RESUMO

O início de fevereiro de 2001, na região de Bauru, foi caracterizado por condições de tempo típicas de verão. Três tempestades, relativamente isoladas e quasi-estacionárias se desenvolveram em células extremamente intensas acumulando vastas quantidades de precipitação e granizo acima da base da nuvem por aproximadamente 30 minutos, mantidas por intensos “updrafts” induzidos por cisalhamento ciclônico observado no campo das velocidades radiais, a partir dos dados do radar Doppler de Bauru, e localizados próximos à superfície. Uma vez cessado os “updrafts”, toda precipitação acumulada atingiu a superfície num curto espaço de tempo, resultando em várias regiões de Bauru sendo inundadas durante a ocorrência dos três eventos. A tempestade mais severa ocorreu em 8 de fevereiro de 2001, sobre as regiões sul e oeste da bacia hidrográfica do rio Bauru, com intensidades de precipitação em torno de 200 mm/h, durante mais ou menos 15 minutos, causando enchente súbita nos afluentes e no próprio rio Bauru, dessa vez resultando na perda de cinco vidas e num prejuízo material de R$3.5 milhões. A estrutura tri-dimensional dos campos de refletividade e velocidades radiais dessas três tempestades severas serão apresentadas e discutidas nesse trabalho.

1. INTRODUCTION

The beginning of February 2001 was characterized by a number of days when more or less severe flooding occurred within the municipal area of Bauru. In contrast to general expectations, none of these events was caused by large convective systems traversing the region, but rather due to relatively small, isolated storms, which were obviously very efficient in their rain-production mechanism.

The amount and nature of the rainfalls in the State of São Paulo, coupled with specific surface conditions, mainly in urban areas, can lead to the occurrence of damaging, and in many cases life-threatening, floods. One important example within the Bauru radar coverage area is the urban area of the city of Bauru, where flooding frequently occurs. Figure 1a shows the average monthly precipitation in Bauru, as well as the highest recorded 24-hour rainfall total during the period 1962-1971 (after Calheiros and Longley, 1974), clearly indicating the pronounced seasonal variation. The annual mean total is 1149 mm, of which 80% fall from October to March and almost half (49%) from December to February. The least rainfall is generally recorded during July and August (24 and 19 mm per month, respectively). The highest 24-hour totals during the ten-year period had been recorded during December, January and March with 120, 121 and 118 mm, respectively (Figure 1a).

Figure 1. a) Average monthly rainfall totals and highest rainfall in 24 hours in Bauru (1962-1971); b) Average number of calls to the Bauru Fire Brigade due to flooding; c) Average number of days with ≥ 1 mm rain in Bauru and number of days with > 5 mm rain within 150 km range of the Bauru radar.
The monthly average number of calls to the town’s Fire Brigade, relating to either inundated streets or flooded houses, is obviously directly proportional to the number of severe storms over the town and is depicted in Figure 1b. However, the majority of calls for help falls into the period January to March and is thus more skewed towards the second half of the rainy season (January to March, 59% of all calls), indicating that flood-producing rain systems are more frequent during this period, than during the first half (October to December, 20% of all calls). This is in contrast to the seasonal variation of the average number of days with $> 5$ mm rain within the 150 km range of the Bauru radar (CTH, 1987), as well as days with $\geq 1$ mm in Bauru itself (Calheiros and Longley, 1974), which display a more symmetric seasonal distribution (Figure 1c). This is obviously an indication, that storms with high rainfall rates, i.e., relatively large rainfall amounts in a short period of time, are more frequent from January to March. These storms cause rapid overflowing of the inadequate storm water drainage system of Bauru (and similar towns) and subsequent flooding or severe erosion in suburbs where no drainage of storm water is provided (mostly the more recently developed suburbs). Aggravating circumstances are created by the facts, that Bauru is located in a basin and that the vast majority of its urban area and surrounding slopes are paved, with very little space where rain could penetrate into the ground (gardens and parks), thus going straight into the urban drainage system. Furthermore, during the second half of the rainy season, the river catchments are generally saturated (or close to it), which can easily lead to spates and flash floods in the small rivers crossing the town, as a result of even a small isolated storm producing a heavy downpour in a critical area.

