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FORECASTING A SEVERE WEATHER OCCURRENCE IN THE STATE OF SÃO PAULO, BRAZIL, ON 24 MAY 2005: THE INDAIATUBA TORNADO

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1. INTRODUCTION

Severe storms in Southeast Brazil frequently cause enormous damage to agriculture, urban areas, industries, as well as loss of many lives, due to strong winds (relatively frequent microbursts and occasional tornadoes), hailstones, intense lightning and flash floods, resulting in many millions of US Dollar damage annually. Efforts had been concentrated on identifying specific signatures during severe storm events (Gomes *et al.*, 2000, Held *et al.*, 2001, 2005; Held and Nachtigall, 2002), which could be used as indicators of storm severity, as well as to develop algorithms for short-term predictions. However, it is of equal importance to develop an effective alert system for the occurrence of such severe events, ranging from a couple of days (based on model outputs) to 30 min to three hours ahead (nowcasting, using radar information).

The Meteorological Research Institute (IPMet) of the São Paulo State University (UNESP), based in Bauru, in the geographic center of the State, operates a network of two S-band Doppler radars for continuous precipitation monitoring (Figure 1), which provided the ideal tools for testing the model capabilities in terms of the accuracy of predicted parameters, as well as the most reliable time range.

The Bauru radar is located at Lat: 22° 21' 28" S, Lon: 49° 01' 36" W, 624 m amsl, while the second radar is in Presidente Prudente, 240 km west of Bauru (275° azimuth), at Lat: 22° 10' 30" S, Lon: 51° 22' 22" W, 460 m amsl. Both have a 2° beam width and a range of 450 km for surveillance (0° PPI every 30 min), but when operated in volume-scan mode every 7.5 or 15 minutes it is limited to 240 km, with a resolution of 1 km radially and 1° in azimuth, recording reflectivities and radial velocities.

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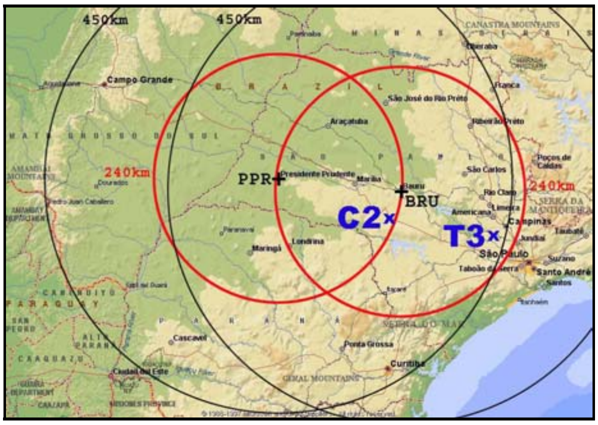

Figure 1. IPMet's Radar Network (BRU = Bauru; PPR = Presidente Prudente), showing 240 and 450 km range rings. The areas where the tornado and the wind storm occurred are marked T3 (Indaiatuba) and C2 (Iaras).

The operational Eta model (Black, 1994) is run by the Center for Weather Forecast and Climatic Studies (CPTEC) twice daily (00 & 12 UTC) for the South American continent and initiated with the NCEP analysis (resolution T126L28; ca 100x100 km). On the boundaries it is updated with the CPTEC Global Model forecasts. The output has a resolution of 40x40 km, for every 6 hours up to 168 hours ahead. The Meso Eta model (Staudenmaier, 1996), running in non-hydrostatic mode, is also initialized with the NCEP analysis, but the boundary conditions are updated with the CPTEC/Eta operational model (resolution 40x40 km). Its domain is 1300x840 km and can be centered over any point. The output resolution is 10x10 km, with variable output intervals up to 96 hours ahead. For this case study, the model domain was centered over Bauru with output every 3 hours.

In a pilot study, the Meso-Eta model in its above configuration was deployed to retro-spectively predict a severe urban flash flood in Bauru (Held and Gomes, 2003). The results showed, that model runs made about 48 hours prior to the flood event yielded the most accurate predictions in terms of onset times of rainfall, regions of rainfall maxima and severity of the event in the Bauru region.

2. SYNOPTIC SITUATION

The synoptic situation on 24 May 2005 showed a true severe weather outbreak, dominated by the passage of a baroclinic system, with a cold front moving rapidly in a north-easterly direction (35-40 km.h^{-1}) from southern Paraná (12UT=09:00 LT) to the central State of São Paulo (21:00 LT). This intensified the already strong divergence at 200 hPa over the south-eastern part of the State (Figure 2), and together with the embedded jet stream, created areas of extreme instability, resulting in widespread pre-frontal rainfalls over the southern parts of the State of São Paulo (Figure 3; all radar images are marked in local time LT=UT-3h). 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. At least one of the cells spawned a tornado in the town of Indaiatuba (ca 25 km south-west of Campinas; T3 in Figure 1) with F3 intensity on the Fujita scale (Fujita, 1981; estimated damage of about US $ 42 million), while another one generated an exceptionally strong windstorm with cyclonic convergence in the small town of Iaras (C2 in Figure 1), about 60 km south-south-west of the Bauru radar, causing an estimated damage of US $ 1 million.

