GROUND2023

&

10th LPE

International Conference on Grounding
&
Lightning Physics and Effects

Belo Horizonte, Brazil - May, 2023

CASE STUDY OF AN UNSEASONAL TORNADIC SUPERCELL IN THE STATE OF SÃO PAULO: RADAR CHARACTERISTICS AND LIGHTNING OBSERVATIONS

Gerhard Held [1*] Kleber Pinheiro Naccarato [2] Ana Maria Gomes [1*]
[1]Meteorological Research Institute (IPMet), São Paulo State University (UNESP), Bauru, Brazil (* Retired)
[2]Division of Meteorological Satellites and Sensors (DISSM), National Institute for Space Research (INPE), São José dos Campos, Brazil

Abstract - The Doppler S-band radar, located in Bauru, tracked a supercell storm lasting 8.5 hours, which traversed the eastern half of the State of São Paulo and spawned a category F2-3 tornado (Fujita scale) in the city of Campinas during the early hours of the morning (Local Time) on 05 June 2016. Despite the radial distance of ≥200 km, the radar observations recorded typical tornado signatures, such as a hook echo and a mesocyclone with a rotational velocity of 12.5 m.s^{-1}, also confirmed by a rotational damage pattern. Along its approximately 20 km west – east track it caused significant damage to solidly built suburban houses, uprooted large trees, destroyed concrete light poles, and consequently resulted in a total blackout in vast areas of the City. The supercell was accompanied by intense lightning activity throughout its life cycle. For the first time in São Paulo state, a "*lightning jump*" from 0 to 55 ground strokes per minute within 12 min was observed just prior to the tornado touch-down, culminating in a frequency of 238 strokes per minute of Total Lightning. This was also the first occurrence of a tornado observed by radar during the dry austral winter season, as well as a nocturnal event. Although tornados are relatively rare in this region of Brazil, the results presented in this paper provide important information of characteristic signatures which would facilitate earlier detection of severe storm events, if applied in Nowcasting.

1 - INTRODUCTION

The formation and life cycles of tornados have been studied extensively in the USA, because of their frequent occurrence, the extremely severe damage they cause, as well as due to the availability of a dense radar and radiosonde network, including some sophisticated, specialized research radars. However, in Brazil, due to the sparse distribution of suitable Doppler S-band radars, as well as the infrequent occurrence of tornados, only few case studies could be documented. The majority of the severe tornado occurrences in the state of São Paulo was reported during the months of May, followed by September, which mark the transition periods of the atmosphere from summer to winter and back, when conditions are more baroclinic and unstable [1].

The very first tornadic storm recorded by a Doppler radar in Brazil occurred in May 1994 [2], but lightning observations did not yet exist. Later occurrences, which also included lightning data, have been documented in [1, 3, 4]. The purpose of this paper is primarily to present the analysis of an unseasonal tornado which spawned from a supercell during the dry austral winter period in the night of 04/05 June 2016. No fatalities were reported by the local Civil Defense Department, probably due to the fact that it occurred during a weekend, but the devastation along its approximately 20 km long track [5] was considerable. Only the first 7 km of the track passed over densely populated middle class suburbs in the northern part of the city of Campinas, while the remainder affected a mostly agricultural region with small settlements (San Conrado) and farms (Figure 1). Based on the damage pattern of solid house structures, as well as twisted tree branches and metal pieces blown around, this event can be classified as an F2-3 category tornado according the Fujita scale [6]. More details of its track, as well as photos of the damage can be found in [5].

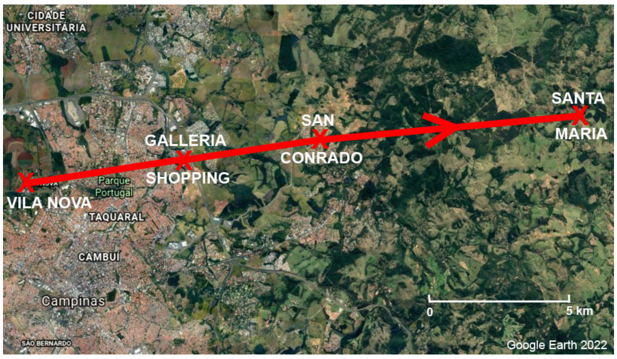

Figure 1 - Tornado track on 05 June 2016 (after [5])

2 - DATA AND METHODS

This study is based on the interpretation of data from the Doppler S-band radar in Bauru (BRU; 22.36° S, 49.03° W) operated by the *Centro de Meteorologia de Bauru* of the *Universidade Estadual Paulista* (UNESP). Volume scans of the original radar data were converted to the MDV format (Meteorological Data Volume) and subsequently processed with the software "TITAN" (Thunderstorm Identification, Tracking, Analysis and Nowcasting; [7]). The radar has a 2° beam width and each volume scan with 16 elevations is completed in 7.5 min within the 240 km quantitative radar range. The range extends to 450 km in surveillance mode (PPI only at 0.3° elevation every 30 min). TITAN is a Software producing a variety of important storm 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 lightning flashes with the radar echoes, including a separation into positive and negative cloud to ground strokes (CG). For this analysis TITAN was configured with a resolution of 750 m (also 250 m during the tornado) in the horizontal and 750 m in the vertical. A reflectivity threshold of 35 dBZ, as well as 30 dBZ, with a volume of ≥16 km^3 was chosen for tracking the cells observed by the BRU radar. Furthermore, it is important to point out that TITAN not only identifies potentially severe cells, based on a pre-defined reflectivity threshold and volume, but also tracks them along their life cycle, and additionally provides forecasts of their estimated future positions up to 60 min. The latter facility assists the meteorologist with the issuing of short-term severe storm warnings (nowcasting).