During mid-summer of 2001, parts of Bauru were flooded on several occasions, but two events were remarkable, one due to serious damage to streets in the center of the city, causing subsequent traffic disruptions for several days. The other one, because it produced a flash flood in the Córrego Água do Sobrado and Rio Bauru, inundating some of the lower-lying suburbs, which resulted in the death of five people due to drowning in the floods, three persons being killed as a result of erosion (landslides and collapsing structures), seven cars being swept away, as well as widespread damage to houses and roads (Jornal da Cidade, 9 de fevereiro de 2001 and 8 de fevereiro de 2002). One of the bodies still has not been recovered (Jornal da Cidade, 8 de fevereiro de 2002). The total material damage was estimated at R$ 3.5 million.

In order to devise an effective Nowcasting System, providing a warning at least one hour ahead, but preferably more, one has to look into the synoptic situations leading to the development of these storms, as well as characterize their three-dimensional radar reflectivity and air flow structure.

### 2. SYNOPTIC SITUATION

The beginning of February 2001 was characterized by synoptic situations typical for summer in the interior of the State of São Paulo. In broad terms, it can be summed up by a high pressure system situated off the coast between the State of São Paulo and southern Brazil and ridging in over the continent, with a weak cold front extending along its northern flank across Rio de Janeiro into Minas Gerais. The other component was a large cyclone initially centered over north-western Argentina from where a tongue of moist air extended across Paraguay, Paraná and the State of São Paulo into Mato Grosso do Sul. An other important fact was the strong confluence of wind in the 700 hPa level over the State of São Paulo, overlain by an exceptionally strong divergence $\geq 500$ hPa. Thus, the prevailing instability within this region created favorable conditions for the development of scattered thunderstorms, occasionally in form of squall lines.

On 8 February 2001, such a squall line had formed during the early afternoon over Mato Grosso do Sul, orientated from south-west to north-east. It moved in a south-easterly direction across the western part of the State of São Paulo towards the central interior. It is noteworthy, that a deep cyclone, which had developed over the southern part of the continent on 6 February had drastically intensified while moving south-eastwards, pushing the anticyclone eastwards off the central part of the continent and towards the ocean. This resulted in extremely strong confluence of moist maritime air near the surface over the State of São Paulo. North-east to south-west orientated divergence over the States of Rio de Janeiro and central São Paulo could already be seen at 700 hPa, resulting in a very strong vertical shear in this region.
It is important to note, that on all three days it was a single storm complex which produced high rainfall intensities in a short time, resulting in the flooding of certain suburbs of Bauru. Due to the gradual saturation of the catchment of the Rio Bauru during the preceding days, as well as the mostly paved urban area, most of this rainfall ran off into inadequately dimensioned storm-water drains, which quickly overflowed, causing serious damage to road surfaces, as well as the sudden rise in the level of the Rio Bauru and its tributaries, which then took the lives of five persons, being caught unaware of the flash flood. IPMet had issued a severe weather warning for these days and the Bauru Civil Defense had been informed of possible heavy rainfalls over the urban area of Bauru.

3. DATA AND METHODS

The Bauru S-band radar is located about 6 km south-east of the City center (Lat: 22°21’28” S, Long: 49°01’36” W, 624 m above mean sea level). Since the three storms discussed in this paper were relatively close to the radar (≤ 25 km range), the vertical and horizontal resolution of the reflectivity and radial velocity fields was very high, despite the 2° antenna beam width. Volume scans (elevation 0.3° to 35°) were recorded every 15 minutes on the 240 km range. However, the echo tops (10 dBZ) could not always be observed when the storms were too close to the radar. Although IPMet’s second radar at Presidente Prudente was observing the storms, the spatial resolution of the Bauru storms was poor due to the fact that they mostly occurred at the edge of its 240 km range.

The post analysis of the archived data was performed using the IMAGE and ANALYSIS Software packages. All times quoted in this paper are Local Time as recorded by the radars (LT = GMT+3h), thus Summer Time would be LT+1h; all heights are above mean sea level (amsl). The reflectivity threshold for the analysis was set to 10 dBZ. Radial velocities away from the radar are depicted in warm colors (positive velocities), while cold colors indicate that the radial velocity component was towards the radar (negative velocities).

4. RADAR OBSERVATIONS ON 3 AND 4 FEBRUARY 2001

On both days, flooding of the streets in the suburb of Vila Universitária (and possibly other suburbs), as a result of overflowing storm drains, was caused by an isolated, small, but intense storm complex, which lasted in the order of 45 minutes.