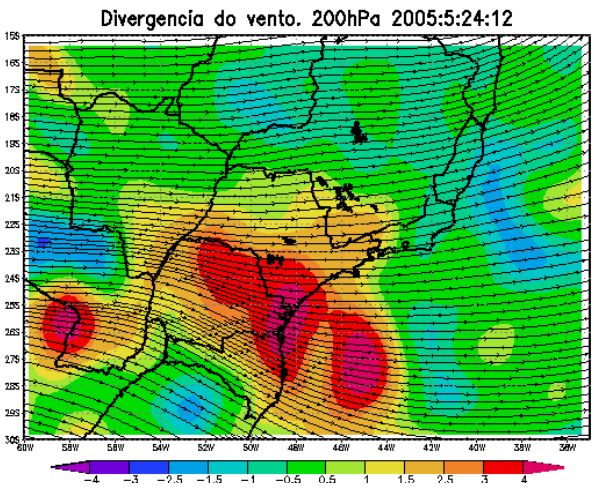

Figure 2. Divergence and air flow at 200 hPa on 24 May 2005, 1200UT (09:00 LT), Regional Eta analysis (40x40 km; units $10^5 s^{-1}$). (Source: CPTEC/INPE).

The destruction path of the tornado extended for approximately 15 km, with a width of up to 200 m, traversing the outskirts and industrial district of Indaiatuba. Several motor cars were overturned, roofs, concrete walls and pillars demolished, electricity lines interrupted, as well as 22 railroad cars pushed off their track (Nascimento and Marcelino, 2005). The trajectory of the tornado followed more or less the motion of the parent thunderstorm, viz., from west-north-west to east-south-east.

3. RADAR OBSERVATIONS

The first small echoes were observed in the far south-western part of the State of São Paulo shortly before midnight on 23 May 2005, rapidly developing into a significant system of storms which moved eastwards. This resulted in considerable rainfall rates over many parts of the State. At 04:00 new cells began to develop over eastern Mato Grosso Sul and western Paraná, also rapidly expanding and moving across southern São Paulo and northern Paraná, as shown in Figure 3 for selected times. The remainder of the earlier storms can be seen over

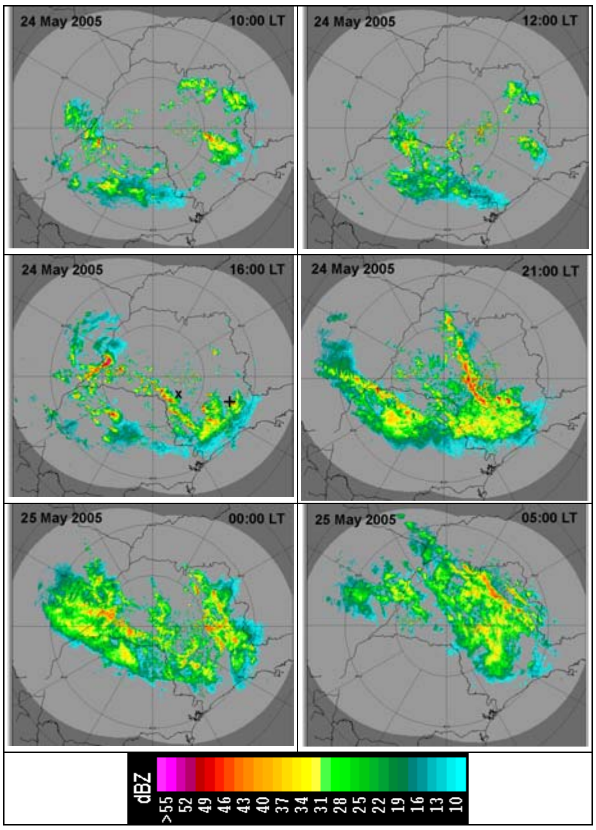

Figure 3. Composite radar images on 24/25 May 2005: PPIs at 0° elevation, range 450 km. (x and + at 16:00 LT indicate the towns of Iaras and Indaiatuba, respectively).

the eastern State at 10:00 and 12:00. More storms developed in the north during late evening, as shown at 21:00, resulting in rain over most parts of the State until after 09:00 the next morning.

A detailed study of the three-dimensional structure and behavior of the severe storms, which occurred on 24 May 2005, as well as tracks and various radar-derived parameters, are presented in a companion paper (Held *et al*., 2006). In the present paper, the radar observations were used to verify the Meso-Eta model predictions, especially the accumulated rainfall.

Hourly accumulated rainfall was derived from 3.5 km composite CAPPIs of the PPR and BRU radars, generated from Volume Scans every 7.5 min and using the Marshall–Palmer Z-R relationship (Marshall and Palmer, 1948) to convert the radar reflectivity (Z in dBZ) to actual rainfall (R in mm). These hourly rainfall totals were subsequently integrated for 3 and 24 hours, respectively, using GrADS.

4. EVALUATION OF MODEL PREDICTIONS

A variety of global and regional models is in operational use in Brazil and forecasts are being disseminated by the Center for Weather Prediction and Climate Studies (CPTEC/INPE), the Brazilian Meteorological Office (INMET) and the Department of Atmospheric Sciences (IAG) of the University of São Paulo (USP). However, in this study only output from the operational Eta model from CPTEC, as well as from the non-operational Meso-Eta model installed at IPMet in Bauru, was used to examine the atmospheric environment in which the tornadic thunderstorm on 24 May 2005 developed.

