

REGIONAL CIRCULATION DIFFERENCES BETWEEN A RAINY EPISODE AND A NONRAINY EPISODE IN EASTERN SÃO PAULO STATE IN MARCH 2006

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ABSTRACT

The differences between the regional flow characteristics of a rainy episode and a nonrainy episode in March 2006 in eastern São Paulo state are discussed. The surface humidity and temperature characteristics do not show significant differences between the two cases. The composites of the middle tropospheric geopotential field and the lower-tropospheric wind field show a short-wave trough in the Atlantic off southern Brazil during the rainy episode. In the upper troposphere, the Bolivian high is stronger during the rainy episode than during the nonrainy episode, indicating that the troposphere over tropical South America is warmer during the rainy episode. The low-level jet in the rainy case does not penetrate northern Argentina, and is more NW-SE oriented, indicating that the humidity transport is more toward the southeastern Brazil. The moisture flux convergence over the eastern São Paulo at the 850-hPa is fairly strong in the rainy case whereas it is divergent in the nonrainy case. The presence of a low pressure area in the South Atlantic with westward tilt in the vertical provides synoptic forcing for the rising motion over eastern São Paulo state. These differences seem to be useful indicators for distinguishing rainy and nonrainy episodes.

Keywords: Rainy episode, Non-rainy episode, State of São Paulo

RESUMO: DIFERENÇAS NA CIRCULAÇÃO REGIONAL ENTRE UM EPISÓDIO CHUVOSO E UM EPISÓDIO NÃO-CHUVOSO NO LESTE DO ESTADO DE SÃO PAULO EM MARÇO DE 2006.

As diferenças nas características do escoamento atmosférico regional entre um episódio de chuva e outro de não-chuva sobre a parte leste do estado de São Paulo durante março de 2006 são discutidas. Os compostos dos campos de umidade e temperatura próximos à superfície durante os dois episódios distintos não mostram diferenças significativas. Os compostos de geopotencial em 500-hPa e ventos na baixa troposfera mostram um cavado de onda curta no Atlântico a leste da costa da Região Sul do Brasil durante o episódio chuvoso. O jato de baixos níveis tem uma orientação noroeste-sudeste sobre o norte da Bolívia durante o episódio chuvoso, indicando que o transporte de umidade é dirigido para a região Sudeste do Brasil. A convergência do fluxo de umidade na baixa troposfera sobre a região de chuva é moderada, enquanto que no episódio não chuvoso o fluxo é divergente. Na alta troposfera a Alta de Bolívia é mais intensa e os ventos fortes sobre a Região Sul do Brasil são de sudoeste, durante o episódio chuvoso, indicando que a troposfera é mais quente sobre a América do Sul durante o episódio chuvoso. A presença de uma região de baixa pressão no Atlântico, com uma inclinação na vertical para oeste, constitui uma forçante de escala sinótica para movimento ascendente necessário para atividade convectiva. Estas diferenças devem ajudar os meteorologistas para distinguir os episódios chuvosos e não chuvosos.

Palavras Chaves: Episódio chuvoso, Episódio não-chuvoso, Estado de São Paulo

1. INTRODUCTION

The eastern parts of São Paulo state receive considerable amounts of rainfall in March, the month following the three-month rainy season December through February (Rao and Hada 1990). The March rainfall has special significance for the region because a large number of disasters associated with rainfall, such as soil erosion, floods and mudslides, are registered in this month. The rainfall in March is more episodic, unlike the rainfall in the rainy season, which tends to be more continuous. Moreover, during the transition month of March the variability of rainfall is larger than the variability in the rainy season months DJF. This variability is essentially due to the intraseasonal variability of regional circulation features. Understanding of the intraseasonal variability of rainfall is important for extending predictability beyond short-range forecasts. Medium-range (beyond 72 hours) forecasts are especially important for eastern parts of São Paulo state, which is a densely populated and highly industrialized mountainous region.

Eastern São Paulo, including greater São Paulo city, receives heavy rainfall during active South Atlantic Convergence

Zone (SACZ) episodes in the months of November through March. When the soil in the mountain slopes is saturated with water during the rainy season (DJF), more-than-normal rainfall in March proves to be disastrous for the region. Therefore, meteorologists must keep vigil on the March rainfall in the city of São Paulo and in the Vale do Paraíba and Serra de Mantiqueira regions.

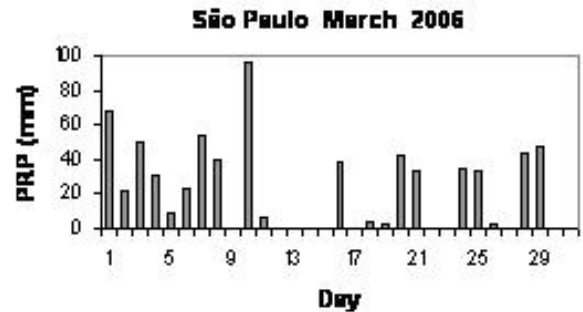


Figure 1 – Daily distribution of precipitation (mm) at São Paulo (Mirante de Santana Meteorological Station) for March 2006.

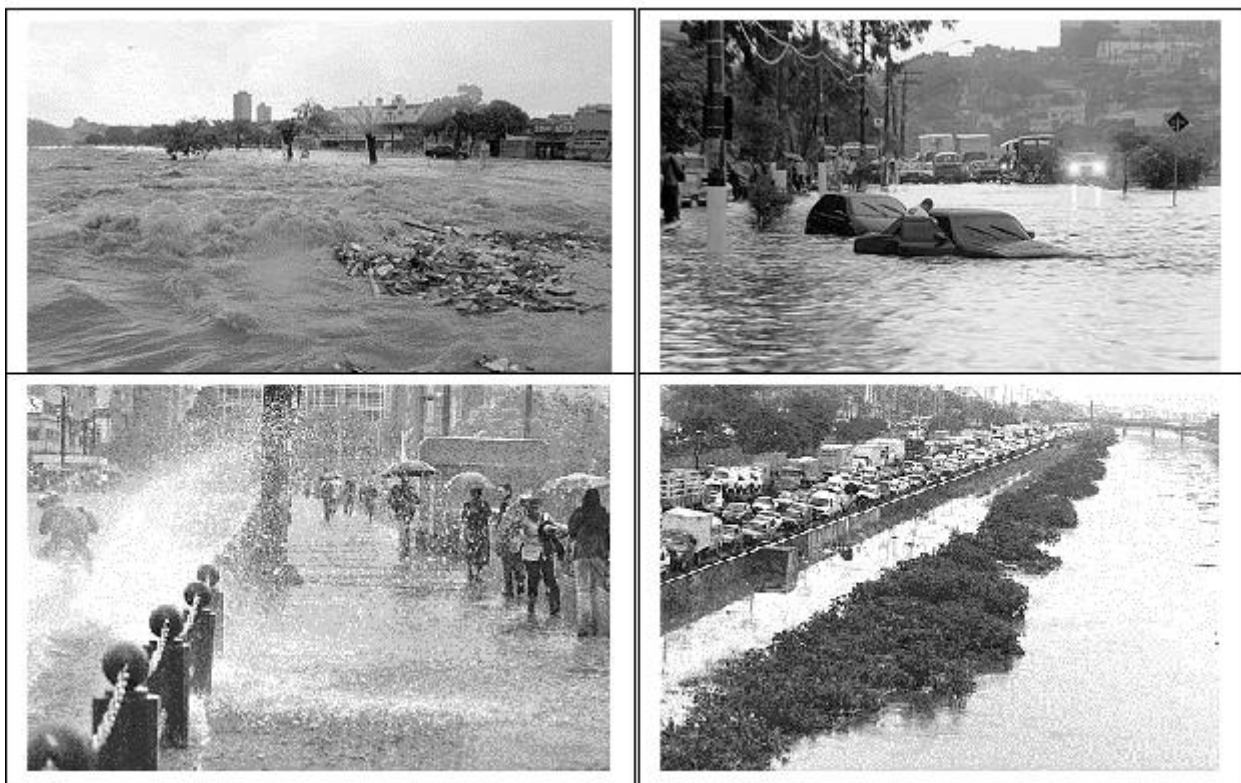


Figure 2 – Some scenes of floods and mudslides on 10 March 2006 in São Paulo.