Additonal data from the S-band radar at São Roque (SRO), operated by the *Departamento de Controle do Espaço Aéreo*, is supplementing the study of convective activity, but only qualitatively for this case, due to differences in data quality and scanning cycles.

The Brazilian Lightning Detection Network (*Rede Brasileira de Detecção de Descargas Atmosférica,* [8, 9]), operated by the *Divisão de Sensores e Satélites Meteorológicos* (DISSM) of the *Coordenação-Geral de Ciências da Terra* (CGCT) of the *Instituto Nacional de Pesquisas Espaciais* (INPE), provided "stroke-level" total lightning (TL) data. BrasilDAT is based on the Earth Networks technology, with its first sensors deployed in Brazil in 2010. It was gradually expanded and reached an optimal coverage of the state of São Paulo in 2012, with the highest detection efficiency of the network due to the installation of >10 sensors in the State and around it. Subsequently, the network expansion continued and it now comprises 65 sensors covering 10 states from the south up to the northeast of Brazil.

3 - DEVELOPMENT OF THE CAMPINAS SUPERCELL

On 04 June 2016, a strong anticyclone was centered over the northern half of South America at the 250 hPa level and bounded by a strong zonal Subtropical Jet in the south [10]. The consequential circulation advected moist air from the Amazon and Pacific Ocean region throughout the troposphere, resulting in a baroclinic flow with unstable conditions favorable for the development of severe thunderstorms in the state of São Paulo, even during the night, as observed by the radars in Presidente Prudente and Bauru.

Figure 2 shows areas along polygons where intense convective activity of ≥35 dBZ reflectivity occurred between 20:21 LT and 00:52 LT (Local Time) when reaching the edge of the quantitative 240 km range, based on TITAN-generated cell tracks. Each of the beige elements of the polygon corresponds to a Volume Scan at 7.5 min intervals. The last elements of each track are shown in blue. The tornadic cell passed over Campinas at about 00:22 LT (03:22 Universal Time; LT=UT-3h), causing severe damage at the surface. It continued eastwards, also causing damage in Morungaba at around 00:52 LT (blue area at the end of the track). The lifetime of many cells during this event exceeded four hours while traversing the region with velocities of >50 km.h^{-1}, characteristic of severe storms associated with supercells as observed previously in the state of São Paulo [4]. The cell which spawned a tornado over the Campinas region can certainly be classified as a supercell, based on several of its characteristics, such as velocity, echo tops penetrating the tropopause, as well as "severe storm parameters" generated by the TITAN analysis, which will be discussed later. Due to the 2° beam width of the BRU radar (at 240 km range the aperture already has a diameter of 8 km) and that the reflectivity is not range-corrected, reflectivity values and some parameters derived by TITAN might be slightly underestimated. In this respect, the SRO radar would have been in a more favorable position to track the tornadic cell, being only 75 km south of Campinas.

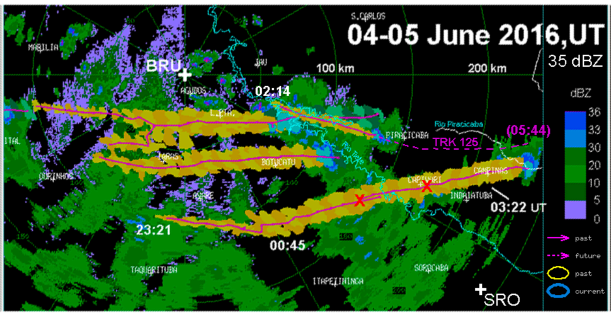

Figure 2 - Polygons showing the temporal sequence of areas with a reflectivity of ≥35 dBZ, generated with the cell tracking capability of TITAN (LT=UT-3h) until the cell reached the 240 km limit of quantitative observations. BRU marks the origin of the Bauru Doppler radar and SRO the location of the Radar at São Roque. The red x mark positions of earlier strong convective activity (01:37 and 02:22 UT, respectively).

In order to support the finding that the tornado had been spawned by a supercell, raw data (HDF5 format) from the S-band radar at São Roque (SRO) had also been converted to MDV, allowing the generation of cell tracks with a reflectivity threshold of 40 dBZ to be expanded beyond the 240 km range of the BRU radar (Figure 3). It clearly shows that the supercell spawning the tornado over Campinas had a lifetime of ca 8.5 hours from its first echo (FE) at 22:59 UT until it finally dissipated 205 km northeast of the SRO radar at 07:30 UT, although the actual tracking of the 40 dBZ echo core stopped at 06:50 UT.