4.1 Operational Eta Model

Despite the relatively low latitude of the region, the synoptic pattern over the State of São Paulo on 24 May 2005 displayed characteristics often associated with classic mid-latitude severe weather outbreaks. Severe convective storms developed ahead of a migratory baroclinic system, shown as a 500 hPa trough in Figure 4, where synoptic-scale upward motion was favored (shaded areas). Thus, large-scale destabilization was in effect over the State that afternoon. In fact, the Eta-CPTEC 6-hr forecast sounding for the nearest grid point to the tornado occurrence displayed a relatively high surface-based convective available potential energy (CAPE) of 1700 $J.kg^{-1}$.

Moderately strong mid-level westerly winds around 20 $m.s^{-1}$ (Figure 4) were also predicted (the 12UT model analysis already showed this pattern), with the bulk Richardson number shear over Indaiatuba reaching 70 $m^2.s^{-2}$. Predicted storm-relative helicity (SRH) in the first 3 km, using observed storm motion determined by radar data analysis, reached -134 $m^2.s^{-2}$, which does not seem a significantly low value for SRH for the southern hemisphere (Nascimento, 2005a). However, the lack of a climatology of SRH during severe weather episodes for South America precludes any conclusive remark regarding the actual significance of the SRH magnitude found. Nevertheless, the concomitant presence of convective instability and moderate vertical wind shear was characterized.

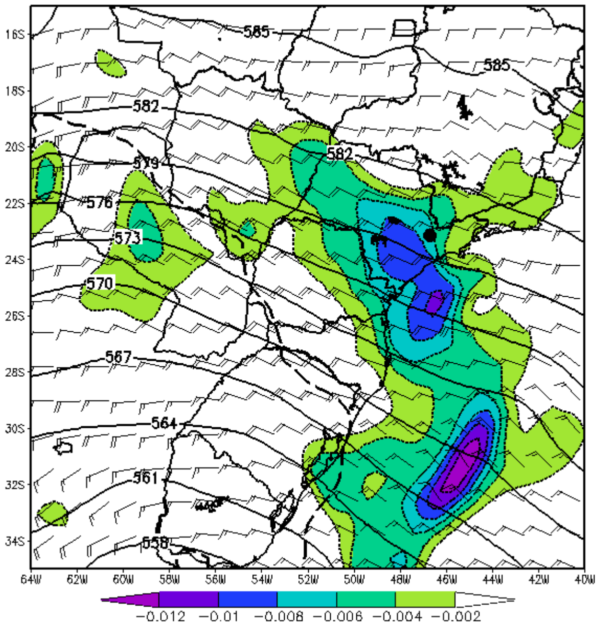

Figure 4. Eta-CPTEC 6-hour model forecast for 500 hPa geopotential heights (contours in dam), winds (barbs in 5 and 10 $m.s^{-1}$) and upward motion (shading in $2 \cdot 10^{-3}$ $Pa.s^{-1}$ intervals), valid at 18UT (15:00 LT) of 24 May 2005. The bold dashed line indicates the predicted position of the wind shift associated with the surface cold front, and the black dot marks the geographic location of Indaiatuba.
(Source: CPTEC/INPE).

At the surface, a wind shift associated with the cold front advanced over southern Brazil (long-dashed line in Figure 4), with line-oriented convective storms developing along the frontal convergence and isolated storms forming ahead of it. Low-level moisture advection was promoted by north-westerly winds of >15 $m.s^{-1}$ at 850 hPa.

Surface winds over the State of São Paulo, predicted by the Regional Eta-CPTEC model were from north-west. However, METAR observations at Campinas airport, only about 12 km north-east of Indaiatuba, reported persistent winds from the northeast that afternoon, indicating that the actual directional vertical wind shear was more intense than that predicted by the Eta-CPTEC model. Isolated tornadic supercells are indeed favored in environments with strong directional vertical wind shear at low-levels (Klemp, 1987). It is important to mention that, for the computation of the shear parameters mentioned above, the model-predicted surface winds were replaced by the 18UT METAR-observed wind at Campinas airport, representative of the storm inflow. Thus, the wind profile was modified at the surface to better represent the observation. The high-CAPE and high-shear environment predicted by the model (with observed surface wind) yielded the significant values of energy-helicity and supercell-composite parameters of -2.2 and -4.8, respectively, which are potentially indicative of supercell formation for the Southern Hemisphere (e.g., Nascimento 2005a). Hence, the predicted severe weather parameters did display skill in highlighting the existence of a pre-storm environment that was favorable for significant severe weather development in the Indaiatuba region that afternoon.

