ANALYSIS OF SEVERE THUNDERSTORMS IN THE STATE OF SÃO PAULO, BRAZIL, USING "TITAN" TO IDENTIFY THE POSITION OF POSITIVE AND NEGATIVE GROUND STROKES RELATIVE TO RADAR ECHOES

Conference Paper · November 2006

Gerhard Held
São Paulo State University

Ana Maria Gomes Held
São Paulo State University

Kleber P. Naccarato
National Institute for Space Research, Brazil

GROUND'2006

and

2nd LPE

International Conference on Grounding and Earthing
&
2nd International Conference on
Lightning Physics and Effects

Maceió - Brazil November, 2006

ANALYSIS OF SEVERE THUNDERSTORMS IN THE STATE OF SÃO PAULO, BRAZIL, USING "TITAN" TO IDENTIFY THE POSITION OF POSITIVE AND NEGATIVE GROUND STROKES RELATIVE TO RADAR ECHOES

Gerhard Held[1], Ana Maria Gomes[1], Kleber P Naccarato[2] and Osmar Pinto Jr[2]
[1] Instituto de Pesquisas Meteorológicas, Universidade Estadual Paulista, Bauru, S.P., Brazil
[2] Grupo de Eletricidade Atmosférica, Instituto de Pesquisas Espaciais, São José dos Campos, S.P.

Abstract - Criteria for early detection of severe wind and hailstorms have been sought by re-analyzing three tornado-spawning cells and one supercell storm, using TITAN Software. Standard Doppler radar observations point at cell motion of >50 km.h^{-1}, VIL, Weak Echo Regions, hook echoes and strong rotational shear to be good indicators of possible severe storms, including tornadoes. However, TITAN, when operated in real time, can provide the temporal history of many severe storm indicators along all cell tracks, yielding valuable signatures for Nowcasting. Adding lightning observations, the decaying stage of severe convective cells and stratiform regions can be identified from the ratio of positive to negative flashes, while tornadic and supercell storms generate predominantly negative flashes, being located around or ahead and throughout the cell, respectively.

1 - INTRODUCTION

The Instituto de Pesquisas Meteorológicas (IPMet) of the Universidade Estadual Paulista has observed the three-dimensional structure of severe thunderstorms, including the radial velocities inside and near these storms, since 1992 and 1994, respectively, when the two S-band Doppler radars were installed, at first one in Bauru and later the other one in Presidente Prudente, in the central and western part of the State of São Paulo (Figure 1). Criteria for the early detection of severe wind and hailstorms have been sought and are already, at least in part, incorporated in the real-time monitoring and alert system. However, research into the relationship between radar echoes and lightning discharges only commenced in 2004. Preliminary results from two storm days with three confirmed tornadoes and a supercell storm within radar range were presented in [1, 2]. In this paper, the findings of the re-analysis of those radar observations will be demonstrated, after the latest version of NCAR's (National Center for Atmospheric Research) TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting, [3]) Software had been implemented at IPMet and adapted for local requirements.

2 - METHOD

IPMet's radars have a 2° beam width and a range of 450km for surveillance, but when operated in volume-scan mode every 7.5 minutes it is limited to 240km, with a resolution of 1km radially and 1° in azimuth, recording reflectivities and radial velocities. In this study, the reflectivity threshold was set at 10 dBZ.

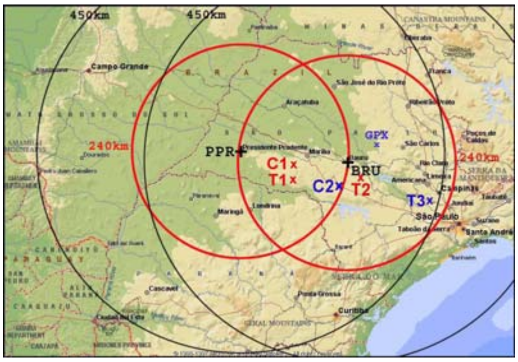

Figure 1 - IPMet's Radar Network (BRU = Bauru; PPR = Presidente Prudente), showing 240 and 450 km range rings. The areas where the tornadoes occurred are marked T1 (Palmital), T2 (Lençois) and T3 (Indaiatuba). C1 and C2 are severe storm cells moving on parallel tracks of T1 and T3, respectively.