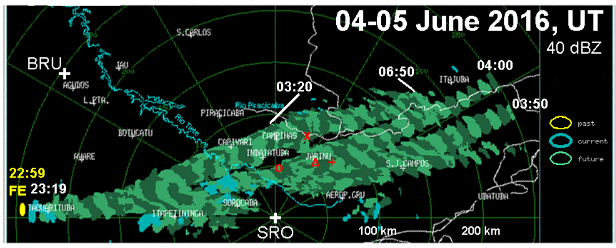

Figure 3 - Polygons showing the temporal sequence of areas with a reflectivity of ≥40 dBZ, as observed by the Radar at São Roque (SRO) from 23:00-04:00 UT. Blue elements show simultaneous complexes at 23:19/23:20 UT with forward projection at 10 min intervals in green. The red symbols mark the following towns: x Morungaba, o Itupeva, Δ Jarinu, + Atibaia.

An earlier cell to the right (south) of the cell which traversed Campinas rapidly grew in volume while moving towards east-northeast (blue area at 23:20 UT north of Sorocaba, Figure 3), later also turning into a supercell. It continued on its initial track east-northeastwards at a speed of ±60 km.h^{-1}, causing severe damage in the small town of Itupeva (at around 00:30 UT), before reaching Jarinu and Atibaia (00:50-01:19 UT), about 40 and 50 km, respectively, southeast of Campinas. While passing over Jarinu, it spawned an EF3 tornado between 00:50-01:10 UT, causing enormous damage in the town, including two overturned semi-truck trailers, as well as one fatality. No rotation inside the cell could be detected due to the lack of radial velocity data from SRO.

4 - DETAILS OF THE CAMPINAS SUPERCELL

Figure 4a shows a zoom of the cell track above the Campinas region. The light-blue area of the polygon identifies the cell at 00:22 LT (03:22 UT), which is more or less the time when the tornado had touched down, while yellow and beige areas indicate the storm position every 7.5 min before, and green areas mark its future track until reaching the 240 km range from the radar. Furthermore, the cross-section in Figure 4b also provides details of the vertical structure of the cell along the base line A-B, oriented perpendicular to the cell motion, over the urban region of Campinas, with a reflectivity maximum of 46 dBZ extending to >6 km of altitude and echo tops reaching ≤18 km (the 10 dBZ reflectivity contour has been extrapolated, based on overshooting cloud top temperatures). These parameters indicate extremely strong convective activity, considering the fact that this storm occurred during the generally dry month of June. Coincidental with the area of maximum reflectivity, a typical characteristic of tornadic cells can also be observed in Figure 4c, viz., an area of maximum radial velocities away from the radar (positive velocities; warm colors) opposing in azimuth radial velocities towards the radar (negative velocities; cold colors). This pair of opposite radial velocities ("*couplet*") identifies the presence of a mesocyclone, indicative of the existence of rotation within the storm, which can spawn a tornado.

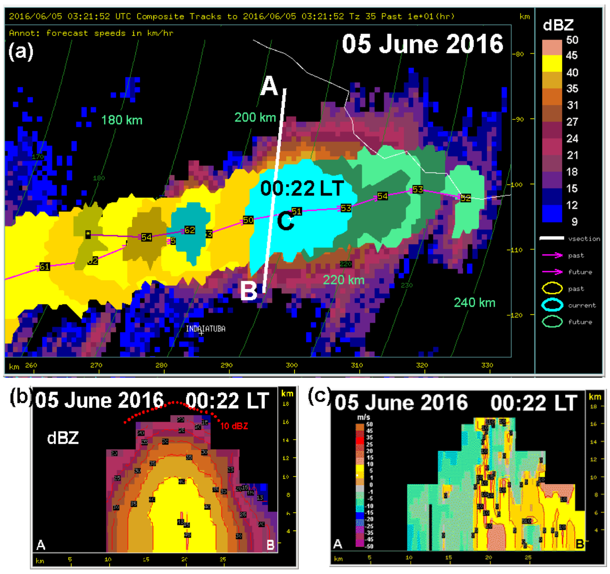

Figure 4 - **(a)** Polygons representing areas of reflectivity ≥35 dBZ identified and tracked using the software TITAN.
(b) Vertical cross-sections along the line A-B show the vertical extent and reflectivity structure and **(c)** radial velocities associated with the tornadic cell impacting Campinas at 00:22 LT.

The rotational velocity is defined as modulus of the radial velocities divided by 2, viz., ($|V_{in}| + |V_{out}|$)/2, which then permits the calculation of the relative rotational velocity of the tornadic cell affecting Campinas during this event. The radial velocities found in this analysis ranged between -25 m.s^{-1} (towards the radar) and +15 m.s^{-1} (away from the radar). Based on these radial velocities recorded by the Doppler radar in Bauru, a value of 12.5 m.s^{-1} is derived for the rotational velocity V_r, where the centers of maximum radial velocity were separated by a distance of 5 km. It should be pointed out that this *velocity couplet* was observed despite its radial distance of just over 200 km from the origin of the radar in Bauru. Considering the beam width of the Bauru radar, a significant degradation of the vortex at that distance should be expected [11]. The rotational vorticity ('azimuthal shear') can be calculated from the ratio between the speed and the distance between the pair of opposing radial velocities, yielding a value of $2.5 \cdot 10^{-3}$.s^{-1} for this case. From studies of tornadic storms in the USA, threshold values of $V_r \geq 12.5$ m.s^{-1} within a radius of 150km, and ≥8.5 m.s^{-1} for distances further than 150km were defined [12]. Thus, the values associated with the Campinas cell can be considered to characterize an intense tornadic event.

