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THE INTEGRATED USE OF A LIGHTNING NETWORK AND DOPPLER RADARS IN THE STATE OF SÃO PAULO TO IDENTIFY AND FORECAST SEVERE STORMS AND ITS APLICATION TO POWER ELECTRIC UTILITIES

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Abstract - The structure of three storm cells spawning tornadoes, of which two occurred on 25 May 2004 in the west of the State of São Paulo, and another one on 24 May 2005 near Campinas, had been observed by IPMet's S-band Doppler radars, located in Bauru and Presidente Prudente, respectively. The development of these three storms (plus a supercell), as well as their three-dimensional fields of reflectivity and air flow relative to the occurrence of lightning, based on RINDAT data, are described in this paper. Signatures, such as a hook-echo and a strong cyclonic vortex ("velocity couplet") in the radial velocity field, typical for the formation of tornadoes, were observed about 30 min before the tornadoes touched down. The temporal evolution of VIL values (maximum ≤50 kg.m^{-2} in the four cases discussed) shows a rapid decrease close to the time of the observed destructive winds at ground level (e.g., tornado). During the touch-down of the tornadoes, the electrical activity dropped to very low stroke frequencies. Results from a 3-D lightning detection network demonstrate the importance of also capturing intra-cloud activity for improving nowcasting of severe storm events. These various signatures, if observed during synoptic situations with high instability, can be used for an automatic alerting system for Power Electric Utilities.

1 INTRODUCTION

Severe storms have a significant impact on power electric systems. Their strong winds, intense lightning activity and, occasionally, the formation of tornadoes, might cause outages in transmission and distribution lines, leading to a significant impact on the quality average indices FEC ("Yearly Interruption Frequency Index") and DEC ("Yearly Interruption Duration Index").

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. However, two tornadoes, which occurred during the afternoon of 25 May 2004 in the western part of the State of São Paulo, had been observed by the S-band Doppler radars of IPMet (Instituto de Pesquisas Meteorológicas) located in Bauru (BRU) and Presidente Prudente (PPR), respectively [1]. Almost exactly one year later, viz. on 24 May 2005, another severe tornado was observed in Indaiatuba, near Campinas, S.P. These three 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 for the electrical industry and the population in Southeast Brazil.

In order to highlight the importance of intra-cloud lightning activity (IC), as well as cloud-to-cloud (CC) flashes, for the early detection of possibly severe convective storm cells, results from observations recorded by the 3-D VHF Broadband Digital Interferometer (DITF) sensors during a joint experiment with Osaka University, Japan, conducted as part of the TroCCiBras (Tropical Convection & Cirrus Brasil) Project in 2004 [2], are also demonstrated.

2 DATA AND METHODS

2.1 Radar observations (IPMet)

IPMet's S-band Doppler radars are located in the central and western State of São Paulo, viz. in Bauru and Presidente Prudente, which is 240 km west of it (275° azimuth; Figure 1). Both have a 2° beam width and a range of 450 km for surveillance (0° PPI every 30 min), 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 the case studies presented for 25 May 2004 and 24 May 2005 was set at 10 dBZ (corresponding to 0,15 mm.h^{-1} rainfall rate), while for the comparison with the 3-D lightning images it was –15 dBZ.

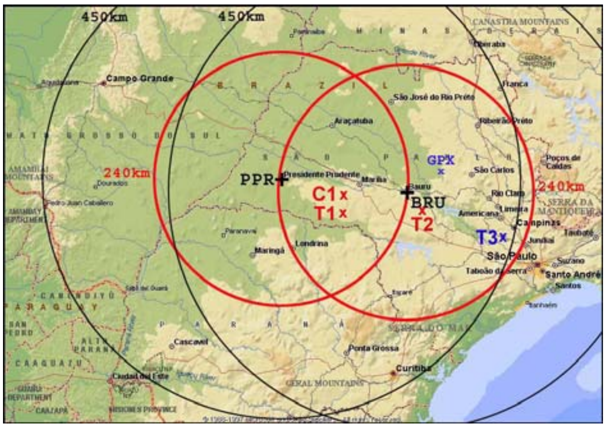

Fig. 1 - IPMet's Radar Network (BRU = Bauru; PPR = Presidente Prudente), showing 240 and 450km range rings. The areas where the tornadoes occurred are marked T1 (Palmital), T2 (Lençois) and T3 (Indaiatuba).

