontal rainfalls over the southern parts of the State of São Paulo (Figure 10). Embedded nuclei of extremely intense precipitation were accompanied by strong winds, causing severe damage in several towns of the central interior and a major flood in the City of São Paulo (Held et al., 2005a, 2006). At least one of the cells spawned a tornado in the town of Indaiatuba (about 25 km south-west of Campinas; T3, Figure 1) with F3 intensity on the Fujita scale (estimated damage of about US $ 42 million), while another one created an exceptionally strong windstorm with cyclonic convergence in the town of Iaras, about 60 km south-south-west of the Bauru radar. This is probably the first time that a multiple-vortex tornado had been recorded on a video in the southern hemisphere, clearly showing small sub-vortices rotating around the main tornadic axis. This phenomenon is often observed with significant tornadoes generated by supercells.

3. RADAR OBSERVATIONS

Although preliminary results, emphasizing different aspects of the radar and lightning analysis, had already been published (Held *et al.*, 2005a, 2005b), the purpose of this paper is to present new and more detailed findings, after the two data sets were analyzed with TITAN (Thunderstorm Identification Tracking Analysis & Nowcasting) subsequent to its installation at IPMet at the end of 2005, in collaboration with the National Center for Atmospheric Research (NCAR) in Boulder.

For the purpose of this analysis, the primary parameters of TITAN were set to: reflectivity threshold 40 dBZ; minimum volume 16 km^3. It should be noted, that all TITAN-generated products are marked in UT (designating the *end time of a volume scan*), but the times inserted in figures are in LT. IRIS-generated products indicate LT, using the *start of a volume scan*.

3.1 *Tornadic storms on 25 May 2004*

This day was characterized by the occurrence of two tornadoes (F2-F3 and F2, respectively, on the Fujita scale) and a supercell storm, for which no tornado touch-down was observed, nor damage reported, despite the fact, that all three cells had the same rotational signatures in the radial velocity fields.

The approaching cold front could already be seen at 10:01LT in form of scattered storms in the western half of the PPR radar (Figure 2), rapidly moving eastwards at 50-60 km.h^{-1}. With the warming of the ground due to the increasing solar radiation towards noon, convection became vigorous at the leading edge, as the now well-defined line of storms approached the radar at PPR (11:00). Echo tops (10 dBZ) reached up to 10-11 km, with maximum reflectivities ≤47 dBZ. By 12:01 a large, multi-cellular storm complex had developed on the southern flank of the line in the south-east sector (Figure 2), with individual cells being embedded within a stratiform precipitation field and extending up to 11.5 km. It was exactly this complex, which later intensified at its rear and spawned at least one confirmed tornado.

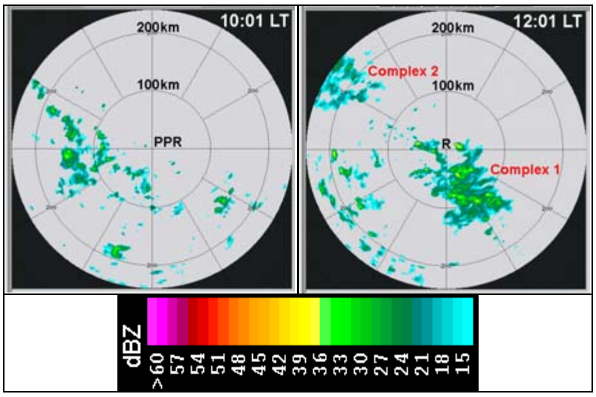

Figure 2. Presidente Prudente Radar, 25 May 2004: CAPPIs at 3.5 km above msl, range 240 km.

An overview of cell tracks (40 dBZ centroids) during the afternoon showed that the average speed of individual cells was 55 km.h^{-1} towards east-south-east (Held *et al.,* 2005a).

Detailed analysis of the rain area in the south-east sector of the PPR radar revealed, that from 12:01 onwards (Figure 2), it shifted south-eastwards at a rate of 60 – 80 km.h^{-1} until it faded out nearly 240 km down its track. It was primarily of stratiform-type (generally ≤30 dBZ or ≤5.6 mm.h^{-1}, using Marshall-Palmer Z-R relationship; not exceeding 7 - 8 km in height), with small cells embedded, occasionally reaching up to 8 – 9 km and having maximum reflectivities of ≤50 dBZ (Held *et al*., 2004).

One cell, designated C1, which had actually developed at about 10:00 some 110 km north-west of PPR, west of the Rio Paraná, intensified dramatically after 11:30 just behind the trailing edge of the stratiform complex, moving at a steady speed of 65 km.h^{-1} south-eastwards. TITAN identified the first 40 dBZ centroid at 10:37 and tracked it continuously for 8 h 38 min (Figure 3), with an overall average speed of 57 km.h^{-1}, traversing most of the State of São Paulo.

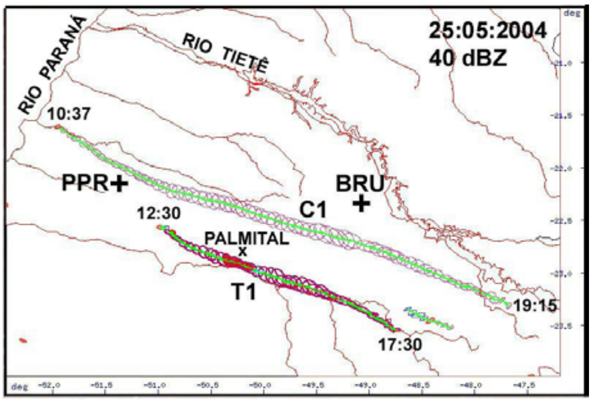

Figure 3. Tracks of 40 dBZ centroids of supercell C1 and tornadic cell T1 (Palmital) on 25 May 2004. Times of first and last detection in LT. Not all simultaneous tracks are shown. Red centroids indicate the confirmed tornado.

Although such a rapid cell displacement is unusual for the majority of storm situations in Southeast Brazil, it had been found in the past, that extremely intense cells or severe storms usually move at speeds of >50 km.h^{-1} (Gomes *et al.*, 2000). The generally high speeds with which the cells and complexes moved on this day were certainly enhanced by the rather strong west-north-westerly winds in the mid-troposphere.