Time sequences of a variety of severe storm parameters were calculated by TITAN for all cell tracks shown in Figure 2. However, only the following were considered from the supercell that passed over Campinas and are graphically presented for BRU in Figure 5: Echo Top (10 dBZ contour), Max Reflectivity (dBZ), VIL (kg.m^{-2}) and propagation velocity of the 35 dBZ echo cores. In addition, Figure 5 also shows the Total Lightning (number of strokes per 7.5 min Volume Scan within the 30 dBZ reflectivity contour).

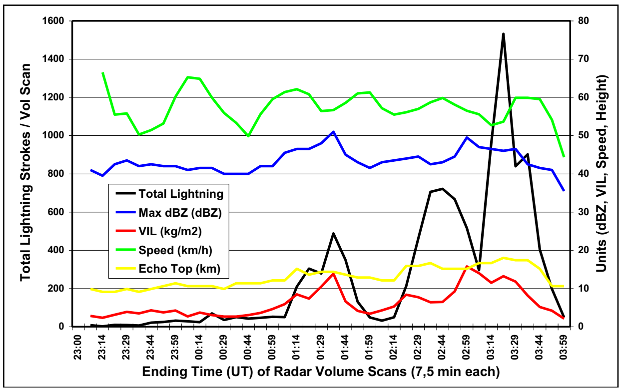

Figure 5 - Time sequence of TITAN-generated storm parameters per Volume Scan of the Bauru Radar (Campinas track; 04 June 2016, 23:00 UT to 05 June 2016, 04:00 UT): Reflectivity maximum (dBZ), VIL (kg.m^{-2}), Speed of Cell Propagation (km.h^{-1}) and Top of 10 dBZ reflectivity contour (km amsl), compared to the number of CG-negative strokes (black line) per Volume Scan.

It is estimated that the tornado occurred during the 03:14–03:29 UT Volume Scans, with maximum intensity at around 03:22 UT. As can be seen from Figure 5, the maximum reflectivity and VIL reached a peak during the 02:59 UT Volume Scan, well before the tornado had spawned and touched ground. Their observed values of 49.5 dBZ and 15.8 kg.m^{-2}, respectively, are certainly an underestimate, and considerably lower than those recorded during the Indaiatuba EF3 tornado (about 25 km south-southwest of Campinas, also at a range of ≥200 km from BRU), viz., 57.5 dBZ and 40.5 kg.m^{-2}, respectively [4, 13]. Although both cases must be regarded as underestimates due to the large distance of >200 km [14], there may also be other reasons to be considered. The tornado in Indaiatuba was certainly more severe, based on the damage, but also it occurred during the meteorological transition phase of austral autumn, while the current case happened during the dry winter season, when convective cells are less intense. Figure 5 also shows that the speed with which the tornadic cell propagated throughout its lifetime varied between 50-65 km.h^{-1}, which is characteristic for rapid new cell development in the immediate vicinity, and especially ahead of the mother cell. This is also related to peaks in VIL and lightning stroke frequency during the earlier life cycle of the supercell, at around 01:37 UT and 02:22 UT, identified in Figure 2 with x. During the first two hours of the super cell's lifetime the echo tops (10 dBZ) fluctuated around 10 km, but began to rise after 01:00 UT as the storm intensified, occasionally penetrating the tropopause at 16 km, also indicated by the other parameters shown in Figure 5. The over-shooting echo top reached a maximum of 18 km, simultaneously with a well-pronounced peak in lightning activity. While the tornadic cell passed over Campinas, TITAN indicated a "Probability of Hail" (PoH) of 60-80%, but FOKR (Foote Krauss Index; [15]) only category 2 (of 4). This PoH is in accordance with ground observations during the first minutes of 05 June 2016 (LT), when the storm impacted the urban area of Campinas. During this period, the "HailMassAloft" reached a maximum of 10.8 ktons. Hail falling on the ground was reported by residents around this time [5].

It is noteworthy that the Campinas tornado was spawned directly from the mother cell, while all earlier case studies [4] showed the tornado-spawning cell to be an isolated cell trailing the storm complex.

5 - ANALYSIS OF LIGHTNING OBSERVATIONS

Lightning strokes (not referring to the numerous return strokes that make up each individual flash) recorded by BrasilDAT provided the data utilized in the subsequent analysis [7, 8].