4.1 3 February 2001

On 3 February 2001, a storm just west-north-west of Vila Universitária was observed shortly before 14:00, about 13 km north-west of the radar (Cell 1). The first echo was detected aloft between 3 and 7 km amsl at 13:46, but by 14:01 it had already reached the ground, with its echo core (≥ 30 dBZ; maximum reflectivity ≤ 60 dBZ) extending to 5 km and its echo top (10 dBZ) up to 7.2 km.
The radial velocity field was relatively weak (\( \leq -5 \) m.s\(^{-1}\)) in the core region, but a strong downdraught (radial velocities \( \leq +14 \) m.s\(^{-1}\)) initiated development of new cells on its western flank (Figure 2, left). The cell movement was towards east-south-east at about 18 km.h\(^{-1}\). It reached its maximum intensity between 14:01 and 14:16, but by 14:31 almost all the rain had reached the ground, while the cell was in the process of collapsing. It totally dissipated before 15:00. A second cell (C2), which had developed simultaneously about 15 km further to the north-west, developed stronger in its horizontal and vertical extent due to a strong updraught with radial velocities of up to \(-15\) m.s\(^{-1}\) in the core, but \(+15\) m.s\(^{-1}\) exiting through its anvil > 10 km amsl in a north-westerly direction, resulting in a longer lifetime (Figure 2, right). Echo tops (10 dBZ) reached 15 km, new cells developed on its north-western flank, stimulated by a strong downdraught (radial velocities \(+7\) m.s\(^{-1}\)) from the mother cell (Figure 2, right), while the complex also moved towards east-south-east at 18 km.h\(^{-1}\), like Cell 1. By 15:16 the whole multicellular complex had collapsed, producing more rain over the catchment area and thus also contributing to the observed flooding.

Larger complexes were observed in the north-west (Held and Calheiros, 2001), as well as in the western and south-eastern sectors (Figure 2, right), but none of these storms actually reached Bauru.

4.2 4 February 2001

On 4 February 2001, an isolated, small storm complex, comprising three cores, developed shortly before 15:46 just west-south-west of Bauru, with new cell development taking place on its eastern flank. Figure 3 shows its position between 15:46 and 16:31. The easternmost cell was due south of Vila Universitária at 16:01, propagating in a northerly direction across the suburb at 13 km.h\(^{-1}\) and producing pea-sized hailstones along its paths. At 15:46 the PPIs indicated radial velocities of up to \(-6\) m.s\(^{-1}\) for the Vila Universitária storm, with no horizontal or vertical shear. However, vertical cross-sections showed an intense core (\(\pm 55\) dBZ) suspended above cloud base (1.5-2 km amsl). Vertical section some 15 minutes later confirmed the core to be still accumulating aloft, with reflectivities of up to 60 dBZ. This would require a strong updraught, which was not well captured by its radial-component velocity field. However, at 16:01 the low-level PPIs showed a radial shear on the eastern flank of the cell, probably inducing a cyclonically (clockwise) rotating updraught, which could support the accumulated rain and hail aloft in the intense core.
The radial velocity shear was in the order of –7 to +7 m·s⁻¹ and could still be observed at 16:16. However, at that stage the updraught began to weaken and the precipitation, including hail, suddenly dropped to the ground. The storm disintegrated before 17:00 with all precipitation having reached the ground. Due to the close proximity to the radar of the cell moving across Vila Universitária, its vertical extent can only be extrapolated from its neighboring cells. Echo tops (10 dBZ) are estimated at > 10 km, with its core (≥ 30 dBZ) extending to at least 10 km (maximum reflectivities ≥60 dBZ).

Again, large storm complexes brought good rains in the western sector of the Bauru radar (> 40 km). Later during the afternoon, the storms in the south-eastern sector developed into very large and intense Complexes (Held and Calheiros, 2001).

The flooding of Vila Universitária caused by this isolated cell described above, has been documented in Figure 3. The photographs were taken from the 8th floor of Residencial Tahiti. Figure 4a shows the storm water running down in Rua São Gonçalo, after lifting several storm drain covers in the process of overflowing the drains, and then turning into Rua Joaquim da Silva Martha towards Avenida Nações Unidas. Figure 4b provides an indication of the depth and forces of the water - the parked cars are in fact floating down Rua São Gonçalo. The flood waters stripped large areas of the tarred surface in Rua Joaquim da Silva Martha and left deep holes.