Figure 4 shows a cross-section through C1 at a stage when it could already be considered a

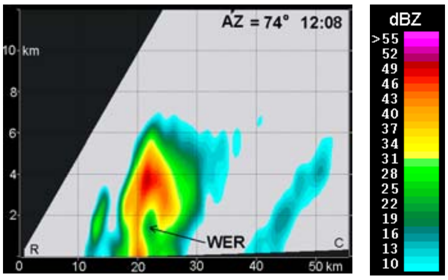

Figure 4. Radial cross-section through Cell C1, 25 May 2004, 12:08 (the base line R - C is along azimuth 74°.

supercell storm. Characteristic are the well-formed 'Weak Echo Region' (WER) on its left leading edge, as well as a forward tilt of the echo core (Chisholm and Renick, 1972), visible for ≤90 min (Held *et al.,* 2004). Although its echo top only maintained heights around 10 km, it occasionally penetrated through the 12 km level during its most mature stage, as shown in Figure 5 (bottom row). Radial velocities inside the echo core were about 35 m.s^{-1}, indicating a strong updraft and cyclonic rotational forces between 4-9 km height (Figure 6). Maximum reflectivities were >60 dBZ at times. Since it lasted for more than 8.5 hours, demonstrating above characteristics and maintaining maximum reflectivities of 50 – 60 dBZ for most of the time, it definitely can be classified as a supercell storm, despite the lack of severe weather reports associated with it.

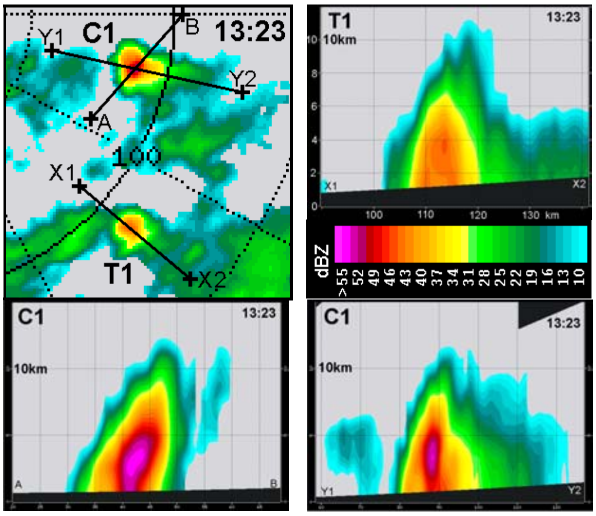

Figure 5. *Top:* CAPPI at 3.5 km and cross-section of T1. *Below:* Cross-sections of C1 along the base lines shown

At about the same time as C1 had reached the peak of its maturity, another cell, about 60 km south of it (T1 in Figure 3), commenced to turn into a vicious storm. Radar observations indicate, that at 13:23 a "hook echo", typical for supercell storms

(Chisholm and Renick, 1972; Markowski, 2002), especially when they are in the process of spawning tornadoes (Held *et al.,* 2001), had developed (Figure 5), but no significant features in its vertical structure, like in C1, were found. The storm moved in an east-south-easterly direction at about 55 km.h^{-1}. The radial velocities near ground level showed the formation of an "echo couplet" with opposing directions of rotations and speeds ranging from about –28 to +9 m.s^{-1}, inducing a local shear with a maximum of $-5.2\text{x}10^{-3}\text{s}^{-1}$ at 13:46 and 13:53 and thus resulting in tremendous rotational forces just before the touch-down of the tornado (Figure 6). The tornado lasted for about 20 min, travelling with its mother cell along a 15 km path east-south-eastwards (red centroids in Figure 3).

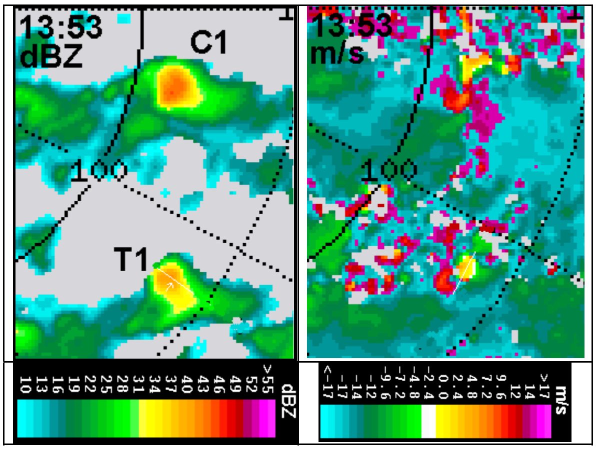

Figure 6. CAPPI at 3.5 km on 25 May 2004, 13:53. *Left:* reflectivity, showing the development of a "hook echo" (T1). *Right:* radial velocity field, showing the "velocity couplets" for C1 and T1.

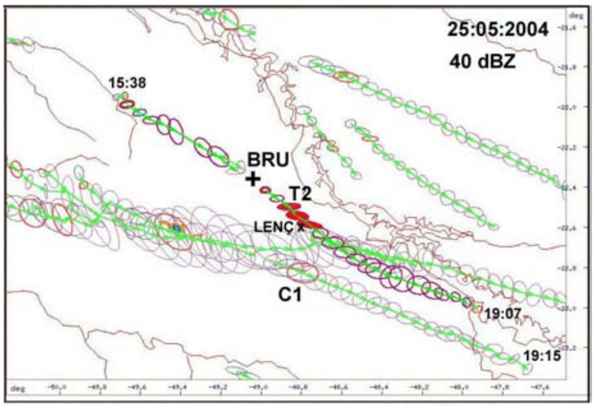

Figure 7. Tracks of 40 dBZ centroids of tornadic cell T2 (Lençois Paulista = LENÇ) and continuation of supercell C1 on 25 May 2004. Times of first and last detection in LT. Not all simultaneous tracks are shown. Red centroids indicate the confirmed tornado.

A second tornado was observed at around 17:00 near the town of Lençois Paulista (T2, Figure 1), being spawned from a storm which had initially developed at 15:00 about 105 km west-north-west of the BRU radar, moving south-east-wards across the radar at speeds of 55–65 km.h^{-1}. TITAN identified its 40 dBZ centroid at 15:38 and tracked it for 3.5 hours (Figure 7).