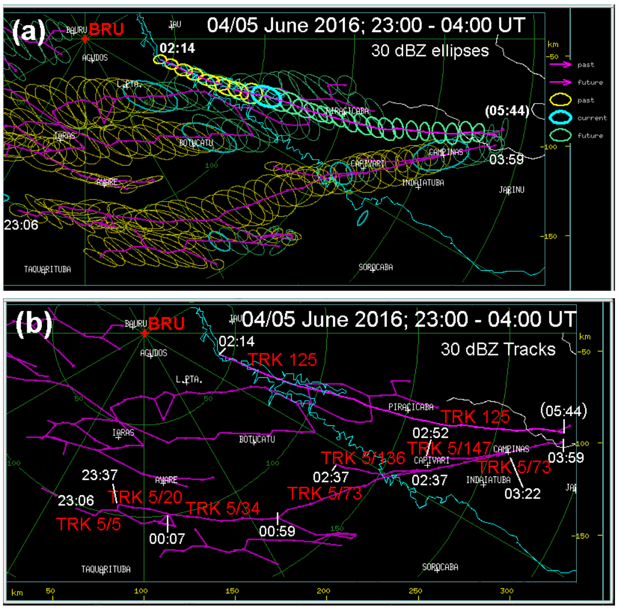

Figure 6 - TITAN-generated cell tracks from 20:00 LT on 04 June 2016 until 01:00 LT on 05 June 2016 for a reflectivity threshold of 30 dBZ. **(a)** Ellipses for every volume scan; **(b)** Track vectors, also showing merging and splitting of cells. BRU marks the origin of the Bauru Doppler radar.

The TITAN storm tracking software was run with reflectivity thresholds of 30 and 35 dBZ to generate ellipses for each 7.5 min volume scan. Figure 6a shows these ellipses for the 30 dBZ threshold from 23:00 UT (20:00 LT) until 04:00 UT (01:00 LT). Figure 6b highlights the vector track of the supercell (marked as "TRK 5/"), which finally spawned the tornado in Campinas, from its origin at 23:06 UT until it reached the 240 km quantitative range of the Bauru radar (BRU) as TRK 5/73. These tracks are based on the center point of the ellipsoids around the 30 dBZ reflectivity contour (Figure 6a). Since TITAN allows merging or splitting of cells, the sub-number of the complex (TRK 5/…) changes along its path, as can be seen in Figure 6b.

The ellipses from the tornadic cell "TRK 5/" were consolidated into a continuous polygon, which delineated the area for which stroke data were extracted for the period 23:00 UT until 04:00 UT, capturing the vast majority of strokes emanating from cells of this track, with very few lateral occurrences. Subsequently, they were separated into positive and negative cloud to ground (CG) strokes, as well as intra-cloud stokes (IC) for further analysis.

A first glance at the lightning stroke data reveals an exceptionally large number of negative CG and IC strokes within the 30 dBZ polygons, viz., 2145 negative CG strokes and 8689 discharge events classified as IC, during the period 23:00-04:00 UT. It is also noteworthy, that 52.5% of the ground strokes recorded within the 30 dBZ contour were confined within the 35 dBZ envelope, while 58.1% of IC activity occurred within the 35 dBZ contour. Maximum Peak Currents recorded for CG-neg and CG-pos strokes were -131 kA and +133 kA, respectively, with the most frequent intervals being 10-19 kA and 20-29 kA, respectively. However, only 0.8% of the CG-neg strokes were ≥50 kA. The extreme peak currents are actually isolated outliers, which occurred during the most intense phase of the supercell (03:17-03:18 UT), which is coincident with the tornado having touched down on the ground.

The time sequence of these lightning strokes per minute (herein generically referred to as flash rate) is presented in Figure 7. Three distinct peaks can be seen, of which the first two are associated with rapid cell development and marked with x in Figure 2. The large increase in the lightning flash rate (third peak in Figure 7) produced by the storm, represents a *lightning jump*, which is a very rapid intensification of electrical activity inside the convective cell, starting just after 03:00 UT and reaching a maximum of 238 strokes min^{-1} (total lightning) about 14 minutes later, preceding the assumed touch-down time of the tornado (estimated at about 03:22 UT). The green arrows mark the peak of the *IC lightning jump* with 185 strokes min^{-1} at 03:14 UT, followed by a sharp drop to 72 strokes min^{-1} at 03:25 UT, just 3 minutes after the tornado touch-down. Five minutes later, the IC flash rate increased very quickly again, reaching >110 IC pulses min^{-1}, in accordance with studies in [16]. These rapid increases of strokes were not due to any cell mergers in the Campinas metropolitan region (Figure 6b).

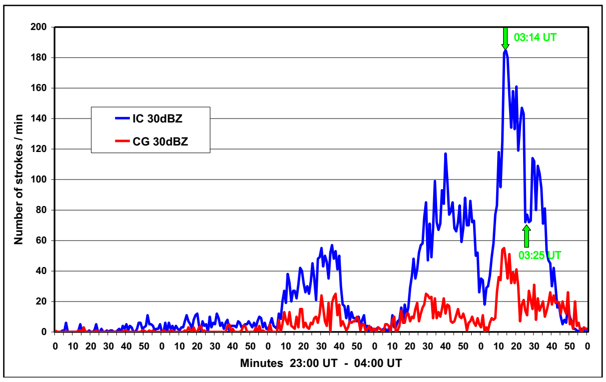

Figure 7 - Number of CG-neg strokes and IC pulses per minute within the 30 dBZ reflectivity contour of the tornadic cell on 04/05 June 2016, 23:00 to 04:00 UT.