In March 2006, the rainfall in eastern São Paulo was more than normal in many places, especially in the city of São Paulo. There were some episodes of heavy rain and some with very little rain. Figure 1 shows the daily distribution of rainfall in the city of São Paulo (Mirante de Santana Meteorological Station) for the month of March 2006. It is very clear from the figure that the period 02-11 received copious amounts of rainfall while the period 12-15 did not receive any. The rainfall on the 10th (accumulated in the 24-hour interval from 09 LT on the 10th to 09 LT on the 11th) was very heavy and many places in and around the city of São Paulo were affected by floods and mudslides which disrupted the normal life of the population. Actually, there were many reports of disasters during the month of March 2006 in the media. Figure 2 shows some pictures of the disasters registered on 10 March 2006.

The objective of the study is to obtain the atmospheric circulation differences between the contrasting episodes, in terms of rainfall, during March 2006. This is a first step to

understanding what characteristics of the atmospheric circulation are essential for making an episode a heavy rainfall episode. So far, such differences are not studied by the meteorologists of the region even qualitatively. These differences will possibly help the meteorologists to identify precursors of heavy rainfall in southeastern Brazil during the transition month of March.

2. DATA AND METHODOLOGY

The daily rainfall data for March 2006 and the monthly normals for the stations São Paulo, São José dos Campos, Campos do Jordão and Ubatuba, are obtained from the Instituto Nacional de Meteorologia (INMET, National Institute of Meteorology). These data are used for the characterization of the March 2006 rainfall in relation to the climatology and the rainy-season rainfall.

The rainfall in southeastern Brazil is mainly from frontal activity and the SACZ (which is viewed as a stationary

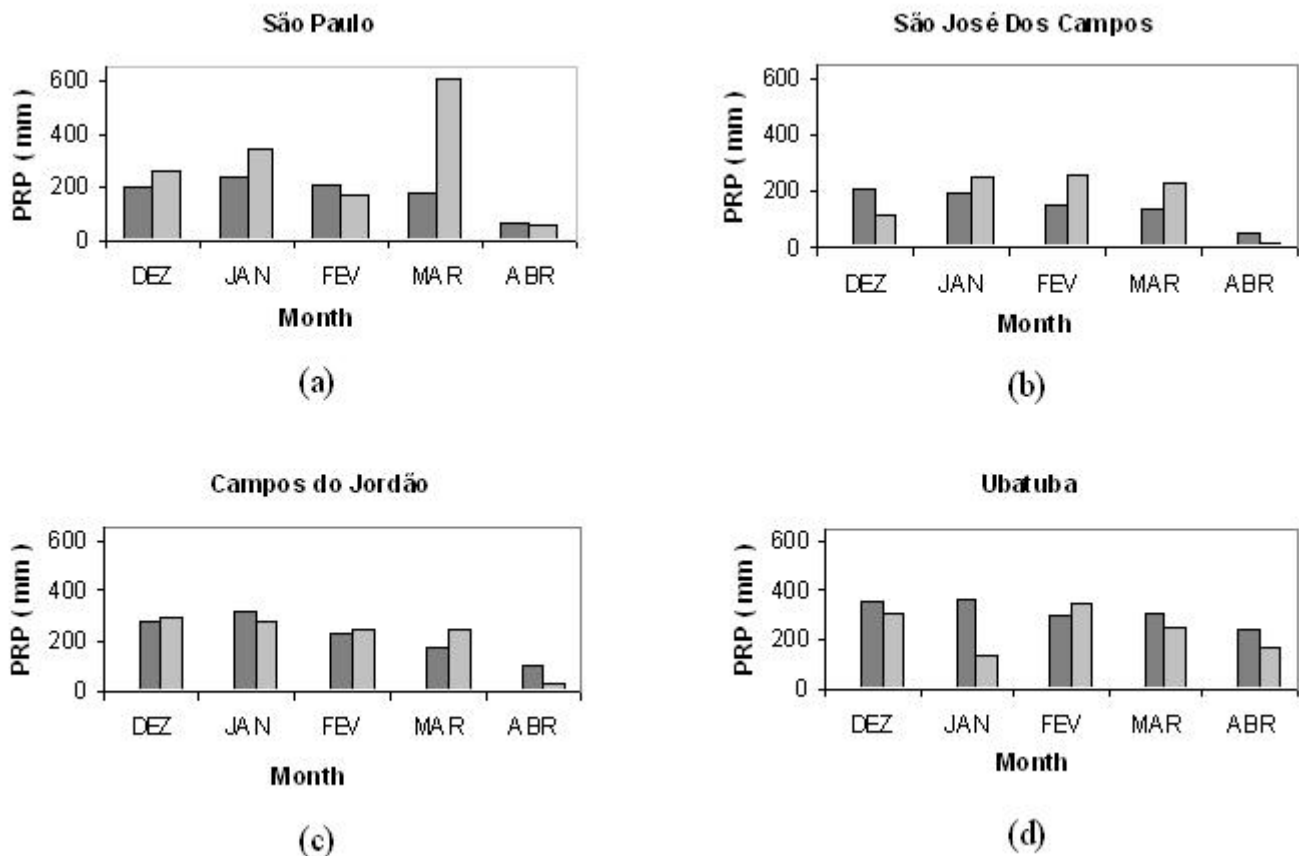


Figure 3 – Monthly accumulated precipitations (mm) recorded at São Paulo (a), São José dos Campos (b), Campos do Jordão (c) and Ubatuba (d) in the eastern parts of São Paulo state in the period December 2005 through April 2006. The 30-year normals are shown with dark rectangles for comparison.

front) formation. In order to compare the daily rainfall data with the frontal activity the frontal incursion data is obtained from Climanalise which presents graphically the northward progression of cold fronts along the east coast of South America.

The daily 00 UTC and 12 UTC data sets for the surface pressure and temperature, the geopotential at 500-hPa level and the winds and humidity in the lower troposphere and winds in the upper troposphere are obtained from the NCEP-NCAR analyses (Kalnay et al. 1996). These data sets, with a resolution of 2.5° longitude x 2.5° latitude, are used to obtain the composites of the atmospheric variables for a rainy episode and a nonrainy episode in the eastern parts of São Paulo. As all datasets the NCEP reanalyses have many problems too. As there are very few synoptic and upper air meteorological stations over tropical and subtropical South America, the reanalysis data mainly represent the satellite observations and the global model behavior. Any increase in resolution of the data will not improve the quality of the analysis significantly, as the high-resolution data set is just a re-rendering of the original data by

interpolation methods. Moreover, for a study of the five-day long episodes the resolution of 2.5° latitude by 2.5° longitude is not altogether insufficient.