Figure 3. Development of the flood-producing storm on 4 February 2001 from 15:46 to 16:31. The height of CAPPIs is shown in the individual scans (radar reflectivity in dBZ).

Martha towards Avenida Nações Unidas. Figure 4b provides an indication of the depth and forces of the water – the parked cars are in fact floating down Rua São Gonçalo. The flood waters stripped large areas of the tarred surface in Rua Joaquim da Silva Martha and left deep holes.

Figure 4. Bauru, Vila Universitária, 4 February 2001. a) 16:20, looking uphill in Rua São Gonçalo at the intersection with Rua Joaquim da Silva Martha; b) 16:23, parked cars floating in Rua São Gonçalo.
5. RADAR OBSERVATIONS ON 8 FEBRUARY 2001

The Bauru radar observed initially small, scattered thunderstorms in the north-west to east sector from shortly after noon onwards. By mid-afternoon, some of these storms had consolidated and intensified into large multicellular complexes, especially in the east and north-east between 70 and 200 km from Bauru (Figure 5). The complex in the east developed rapidly on its southern flank and towards the radar (16:46 to 18:16). At the same time, a storm complex in the north-north-east (at 17:01 it was about 70–150 km from the radar, Figure 5), rapidly developed new cells with high reflectivity on its south-western flank.

From 18:31 onwards, these eventually formed into a narrow line of storms from about 70 km north-west to 50 km south-east of the radar (Figure 5) along the boundary between dry and moist air, as can be seen from the satellite picture at 15:00 (Figure 6).

The IMAGE post-analysis Software Package can identify microbursts from the radial velocity field. The first such signature was observed at 17:01, about 18 km north-west of the radar, and at 18:31 a microburst warning was identified already over the north-western catchment area of the Rio Bauru, while only relatively light rain fell over the catchment (Figure 7). This was more than one hour before the heavy downpour which caused the floods. Microburst warnings over the larger catchment of the Rio Bauru were regularly calculated by IMAGE between 17:01 and 20:31, thus identifying small areas of strong divergence and convergence, being indicative of the likely development of severe storms.

Figure 5. Scattered storms during the afternoon of 8 February 2001 leading to the formation of the line of intense small cells across Bauru (radar reflectivity PPIs at 0.3° elevation, range 240 km of the Bauru radar).

Figure 6. Meteosat-7 infrared image, 8 February 2001, 18:00 UT (15:00 LT). Source: INPE.

Figure 7. Microburst signature within the catchment of Rio Bauru on 8 February 2001, 18:31. The watershed is indicated by the black arch and the severest flood area by an X.
The series of images of the radar reflectivity and radial velocity depicted in Figure 8 clearly show the development of the sudden downburst over the western suburbs of Bauru (Vila Falcão, where the flash flood took three lives in two separate incidents, is about 7 km north-west of the radar). The Bauru radar gave the very first indication of the development of an extremely severe cell at 18:16. Figure 8a shows a cross-section through the storm before any rain reached the ground. Radar reflectivities in the core exceeded 60 dBZ, supported aloft by strong radial velocities of up to +7 m.s\(^{-1}\), also causing a dramatic tilt of the core towards north-west, i.e. away from the catchment. A significant shear of radial velocities (-5 m.s\(^{-1}\)) is indicated above 7.5 km. Unfortunately, actual echo tops cannot be seen, because the storm was very close to the radar.

At 18:31, the storm was still not reaching the ground level, as can be seen in the traverse cross-section (Figure 8b). The radial cross-section at this time (far right) indicates an increase in radial shear to about +13 m.s\(^{-1}\) in the core and -11 m.s\(^{-1}\) near the top. The situation over the catchment remained unchanged, except that a strong shear of radial velocities occurred along the 330° radial at 18:46, which induced a cyclonic (clockwise) rotation, forming a strong updraught capable to support the vast amount of precipitation above cloud base.