A number of authors [16, 17, 18, 19, 20] presented studies in which storms demonstrated a sudden increase in lightning activity just before the occurrence of a severe event, such as hail, tornado, wind gusts, downbursts or microbursts. This relation of the electrical activity with the severe weather occurrence can be explained by the interaction between strong updrafts within the cloud and the electrification of hydrometeors. The updrafts, together with gravitational forces distribute hydrometeors within the cloud according to their size, which are then quickly electrified by non-inductive electrification processes. The result is a rapid formation of positive and negative charge centers within the cloud that leads to an enhancement of the lightning production [21]. In general, the speed by which the *lightning jump* phenomena (curve slope) intensifies is directly related to the increase of the updrafts (or convection invigoration), which produces much more ice within the cloud, but with smaller size and density, leading to a higher number of collisions, higher charge transfers and consequently more intense and larger charge centers.

Figures 8 and 9 depict the tornadic cell at 03:07 UT (00:07 LT) while the lightning frequency was at a low (33 CG-neg strokes per 7.5min), just before the *lightning jump* and at 03:22 UT (00:22 LT) while it traversed densely populated suburbs of the city of Campinas. These times were selected based on Severity Parameters calculated by TITAN, as well as witness reports [5], which identified this period as the most critical of the event. Each of the volume scans has a duration of 7.5 min and all negative CG lightning strokes, represented by a yellow + during the corresponding time period, are superimposed on a CAPPI reflectivity image. The exceptionally high number of strokes, with a frequency of up to 301 CG-neg strokes per 7.5 min during the 03:14-03:22 UT Radar Volume Scan (Figure 5), includes the maximum of the *lightning jump* in Figure 7 (185 CG-neg strokes per minute at 03:14 UT). It is also noteworthy, that from 03:17 UT to 03:24 UT only three positive CG strokes were recorded, while thereafter until 03:40 UT no positive strokes were observed.

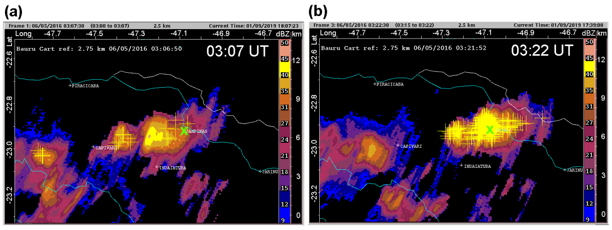

Figure 8 - Tornadic cell approaching / traversing Campinas on 05 June 2016, at **(a)** 03:07 UT and **(b)** 03:22 UT, respectively; reflectivity field (CAPPI at 2.75 km amsl) with superimposed negative CG lightning strokes. The green "X" marks Campinas.

Vertical cross-sections for the above Volume Scans are shown in Figure 9. The respective base lines are indicated in the zoomed CAPPIs of the principal tornadic cell, and the different electrical behavior before and during the tornado touch-down is shown at the base of the cross-sections (red lines), representing regions with CG activity. The characteristic hook echo in the CAPPI of 03:22 UT marks the low-level inflow region into the mesocyclone at the time the tornado was spawned. This also coincides with a sharp lightning drop (Figure 5). The dotted line indicates the position of the cross-section showing radial velocities in Figure 4, while the blue and red arrows represent the opposite radial air flow ("*couplet*") powering the mesocyclone in the supercell.

Furthermore, the vertical cross-sections in Figures 9c and d show that all echo cores were upright, with neither a tilt or overhang in the direction of propagation, nor any lateral tilt (Figure 4b), while most supercells or fast-moving severe storms tracked in the state of São Paulo displayed significant forward tilts [1, 22].

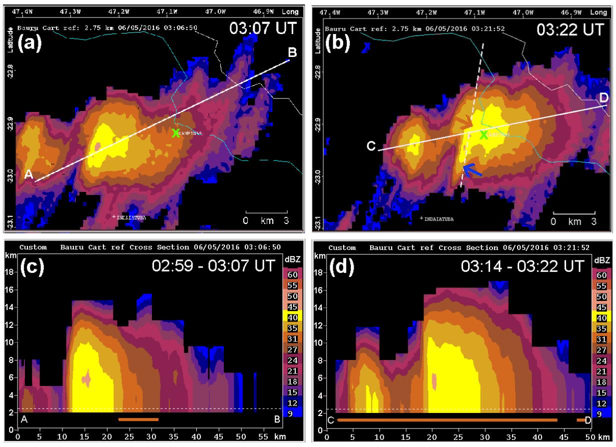

Figure 9 - Zoom of the tornadic cell on 05 June 2016
(a) 03:07 UT and **(b)** 03:22 UT; CAPPI at 2.75 km, reflectivity field with the respective base line of the vertical cross-sections. "X" marks the center of Campinas. The dotted base line in **(b)** indicates the position of the vertical cross-section in Figure 4 and the short arrows represent the radial air flow towards (blue) and away (red) from the radar, characterizing the mesocyclone.
(c) and **(d)** Vertical cross-sections with ground positions of CG-neg strokes (red horizontal lines).