TITAN produces a variety of important parameters for a chosen reflectivity threshold throughout the life time of storms, such as Area, Volume, Precipitation Flux, VIL (Vertically Integrated Liquid water content), Maximum Reflectivity, Hail Metrics, speeds and direction of propagation, etc, per volume scan. The IPMet version also has the facility to collocate flashes with the radar echoes, including a separation into positive and negative strokes, based on records from the Brazilian Lightning Detection Network (RINDAT). However, only the most significant results will be discussed in this paper and related to the frequency of electric activity.

3 - OBSERVATIONS

Until recently, tornadoes were believed to be rather rare and exceptional events in Brazil, and very few radar observations had been available. The only Doppler radar observations of a tornado occurring in the State of São Paulo before 2004 were reported in [4]. However, during the southern hemisphere autumns in 2004 and 2005, three confirmed tornado-spawning storms and a super-cell storm were observed in the State of São Paulo by IPMet's S-band Doppler radars. Simultaneous lightning data were also available from RINDAT. This allowed a detailed analysis of the 3-dimensional structure of the radar reflectivity and radial velocity fields of the tornadic cells and relate it to their lightning activity. The ultimate goal is to derive characteristic signatures, which could aid the nowcaster to identify severe weather and disseminate early warnings to Civil Defense Organizations, the electricity sector and the public.

3.1 - SYNOPTIC SITUATION

Several 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.

More detailed descriptions of the synoptic situations as well as the damage caused by the tornadoes, can be found in [1] for the 25 May 2004 and in [5] for the 24 May 2005 case.

3.2 - RADAR OBSERVATIONS

Detailed findings of the conventional radar analyses of both days have already been presented in various Conference papers [1, 2, 5], and therefore only the most characteristic signatures identified will be described briefly in this paper, before presenting the new results from the powerful TITAN Analysis.

The 25 May 2004 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 was already well-defined during the morning, as it rapidly crossed the western State of São Paulo. The convective activity intensified with the increase in surface temperatures towards noon. By 12:01 LT (LT=UT-3h; all subsequent radar times are in LT) a large, multi-cellular storm complex had developed on the southern flank of the line in the south-east sector of the PPR radar, 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 (T1), causing enormous damage to sugar plantations and overturning a large bus, killing two persons and injuring most of its 53 passengers.

An isolated cell, C1, which had developed at about 10:00 some 110 km north-west of PPR, intensified dramatically after 11:30 just behind the stratiform complex, moving at a steady speed of 65 km.h^{-1} south-eastwards for >8.5 hours. Although this rapid cell displacement is unusual for most storms in Southeast Brazil, it had been found in the past, that extremely intense cells or severe storms commonly move at speeds of >50 km.h^{-1} [5].

At about the same time as C1 began to reach the peak of its maturity, demonstrating typical features of a supercell storm [6], such as a well-formed ‘Weak Echo Region’ (WER, Figure 2), another cell, about 60 km south of it, also turned into a vicious storm (T1). Radar observations indicate, that at 13:23 a “hook echo”, typical for supercell storms [7], especially when they are in the process of spawning tornadoes, had developed. Both cells are depicted in Figure 3. However, no significant features in the vertical structure of T1, like in C1, were found, while the cell moved in an east-south-easterly direction at about 55 km.h^{-1}.

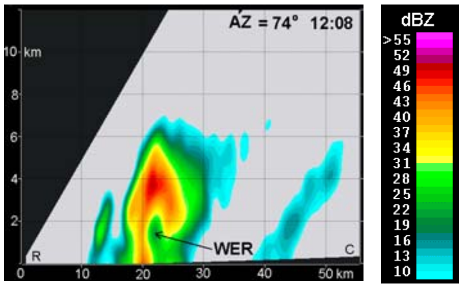

Figure 2 - Radial cross-section through supercell C1, 25 May 2004, 12:08 (the base line R - C is along azimuth 74º.