The composites of an episode are obtained by simply taking the average of the 00 UTC and 12 UTC reanalysis over five days of the episode, for the following fields: (1) sea-level pressure (ps), (2) sea-level temperature (Ts), (3) 850-hPa wind (V850), (4) 500-hPa geopotential (ϕ_{500}), (5) 200-hPa wind (V200), (6) thermal advection ($-V \cdot \nabla T$) at 850-hPa, (7) humidity transport (qV) and (8) convergence of humidity ($-\nabla \cdot \{qV\}$) at 850-hPa. The symbols used above have their usual meaning. The relevance of these variables to study meteorological circulations associated with rainy and nonrainy episodes is briefly explained in the following lines. It is well known since the beginning of the last century that synoptic scale meteorological activity is associated with low-pressure centers at the surface. Sea-level temperature affects convective activity such that anomalously higher temperatures near the surface cause rising motion of air that is needed for the formation of rain. The 850-hPa wind field shows the position and orientation

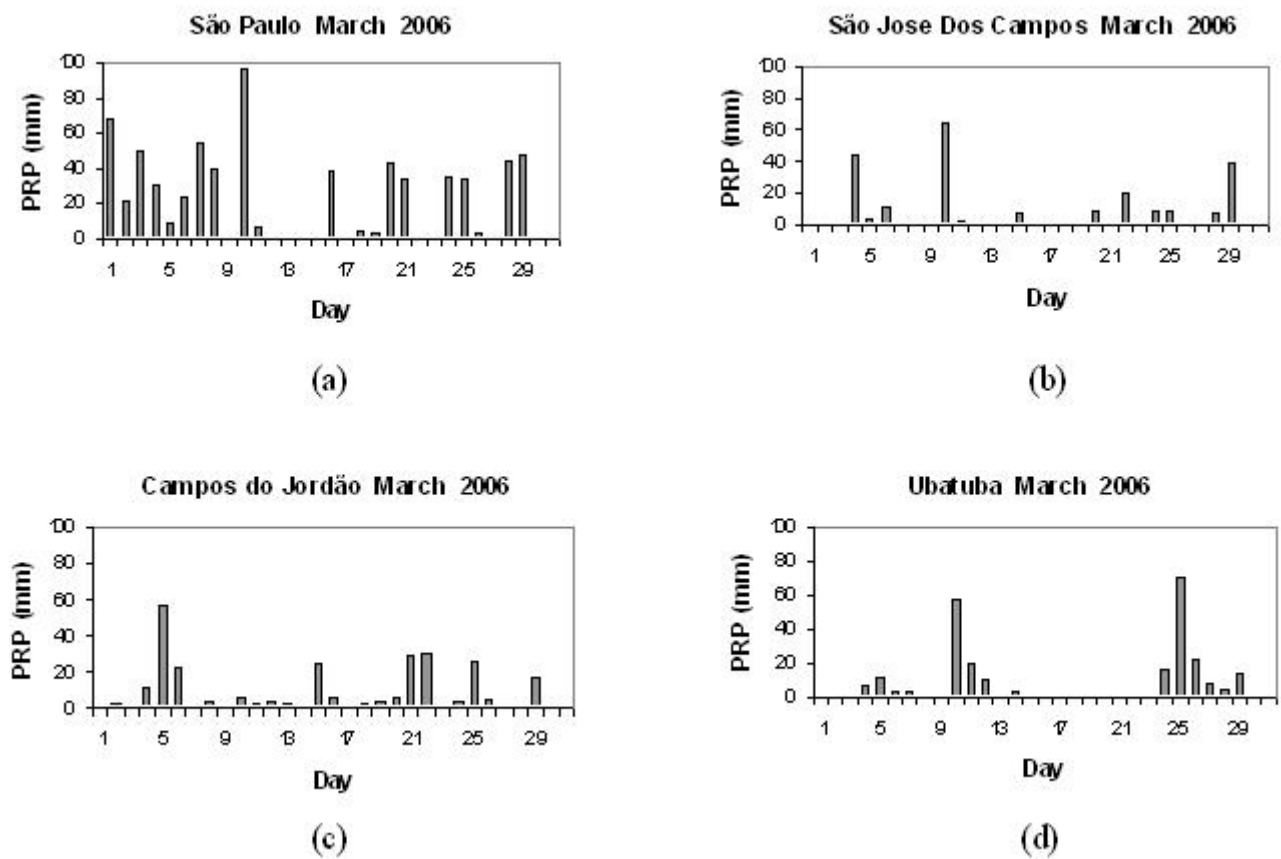


Figure 4 – Daily distributions of precipitation (mm) at São Paulo (Mirante de Santana Meteorological Station) (a), São José dos Campos (b), Campos do Jordão (c) and Ubatuba (d) for March 2006.

of low level jets which are conveyer belts of sensible and latent heat. Midtropospheric troughs and ridges and the upper tropospheric jetstreams are good indicators of the position and intensity of extratropical synoptic systems. Thermal advection field in the lower troposphere diagnoses the frontal activity. The transport of humidity field indicates the region from where the water vapor is brought and the convergence of humidity quantifies the amount of moisture available for moist convection. Moisture convergence or divergence in a given vertical column mostly occurs in the lower troposphere, as there is very little moisture above 500 hPa. In this study, the moisture transport and convergence at 850-hPa level are considered to represent the entire column.

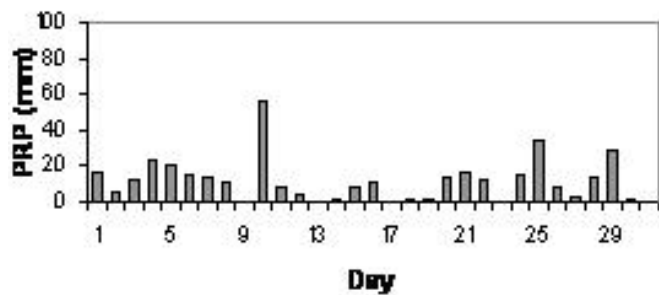


Figure 5 – Daily distribution of mean precipitation (mm) over eastern São Paulo state for March 2006.

3. CHARACTERIZATION OF PRECIPITATION

Figure 3 shows monthly rainfalls in December 2005 through March 2006, as compared to the monthly normals, at the four stations, São Paulo, São José dos Campos, Campos do Jordão and Ubatuba. The rainfall in March 2006 at the São Paulo station exceeded 600 mm while the normal for the month of March is less than 200 mm. The March rainfall was almost equal to the total Dec-Jan-Feb seasonal rainfall. At the São José dos Campos and Campos do Jordão stations the rainfall in March exceeded significantly the respective normals for that month. At Ubatuba station the March rainfall was slightly less than the normal, but nonetheless it was more than 200 mm. The climatological value of the number of rainy days with rainfall > 5 mm/day in March in São José dos Campos, based on the data collected at the airport for 1974-2006, is 8 (Calbete 2007, personal communication). In March 2006, however, the number of such rainy days was 11. From these data we conclude that March 2006 was a more-than-normal rainy month in the eastern parts of the state of São Paulo.

The daily distributions of rainfall in March for the four stations are shown in Figure 4. It is clear from the figure that the rainfall was not uniform over the month. In São Paulo, the first 1/3 of the month was very rainy and the middle 1/3 was less rainy. The other three stations also show rainy and nonrainy