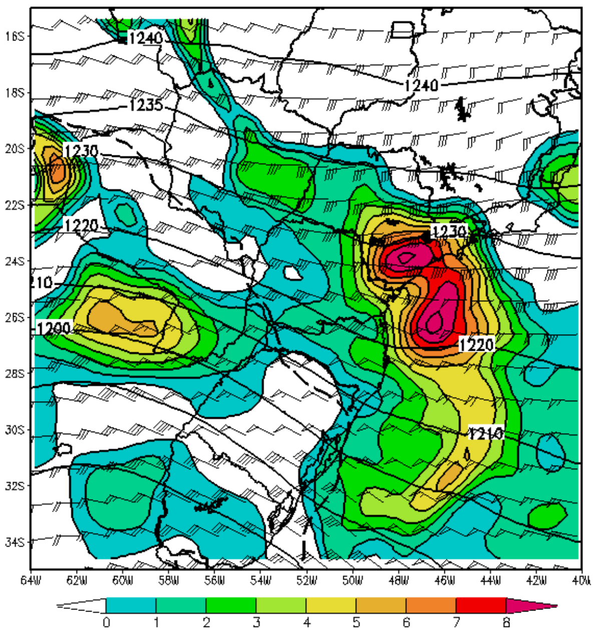

Figure 5. Eta-CPTEC 6-hour model forecast for 200 hPa geopotential heights and divergence ($10^{-5}s^{-1}$) valid at 18UT (15:00 LT) of 24 May 2005 (as in Figure 4). (Source: CPTEC/INPE).

Upper-level divergence was predicted over most of the State of São Paulo that afternoon (Figure 5), with diffluent flow over the eastern sections of the State. This upper-level pattern provided further support for strong deep convection.

In order to better characterize the severe weather environment over Indaiatuba, high resolution idealized numerical experiments were conducted, using Eta-CPTEC sounding forecasts for Indaiatuba as background horizontally-homogeneous environments with convection being initiated by the specification of a low-level thermal. However, simulations failed to produce long-lived thunderstorms, which may indicate a limitation of such approach for operational purposes (Nascimento, 2005b).

Given that the analysis of severe weather indices still represents an ongoing work in Brazil and that the idealized high resolution numerical experiments did not provide useful information regarding the characterization of the severe weather environment in the Indaiatuba case, additional justification exists to explore the importance of radar and lightning data for nowcasting and alert purposes in Brazil (Held *et al.*, 2006).

4.2 Meso-Eta Model: Bauru

IPMet, in collaboration with CPTEC, runs the Meso-Eta model, centered over the Bauru radar, with a temporal resolution of 3 hours up to 48 hours and a grid spacing of 10x10 km, in a non-operational research mode (Held and Gomes, 2003). The model, initialized on 23 May 2005, 00UT, already predicted the incoming baroclinic system for the afternoon of 24 May 2005 (12:00, 15:00, 18:00 LT) quite accurately in various fields of variables, viz., CAPE, divergence and airflow at 300 hPa, K-index, humidity convergence at 850 hPa and also Omega (uplifting motion) above 850 hPa. It is especially noteworthy, that the region around Indaiatuba was already indicated for the development of severe storms in most of the predictants (e.g., CAPE at 18:00 around 1200 $J.kg^{-1}$, with a nearby maximum of $\leq$1800 $J.kg^{-1}$), but especially the 300 hPa divergence and the 850 hPa humidity convergence fields, as well as the Omega at 500 and 300 hPa, as shown in Figure 6.

Since no radiosonde data are available from Bauru for this day and the nearest stations are São Paulo (285 km south-east), Curitiba (upstream, 360 km south) and Campo Grande (downstream, 610 km north-west), vertical "radiosonde" profiles were derived from the model for Bauru, Indaituba and Iaras from runs initiated up to 48 hours ahead of the severe storms (Figures 7 - 9) and compared to the analysis for Bauru and the actual radio-sounding from São Paulo on 24 May 2005, 12UT (09:00 LT).