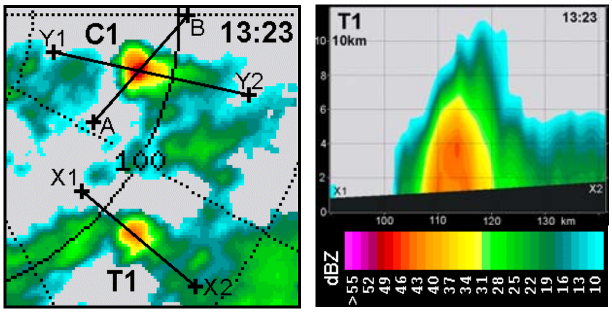

Figure 3 - The two supercells on 25 May 2004, 3.5 km CAPPI at 13:23 (*left*), and cross-section of T1 (*right*). Cross-sections of cell C1 are shown in [5].

The radial velocities near ground level of both cells showed the formation of a characteristic “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 –5.2x10^{-3}s^{-1} at 13:46 and 13:53 and thus resulting in tremendous rotational forces just before the touch-down of the tornado [1, 2, 5]. The tornado lasted for about 20 min and traveled with its mother cell along a 15 km path east-south-eastwards.

A second tornado of lesser intensity was observed on the same day 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-eastwards across the radar at speeds of 55–65 km.h^{-1}. Its characteristics were very similar to those of T1 [2, 5].

A third tornado occurred one year later, on 24 May 2005. It reached F3 intensity of the Fujita scale during its most intense phase, killing one person and causing an estimated damage of US$ 42 million in the urban and industrial areas of Indaiatuba, south of Campinas, along its path of approximately 15 km, with a width of up to 200 m [5]. The characteristics of this tornadic cell were again very similar to those of T1, commencing as an isolated cell, which developed into a small supercell within 30 min, lasting for more than 3 hours, while it moved towards east-south-east at 64 km.h^{-1} [2, 5]. A hook echo, characteristic of tornadic storms [7], was observed at 16:08 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). The first touch-down occurred at around 17:00, followed by another one just before 17:30 in Indaiatuba.

3.3 - LIGHTNING OBSERVATIONS

The Brazilian Lightning Detection Network (RINDAT) became almost fully operational in 1999. During 2004 and 2005, 24 sensors (8 IMPACT, 16 LPATS) were operating, covering approximately 40% of Brazil [8]. Its average detection efficiency is about 80-90 %, with an intracloud discrimination of 80-90 % and a location accuracy of 0.5-2.0 km.

The analysis of Cloud-to-Ground (CG) lightning records indicated that 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 [2, 5].

It is important to note that for the 25 May 2004 events, reprocessed CG flash data were available. However, for 24 May 2005, only CG lightning stroke data could be used, since the 2005 database has not yet been reprocessed for CG flashes.

4 - TITAN-DERIVED STORM PROPERTIES

Once the TITAN Software [3] was fully implemented at IPMet, a re-analysis project for all severe storms observed in the State of São Paulo during the past 12 years was initiated at the beginning of 2006. In this Section we describe the results obtained from applying TITAN to both days when tornadoes occurred. An important feature of TITAN is, that it can merge observations from several radars, thus allowing extended cell tracking, which was specifically important on 25 May 2004, providing more continuity and accuracy of the storm tracks.

For the purpose of this analysis, the primary parameters of TITAN were set to: reflectivity threshold 40 dBZ, with a minimum volume of 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*.

4.1 - STORM TRACKS

Figure 4 shows the tracks of the cell which spawned the Palmital tornado (T1), as well as that of the supercell C1, which had actually developed at about 10:00 some 110 km north-west of PPR, west of the Rio Paraná, moving at a steady speed of 65 km.h^{-1} south-eastwards. TITAN identified its first 40 dBZ centroid at 10:37 and tracked it continuously for 8 h 38 min, with an overall average speed of 57 km.h^{-1}, traversing most of the State of São Paulo. The centroid of cell T1 was first identified at 12:30, about 60 km south of the concurrent supercell (Figure 4), moving in parallel at 55 km.h^{-1}, as described in Section 3.2.