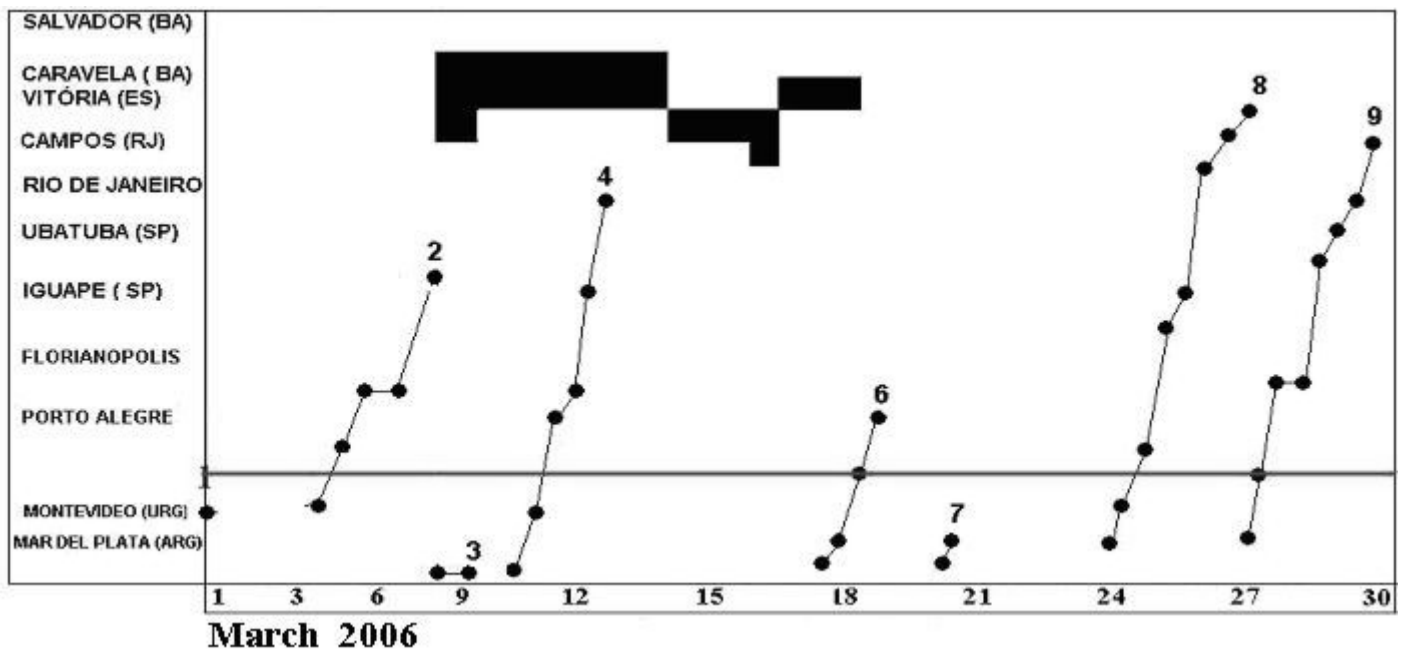


Figure 6 – Frontal system incursions along the east coast of South America during March 2006. The horizontal line north of Montevideo demarks the border between Uruguay and Brazil. The dark areas indicate the position of the SACZ. SOURCE: Climanalise

episodes during the month. The episodic characteristic is clear from the rainfall distribution at the Ubatuba and Campos do Jordão stations. We can see that at Campos do Jordão the periods 04-06 and 20-22 recorded more than 70 mm in 3 days, whereas the periods 11-14, 17-19 and 26-28 received less than 8 mm in 3 or 4 days.

Figure 5 presents the four-station average daily rainfall, from which we can see that the 5-day periods (pentads) 6-10 and 25-29 received nearly 100 mm. The 5-day periods 12-16 and 17-21 received less than 10 mm. The two distinct pentads 06-10 and 12-16 are chosen to characterize, respectively, a rainy episode and a nonrainy episode. Thus, these two pentads are used to study the differences in the regional atmospheric circulation characteristics. The difference patterns may constitute a conceptual model for heavy rainfall situations in the region. Thus, during the transition month, the meteorologist is encouraged to look for patterns similar to the ones obtained here in the outputs of medium-range numerical forecast models in his or her operational routine.

4. MONTHLY MEAN CIRCULATION CHARACTERISTICS

The frontal activity over the eastern parts of South America during March 2006 is shown in Figure 6. Three

systems reached Ubatuba during the month. The SACZ was active in the state of Espírito Santo during the period 7-18. Both the rainy episode of 06-10 and the nonrainy episode of 12-16 occurred during active SACZ periods. This indicates that the formation of SACZ is not a sufficient condition for the occurrence of heavy rainfall in eastern southeastern region of Brazil. This makes the study of the differences between the rainy episode and the nonrainy episode more interesting.

The monthly mean charts of 850-hPa and 200-hPa wind fields for March 2006 are shown in Figure 7. The lower tropospheric winds (Fig. 7a) were strong east-northeasterlies in the equatorial South America. In the region between 10°S-30°S the winds had a strong northerly component, with stronger northwesterlies over northern Bolivia and central-western Brazil and with northeasterlies over Bahia and Minas Gerais states. These winds formed a confluence region over Goiás, Minas Gerais and São Paulo states. It is important to note that the low-level jet over Bolivia in this month, with its NW-SE orientation, did not penetrate into Argentina. Thus the transport of latent heat from Amazon region was more directed into Southeast Brazil. The winds in the upper troposphere (Fig. 7b) show a huge anticyclone over the zonal belt of 5°S-30°S. This is the Bolivian high with elongated zonal dimension from 100° W to 25° W. The westerly jet to its south is situated over northern Argentina, Uruguay and the state of Rio Grande do Sul. The

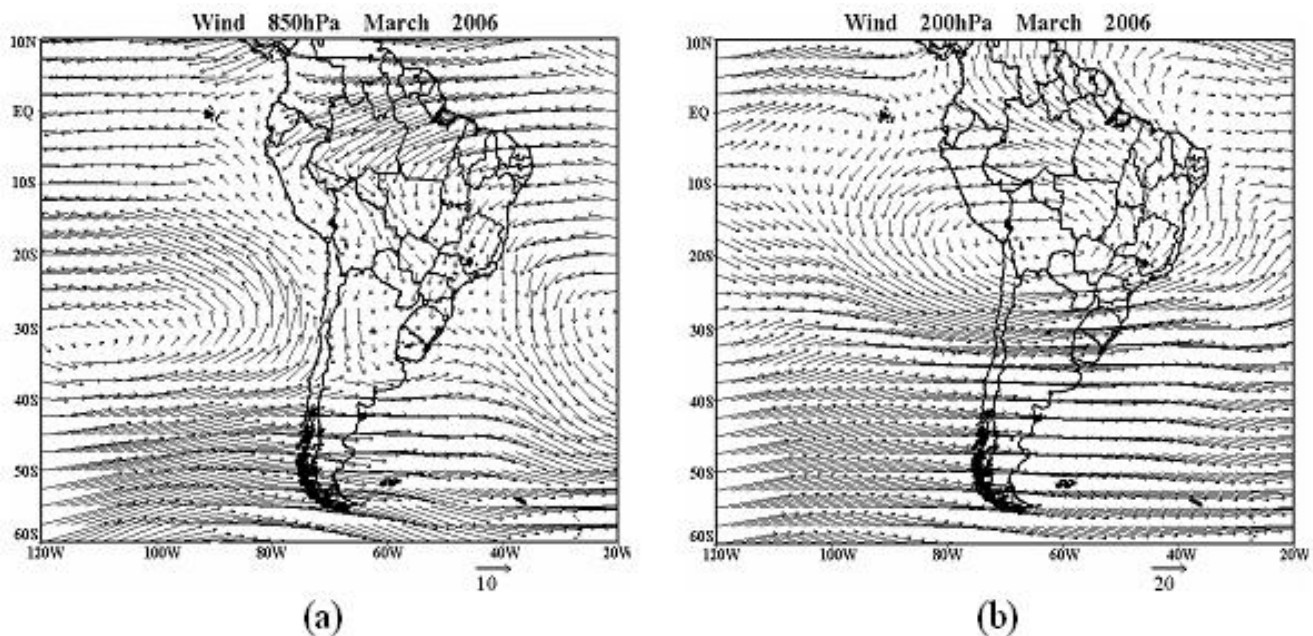


Figure 7 – Monthly mean wind (ms^{-1}) fields at 850 hPa (a) and 200 hPa (b) over the South American region for March 2006.