The storm was embedded within an unusually strong airflow from the north-west, resulting in up to three times folding of radial velocities (Nyquist velocity 16.5 m.s^{-1}). Reflectivity and radial velocity fields observed by the BRU radar indicate a strongly sheared storm environment, both horizontally and in the vertical, confirmed by vertical cross-sections, which show a Bounded Weak Echo Region (BWER) on the eastern flank of the storm between 17:00 and 17:30 (Figure 8). This would indicate a persistent strong updraft almost perpendicular to the general flow. Echo tops (10 dBZ) initially reached up to 11 - 12 km, but decreased to about 10 km during the tornadic stage, increasing again to 11.2 km from 17:23 onwards. Throughout its lifetime, the maximum reflectivity was between 55 and 60 dBZ. It is noteworthy, that the echo tops of the storms surrounding the isolated tornadic cell (e.g., south-west of it, Figure 8) reached up to 17 km. This difference in structure could be attributable to the vigorous updrafts and vertical shear during the formation of the tornado.

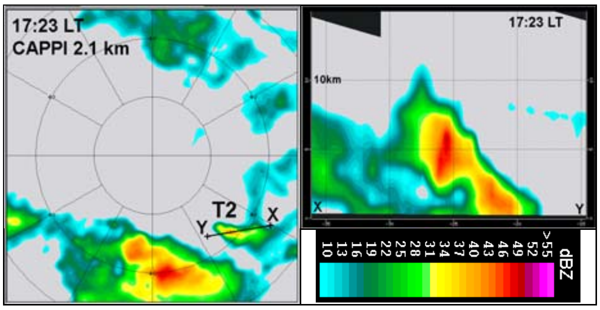

Figure 8. CAPPI on 25 May 2004, 17:23 (reflectivity at 2.1 km) and vertical cross-section showing the BWER at the rear of Tornado Cell T2.

At 17:00, its echo core (60 dBZ at ±1.7 km was situated 15 km south-east of the radar. The radial velocity field showed a maximum of +44m.s^{-1} just above the reflectivity maximum, with a clear indication of cyclonic rotation on the 11° elevation PPI, with a local shear of $-3.0\text{x}10^{-2}\text{s}^{-1}$ at around 2 km. As the storm continued along its track, the rotational signature intensified to reach a maximum of $-5.0\text{x}10^{-2}\text{s}^{-1}$ at 17:16 between 2 and 4 km and began to decrease in intensity and descend from

17:23 onwards (Figure 9). The path of the tornado was about 8 km long and 100 m wide.

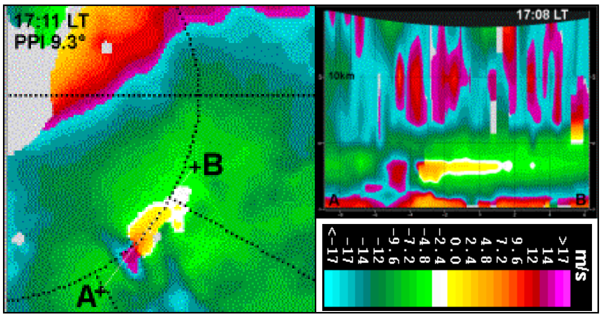

Figure 9. Radial velocity field of T2 (PPI at 9.3° elevation) and vertical cross-section along A–B at 17:08.

3.2 *Tornadic storms on 24 May 2005*

Widespread pre-frontal rain occurred during most of this day in the southern half of the State of São Paulo (Figure 10). At least one isolated cell embedded in the general precipitation, spawned a tornado (T3), killing one person in Capivari and causing great damage in Indaiatuba, while another cell with cyclonic convergence (C2) created an unusually strong and damaging windstorm in the town of Iaras. Their tracks are shown in Figure 11.

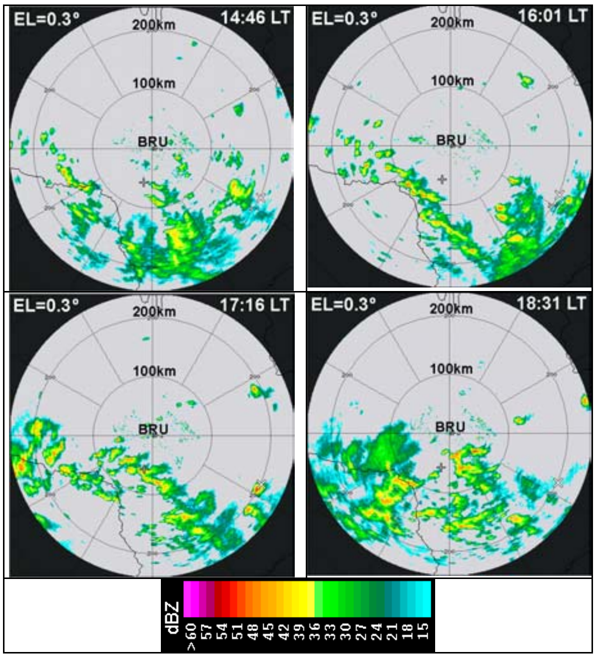

Figure 10. Bauru Radar, 24 May 2005: PPIs at 0.3° elevation, range 240 km. The symbols + and x indicate the towns Iaras and Indaiatuba, respectively.

At 14:31, an isolated cell was detected about 50 km east-south-east of the Bauru radar, which

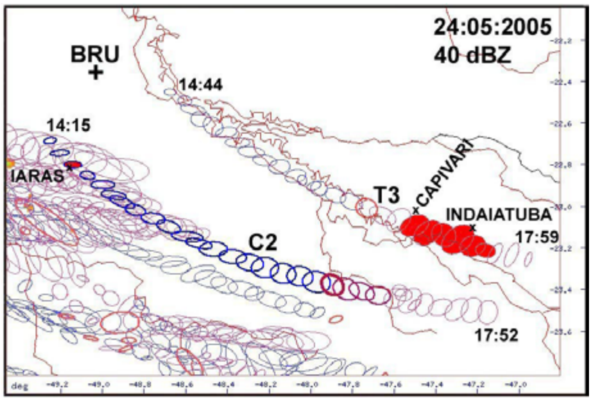

Figure 11. Tracks of 40 dBZ centroids of tornadic cell T3 (Indaiatuba) and cell C2 on 24 May 2005. Times of first and last detection in LT. Red centroids indicate the confirmed tornado activity of cell T3 and the devastating windstorm associated with cell 2.

developed into a small supercell within 30 min, with Z ≥50 dBZ and echo tops (10 dBZ) around 13 km, lasting for more than 3 hours, while it moved towards east-south-east at 64 km.h^{-1}. A hook echo, characteristic of tornadic storms (Chisholm and Renick, 1972; Markowski, 2002), was already observed at 16:08 (Figure 12, left) at a range of 130 km, together with a strong cyclonic circulation visible in the radial velocity field (Vr ranging from –22 to +12 m.s^{-1} indicative of rotation; Figure 12, right). The first touch-down occurred at around 17:00, near the small town of Capivari, followed by another one shortly before 17:30, confirmed by the time history of VIL (Vertically Integrated Liquid water content; cf Figure 15) provided by TITAN and a sudden absence of cloud-to-ground strokes from this cell, as observed by the Lightning Detection Network (cf Figure 22).