6 - CONCLUSIONS

The purpose of this paper is primarily to present the analysis of an unseasonal tornado which spawned from a supercell during the dry austral winter period in the night of 04/05 June 2016 and to derive indicators that might help meteorologists to improve Nowcasting.

On 04 June 2016, a strong anticyclone was centered over the northern half of South America at the 250 hPa level and bounded by a strong zonal Subtropical Jet in the south, advecting moist air from the Amazon and Pacific region throughout the troposphere. The resulting baroclinic flow created unstable conditions favorable for the development of severe thunderstorms in the state of São Paulo, which led to the formation of several supercell storms, some of them lasting up to 8.5 hours, traversing the state during the day and continued into the early hours of the next morning. Two of these spawned a tornado in Campinas and Jarinu, respectively, causing considerable damage.

This event differed in several aspects from previously studied supercell and tornado situations: Firstly, it was the first time that such an event occurred during the dry winter season and could be tracked by radar at night, despite a radial distance of about 200 km. The second important fact was the observation of a *lightning jump* prior to the tornado touch-down, also a first for this region. An analysis of the Doppler radar data with "TITAN" (Thunderstorm Identification, Tracking, Analysis and Nowcasting) provided several important severe storm parameters and signatures to facilitate earlier detection of such severe events for Nowcasting. No funnel was observed due to being a nocturnal occurrence, as well as a widespread power failure disabling surveillance cameras.

Typical tornado signatures were recorded, such as a hook-echo and a mesocyclone with radial velocities ranging between -25 m.s^{-1} (towards the radar) and +15 m.s^{-1} (away from the radar). From these radial velocities recorded by the Doppler radar in Bauru, and based on a 5 km separation of maximum radial velocities (*echo couplet*), the rotational velocity V_r = 12.5 m.s^{-1}. Due to the long radial distance from the radar, the values of the storm parameters are certainly underestimated. The rotational vorticity ('azimuthal shear') can be calculated from the ratio between the speed and the distance between the pair of opposing radial velocities, yielding a value of $2.5 \cdot 10^{-3}$.s^{-1}, which is indicative of a severe event. Time sequences of a variety of severe storm parameters were calculated by TITAN: the maximum reflectivity and VIL (Vertically Integrated Liquid water content) reached a peak well before the tornado had spawned and touched ground (49.5 dBZ and 15.8 kg.m^{-2}, respectively); propagation of all long-lasting supercells was east-northeastwards at varying speeds of 50-70 km.h^{-1}; maximum echo tops (10dBZ) were ≤18 km, occasionally overshooting into the lower stratosphere, with maximum reflectivities between 55 and 65 dBZ during their mature stages. In contrast to previous studies, this tornado was spawned directly from the mother cell and not from a trailing isolated cell; also, the echo core was not tilted as in most other cases before.

~~A~~ *lightning jump* was documented starting about 20 min before touch-down of the tornado (around 03:21 UT) in Campinas. It reached a maximum of 238 strokes min^{-1} (total lightning) and 12 minutes later, was followed by a sharp drop of the lightning frequency (from 185 to 72 IC strokes min^{-1}), and again after about five minutes by a very rapid increase. Previously, an absence of lightning strokes to ground during the tornado touch-down was documented. However, in the current case very few CG strokes were recorded shortly before the *lightning jump*.

This, as well as previous case studies clearly identify the need for a denser integrated radar network, as well as more radio soundings to study the near-storm environment, including vertical atmospheric profiles from high-resolution models.

7 - ACKNOWLEDGEMENTS

The *Centro de Meteorologia de Bauru* (UNESP) is thanked for providing the Bauru and Presidente Prudente radar data in IRIS format, and the *Centro de Previsão de Tempo e Estudos Climáticos* (CPTEC/INPE) for the raw data (HDF5 format) from the São Roque radar, kindly converted to MDV by Rafael Vernini.

8 - REFERENCES

[1] HELD, G., GOMES, A.M., NACCARATO, K.P., PINTO, Jr.O. and NASCIMENTO, E., "The Structure of Three Tornado-Generating Storms Based on Doppler Radar and Lightning Observations in the State of São Paulo, Brazil", *Proceedings, 8th Intern. Conference on Southern Hemisphere Meteorology and Oceanography*, Foz do Iguaçu, Brazil, pp.1787-1797, April 2006

[2] GOMES, A.M., HELD, G, LIMA, M.A. e CALHEIROS R.V., "Estudo da Evolução de Tempestades Severas na Área Central do Estado de São Paulo por Radar Doppler", *Anais, XI Congresso Bras. de Meteor.*, Paper MR00006, pp.1921-1929, Rio de Janeiro, Brazil, October 2000