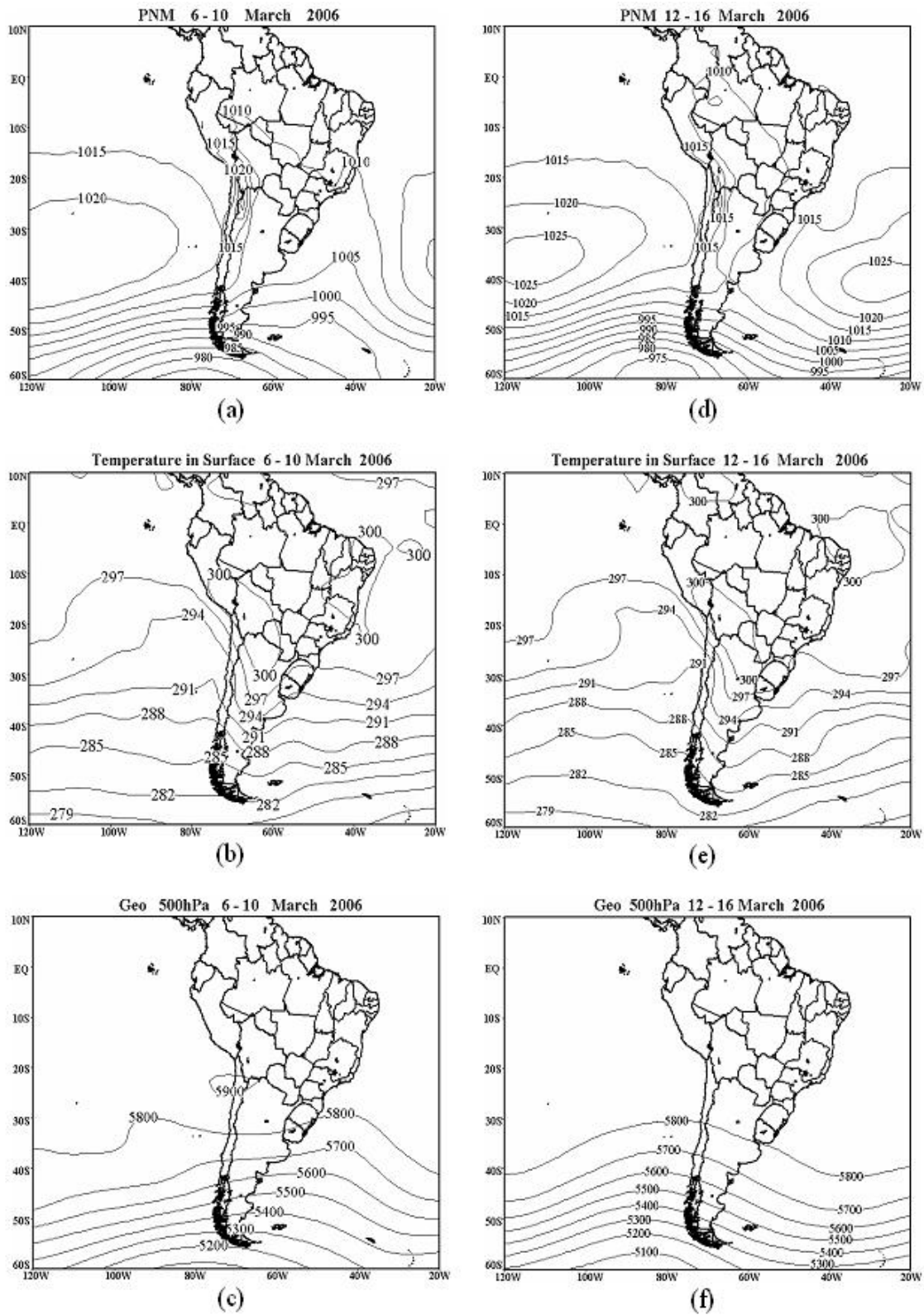


Figure 8 – Composites of sea-level pressure (hPa), surface temperature (°K) and 500-hPa geopotential height (m) for a rainy episode (a, b, c) and a nonrainy episode (d, e, f).

upper level anticyclone is an indication of a warm troposphere. The upper air trough down stream of the Bolivian high is away from the continent in the Atlantic near 20°W. This is perhaps a favorable condition for the SACZ formation north of 20°S, since SACZ region is known to present a ridge in the upper troposphere (Figueroa 1999).

5. RAINY AND NONRAINY EPISODES

Here we draw comparisons and contrasts between the composites for rainy and nonrainy episodes of, respectively, 06-10 and 12-16 March 2006, to be able to appreciate why the episodes behaved distinctly. To achieve this we present first the atmospheric variables for the two episodes side by side.

Figure 8 shows the composite p_s , T_s and ϕ_{500} fields for the two episodes. The surface pressure fields for the two episodes almost look alike and normally large differences are not

expected. However, there are some differences. The subtropical highs in the Pacific and the Atlantic are farther from the continent and there is a fairly strong S-N oriented short-wave trough off the Uruguay coast during the rainy episode. In the case of the nonrainy episode the trough in the Atlantic is very weak and is perhaps associated with the monthly mean SACZ north of São Paulo. The mean high pressure values in the subtropical highs (1020 hPa) (Fig. 8a) during the rainy episode is weaker than during the nonrainy episode (1025 hPa) (Fig. 8d).

The surface temperature patterns (Fig. 8b,e) are quite similar in the two cases, especially because the horizontal temperature variability in the tropics is small. In both cases the continent is warmer than the surrounding oceans, consistent with the upper air anticyclonic circulation. However, a cool air tongue is seen over Rio Grande do Sul state and Uruguay in the rainy case and the tongue is found over the coastal waters in the nonrainy episode. These details cannot be taken too seriously