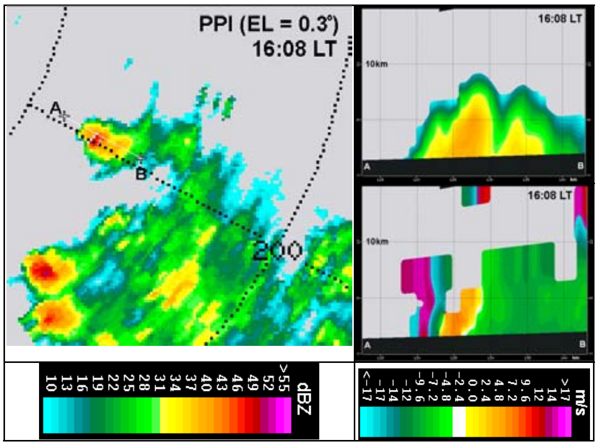

Figure 12. Tornado cell T3 on 24 May 2005, 16:08: PPI at 0,3° elevation (reflectivity, left) and vertical cross-section along A-B of reflectivity (right, top) and radial velocities (right, bottom; negative velocities are folded).

The tornado reached F3 intensity of the Fujita scale during its most intense phase, characterizing a significant event, with an estimated damage of US $ 42 million in the urban and industrial areas of Indaiatuba. The destruction path of the tornado extended for approximately 15 km, with a width of up to 200 m, with several motor cars being overturned, roofs, concrete walls and pillars demolished, electricity lines interrupted, as well as 22 railroad cars having been pushed off their track (Nascimento and Marcelino, 2005). The trajectory of the tornado followed more or less the motion of the parent thunderstorm, viz., from west-north-west to east-south-east.

3.3 *TITAN-derived storm properties*

TITAN produces a variety of output parameters for a chosen reflectivity threshold, such as Area, Volume, Precipitation Flux, VIL, Max Reflectivity, Hail Metrics, speeds and direction of propagation, etc, per volume scan, but only the most significant results will be discussed below.

The supercell C1 certainly reached the highest values for all severity parameters, even when compared to the tornadic cells T1 and T3, and it persisted for most of its 8.5 hour life time.

VIL is a good indicator of storm severity, with VIL ≤7 kg.m^{-2} generally indicating non-severe storms within the range of the Bauru and Presidente Prudente radars (Gomes, 2002). In the case of C1 it exceeded 50 kg.m^{-2} on several occasions between 12:50 and 16:40, with a maximum of 70.6 kg.m^{-2} and a marked minimum of 8.6 kg.m^{-2} at 14:00 (Figure 13). All parameters followed more or less the same pattern. It is noteworthy, that the rapid increase of VIL after 14:00 coincided with a drastic increase of the CG frequency (cf Figure 16).

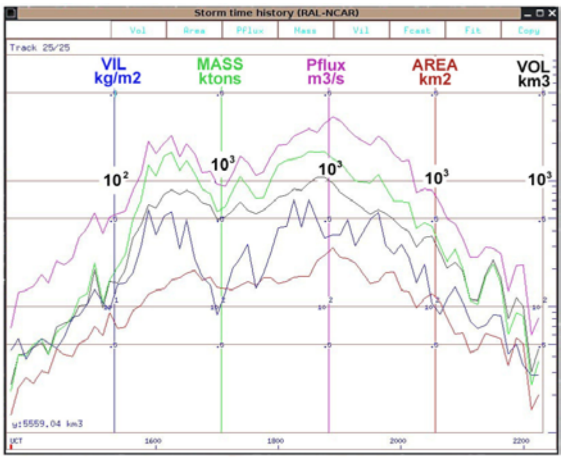

Figure 13. Storm Time History of supercell C1.

During the two peak periods (12:40-13:45 and 15:00-17:00) the maximum reflectivity was ≥60 dBZ, with the 40 dBZ reaching up to 11.4 and 12.9 km, respectively. The 40 dBZ volume was 900 to >1000 km^3 (Figure 13). After 16:00, all parameters began to decrease gradually until just after 19:00, indicating the decaying stage of the supercell.

The VIL of the simultaneous tornadic cell T1 only reached 11.3 kg.m^{-2} at the time of the tornado touch-down (Figure 14), but shortly afterwards it increased rapidly to just below 50 kg.m^{-2}, decreased briefly and then reached its absolute maximum of 60.2 kg.m^{-2} . Again, all parameters displayed the same tendencies. The maximum reflectivity during the tornado touch-down was ≥50 dBZ, but around 60 dBZ during the later peaks (15:00-15:30). The 40 dBZ volume was about 350 and 1000 km^3, respectively (Figure 14). After 15:30 all parameters decreased until 17:30, indicating the end of cell T1.

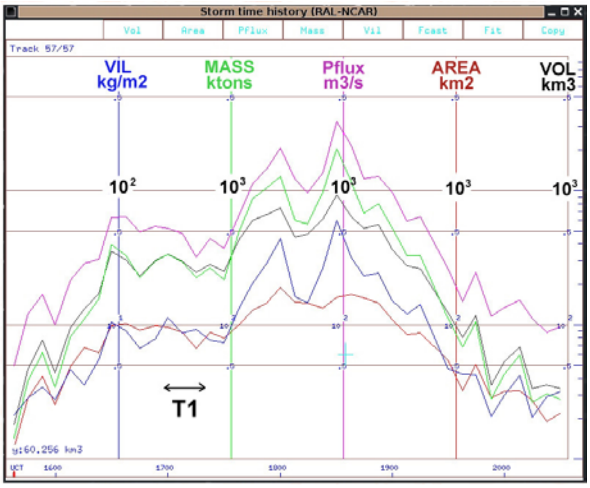

Figure 14. Storm Time History of tornadic cell T1.

In contrast to T1, the tornadic cell T2 had VIL values of 15.5 kg.m^{-2} at the time of the tornado touch-down, but thereafter increased to 31.9 kg.m^{-2} at 18:00. The 40 dBZ volume was about 85 and 420 km^3, respectively. The maximum reflectivity was ±55 dBZ during most of its life time, with reflectivities around 60 dBZ during the 30-minute period preceeding the tornado touch-down. The height of the 40 dBZ contour was around 8 km for most of the time, but increased to 11.4 km by 18:40. Shortly thereafter, the cell started to decay and all parameters decreased rapidly until 19:00.