[3] HELD, G., GOMES, A.M., NACCARATO, K.P., PINTO, O. Jr., NASCIMENTO, E.L, 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", (Paper P3R.9, 10pp). *Preprints, 32nd Conference on Radar Meteorology,* Albuquerque, USA, October 2005

[4] HELD, G., GOMES, A.M. and NACCARATO, K.P., "The structure and behaviour of supercell storms in the State of São Paulo, Brazil", *Proceedings, 6th European Conference on Radar in Meteorology and Hydrology*, 7pp, Sibiu, Romania, Sept.2010

[5] NUNES, L.H., GOMES, A.M., HELD, G., NACCARATO, K., DE BONA, L., AMORIM, R.R. e MACHADO, J.P., "Evidências de um tornado em Campinas em junho de 2016: considerações preliminares", *Os Desafios da Geografia Física na Fronteira do Conhecimento*, (Perez Filho,A; Amorin, RR; Eds), pp.1948-1962, IG/Unicamp, Campinas S.P., 2017

[6] FUJITA, T.T., "Tornadoes and downbursts in the context of generalized planetary scales", *J. Atmos. Sci.*, 38, pp.1511-1534, 1981

[7] NACCARATO, K.P., PINTO, Jr.O. and PINTO, I.R.C.A., "Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of Southeastern Brazil", *Geophys. Res. Lett.,* 30(13), pp.1674-1677, 2012

[8] NACCARATO, K.P. and PINTO, Jr.O., "Lightning detection in Southeastern Brazil from the new Brazilian Total Lightning Network (BrasilDAT)", Proceedings, *International Conference on Lightning Protection*, 9pp., Vienna, Austria, September 2012

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

[10] CPTEC, "Boletim Técnico - Análise Sinótica: 04-05/06/2016-00Z", 2pp, 2016

[11] BROWN, R.A. and WOOD, V.T., "Development of New WSR-88D Scanning Strategies for Convective Situations", *Final Report (Task 8.2)*, NSSL, Norman, OK, USA, 1999

[12] NSSL, "The National Severe Storms Laboratory: Convective Storms: Structure, Evolution, and Depiction - Warning Guidelines: Mesoscale Convective Systems", Norman, OK, USA, 1985

[13] NASCIMENTO, E.L., HELD, G. and GOMES, A.M., "A Multiple-Vortex Tornado in Southeastern Brazil", *Mon. Weather Rev.,* 142, pp.3017-3037, 2014

[14] CALHEIROS, R.V. and D'OLIVEIRA, A.B., "Retrieval of the gross structure of reflectivity: Correcting for degraded peak values", *Proceedings, 33rd International Conference on Radar Meteorology*, P6B.3, 7pp, Cairns, Australia, August 2007

[15] MAKITOV, V.S., FOOTE, B. and KRAUSS, T.W., "Hail metrics using conventional radar", *Proceedings of the 85th AMS Annual Meeting*, 6pp, San Diego, CA, USA, January 2005

[16] STOUGH, S.M., CAREY, L.D., SCHULTZ, C.J. and BITZER, P.M., "Investigating the relationship between lightning and mesocyclonic rotation in supercell thunderstorms", *Weather and Forecasting*, 32(6), pp.2237–2259, 2017

[17] GOODMAN, S.J., BLAKESLEE, R., CHRISTAIN, H., KOSHAK, W., BAILEY, J., HALL, J., MCCAUL, E., BUECHLER, D., DARDEN, C., BURKS, J., BRADSHAW, T., and GATLIN, P., "The North Alabama Lightning Mapping Array: Recent severe storm observations and future prospects", *Atmos. Res.,* 76, pp.423–437, 2005

[18] GATLIN, P.N. and GOODMAN, S.J., "A total lightning trending algorithm to identify severe thunderstorms", *J. Atmos. Oceanic Technol.,* 27, pp.3–22, 2010

[19] SCHULTZ, C.J., PETERSEN, W.A., and CAREY, L.D., "Preliminary development and evaluation of lightning jump algorithms for the real-time detection of severe weather", *J. Appl. Meteor. Clim.*, 48(12), pp.2543–2563, 2009

[20] SCHULTZ, C.J., PETERSEN, W.A., and CAREY, L.D.: Lightning and severe weather: A comparison between total and cloud-to-ground lightning trends, *Weather Forecasting*, 26(5), pp.744-755, 2011

[21] DEIERLING, W., PETERSEN, W.A., LATHAM, J., ELLIS, S. and CHRISTIAN, H.J., "The relationship between lightning

activity and ice fluxes in thunderstorms", *J. Geophys. Res. D: Atmos.*, 113, D15210, 2008

[22] HELD, G., GOMES, A.M. and NACCARATO, K.P., "The Structure of Severe Storms and Associated Lightning in the State of São Paulo, Brazil", *Proceedings, 14th Internat. Conference on Atmospheric Electricity*, 4pp, Rio de Janeiro, Brazil, August 2011

Main author
Name: Gerhard Held
Address: Avenida São João 2400; Apto. 221-D
12242-000 São José dos Campos, SP; Brazil
Phone: +55 12 3019-9077
E-mail: gerhard@gheld.net.br