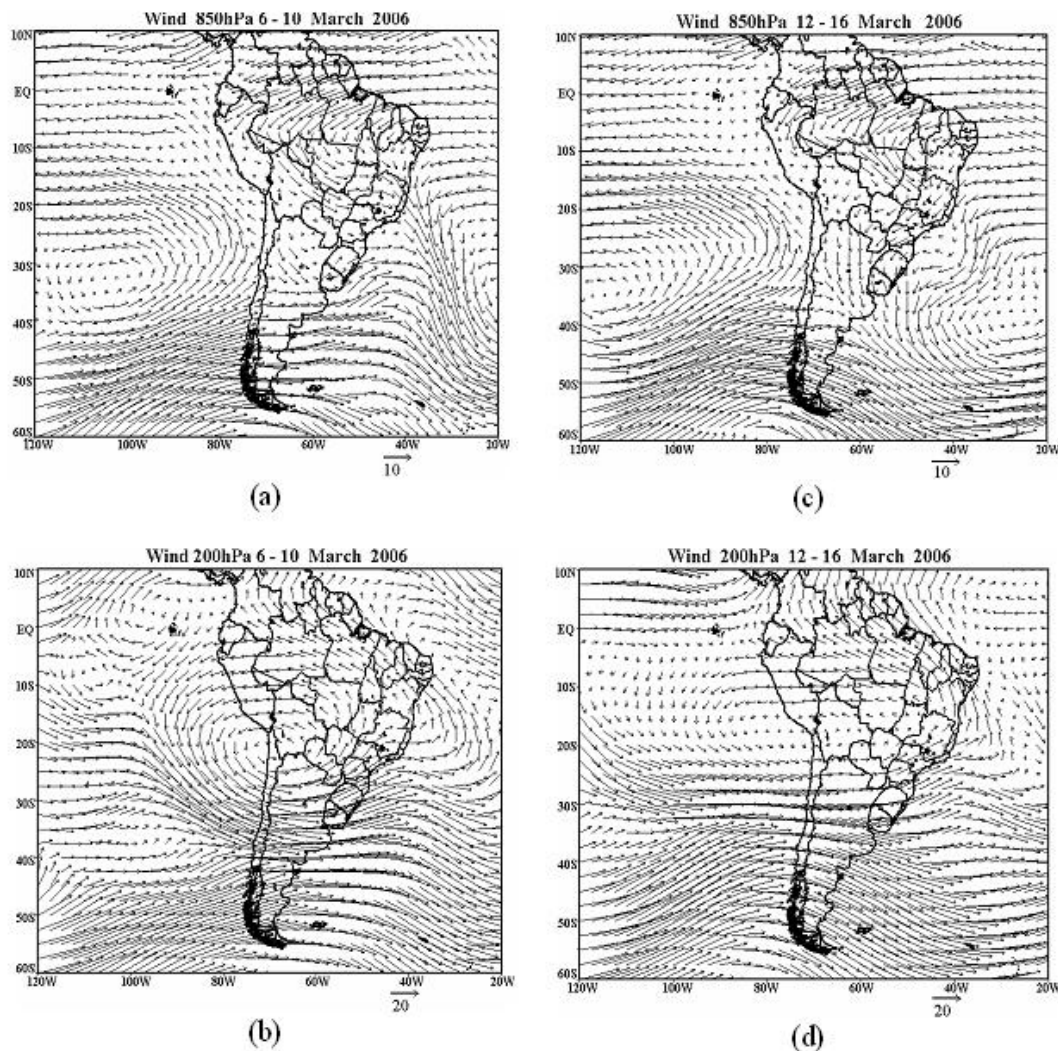


Figure 9 – Composites of 850-hPa wind and 200-hPa wind (m s^{-1}) for a rainy episode (a, b) and a nonrainy episode (c, d).

because of the inherent errors and the coarse resolution of the NCEP data for this purpose. Significant differences are not observed in the specific humidity composites also (not shown). The relative humidity composites (also not shown) essentially present the same characteristics in both the episodes, with 90% humidity over Minas Gerais state and eastern parts of São Paulo state. These observations indicate that the upper air flow characteristics are perhaps more important to determine if an episode is rainy or not. The whole idea is to caution the meteorologist that searching for significant differences between rainy and nonrainy episodes in the T, ps and RH fields is not very productive. Instead, it is more beneficial to examine the upper

air flow characteristics to forecast prolonged heavy rainfall periods in eastern São Paulo.

The 500-hPa geopotential field (Fig. 8c,f) shows some significant differences. The nonrainy episode shows a trough near the Chile coast and a ridge in the Atlantic, forming a long wave. The rainy episode shows two short wave troughs, one at 100°W and the other at 45°W in the latitude belt 30°S-50°S. The trough in the Atlantic, along with the trough at the surface slightly to the east, seems to be important for the convective activity responsible for the rains during this episode.

The motion field in the trough region provide the dynamical synoptic-scale forcing necessary for upward motion

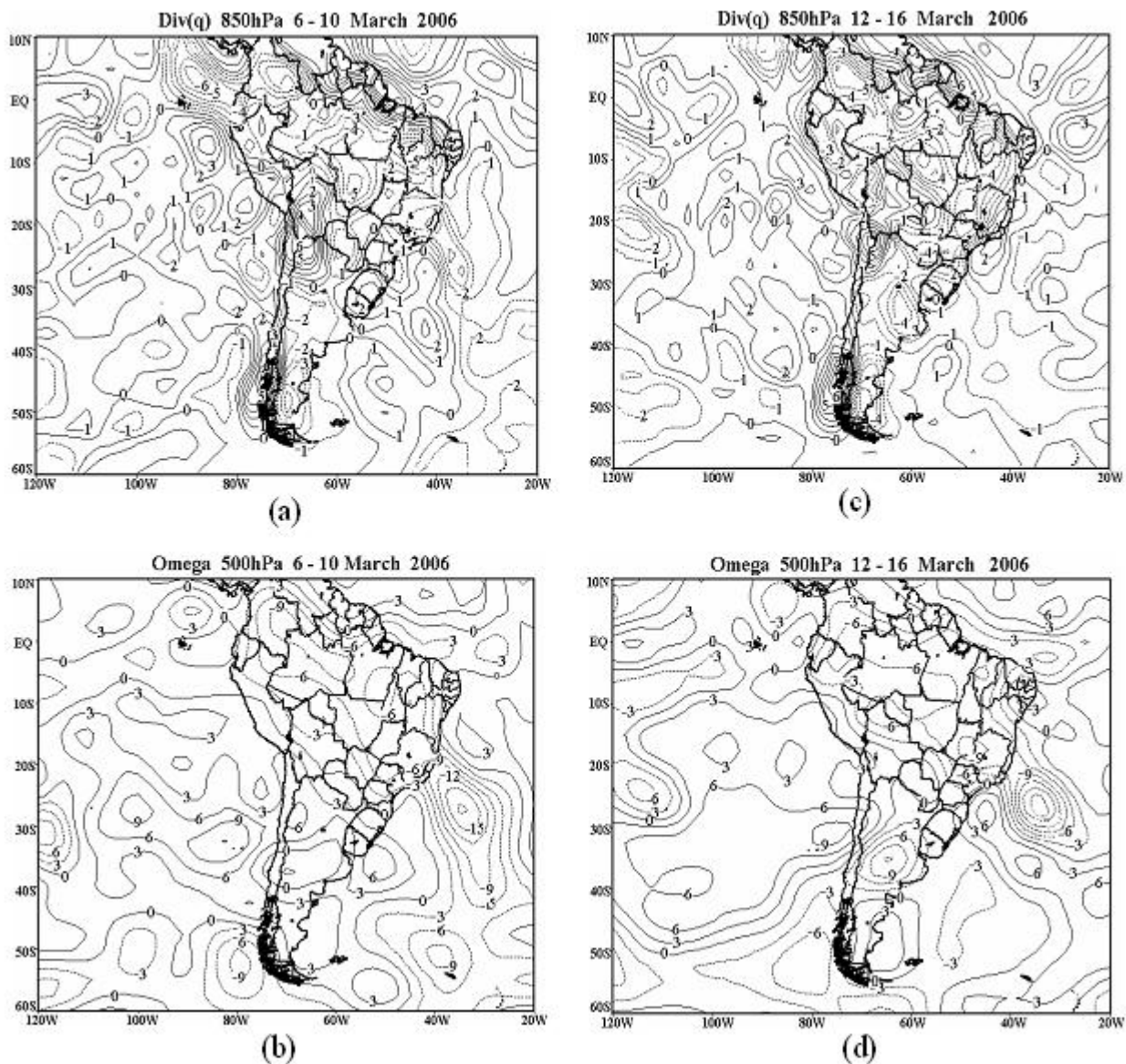


Figure 10 – Composites of 850-hPa moisture flux divergence (10^{-6} s^{-1}) and 500-hPa vertical velocity (Pa s^{-1}) for a rainy episode (a, b) and a nonrainy episode (c, d).