During its first half of life time, the tornadic cell T3 had VIL values of 5-12 kg.m^{-2}, but during the second half it developed a double peak of VIL, the first one after a sharp increase to 40.5 kg.m^{-2} ca

15 min prior to the first touch-down at 17:00. During the next 20 min it dropped to 11.4 kg.m^{-2} and increased again to 20.3 kg.m^{-2}, dropping to 5 kg.m^{-2} as the tornado faded out (Figure 15). The maximum reflectivity was around 55 dBZ during the first 1.5 hours, then increasing to 57.5 dBZ with the 40 dBZ now reaching up to 10.6 km shortly before 17:00. Thereafter, Max Z dropped together with the other parameters to 49.4 dBZ and increased during the second peak to 54.5 dBZ (40 dBZ at 10 km). The volume fluctuated between 90 and 150 km^3 during the first part of the track, but increased to 500-700 km^3 during the peak period (Figure 15).

In terms of storm statistics, cell C2 was very much average. During the windstorm at Iaras the VIL was <5 kg.m^{-2} and only increased to 15.7 kg.m^{-2} towards the end of its life time. Maximum reflectivities were around 50 dBZ, but the height of the 40 dBZ contour rose to 7.0-8.5 km only during the second half.

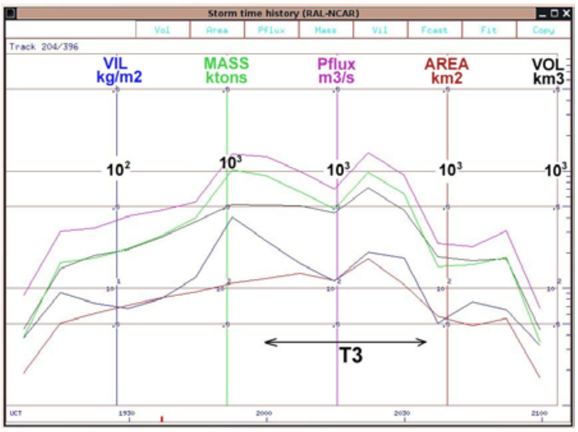

Figure 15. Storm Time History of tornadic cell T3 during the second half of its life time (19:08-18:00).

4. LIGHTNING OBSERVATIONS

The Brazilian Lightning Detection Network (RINDAT) became almost fully operational in 1999, although the first four sensors had already been installed in 1988. In June 2003, RINDAT became a Nationally Integrated Network, managed by a four-member Consortium, comprising three power utility companies and the National Institute for Space Research (INPE). During 2004 and 2005, 24 sensors (8 IMPACT, 16 LPATS) were operating, covering approximately 40% of Brazil (Held *et el.,* 2005a). The average detection efficiency is 80 - 90%, with an intracloud discrimination of 80 - 90% and a location accuracy of 0.5–2.0 km. More technical details are provided by Pinto Jr. (2003).

Information on Cloud-to-Ground (CG) flahes, extracted from the RINDAT database, was ingested by TITAN to correlate the position of CGs with the radar echoes. The flashes were grouped into 7.5 min intervals, corresponding to the radar volume scans, but flash frequencies per minute, as well as other stroke properties, were analyzed too.

To visualize the CG flashes superimposed on the storm echoes, a composite reflectivity CAPPI was generated for each volume scan of 7.5 min (MDV format) by TITAN/CIDD, showing the maximum reflectivity throughout the volume scan and the CGs during the same time interval.

4.1 *Lightning on 25 May 2004*

Based on observations of cloud-to-ground (CG) flashes from RINDAT, the earlier Complex 1 (identified at 12:01 in Figure 2), which encompassed the supercell C1 and Tornado T1, produced almost 10 times more CG events during its peak activity, than Complex C2 trailing it (Figure 16, top). The intensive lightning activity of the cells prior to the tornado touch-down, dropped to very low flash frequencies during the mature tornado stage, after which it increased again. In contrast, the supercell storm had relatively constant flash rates of about 6 events per minute (occasionally ≤15 min^{-1}; Held *et al.*, 2004). A preliminary analysis of other CG lightning characteristics does not show any significant variation of peak current values, multiplicity and polarity.

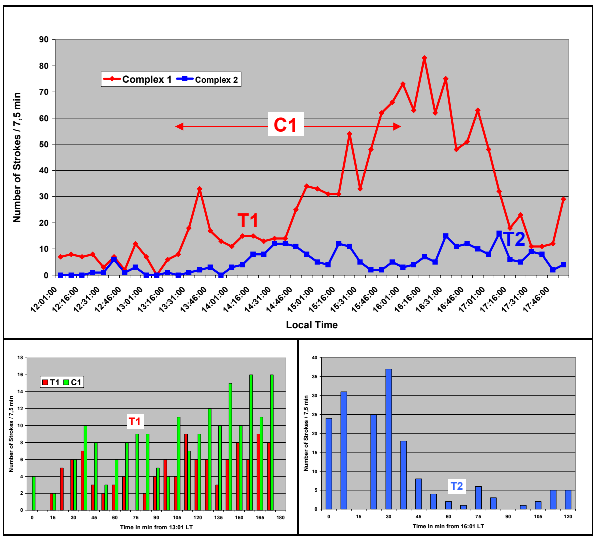

Figure 16. 25 May 2004. *Top:* Flash frequencies per radar volume scan (7.5 min intervals) for the two storm complexes identified in Figure 2. *Bottom:* Number of CG per radar volume scan per individual cell (C1, T1, T2).

A comparison of lightning records with radar observations indicates, that supercell C1 did not produce any CG until 12:20 (with exception of a couple of isolated CG flashes at around 11:00), while the first three CGs associated with T1 were only recorded at 13:23 ahead of the echo core. The frequency of ground flashes from the first tornado cell (T1) was significantly higher before the tornado touched down (Figure 16, bottom left). The first CG flashes were observed at the time the hook echo developed (13:23), gradually increasing in frequency from 1-2 per km^2 over a 15x15 km area (7.5 min time intervals, corresponding to the radar volume scans), with almost all flashes being ahead of the cell core, until 13:46. Thereafter, the frequency dropped off, but flashes appear to be grouped around the updraft center (Held *et al.*, 2004), and not within the cell core from 14:01 to 14:16 (Figure 17). From 14:23 onwards, only isolated flashes were recorded. In contrast, the supercell (C1) to the north showed a slightly different behavior in flash rates and distribution, producing $\leq$7 flashes per km^2 within the volume scan intervals of 7.5 min from 13:38 onwards until 15:23, when up to 9 flashes per km^2 were recorded (Figure 16, bottom left), all more or less equally distributed within the cell core (Figure 17).