The second tornado (T2) observed on this day was spawned from a cell, which had initially developed at 15:00, as discussed in Section 3.2. TITAN identified its 40 dBZ centroid at 15:38 and tracked it for 3.5 hours (Figure 5). The storm was embedded within an unusually strong airflow from north-west (radial velocity component: 44 m.s^{-1}), resulting in a strongly sheared storm environment, both horizontally and in the vertical, confirmed by vertical cross-sections, which show a Bounded Weak Echo Region on the eastern flank of the storm

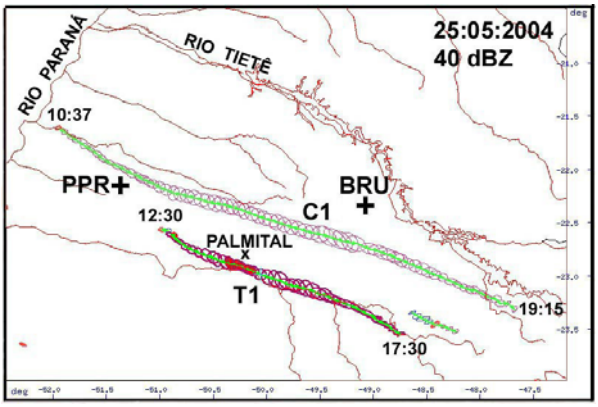

Figure 4 - Composite radar image, showing the tracks of 40 dBZ centroids of supercell C1 and tornadic cell T1 (Palmital) on 25 May 2004. Times of first and last detection in LT. Not all simultaneous tracks are shown. Red centroids indicate the confirmed tornado.

between 17:00 and 17:30 [2, 4], which was about the time of the tornado touch-down. This would indicate a persistent strong updraft almost perpendicular to the general flow. As the storm continued along its track, the rotational signature intensified to reach a maximum of –5.0x10^{-2}s^{-1} at 17:16 between 2 and 4 km amsl.

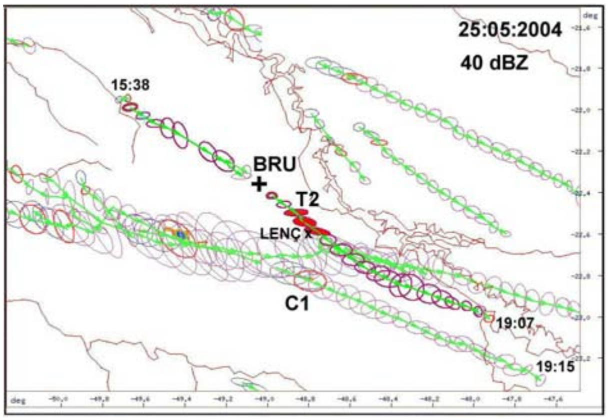

Figure 5 - Tracks of 40 dBZ centroids of tornadic cell T2 (Lençois Paulista = LENÇ) and continuation of supercell C1 on 25 May 2004. Times of first and last detection in LT. Not all simultaneous tracks are shown. Red centroids indicate the confirmed tornado.

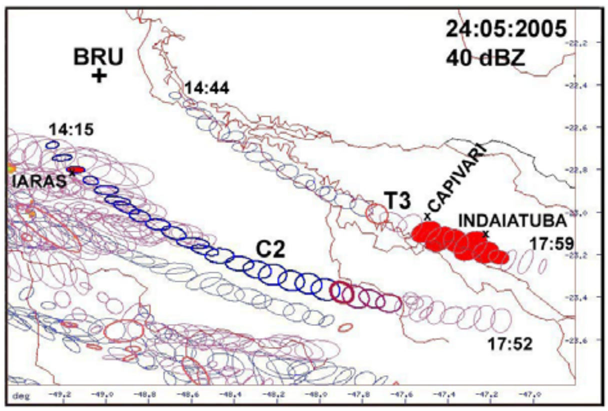

Figure 6 - Tracks of 40 dBZ centroids of tornadic cell T3 (Indaiatuba) and cell C2 on 24 May 2005. Times of first and last detection in LT. Red centroids indicate the confirmed tornado activity of cell T3 and the severe windstorm associated with C2.