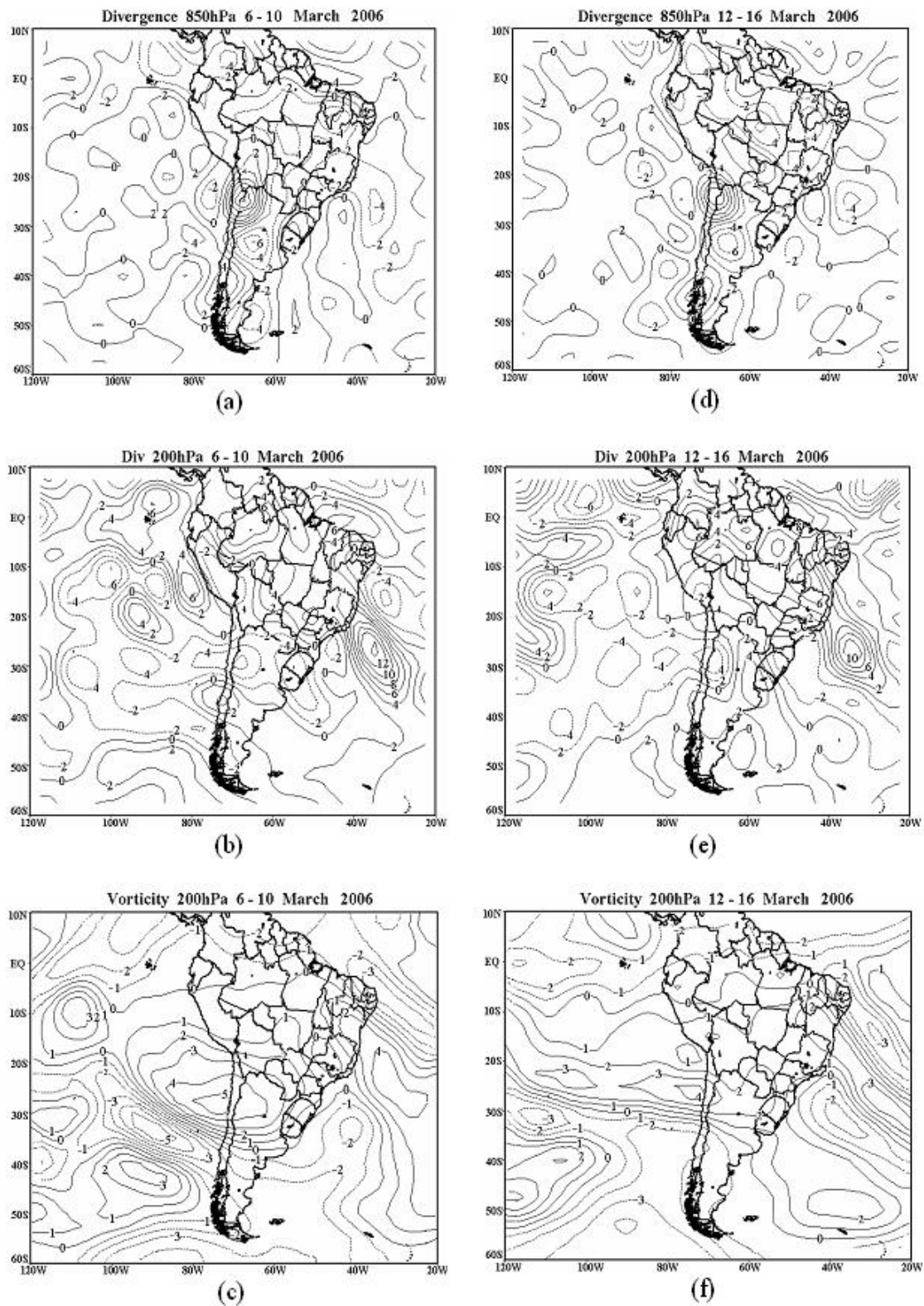


Figure 11 – Composites of 850-hPa divergence (10^{-5} s^{-1}), 200-hPa divergence (10^{-5} s^{-1}) and 200-hPa relative vorticity (10^{-5} s^{-1}) for a rainy episode (a, b, c) and a nonrainy episode (d, e, f).

through advection of absolute vorticity by thermal wind. We can see the wind field composites at 850-hPa and 200-hPa for the two episodes in Figure 9. The thermal wind (the difference between the 200 hPa and 850 hPa levels) is southerly and the advection is cyclonic in the rainy case. This effect is weak in the nonrainy case composites.

The lower tropospheric winds in the two cases show some regional differences. A cyclonic center in the Atlantic, associated with the trough at the sea level discussed above, is situated off Uruguay coast and the strong northwesterly winds are situated over Bolivia and Mato Grosso and Mato Grosso do Sul states in the rainy case (Fig. 9a). In the nonrainy case (Fig. 9c) the winds are stronger over Mato Grosso state with an indication of confluence and convergence in the western Minas Gerais state with the northeasterlies over Minas Gerais. At the 200-hPa there are some noticeable differences between the two episodes. During the rainy episode the Bolivian high is stronger and the jet core is oriented SW-NE over southern Brazil (Fig. 9b). This indicates that the troposphere in the tropics of South America is warmer during the rainy episode.

Figure 10 shows the composites of moisture flux convergence at 850 hPa and vertical velocity field at 500 hPa for the two contrasting episodes. Over the eastern parts of São Paulo state there is convergence of the order of $2 \times 10^{-5} \text{ g kg}^{-1} \text{ day}^{-1}$ during the rainy episode (Fig. 10a) while there is divergence of the same order during the nonrainy episode (Fig. 10c). The vertical velocity is -3 Pa s^{-1} (rising motion) over eastern São Paulo during the rainy episode (Fig. 10b) and it is near zero during the nonrainy episode (Figs. 10d), in agreement with the rising motion inferred above.

That is, the lower-tropospheric moisture convergence and the midtropospheric large-scale rising motion show favorable conditions for the rainfall to occur in the rainy episode.

Figure 11 presents the mass divergence composites for 850 hPa and 200 hPa and the relative vorticity composites for 200-hPa level for the two contrasting episodes. During the rainy episode the convergence in the lower troposphere over eastern São Paulo is of the order of $2 \times 10^{-5} \text{ s}^{-1}$ (Fig. 11a) while during the nonrainy episode it is zero convergence or divergence of the same order (Fig. 11d). This suggests that the mass convergence in the lower levels is a major contributor for the moisture convergence and midtropospheric upward motion necessary for convective activity. The moisture convergence has two terms: $\nabla \cdot (qV) = q\nabla \cdot V + V \cdot \nabla q$. As the humidity is uniform, the second term does not contribute much in the tropics and perhaps subtropics. So the first term is the major contributor. The mass divergence at 200 hPa shown in Figures 11 b and e does not show significant differences between the two episodes over eastern São Paulo. The relative vorticity composite fields at 200 hPa are presented in Figures 11 c and f. The elongated region of