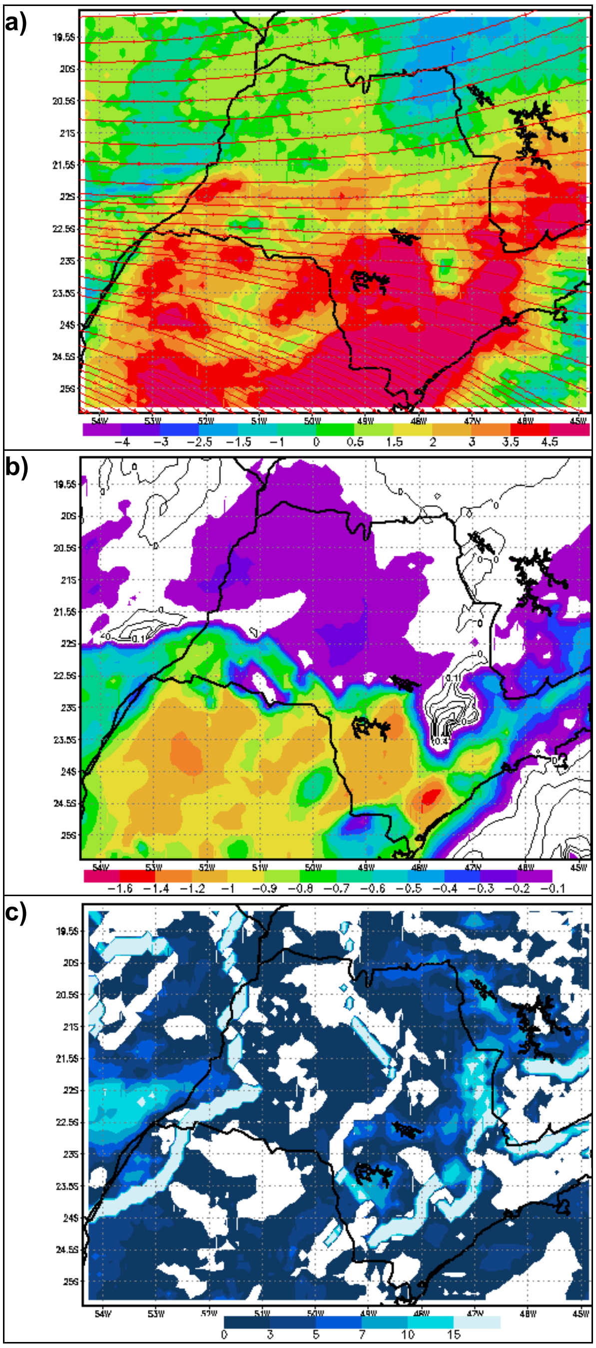

Figure 6. Outputs from the Meso-Eta model, initiated on 23 May 2005, 00UT, for 24 May 2005, 21UT (18:00 LT): **a)** Divergence at 300 hPa ($10^5 s^{-1}$); **b)** Omega ($Pa.s^{-1}$); **c)** Convergence of humidity (units: $[(kg/kg)/s]x10e^7$).

The two profiles for Bauru in Figure 7 agree reasonably well, indicating a good forecast. Obviously, the CAPE at 09:00 LT in the analysis was lower than the one predicted for the afternoon (15:00 LT), viz., 412 and 896 $J.kg^{-1}$, respectively. In contrast, the analysis (09:00) for Iaras and Indaiatuba, respectively, indicated a CAPE of 298 and already 1264 $J.kg^{-1}$. The 6-hour forecast gave the CAPE values at 3387 and 3615 $J.kg^{-1}$, respectively, which is more than twice that predicted by the regional Eta model. Since the CAPE represents the surface-based convective available potential energy, the values predicted for Iaras and Indaiatuba, being about four times greater than for Bauru, signal the likelihood of severe events in those two regions.

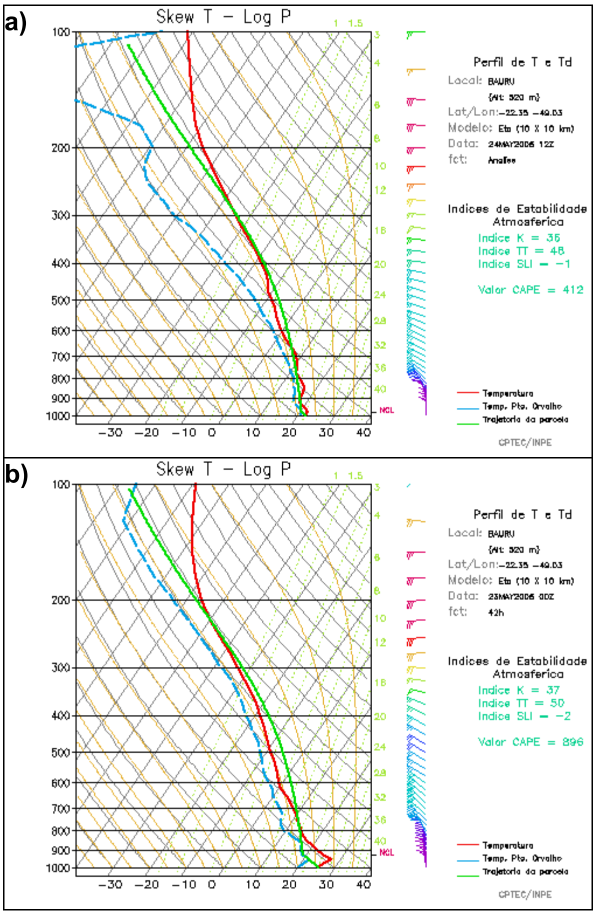

Figure 7. Vertical sounding profile generated by the Meso-Eta model for Bauru, 24 May 2005. **a)** Analysis at 12UT (09:00 LT); **b)** 42-hour forecast for 15:00 LT, initiated on 23 May 2005, 00UT.

The CAPE predicted for Iaras 42 hours before the severe wind storm occurred there, was 2403 $J.kg^{-1}$ (Figure 8), also a good indication for severe convection to take place.

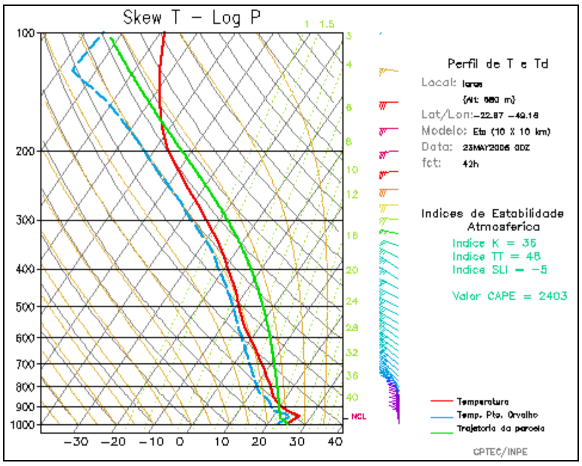

Figure 8. Iaras: Vertical sounding profile generated by the Meso-Eta model, 42-hour forecast for 24 May 2005, 15:00 LT, initiated on 23 May 2005, 00UT.