The tracks of the two dominant cells on 24 May 2005 are shown in Figure 6. TITAN identified the 40 dBZ contour of the tornadic cell T3 at 14:44 and tracked it for >3 h while moving at 64 km.h^{-1}. The solid red area indicates where the tornado touched down, first at 17:00 and later again at shortly before 17:30. Almost simultaneously, another supercell moved on a parallel track at 68 km.h^{-1}, lasting for >3.5 h, but the rotational shear only caused a severe wind storm in its early life time (C2 in Figure 6).

4.2 - SEVERITY PARAMETERS

The supercell C1 certainly exhibited the highest values for all severity parameters analyzed in this study, persisting for most of its 8.5-hour life time, even when compared to the severe tornadic cells T1 and T3.

The 'Vertically Integrated Liquid water content' (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 [9]. In the case of C1, on 25 May 2004 (Figure 4), 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 7). 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 [2]. 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 7). After 16:00, all parameters began to decrease gradually until just after 19:00, indicating the decaying stage of the supercell.

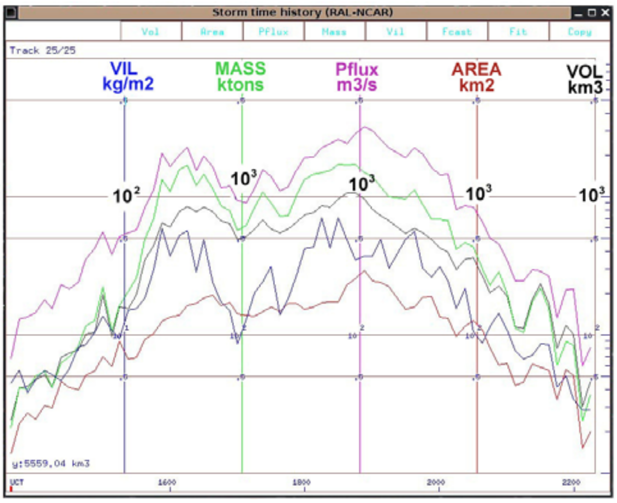

Figure 7 - 25 May 2004: Storm Time History of supercell C1 from 10:45 – 19:15 LT.

The VIL of the simultaneous tornadic cell T1 only reached 11.3 kg.m^{-2} at the time of the tornado touch-down (Figure 8), 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 8). After 15:30 all parameters decreased until 17:30.

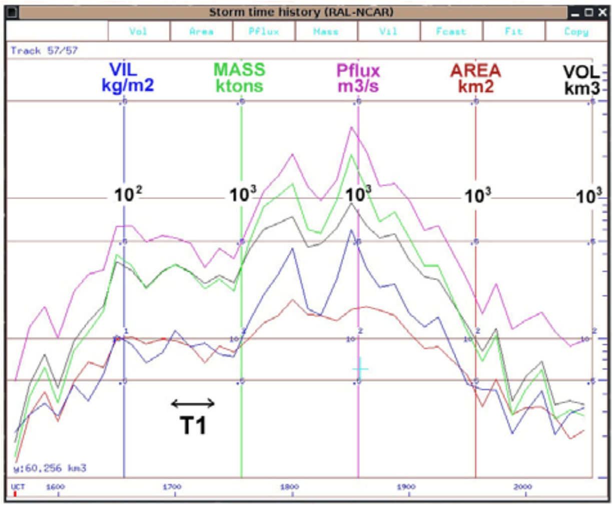

Figure 8 - 25 May 2004: Storm Time History of tornadic cell T1 from 12:45 – 17:30 LT.

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, and 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.

On 24 May 2005, the tornadic cell T3 (Figure 6) had VIL values of 5-12 kg.m^{-2} during its first half of life time, 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} about 15 min prior to the first touch-down at 17:00. During the next 20 min it dropped to 11.4 kg.m^{-2}, but increased again to 20.3 kg.m^{-2}, dropping to 5 kg.m^{-2} as the tornado faded out (Figure 9). The maximum reflectivity was around 55 dBZ during the first 1.5 hours, increasing to 57.5 dBZ with the 40 dBZ reaching up to 10.6 km shortly before 17:00. Thereafter, Max Z dropped together with the other