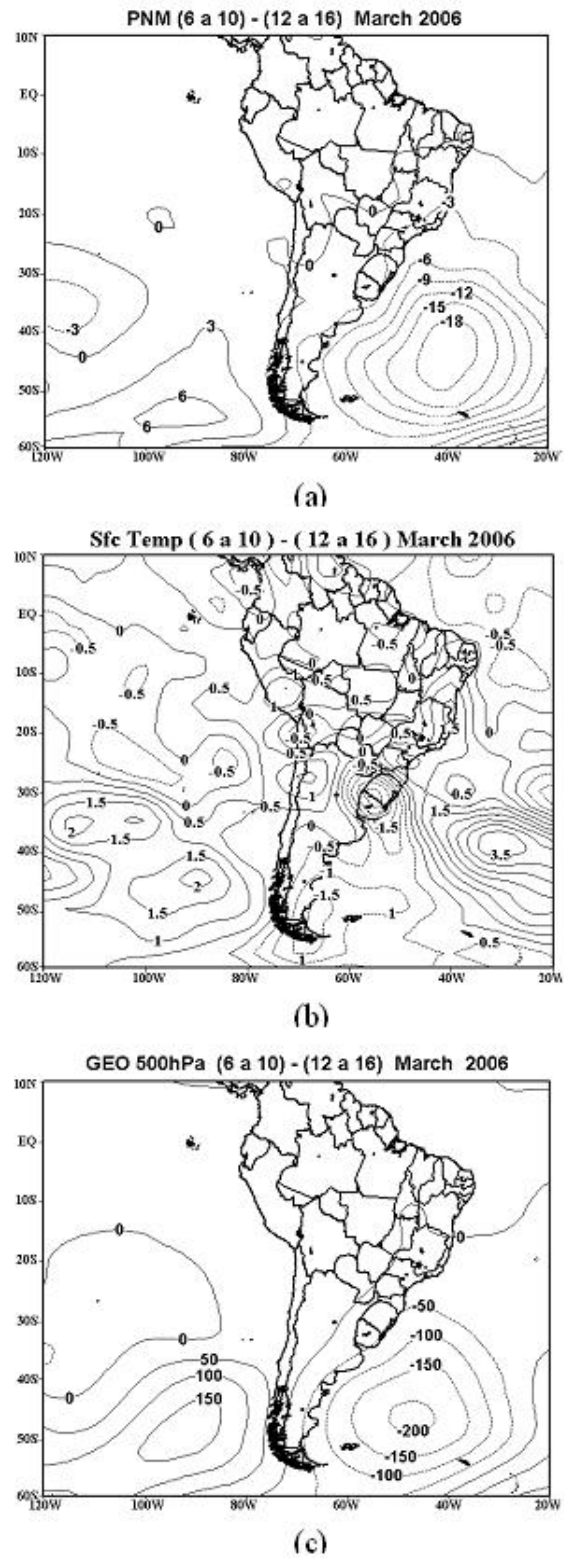


Figure 12 – Differences between rainy and nonrainy episodes. (a) Sea level pressure (hPa), (b) surface temperature ($^{\circ}\text{C}$), (c) 500 hPa geopotential (m). Broken lines indicate negative values.

strong upper tropospheric anticyclonic vorticity is a characteristic of active SACZ. Such a region is observed over Bahia in both the cases. During the nonrainy episode the cyclonic vorticity area is elongated southeastward in the Atlantic, indicating a moving cyclone. However, during the rainy episode a cyclonic vorticity center is observed off the Rio Grande do Sul coast, indicating that a cyclonic system persisted there for the 5-day period (Fig. 11c). It is important to recognize that the transient perturbation near the southern coast of Brazil was stationary or moved slowly during the rainy episode.

The differences between the composites of the two episodes are shown in Figures 12 and 13. The surface pressure differences (Fig. 12a) show a low-pressure center in the Atlantic off Argentina coast with a trough of -3 hPa over the eastern parts of São Paulo state. That is, as expected the surface pressure during the rainy episode is 3 hPa lower than during the nonrainy episode over the region. The differences in near surface temperature (Fig. 12b) show a cool air pool over southern Brazil and a warm air pool over eastern São Paulo showing that there is frontal effect also during the rainy episode, with rising warm air over eastern São Paulo. The geopotential difference (Fig. 12c) shows almost the same pattern as the surface pressure difference, except that the center of the low pressure area at 500 hPa is slightly inclined to the west of the surface low pressure area, showing that the synoptic situation is more baroclinic during the rainy episode than during the nonrainy episode, which is necessary for the maintenance of the system for periods of four days or longer. More moisture convergence and stronger upward motion can be verified over eastern São Paulo state during the rainy episode from Figure 13.

6. SUMMARY AND CONCLUDING REMARKS

Larger than normal rainfall in March 2006 in the eastern parts of the state of São Paulo caused many problems for the population of that region. The rainfall was episodic, i. e., there were periods of three or more days of rainfall interspersed by periods of very little or no rainfall. The question that arises is what special characteristics make a rainy episode. We have presented, in this study, comparisons and contrasts between the composite atmospheric variable fields for a rainy episode (06-10) and a nonrainy episode (12-16) during March 2006.

The surface humidity and temperature composite fields during the two contrasting episodes did not present significant differences, as is expected from near uniformity of the fields in the tropics and subtropics. Thus, the differences in the rainfall characteristics during the two episodes were mainly due to the upper air flow and geopotential field differences. Moreover, there are indications that the thermal advections did not play a significant role for making the episodes rainy or nonrainy, as the thermal gradients are not large in this part of the world. The rainy episode presented an elongated N-S oriented trough in the Atlantic off the coast of Uruguay in the lower and middle tropospheres. The low-level jet during the rainy episode was oriented NW-SE over northern Bolivia directed into the western parts of the state of São Paulo. Southeasterly winds over the state of Minas Gerais and the northwesterly low-level jet converge over the eastern parts of São Paulo. The moisture convergence in the lower troposphere and upward motion in the middle troposphere over the eastern parts of São Paulo during the rainy episode were distinctly different from the

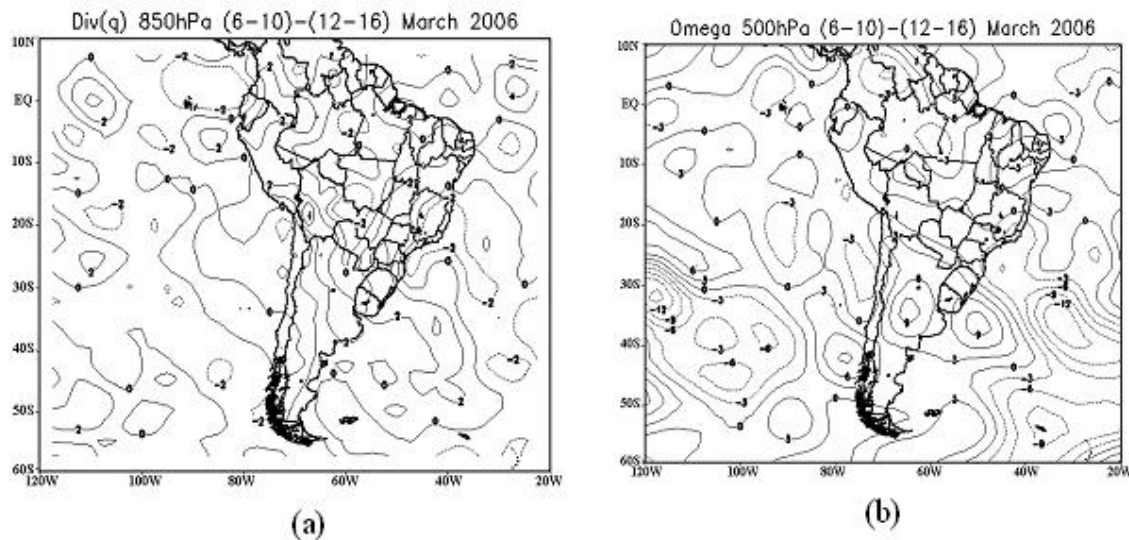


Figure 13 – Differences between rainy and nonrainy episodes. (a) Humidity flux divergence (10^{-6} s $^{-1}$), (b) vertical motion (Pa/s). Broken lines indicate negative values.

subsiding motion and the divergence of moisture flux during the nonrainy episode. In the upper troposphere the Bolivian high was more intense, indicating that the troposphere over tropical SA was warmer, during the rainy episode. Southeast of the Bolivian High the winds were strong southwesterlies over southern Brazil. During the nonrainy episode the anticyclonic circulation was weaker and is more zonally elongated with westerly winds over the southern parts of Brazil. In terms of the 200-hPa relative vorticity, rainy episode showed a more stationary cyclone near the Rio Grande do Sul coast while the nonrainy episode showed a southeastward moving cyclone. The advection of cyclonic vorticity over eastern São Paulo by the thermal wind caused large-scale rising motion, which was necessary for the formation of convection.

These contrasts between the two episodes can assist the meteorologists to distinguish a prolonged rainy episode from a prolonged nonrainy episode during post-summer period over eastern São Paulo. The composite fields are the means of 5 days and therefore the differences between the two episodes are not due to high frequency variability (less than 48 hours). This medium-range variability is part of intraseasonal variability, whose characteristics should be understood for improving the medium-range or intermediate-range weather prediction. The results also suggest that the synoptic features in the pressure, geopotential and wind fields can serve as indicators of a rainy episode.

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