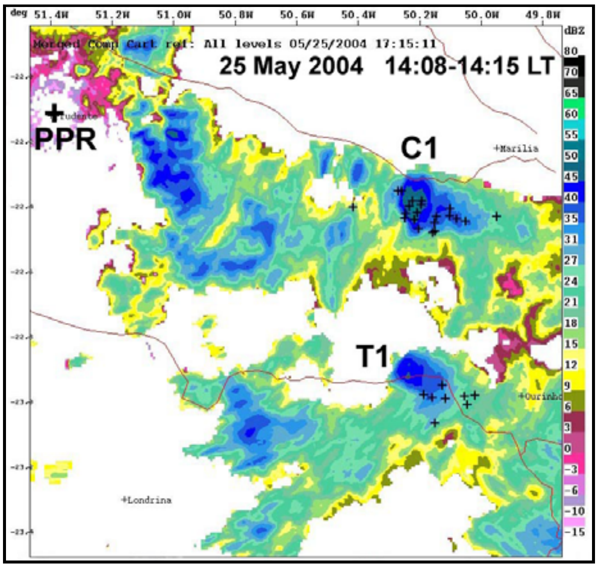

Figure 17. 25 May 2004: Position of CG flashes (+) relative to the echo cores of the supercell C1 and tornadic storm T1 during a 7.5 min interval.

As in the earlier case, intensive lightning activity was observed from the tornadic cell T2 (Figure 16, bottom right) until 17:00, before the tornado touch-down, when no CG flashes were recorded from this cell until 17:30 (Figure 18), with the exception of the volume scan from 17:16 – 17:22 (6 events). At the same time, $\geq$70 CG flashes per 7.5 min interval were recorded from the neighboring storm complex, which was, in fact, the supercell C1, described earlier.

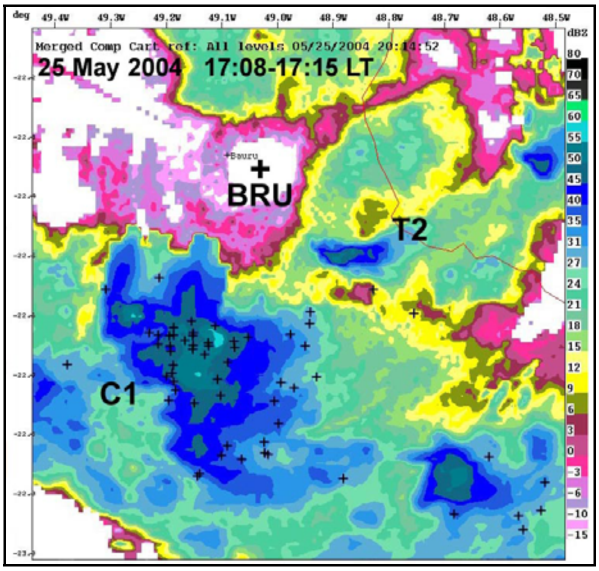

Figure 18. 25 May 2004: Position of CG flashes (+) relative to the echo cores of the tornadic storm T2 and the supercell C1 during a 7.5 min interval.

4.2 *Lightning on 24 May 2005*

It is noteworthy, that during the 24-hour period of this day, about 20 thousand CG lightning strokes were recorded in the State of São Paulo by RINDAT, which is an absolute record for May during seven years of observations. Figure 19 depicts the strokes between 14:00 and 19:00, with those attributed to the tornadic cell (T3) shown in blue.

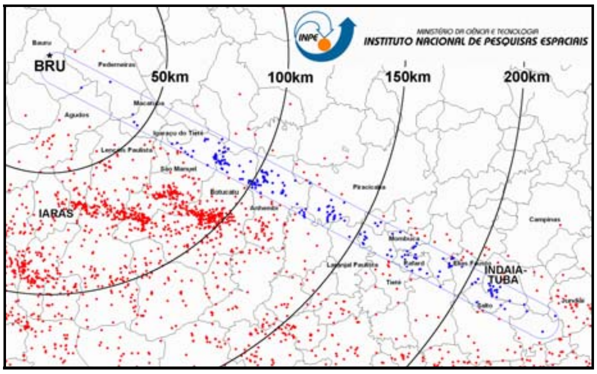

Figure 19. 24 May 2005: CG strokes between 14:00 and 19:00 in the central State of São Paulo (254x153 km). The schematic path of the tornado cell is indicated in blue. Thin black lines delineate Magisterial Districts.

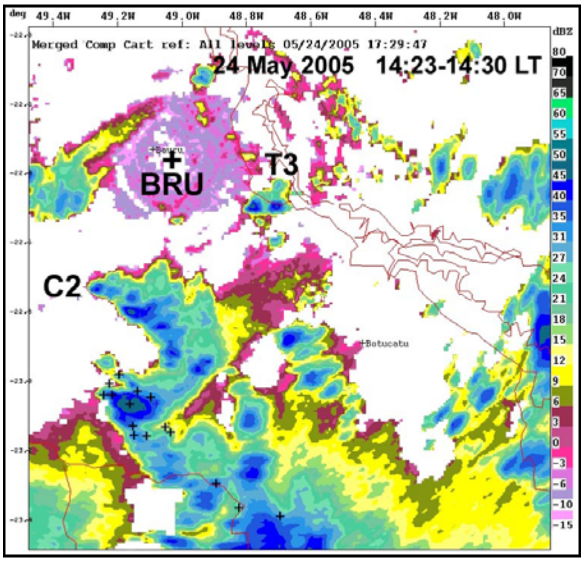

Figure 20. 24 May 2005: Position of CG strokes (+) relative to the echo cores of the cell C2 and its neighbors during a 7.5 min interval.

The first severe event, which occurred on this day, was a tornado-like windstorm at the small town of Iaras (C2), about 60 km south-south-west of the Bauru radar (Figures 1, 10 and 11), where a gasoline service station and several heavy trucks were totally destroyed at around 14:30. Although no tornado funnel was observed, the radar and lightning characteristics were very similar to those of a tornadic cell. Virtually no lightning was recorded at the beginning of the cell track, and only after 14:44 a slight increase occurred. However, its southern neighbor had a very high frequency of CG strokes until it faded out at 14:49. Figure 21 depicts cell C2 at the time of the windstorm, as well as the initial stage of cell T3, before it had reached 40 dBZ.