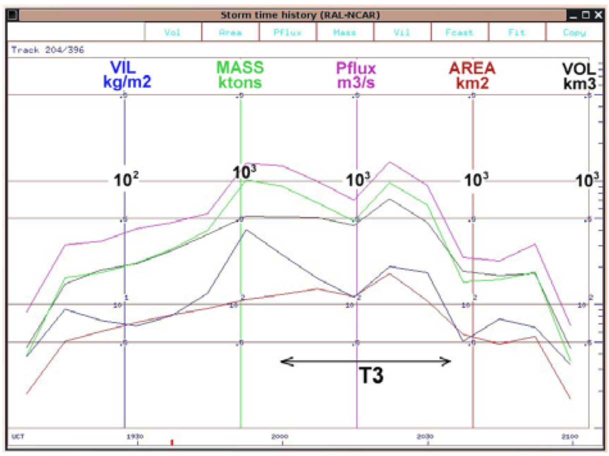

Figure 9 - 24 May 2005: Storm Time History of tornadic cell T3 during the second half of its life time (16:08 - 18:00 LT).

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 9).

In terms of TITAN storm statistics, cell C2 (Figure 6) 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.

5 - LIGHTNING RELATIVE TO RADAR ECHOES

The analysis of lightning observations in relation to radar echoes was accomplished with the TITAN/CIDD visualization software. It should be noted, that one + symbol (white for negative, red for positive charges) may represent more than one flash (25 May 2004) or stroke (24 May 2005) in the same or close-by location during the 7.5 min interval of the radar volume scan. Figures 10-13 show the radar reflectivity of the storms in TITAN MDV format (Meteorological Data Volume, [3]).

A comparison of lightning records with radar observations indicates, that supercell C1 did not produce any significant CG flashes until 12:20, while the first three CGs associated with tornadic cell T1 were only recorded at the time the hook echo developed (13:23), ahead of the echo core. The frequency of CG flashes from T1 was significantly higher before the tornado touched down [2] and flashes appear to be grouped around the updraft center or ahead, and not within the cell core from 14:01 to 14:16 (Figure 10). From 14:23 onwards, only isolated flashes were recorded. In contrast, the supercell (C1) to the north showed a different behavior in flash rates and distribution, producing ≤7 flashes per km^2 within the volume scan intervals of 7.5 min from 13:38 until 15:23, when up to 9 flashes per km^2 were recorded [2], about equally distributed within the cell core (Figure 10). Almost no positive CG flashes were observed from cells C1 and T1 during their mature stages. Very few CG flashes were recorded within the stratiform precipitation areas, but their majority was positive.

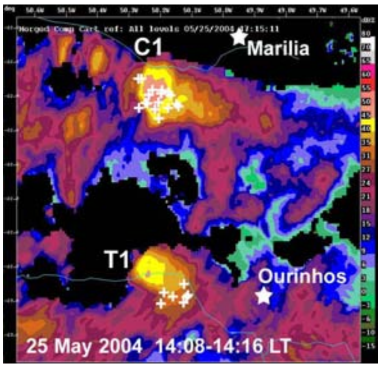

Figure 10 - 25 May 2004: Position of CG flashes (**+** negative; **+** positive, but none observed at this time) relative to the echo cores of the supercell C1 and tornadic storm T1 during a 7.5 min interval.

As for T1, intensive lightning activity was observed from the tornadic cell T2 until 17:00, before the tornado touch-down [2], when no CG flashes were recorded until 17:30 (Figure 11), with the exception of the volume scan from 17:16–17:22 (6 events). At the same time, ≥70 CG flashes per 7.5 min interval were recorded from the neighboring supercell C1 [2], with a relatively large portion of these being positive (Figure 11). During the second half of C1's life cycle, viz. from about 16:00, the number of positive CGs increased significantly, coinciding with a gradual decrease of severity parameters (Fig. 7).

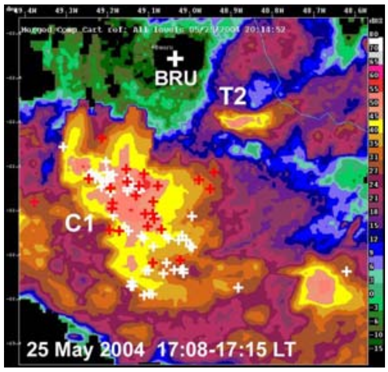

Figure 11 - 25 May 2004: Position of CG flashes (**+** negative; **+** positive) relative to the echo cores of the tornadic storm T2 and the supercell C1 during a 7.5 min interval.