2.2 Lightning observations (RINDAT)

Information on Cloud-to-Ground (CG) strokes was extracted from the RINDAT Data Base, using a geo-referenced system to directly correlate the lightning observations 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 also analyzed.

2.3 Three-dimensional DITF lightning observations

During the TroCCiBras experiment at the beginning of 2004, the LRGOU (Lightning Research Group of Osaka University) operated two DITF systems from 13 February to 25 May 2004, one near the BRU radar (UNIP) and the other one along a 28,6 km base line to the south-east (USJ), as shown in Figure 8 (top).

The main feature of the broadband DITF, which can image precise lightning channels and monitor lightning activity widely, is its bandwidth (from 20MHz to 100MHz) and implicit redundancy for estimating VHF source locations [3]. Based on phase differences for all Fourier components of broadband EM signals, captured by two properly separated antennas, the incident angle of EM signals against the DITF can be estimated. In other words, to obtain one VHF source location, some tens Fourier components contribute, and this "*implicit redundancy*" is the noticeable superiority to any other source location technique. According to initial observations and numerical calculations, an accuracy of 0,01 radians may be feasible. Since it is known that VHF impulses are mainly radiated from the tip of the breakdown-like stepped leader, the VHF impulse source location is equivalent to imaging the lightning channel development, even within a thunderstorm.

A one-system operation only yields azimuth and elevation mapping of lightning channels, which can be related to radar echoes [2]. However, if an area is covered by two or more systems, then it can be used for 3-D imaging.

3 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, accompanied by relatively strong convective activity, due to a strong low-level convergence, overlaid by divergence above 500 hPa, which created very unstable conditions. More details can be found in [4].

Similarly, 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. 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.

4 RADAR ANALYSIS

4.1 Tornadoes and a supercell on 25 May 2004

As the cold front swept across the western part of the State of São Paulo, it was accompanied by relatively strong convective activity. While traversing the farming region of Palmital, one of the storm complexes spawned a tornado 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 (F2-F3 damage on 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, which occurred at around 17:00 about 140 km east of the first one, only caused significant damage to sugar plantations along its 100m wide and 8 km long path, but fortunately no harm was done to persons (F2 damage).
The radar observations from PPR showed the development of a "hook echo", typical for supercell storms in their tornadic stage, at 13:23 (Figure 2, left). 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 a "velocity couplet" with speeds

ranging from about –28 to +9 m.s^{-1}, inducing a local shear reaching –5,2x10^{-3}s^{-1} at 13:46 (Figure 2, right) and 13:53, indicating the presence of a low-level meso-cyclone, typical of tornadic supercells. It is noteworthy, that an even more intense storm, in terms of radar reflectivity (C1), with a well-formed 'Weak Echo Region' at its leading edge, was observed almost 60 km to the north and moving in parallel to the tornadic cell (Figure 3). However, there was no confirmed tornado touch-down. Nevertheless, due to its longevity after first detection at 10:00, as well maintaining radar reflectivities between 50 and 60 dBZ during its four-hour mature lifetime, with radial velocities of up to 35m.s^{-1}, indicating a strong updraft and cyclonic rotational forces between 4 and 9 km height, it is classified as a supercell storm. A more detailed description is given in [4].

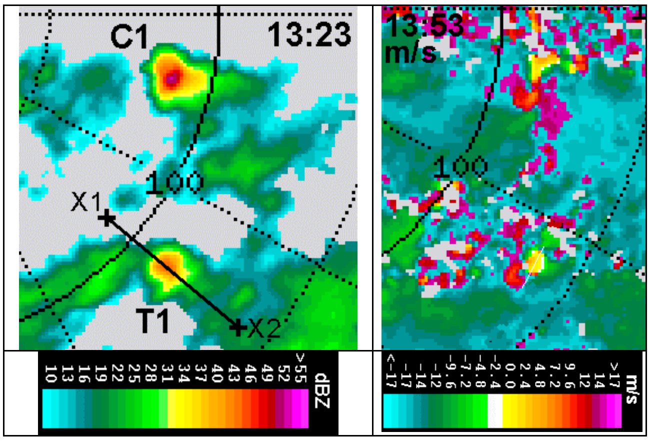

Fig. 2 - CAPPI at 3,5km on 25 May 2004,13:23 (reflectivity, left), showing the development of a "hook echo" (T1), and radial velocity field (right) at 13:53, showing the "velocity couplets" for C1 and T1.