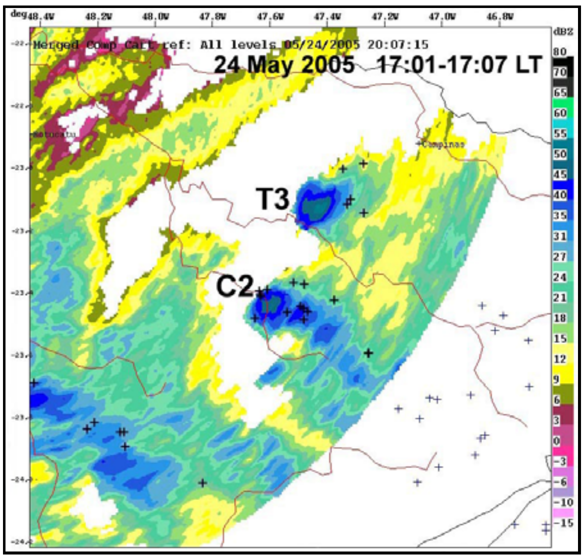

Figure 21. 24 May 2005: Position of CG strokes (+) relative to the echo core of storm T3 during the tornado activity, as well as for cell C2, during a 7.5 min interval.

Figure 22 indicates, that the lightning activity of the tornadic cell T3 also decreased sharply just before the touch-down. In fact, the TITAN analysis clearly showed, that no lightning was associated with its cell until 15:29 (the earlier peaks in Figure 22 are attributable to neighboring storms), and only 1-2 CG strokes per volume scan were recorded until the lightning frequency started to increase gradually from 16:29 onwards. All strokes were located on the outside of the echo core or ahead of it (Figure 21). No strokes were associated with cell T3 after the tornado ceased (17:37-17:45) and the frequency was low thereafter.

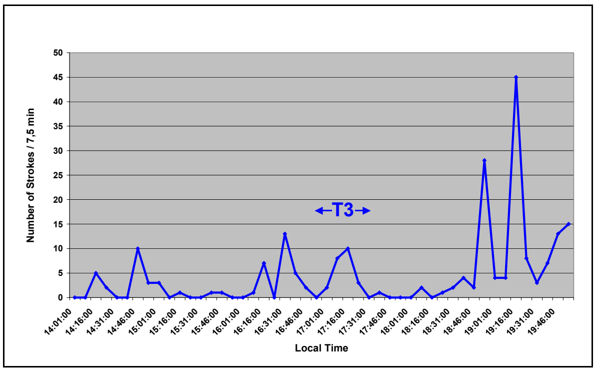

Figure 22. 24 May 2005: Stroke frequencies per radar volume scan (7.5 min intervals) for the tornado cell T3.

Again, no variation of lightning peak current value and polarity was found for the tornadic cell. Since only CG lightning stroke data were available for this case, it was impossible to make inferences on the multiplicity.

5. SEASONALITY OF TORNADOES

Considering the occurrence of these tornadoes during the past two years, as well as the historic case of 14 May 1994 (Gomes *et al.*, 2000; Held *et al.*, 2001), one could conclude, that there is a prevalence of synoptic situations favoring the development of tornadoes in the State of São Paulo during the austral autumn, although the storms are less intense in terms of echo tops and radar reflectivity, than during summer. In order to support or reject such an assumption, newspaper records and the Internet were searched for dates of tornado reports within the State of São Paulo from January 1991 until March 2006. In total, seven tornado occurrences could be confirmed, of which four occurred during the austral autumn (May) and three during spring (September / October). Since the population has become more aware of the phenomenon during the past two years, several sightings of small tornado funnels had also been reported during mid-summer, but verification with radar observations did not confirm any touch-down, and therefore, these cases are not included here. This preliminary survey 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. In contrast, records from the southernmost States (Paraná, Santa Catarina, Rio Grande do Sul) indicate, that tornadoes can occur there virtually any time of the year (Nascimento, 2005; pers. comm.). A possible reason for this different frequency pattern could be, that baroclinic systems are more frequent in the southernmost part of Brazil, while the atmosphere in the State of São Paulo is predominantly barotropic during the summer months. The most severe tornadoes in the State of São Paulo were F3 according to the Fujita scale (Fujita, 1981). The relatively low number of observed tornadoes is possibly also due to a sparse population density in the State, where large areas are being used for agricultural purposes.

6. CONCLUSION

Until recently, tornadoes were believed to be rather rare and exceptional events in Brazil, and very few radar observations had been available. However, during the southern hemisphere autumns in 2004 and 2005, three confirmed tornado-spawning storms and one supercell storm were observed in the State of São Paulo by IPMet's S-band Doppler radars. Simultaneous CG lightning data were also available from the Brazilian National Lightning Detection Network (RINDAT). This allowed a detailed analysis of the three-dimensional structure of radar reflectivity and radial velocity fields of the tornadic cells and relate it to their lightning activity, with the ultimate goal to derive characteristic signatures which could aid the nowcaster to identify those and disseminate early warnings to the public.

The storms, associated with areas of strong convective activity created by the passage of a baroclinic system with strong convective instability and vertical wind shear, had been observed by the radars on 25 May 2004 and 24 May 2005, respectively. Since both cases occurred during the southern hemisphere autumn, these cells were not amongst the most intense in terms of radar reflectivity (50-60 dBZ) and their echo tops rarely exceeded 12 km, but exhibited extremely strong radial velocities and rotational shear (up to $-5.0\times10^{-2}s^{-1}$), which initiated a cyclonic vortex in the center of the cells, spawning the tornadoes. On 25 May 2004, a second severe cell, about 60 km north of the tornadic cell and moving in parallel, was classified as a supercell storm, based on its long life cycle of more than 8.5 hours. It had almost identical characteristics as its tornadic partner cell, except for a Weak-Echo-Region. However, when subjected to TITAN analysis (threshold 40 dBZ, minimum volume 16 km^3), it revealed much greater severity parameters (VIL=70.6 $kg.m^{-2}$, MAX-Z=$\geq$60 dBZ, sustained VOL= 500 to >1000km^3 for 4 hours), than the tornadic cells, but no reports of damage or the formation of another tornado were received. The temporal evolution of VIL values shows a rapid decrease close to the time of the observed destructive winds at ground level (e.g., tornado touch-down). However, the highest values of VIL (absolute maxima observed in these three cases: T1=60.2, T2=31.9, T3=40.5 $kg.m^{-2}$) were not necessarily observed close to the time of the tornado touch-down, but generally at a later stage of the cell.