The first severe event on 24 May 2005, was a tornado-like windstorm at the small town of Iaras (C2), about 60 km south-south-west of the Bauru radar (Figures 1 and 6), 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 12 depicts cell C2 at the time of the windstorm, as well as the initial stage of cell T3, before it had reached 40 dBZ, not yet producing any CG lightning during its early stage.

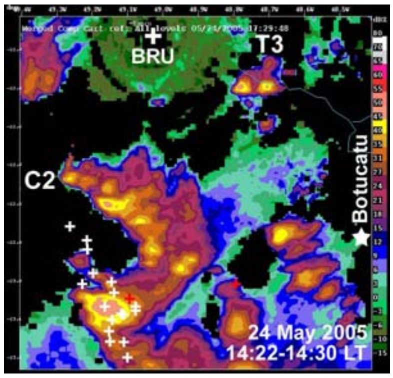

Figure 12 - 24 May 2005: Position of CG strokes (**+** negative; **+** positive) relative to the echo cores of the cell C2 and its neighbors during a 7.5 min interval.

The TITAN analysis clearly showed, that no lightning was associated with tornadic cell T3 before 15:29 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. As in the other cases, the lightning activity decreased sharply just before the tornado touch-down at 17:00 [2], also confirmed in Figure 13. No strokes were associated with cell T3 after the tornado ceased and the frequency was low from

17:45 onwards. Positive CG strokes were extremely rare along both cell tracks (Figures 12 & 13).

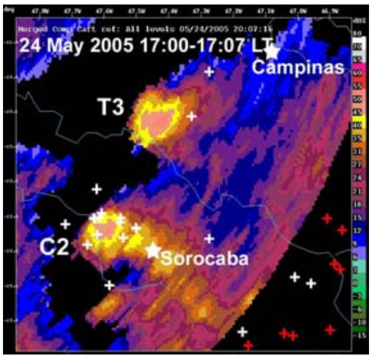

Figure 13 - 24 May 2005: Position of CG strokes (**+** negative; **+** positive) relative to the echo core of storm T3 during the tornado activity, as well as for cell C2, during a 7.5 min interval.

6 - CONCLUSIONS

In an effort to constantly improve Nowcasting and the dissemination of alerts in the State of São Paulo, criteria for the early detection of severe wind and hailstorms have been sought by re-analyzing recent observations of three confirmed tornado-spawning cells and one super-cell storm, using TITAN Software adapted for Brazil. Since they occurred during the southern hemisphere autumn, the cells were not amongst the most intense in terms of radar reflectivity (50-60 dBZ) and their echo tops rarely exceeded 12 km, but they exhibited extremely strong radial velocities and rotational shear (up to $-5.0x10^{-2}s^{-1}$), which initiated a cyclonic vortex in the center of the cells, spawning the tornadoes. One of the severe cells 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. Based on conventional Doppler radar observations, good indicators of possible severe storms, including tornadoes, are cell motion of >50 $km.h^{-1}$, VIL, Weak Echo Regions, hook echoes and strong rotational shear. However, TITAN can provide the temporal history of many severe storm indicators along all cell tracks, providing valuable signatures for Nowcasting. When subjected to TITAN analysis, the supercell revealed much greater severity parameters (VIL=70.6 $kg.m^{-2}$, MAX-Z=≥60 dBZ, VOL = 500 to >1000km^3 sustained for four 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), but the highest values of VIL 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, superimposed on radar images indicated a preferential location of CGs around or ahead of the core of tornadic cells, while in the supercells the CGs were observed within and around the core and with greater frequency. Lightning activity almost ceased shortly before the touch-down of the tornadoes, which is in agreement with observations of tornadoes and supercell storms in Oklahoma [10], but no significant differences of lightning parameters (peak current, multiplicity, polarity) were found for the tornadic and non-tornadic cells. However, flash polarity seems to be a good discriminator between mature convective cells and stratiform rain regions, with the latter producing only few and mostly positive flashes, while even slowly decaying convective cells may still generate large numbers of flashes, but an increasing portion is positive.