A second tornado was observed at around 17:00 near the town of Lençois Paulista, 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}.

The storm was embedded within an unusually strong air flow 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 south-west flank towards the rear of the storm between 17:00 and 17:30 (Figure 4). 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 life time, the maximum reflectivity was between 55 and 60 dBZ. It is noteworthy, that the echo tops of the storms surrounding the isolated tornadic cell 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.

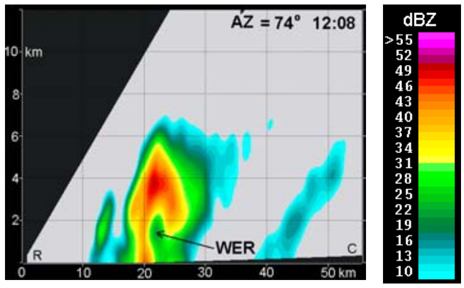

Fig. 3 - Radial cross-section through Cell C1, 25 May 2004, 12:08 (the base line R - C is along azimth 74º.

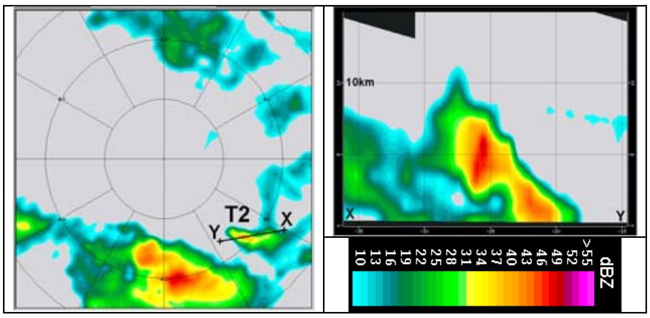

Fig. 4 - CAPPI on 25 May 2004, 17:23 (2,1 km, reflectivity) and vertical cross-section showing the BWER at the rear of Tornado Cell T2.

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 +44 m.s^{-1} just above the reflectivity maximum, with a clear indication of cyclonic rotation on the 11º elevation PPI, with a local shear of –3,0 x10^{-2}s^{-1} at around 2 km. As the storm continued along its track, the rotational signature intensified to reach a maximum of –5,0 x10^{-2}s^{-1} at 17:16 between 2 and 4 km and began to decrease in intensity and descend from 17:23 onwards.

4.2 Tornado on 24 May 2005

At least one of the cells embedded in the general precipitation spawned a tornado, while another one created an exceptionally strong windstorm with cyclonic convergence. This is probably the first time that a multiple-vortex tornado had been recorded on a video in the southern hemisphere, which clearly shows small tornado satellites rotating around the main tornadic axis. This phenomenon is only observed with very intense tornadoes generated by supercells.

At 14:31 (all times in LT=UT-3), an isolated cell was detected about 50km east-south-east of the Bauru radar, which 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, was already observed at 16:08 (Figure 5, left) at a range of 130km, 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 5, right). The first touch-down probably occurred around 17:00, followed by another one shortly before 17:30, confirmed by a sudden absence of cloud-to-ground strokes from this cell, as observed by RINDAT.

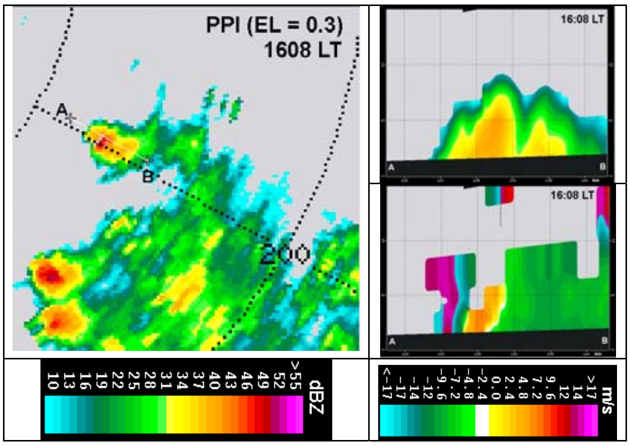

Fig. 5 – Tornado cell T3 on 24 May 2005, 16:08: PPI at 0,3º elevation (reflectivity, left) and vertical cross-section along A-B of reflectivity (right, top) and radial velocities (right, bottom; the negative velocities are folded).