By 19:01, heavy rain began to fall over the south-western part of the Rio Bauru catchment from very intense echo cores (Figure 8c). The 30 dBZ contour reached up to 8.5 km and echo tops (10 dBZ) were between 13-15 km. The shear zone had shifted south-westwards over the western part of the catchment and radial velocities near ground increased to +13 m.s\(^{-1}\) and -8 m.s\(^{-1}\) (Figure 8c), supporting a strong updraught which maintained the accumulated precipitation aloft. Only at 19:16 began the echo core to descend and heavy rain fell over the catchment of the Córrego Água do Sobrado. Echo tops (10 dBZ) were estimated to be ≤ 15 km, with the 30 dBZ contour probably reaching ≥ 11 km. At 19:31 the updraught seems to have collapsed and a deluge of rain came down, mainly over the western part of the Rio Bauru catchment, causing the catastrophic flood at about 19:30 (20:30 summer time). Radar reflectivities between ground level and 4 km were ≤ 55 dBZ, corresponding to a rainfall rate of approximately 150-200 mm.h\(^{-1}\) (Figure 8d). This lasted for more than 15 minutes. Only by 20:01 had the reflectivity over the catchment dropped to ± 45 dBZ (50 mm.h\(^{-1}\)). The rain in the inundated area stopped between 20:16 and 20:31. However, other parts of Bauru still received moderate rain until well after 21:00.
Figure 8. Details of the development of the Bauru flood-producing storm on 8 February 2001 between 18:16 and 19:31, PPIs at 1.7° elevation, radar reflectivity (dBZ) and radial velocities (m.s\(^{-1}\)).

The accumulated rainfall measured at the radar site was about 50 mm within a 45-minute period, amounting to 22% of the rainfall total recorded in February 2001 or 29% of the long-term average (Figure 1).

5. CONCLUSIONS

The findings of these three case studies clearly highlight the importance of identifying severe storms, which could cause serious damage to property or threaten lives, as early as possible in order to be able to issue early warnings to the relevant organizations and authorities.

However, during the first 10 days of February 2001, the synoptic situations were typical of summer conditions, with little indication of severe storm development in specific areas. Furthermore, the flood-producing storms were relatively small and had developed locally within short periods of time and being almost stationary, thus only giving short lead times to IPMet’s meteorologists to issue warnings based on radar observations. Even using the maximum sensitivity of the radar signal, the convergence areas indicating regions of storm development (before the detection of actual rain echoes) could only be detected 15 – 30 minutes prior to the storm formation, but with little indication of the future severity of the storm. However, utilizing the post-analysis IMAGE microburst-detection module, a region of possible severe storm development was indicated for the Bauru area more than one hour prior to the first severe radar echoes on 8 February 2001.
A severe rain warning had been issued to the Civil Defense Organization in Bauru on 8 February 2001. However, due to the suddenness of the downpour, resulting in rapid swelling of the rivers, five lives had been lost. Since in this particular case the lead-time for the Nowcast Warning issued by IPMet for the urban area of Bauru was relatively short, in the order of only two to three hours (but not for any specific suburb), rapid and efficient dissemination of warnings to the public is essential. Furthermore, the Civil Defense Authorities need to improve public awareness of the possible consequences of such events and re-iterate how an individual should deal with such a situation, in order not to endanger his/her own life and possibly those of the rescue team.

The lesson for Bauru’s Municipality is, that the storm-water drainage system of the town needs to be improved as a matter of urgency, including the harnessing and regulating of all river channels within the urban area, in order to avoid more losses of lives. Thunderstorms producing 40-50 mm of rain over a small catchment are not unusual in the Bauru area, resulting in frequent inundation and flash floods.

Finally, the need for monitoring the actual three-dimensional air flow within the storms, rather than only radial velocities, in efforts to improve the understanding of storm mechanisms and structures, has been clearly highlighted through this study. Therefore, high priority should be given to the upgrading of the Bauru radar facility to perform multiple Doppler radar observations, either by adding a C-band Doppler radar or by installing several bistatic Doppler receivers to facilitate the calculation of the three-dimensional air flow inside convective systems at least within a limited range. Also, the microburst-detection algorithm, as well as storm-tracking, need to be implemented for the Bauru radar to run in real time.

6. ACKNOWLEDGEMENTS

HAG França is thanked for assisting with the retrieval and pre-processing of the raw radar data. Defesa Civil and the Corpo de Bombeiros of Bauru are acknowledged for making their records (1995 – 2001) available. J L Gomes of the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) is thanked for supplying the GCM data to visualize the surface pressure and divergence maps, while the Instituto Nacional de Pesquisas Espaciais (INPE) is acknowledged for providing the satellite pictures. Agradecimentos a AM Gomes Held pela versão em português do resumo.

7. REFERENCES