Figure 9a shows the sounding predicted for 15:00 LT at Indaiatuba, about two hours before the tornado was observed (17:00 – 17:35; Held *et al.*, 2006) with an anticipated CAPE of 2199 J.kg^{-1}. This was about one-third lower than the 6-hour forecast mentioned earlier, but considering the 42-hour forecast margin, still an acceptable indicator for severe storms. In contrast, the prediction for Bauru, based on the same model run, was only 896 J.kg^{-1} (Figure 7b), and no severe storms occurred there.

In order to verify the vertical profiles generated by the Meso-Eta model for Indaiatuba, the 36-hour predicted sounding (09:00 LT, Figure 9b), is compared with the actual sounding from São Paulo at 09:00 LT (12UT, Figure 9c), which is only about 85 km south-east from where the tornado occurred. Both temperature and the wind direction profiles agree remarkably well, including the marked wind shear at around 800 hPa. However, observed wind speeds were higher than those in the 36-hour forecast. The CAPE calculated from the actual sounding in São Paulo (09:00 LT) was only 27 J.kg^{-1}, while the predicted value for Indaiatuba was 296 J.kg^{-1}, which could have already signaled the forthcoming severe event there. As can be seen from Figure 9a, this value increased to 2199 J.kg^{-1} during the afternoon (15:00 LT; 42-hour forecast). The other instability indices were similar for the morning soundings (Figure 9b,c), but increased likewise in the 42-hour forecast (Figure 9a).

It is important to mention, that the Meso-Eta model provided an improved forecast for the direction of the surface winds at Indaiatuba in comparison to the solution from the Regional Eta model. Campinas' METAR reported surface winds

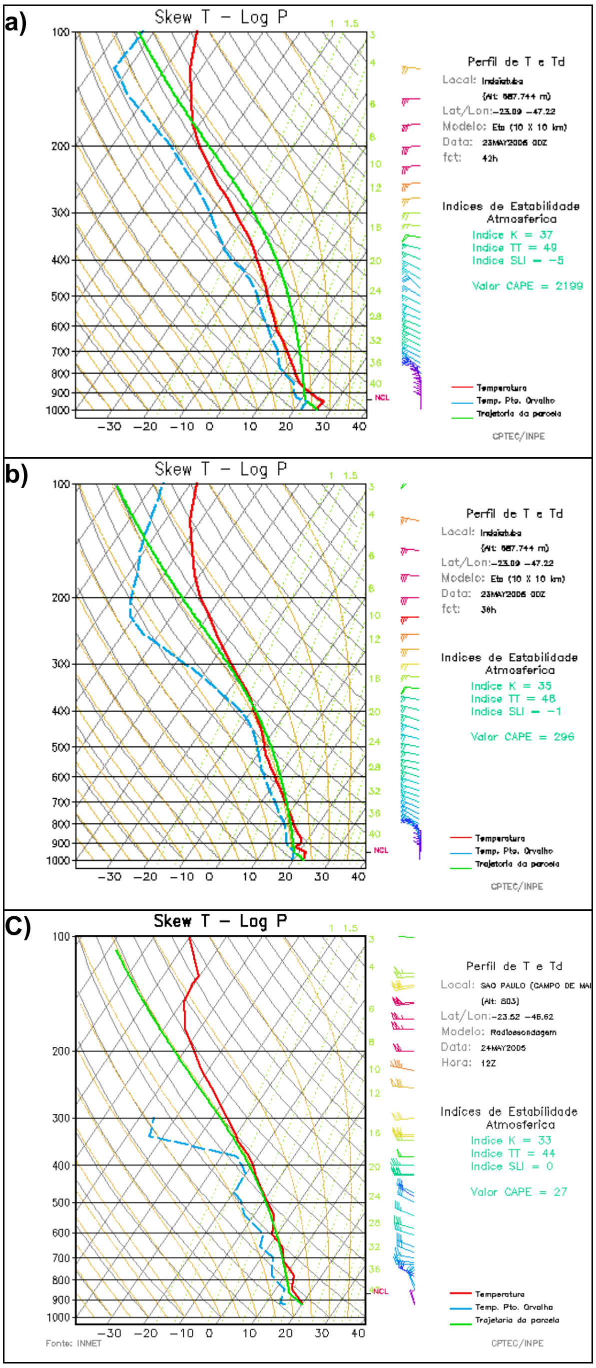

Figure 9. Vertical sounding profile generated by the Meso-Eta model for Indaiatuba, 24 May 2005.
a) 42-hour forecast for 15:00 LT, initiated on 23 May 2005, 00UT. **b)** 36-hour forecast for 09:00 LT, initiated on 23 May 2005, 00UT. **c)** Actual radiosounding from São Paulo at 12UT (09:00 LT).

from north-east at the time of the Indaiatuba tornado. The corre-sponding 18UT (15:00 LT) forecast from the CPTEC/Eta model predicted winds from north-west, whereas the 42-hour forecast from the Meso-Eta model predicted winds from the north, which means that the latter was more successful in veering the winds to the northern quadrant, thus being closer to reality. This is an important result, because the veered surface winds (in the Southern Hemisphere) increase directional wind shear with height, leading to an environment that is more favorable for tornadic supercells.