The tornado reached F3 intensity in the Fujita scale during its mature stage, characterizing a significant event, with an estimated damage of US $ 42 million in the urban and industrial areas of Indaiatuba. Preliminary analysis indicates, that the destruction path of the tornado extended for approximately 15 km, with a width of up to 200 m. The trajectory of the tornado followed more or less the motion of the parent thunderstorm.

4.3 Vertically Integrated Liquid water content (VIL)

VIL is a good indicator of storm severity, with VIL ≤7 kg.m^{-2} generally indicating non-severe storms. Highest values observed for C1, T1, T2 and T3 ranged between 40-50 kg.m^{-2}, with a significant drop in VIL values when destructive winds at the surface, e.g., tornado touch-down, were observed.

5 LIGHTNING FEATURES: RINDAT

5.1 Lightning on 25 May 2004

Based on observations of cloud-to-ground (CG) flashes from the Brazilian Lightning Detection Network (RINDAT), the intensive lightning activity of the cells prior to the tornado touch-down, dropped to very low stroke frequencies during the mature tornado stage, after which it increased again (Fig. 6). In contrast, the super-cell storm had relatively constant flash rates of about 6 strokes per minute (occasionally ≤15 min^{-1} [4]). A preliminary analysis of other CG lightning characteristics does not show any significant variation of peak current values, multiplicity and polarity. Additional data is required to identify possible patterns of these parameters.

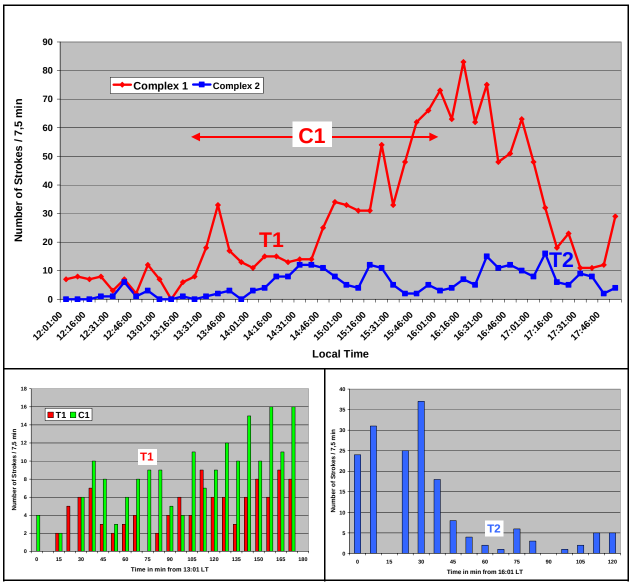

Fig. 6 – 25 May 2004. *Top:* Flash frequencies per radar volume scan (7,5 min intervals) for the tornado and supercell complex, respectively. *Bottom:* Number of CG per radar volume scan per cell (LT=UT-3h).

A comparison of lightning records with radar observations indicates, that the frequency of ground strikes from the first tornado cell was significantly higher before the tornado touched down (Figure 6, bottom left). The first ground strikes 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 [4], and not within the cell core (tornado funnel ?) from 14:01 to 14:16. From 14:23 onwards, only isolated flashes were recorded, which is in agreement with eyewitness reports, stating that it became very dark when the tornado touched down. In contrast, the cell to the north showed a slightly 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 onwards until 15:23, when up to 9 flashes per km^2 were recorded (Figure 6, bottom left), all more or less equally distributed within the cell core [4].

As in the earlier case, intensive lightning activity was observed from the tornadic cell T2 (Figure 6, bottom right) until 17:00, before the tornado touch-down, when no CG flashes were recorded from this cell until 17:30, with the exception of the volume scan from 17:16 – 17:22 (6 strokes). At the same time, ≥70 CG strokes per 7,5 min interval were recorded from the neighboring storm complex.

5.2 Lightning on 24 May 2005

Figure 7 shows, that the lightning activity also decreases sharply just before the touch-down. Again, no variation of lightning parameters (peak current, multiplicity, polarity) was found for the tornadic cell. It is noteworthy, that during a 24-hour period about 20 thousand lightning strokes were recorded in the State of São Paulo by RINDAT, which is an absolute record for May during seven years of observations.