TITAN radar products are already operationally available to IPMet's meteorologists in real time, but mechanisms and algorithms still need to be developed for an automatic alert system. If high-resolution lightning data were also available in real time, they could be integrated into the radar images, yielding a powerful Nowcasting system, with vast benefits, not only for Civil Defense Authorities and the public, but especially for the electricity sector.

7 - ACKNOWLEDGEMENTS

Hermes A.G. França is thanked for assisting with the retrieval and pre-processing of the raw radar data. Mike Dixon and Niles Oien of the National Center for Atmospheric Research are gratefully acknowledged for their advice regarding the implementation and application of the TITAN and CIDD software packages at IPMet, being maintained by Jaqueline M. Kokitsu.

8 - REFERENCES

[1] HELD, G., GOMES, A.M., PINTO Jr., O., ANTONIO, C.A.A. and PORTO da SILVA, A.B., "The Palmital Tornado: Lightning and Radar Observations", *GROUND'2004 Proceedings,* pp. 23-28, Belo Horizonte, Brazil, November 2004.

[2] HELD, G., GOMES, A.M., PINTO Jr., O., NACCARATO, K.P., KAWASAKI, Z. and MORIMOTO, T., "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", *VIII SIPDA Proceedings,* pp. 429-434, São Paulo, Brazil, November 2005.

[3] DIXON, M. and WIENER, G., "TITAN: Thunderstorm Identification, Tracking, Analysis & Nowcasting - A radar-based methodology", *J. Atmos. Oceanic Technol*., **10**, pp 785-797, 1993.

[4] GOMES, A.M., HELD, G., LIMA, M.A. and CALHEIROS R.V., "Estudo da Evolução de Tempestades Severas na Área Central do Estado de São Paulo por Radar Doppler", *Proceedings, XI Congresso Bras. de Meteor.*, pp. 1921-1929, Rio de Janeiro, Brazil, Outubro 2000.

[5] HELD, G., GOMES, A.M., NACCARATO, K.P., PINTO Jr., O, NASCIMENTO, E., CORREIA, A.A. and MARCELINO, I.P.V.O., "Analysis of Tornado Characteristics in the State of São Paulo for the Improvement of an Automatic Alert System", *Preprints, 32nd Conference on Radar Meteorology,* Paper P3R.9*,* 10pp, AMS, Albuquerque, USA, October 2005.

[6] CHISHOLM, A.J. and RENICK, J.H., "*The kinematics of multicell and supercell Alberta hailstorms".* Research Council of Alberta Hail Studies, Report No.72-2, pp 24-31, Red Deer, Canada, 1972.

[7] MARKOWSKI, P.M., "Hook echoes and rear-flank downdrafts: a review", *Mon. Wea. Rev*., **130**, pp. 852-876, 2002.

[8] PINTO Jr., O., NACCARATO, K., SABA, M., PINTO, I. ABDO, R.F., GARCIA, S. de M. and FILHO, A.C., "Recent upgrades to the Brazilian Integrated Lightning Detection Network", *Proceedings*, *19th International Lightning Detection Conference*, Tucson, AZ, USA, Vaisala Inc., April 2006

[9] GOMES, A.M, "Utilização do parâmetro densidade VIL no alerta de tempestades severas na área central do Estado de São Paulo", *Proceedings, XII Congresso Brás. de Meteor.*, pp. 3149-3154, Foz do Iguaçu, Brazil, August 2002.

[10] RISON, W., KREHBIEL, P., THOMAS, R.J. and HAMLIN, T., "Three-dimensional lightning mapping observations as a compliment to radar observations of storms", *Preprints, 32nd Conference on Radar Meteorology,* Poster JP3J.23, AMS, Albuquerque, USA, Oct. 2005.

Main author
Name: Gerhard Held
Address: Instituto de Pesquisas Meteorológicas, UNESP
CX Postal, 281; 17015-970 BAURU, S.P., Brasil
Fax: +14 3203-3649; Phone: +14 3103-6030;
E-mail: gerhard@ipmet.unesp.br