CAPE values on mid-summer days with average-type convective activity in the State of São Paulo are in the range of 1000-2000 J.kg^{-1}. A brief analysis of CAPE values from the São Paulo radiosoundings at 12UT during the TroCCiBras experiment (21 January – 11 March 2004; Held *et al.,* 2004) revealed, that from a total of 39 soundings available during this period, about half indicated a CAPE of >500 J.kg^{-1}, and only one-third had values >1000 J.kg^{-1}. Only on two days did the CAPE exceed 2000 J.kg^{-1} and both days were characterized by severe storms within the State and also the Metropolitan São Paulo area. However, the period of the TroCCiBras experiment can be considered as slightly below-average in terms of thunderstorm activity and rainfall (Gomes and Held, 2005).

Considering that the day, when the severe storms occurred, viz., 24 May, is already in the middle of autumn, with generally less energy being available for convection, then certainly predicted values of CAPE >2000 J.kg^{-1} must be considered as a reasonable warning signal for extreme events.

Accumulated radar rainfall in 3-hourly intervals was calculated for ≥1 mm from composite radar images (PPR + BRU), using the Marshall-Palmer Z-R relationship (Marshall and Palmer, 1948), and compared to the model outputs. They compare very well from 09:00 LT (when the system entered into the radar range of PPR) until 03:00 the next day. Thereafter, the model did not move the rain areas fast enough towards north-east, thus underestimating the rainfall in the north-east of the State and overestimating it in the western parts. Figure 10 shows 3-hourly accumulated rainfall as observed by the radars for the period 15:00 to 18:00 LT and the 45-hour prediction of the Meso-Eta model for the same period, using the same scales for rainfall.

In order to verify the accumulated 24-hour rainfall total derived from the radar observations and the model forecast, the actually observed rainfall totals have been plotted for the two 24-hour periods, starting on 23 May 2005, 09:00 LT, but only the period from 24 May 2005, 09:00 is shown in Figure 11 for comparison. Radar-derived rainfall

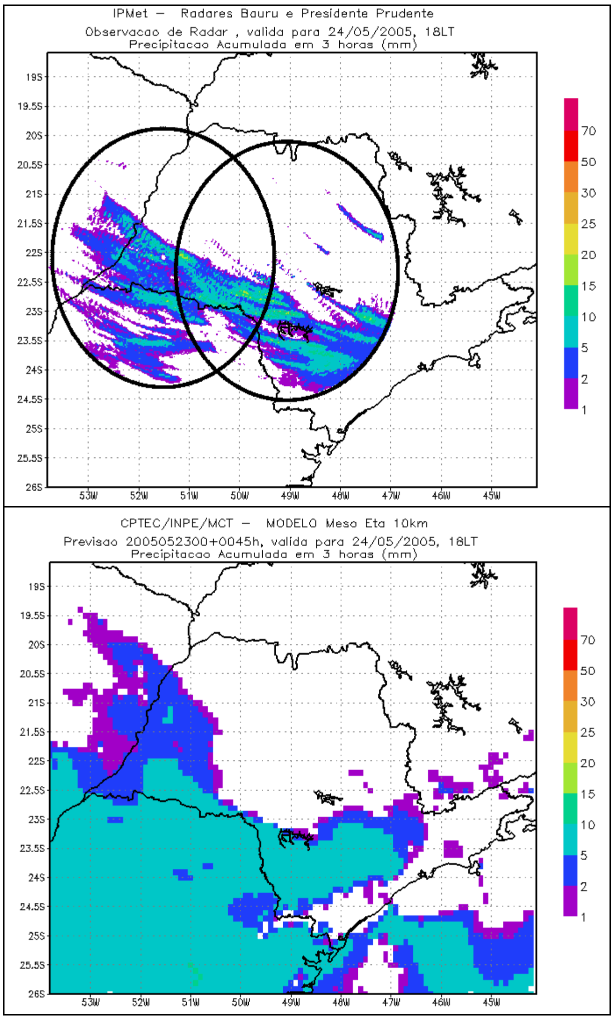

Figure 10. Three-hourly accumulated rainfall on 24 May 2005 for the period 15:00–18:00 LT during intensive storm activity. *Top:* Radar observations (radar ranges 240 km); *Bottom:* 45-hour Meso-Eta forecast.

totals agree very well with the observations. Although the model predicted the general area on this day, but especially the northern boundary of the rainfall area, quite well (excellent fit with the 1 mm rain area), it overestimated the amount of the rainfall <20 mm, mostly in the north of the State and over Minas Gerais, by a factor of about two to three. This could be due to the model not capturing the storm movement well after 54 hours. However, in areas affected by the rapidly passing convective cells (rainfall totals >20 mm), the agreement was remarkably good (Figure 11, bottom). The forecast of 24-hour rainfall totals for the period of 23 May 2005, 09:00 LT, to 24 May 2005, 09:00 LT (model initiated on 22 May 2005, 12UT), also gave a reasonable agreement with observations.