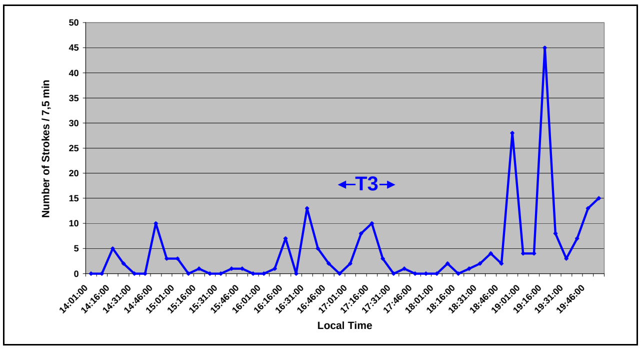

Fig. 7 - 24 May 2005: Flash frequencies per radar volume scan (7,5 min intervals) for the tornado T3.

6 LIGHTNING OBSERVATIONS: 3-D NETWORK

Preliminary single station observations from the VHF Broadband Digital Interferometer network operated in 2004 had already been presented in an earlier paper [2], where the position of the lightning discharges had to be interpolated into the radar echoes. Now, 3-D analysis of lightning discharges observed from the same storm cells had become available. Figure 8 (top) shows the area for which 3-D lightning discharges have been calculated, based on two sets of the DITF, viz. UNIP and USJ. It also shows the various cells (3,5 km CAPPI, volume scan 15:53-16:01), from which the discharges possibly originated, while Figure 8 (bottom) represents the tops of the –15 dBZ echo contour. However, it should be borne in mind, that the radar sensitivity drops off rapidly with distance from the radar, viz. –15 to –10 dBZ is visible up to a maximum of 25 km only.

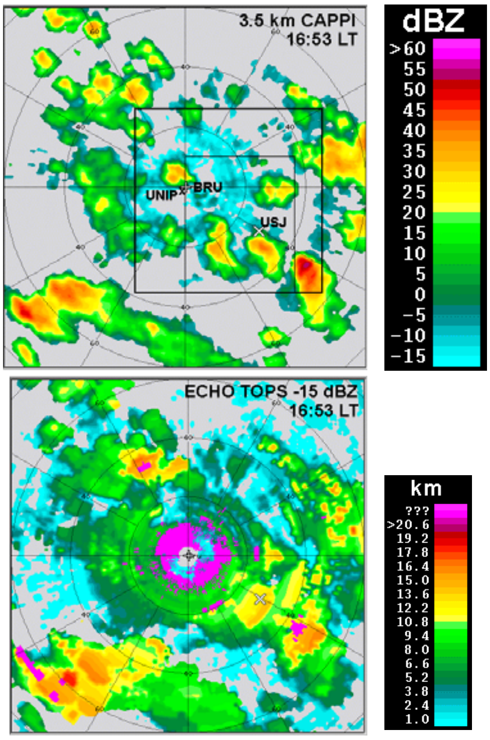

Fig. 8 – *Top:* CAPPI 20 Feb 2004, 16:53 LT, showing the two DITF sites, as well as the frames of 3-D lightning analysis (bold) and the 3-D radar image (thin).
Bottom: Tops of –15 dBZ echo contour at 16:53 LT.

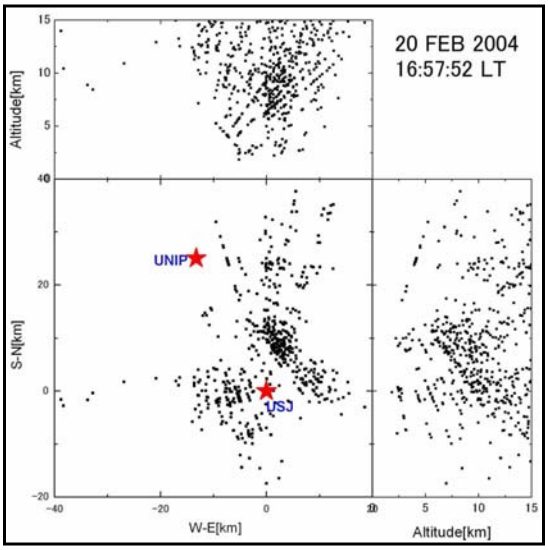

Fig. 9 – X-Y-Z representation of a typical lightning discharge.