Analysis of lightning records from RINDAT superimposed on radar images (TITAN/CIDD) indicated significant differences in the location of CGs relative to the echo core of tornadic cells (around or ahead of the echo core) and the supercell, where CGs were observed within and around the core and with greater frequency. Lightning activity almost ceased shortly before the touch-down of the tornadoes, but no significant differences of lightning parameters (peak current, multiplicity, polarity) were found for the tornadic and non-tornadic cells. Thus, the lightning distribution relative to the echo core, including characteristic CG-free periods, are a good indicator of storm intensity and severity, which is in agreement with observations of tornadoes and supercell storms in Oklahoma (Rison *et al*., 2005).

A survey, based on newspaper records and the Internet, showed that tornadoes are indeed rare events in the State of São Paulo, but more likely to occur during the austral spring and autumn, when the atmosphere is more unstable, due to baroclinic disturbances.

This study highlights the importance of Doppler radar and real-time lightning observations, especially as a useful tool for nowcasting techniques, to predict the development of extremely severe rain, hail or wind storms in Southeast Brazil. However, the signatures obtained so far still need to be fine-tuned with more cases, in order to derive more precise algorithms than those already available in the latest IRIS Software, for providing automatic warnings to the forecaster.

Results from an operational regional model (ETA-CPTEC) and the meso-ETA model (10x10 km resolution) centered over the Bauru radar, as well as their forecast capabilities and limitations, will be discussed for the 2005 event in a companion paper (Held *et al*., 2006).

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8. REFERENCES

Chisholm, A. J. and Renick, J. H., 1972: *The kinematics of multicell and supercell Alberta hailstorms.* Research Council of Alberta Hail Studies, Report No.72-2, pp 24-31, Red Deer, Canada.

Fujita, T. T., 1981: Tornadoes and Downbursts in the Context of Generalized Planetary Scales. J. Atmos. Sci., **38**, 1511-1534.

Gomes, A. M., 2002: Utilização do parâmetro densidade VIL no alerta de tempestades severas na área central do Estado de São Paulo. *Anais XII Comgresso Brasileiro de Meteorologia* (CD-ROM), Foz do Iguaçu, 4-9 Aug. 2002, SBMET, pp 3149-3154.

Gomes, A. M., Held, G, Lima, M. A. and Calheiros R.V., 2000: Estudo da Evolução de Tempestades Severas na Área Central do Estado de São Paulo por Radar Doppler. *Proceedings, XI Congresso Bras. de Meteor.*, SBMET, Rio de Janeiro, 16-20 Outubro 2000, Paper MR00006, p 1921-1929.

Held, G., Gomes, A. M. and Nachtigall, L. F., 2001: Severe Storm Signatures Observed by Doppler Radar in the State of São Paulo, Brazil: From Synoptic Scale to Microburst. *Preprints, 30th International Conference on Radar Meteorology,* AMS, Munich, Germany, 19-24 July 2001, 248-250.

Held, G. and Gomes, J. L., 2003: The Bauru Flash Flood of 8 February 2001 and Options for Improved Warnings, *Preprints, 31st Conference on Radar Meteorology,* AMS, Seattle, E.U.A., 6-12 August 2003, 660-663.

Held, G., Gomes, A. M., Pinto Jr., O., Antonio, C. A. A. and Porto da Silva, A.B., 2004: The Palmital Tornado: Lightning and Radar Obser-vations. *Proceedings, International Confe-rence on Grounding and Earthing (GROUND '2004) & 1st International Conference on Lightning Physics and Effects,* Belo Horizonte, Brazil, 7-11 November 2004, 23-28.

Held, G., Gomes, A. M., Nascimento, E., Pinto Jr., O, Naccarato, K. P., Antonio, C. A. and Porto Da Silva A. B., 2005: Tornado Signatures for Nowcasting Using Radar and Lightning Observations in Brazil. *Geophysical Research Abstracts*, Volume **7**, CD ROM, EGU General Assembly 2005, Vienna, Austria, 24-29 April 2005, 6pp.

Held, G., Gomes, A. M., Naccarato, K. P., Pinto Jr., O, Nascimento, E., Correia, A. A. and Marcelino, I.P.V.O., 2005a: Analysis of Tornado Characteristics in the State of São Paulo for the Improvement of an Automatic Alert System (Paper P3R.9). *Preprints, 32nd Conference on Radar Meteorology, CD,* AMS, Albuquerque, USA, 24-29 October 2005, 10pp.

Held, G., Gomes, A. M., Pinto Jr., O., Naccarato, K. P., Kawasaki, Z. and Morimoto, T., 2005b: The Integrated Use of a Lightning Network and Doppler Radars in the State of São Paulo to Identify and Forecast Severe Storms and its Application to Power Electric Utilities. *Proceedings, VIII International Symposium on Lightning Protection*, São Paulo, 21-25 November 2005, 429-434.

Held, G., Gomes, J. L. and Nascimento, E, 2006: Forecasting a severe weather occurrence in the State of São Paulo, Brazil, on 24 May 2005: The Indaiatuba Tornado, *8th International Conference on Southern Hemisphere Meteorology and Oceanography*, Foz do Iguaçu, 24-28 April 2006 (Accepted for Poster Presentation).

Klemp, J. B., 1987: Dynamics of tornadic thunderstorms. *Ann. Rev. Fluid Mech.*, **19**, 369-402.

Markowski, P. M., 2002: Hook echoes and rear-flank downdrafts: a review. *Mon. Wea. Rev.*, **130**, 852-876.

Nascimento, E. L. and Marcelino, I.P.V.O., 2005: A multiple-vortex tornado in Brazil. To be submitted to *Mon. Wea. Rev.*

Nascimento, E. L., 2005: Personal Webpage - http://www.lemma.ufpr.br/ernani/torbraz.html

Pinto Jr., O., 2003: The Brazilian lightning detection network: a historical background and future perspectives. *Proceedings, VII International Symposium on Lightning Protection*, Curitiba, Brazil, 17-21 November 2003, p. 3-5.

Rison, W., Krehbiel, P., Thomas, R. J. and Hamlin, T., 2005: Three-dimensional lightning mapping observations as a compliment to radar observations of storms (Poster JP3J.23), *32nd Conference on Radar Meteorology, CD,* AMS, Albuquerque, USA, 24-29 October 2005.