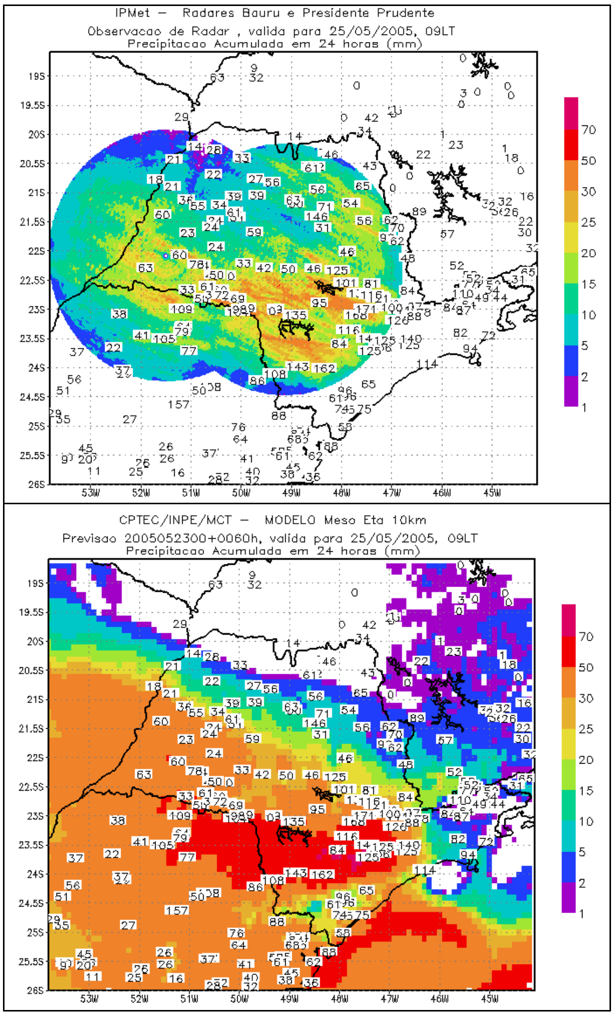

Figure 11. Accumulated rainfall for the 24-hour period of 24 May 2005, 09:00 to 25 May 2005, 09:00 LT.
Top: Radar observations; *Bottom:* Meso-Eta forecast initiated on 23 May 2005, 00UT.

5. CONCLUSION

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 was studied, using radar observations, as well as regional and mesoscale meteorological models. The already strong divergence at 200 hPa over the State intensified, and together with the embedded jet stream, areas of extreme instability were created, 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, and at least one of the cells spawned a multiple-vortex tornado with F3 intensity on the Fujita scale (Fujita, 1981), while another one created an exceptionally strong windstorm with cyclonic convergence (more details are provided in Held *et al.*, 2006).

The objective of this study was to determine the capability of meteorological models to predict the occurrence of severe weather events in a specific region up to two days ahead, thus considerably extending the nowcasting scale, which ranges from 30 min to 3 hours and is mostly based on radar observations. This is extremely important for issuing general warnings to the public in the State of São Paulo. The severe storms observed on 24 May 2005 by the Bauru radar provided an ideal opportunity to test the fore-casting ability of the Meso-Eta Model in order to extend the nowcasting range of the radar obser-vations from a couple of hours to about two days.

For the purpose of this investigation, only output from the operational Eta model from CPTEC, as well as from the non-operational Meso-Eta model installed in Bauru, was used to examine the atmospheric environment in which the tornadic thunderstorm on 24 May 2005 developed.

Based on the operationally available Regional Eta-CPTEC model, the predicted severe weather parameters (6 hours) did display some skill in highlighting the existence of a pre-storm environment that was favorable for significant severe weather development in the Indaiatuba region for the afternoon of 24 May 2005. However, a very good indication for this region was provided by the Meso-Eta model (IPMet/CPTEC) at least 48 hours ahead of the severe event, based on especially the 300 hPa divergence and the 850 hPa humidity convergence fields, the Omega at 500 and 300 hPa, as well as the CAPE and vertical profiles through the tropopause, which were generated for selected regions. However, this forms part of ongoing research and additional convective parameters will be analyzed in order to better characterize the pre-storm environment. The 3-hour accumulated rainfall was also predicted very well by the Meso-Eta model from 36 to 54 hours ahead. The model also yielded acceptable 24-hour totals for areas of intense rainfall, but overestimated in regions of low rainfall. The Meso-Eta model appears to perform best with most predictants for periods of around 48 hours ahead.

This study highlights, that locally available forecast models provide very useful predictions when considering the various dynamic and thermodynamic predictors, but need to be tested further and fine-tuned, in order to achieve an indicative alert system of up to 48 hours ahead of a severe event. However, these models, together with radar and lightning observations used for nowcasting are very important for the SIHESP (Portuguese acronym for "Hydro-meteorological System of the State of São Paulo") Project, which is currently being implemented, to provide early warnings of severe storms to local authorities, Civil Defense Organizations, industry and the general public.

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