Figure 9 shows one event of < 1s duration in an X-Y-Z presentation. Since the storm in the south-east corner of the rectangle shown in Figure 8 was domineering the other cells, a smaller area was chosen for the 3-D comparison of radar contours (10 dBZ) with the lightning discharges (Figure 10; thin rectangle in Fig. 8).

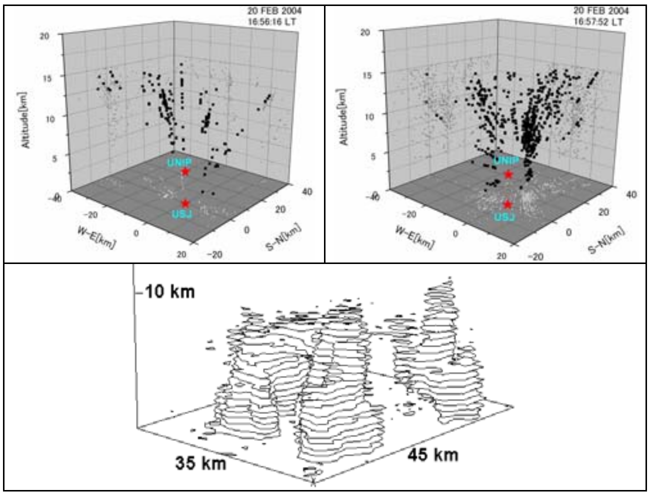

Fig. 10 – Top: 3-D representation of two lightning discharges embedded in the volume scan 16:53-17:01, shown below as a 3-D image of the 10 dBZ echo contour (generated with NCAR's CEDRIC package; small rectangle in Figure 8).

The storm cells producing the lightning discharges were small and in their early life-cycle, but intensified and grew in height as they moved south-eastwards during the subsequent 45 min. It can be concluded from this preliminary analysis, that the top of lightning discharges originates between 10-15 km height, a region of small ice crystals (probably cirrus capping the storm cells; also confirmed in vertical cross-sections), which is well above the normally detectable radar echoes (the 10 dBZ contour reached only up to 9,5 km). This highlights the importance of detecting intra-cloud lightning discharges as an early alert of intensifying cells.

7 CONCLUSION

This study describes an attempt to interpret lightning data from an operational network together with the three-dimensional structure of thunderstorms observed by two S-band Doppler radars in the State of São Paulo.

Three tornados and a supercell storm, linked to isolated cells within an area of strong convective activity created by the passage of a cold front, had been observed by the radars on 25 May 2004 and 24 May 2005, respectively. The synoptic situations were favorable for the development of severe storms, indicated by strong vertical instability on both days. It should be noted, that both cases occurred during the southern hemisphere autumn, and therefore, these cells were not amongst the most intense in terms of radar reflectivity (≤60 dBZ) and echo tops rarely exceeded 12km, but exhibited extremely strong radial velocities and rotational shear (up to $-5{,}0 \times 10^{-2} s^{-1}$ observed so far), which initiated a cyclonic vortex in the center of the cells, spawning the tornadoes. On 25 May 2004, a second severe cell, about 60km north of the tornado and moving in parallel, was classified as a supercell storm, based on its long life cycle of more than four hours. It had almost identical characteristics as its tornadic partner cell, except for a Weak-Echo-Region. However, no reports of damage or the formation of another tornado were received. The temporal evolution of VIL values (maximum ≤50 $kg.m^{-2}$ observed in these four cases) shows a rapid decrease close to the time of the observed destructive winds at ground level (e.g., tornado).

A preliminary analysis of lightning records from the RINDAT Data Base indicated differences in the location of CGs relative to the echo core of tornadic cells and supercells [4], but the strokes need to be positioned more accurately over the radar images. Flash activity almost ceased shortly before the touch-down of the tornadoes.

From 3-D lightning records it is concluded, that during the early stages of cell development, lightning discharges commence up to 5 km above the 10 dBZ radar reflectivity contour, within a layer of small ice crystals. This highlights the importance of detecting intra-cloud lightning discharges as an early indication of intensifying cells.

In this paper, various characteristic storm signatures, based on radar and lightning observations, were identified, that could generate severe cells with a potential of causing destruction, if observed during synoptic situations with high instability. However, more cases of severe storms need to be analyzed, before suitable algorithms can be derived to develop an automatic alerting system for Power Electric Utilities.

8 ACKNOWLEDGEMENTS

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