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ORIGINAL PAPER

Large-scale atmospheric conditions associated with heavy rainfall episodes in Southeast Brazil

Kellen Carla Lima · Prakki Satyamurty · Júlio Pablo Reyes Fernández

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Abstract Heavy rainfall events in austral summer are responsible for almost all the natural disasters in Southeast Brazil. They are mostly associated with two types of atmospheric perturbations: Cold Front (53%) and the South Atlantic Convergence Zone (47%). The important question of what synoptic characteristics distinguish a heavy rainfall event (HRE) from a normal rainfall event (NRE) is addressed in this study. Here, the evolutions of such characteristics are identified through the anomalies with respect to climatology of the composite fields of atmospheric variables. The anomalies associated with HRE are significantly more intense than those associated with NRE in all fundamental atmospheric variables such as outgoing long-wave radiation, sea-level pressure, 500-hPa geopotential, lower and upper tropospheric winds. The moisture flux convergence over Southeast Brazil in the HRE composites is 60% larger than in the NRE composites. The energetics calculations for the HRE that occurred in the beginning of February 1988 strongly suggest that the barotropic instability played an important role in the intensification of the perturbation. These results, especially the intensities of the wind, pressure anomalies, and the moisture convergence are useful for the meteorologists of the Southeast Brazil for forecasting heavy precipitation.

K. C. Lima · P. Satyamurty · J. P. R. Fernández
Centro de Previsão de Tempo e Estudos Climáticos,
Instituto Nacional de Pesquisas Espaciais,
São José dos Campos, São Paulo, Brazil

K. C. Lima (✉)
INPE,
Avenida dos Astronautas, 1758,
12227-010 São José dos Campos, SP, Brazil
e-mail: kellen.lima@cptec.inpe.br

Abbreviations

CF	Cold front
SACZ	South Atlantic convergence zone
ANA	Agência Nacional das Águas
CPTEC	Centro de Previsão de Tempo e Estudos Climáticos
NRE	Normal rainfall events
HRE	Heavy rainfall events
SEB	Southeast Brazil
SP	São Paulo
RJ	Rio de Janeiro
MG	Minas Gerais
ES	Espírito Santo
GNP	Gross national product
NDJFM	November, December, January, February, and March
NCEP-NCAR	National Centers for Environmental Prediction-National Center for Atmospheric Research
PDO	Pacific decadal oscillation
OLR	Outgoing long-wave radiation
SLP	Sea-level pressure
q	Specific humidity
u	Zonal wind component
v	Meridional wind component
W	Omega
Z	Geopotential
AZ	Zonal available potential energy
AE	Eddy available potential energy
KZ	Zonal kinetic energy
KE	Eddy kinetic energy

1 Introduction

Heavy rainfall is arguably the weather-related hazard that is most widespread around the globe. The occurrence of heavy rains, mainly during austral summer, in Southeast Brazil (SEB) causes great impact on the socioeconomic activities of that region (Southeast Brazil comprises of four states, São Paulo (SP), Rio de Janeiro (RJ), Minas Gerais (MG), and Espírito Santo (ES), shown in Fig. 1). Heavy rains cause devastation in urban areas, where the drainage becomes inadequate to accommodate large amounts of sudden rain, and affect the management of freshwater supply to the population. The rural areas can also suffer damages, where loss of crops due to heavy precipitation can cripple the agro-industry. Accurate weather forecasts during heavy precipitation episodes are a necessity. For improving the forecasts, the meteorologist must understand the atmospheric conditions and mechanisms that produce such events.

In SEB during rainy season, 1 December through 31 March, the civil defense organization of Brazil adapts preventive measures and executes contingency plans to minimize the effects of heavy rainfall events. The most frequent consequences, during the summer period are floods, landslides, lightning strokes, windstorms, and hail, causing damages to the essential services like electric power supply, water supply, sanitation, and health care. Ninety one municipal districts were affected by rains leaving 33 dead, 31 wounded and 1982 homeless in the state of São Paulo during the summer season of 2008–2009 (http://www.defesacivil.sp.gov.br). Until February 20, 2009, civil defense organization registered 15 deaths caused by heavy rainfall in the state of São Paulo alone. Whereas an understanding of the occurrence of episodes of intense rain is relevant for any given region, it is all the more important for SEB because it is home for a large population (nearly 73 million inhabitants) and is responsible for 61.5% of the gross national product (GNP) of Brazil (http://www.ibge.gov.br).

Heavy precipitations are mainly caused by two important atmospheric perturbations, the Cold Front (CF) incursion and the South Atlantic Convergence Zone (SACZ) formation, in SEB during austral summer. The atmospheric fronts are zones of strong horizontal thermal gradient accompanied by a marked shift in the wind direction and a significant transition in the moisture field (Bluestein 1993). An observational study of the frequency of frontal systems over South America by Oliveira (1986) showed that the frontal incursions are well spread over all seasons. They are responsible for a large part of the rainfall in northern Argentina, Uruguay, Paraguay, southern, southeastern, southwestern, and central-western Brazil, Bolivia and southern Peru. Their convective activity is very low in austral winter and is high in austral summer.

The SACZ is defined as a zone of enhanced convective activity that is most pronounced during austral summer and is visible on maps of mean precipitation as a band that extends from the Amazon Basin southeastward into the Atlantic, passing over SEB (Nogués-Paegle and Mo 1997). This is one of the three subtropical convergence zones in the Southern Hemisphere (Kodama 1992). The system is responsible for large amounts of rainfall in the states of Rio de Janeiro, northern and eastern São Paulo, southern and western Minas Gerais, Mato Grosso do Sul, and southern and eastern Mato Grosso in Brazil (Satyamurty et al. 1998). The occurrence of daily extreme precipitation events in the São Paulo state and the spatial features of convective activity in the SACZ were investigated by Carvalho et al. (2002). The results indicated that 35% of extreme precipitation events occurred when convective activity in the SACZ was intense over large parts of tropical South America, which includes São Paulo, but with smaller extension into the Atlantic Ocean.

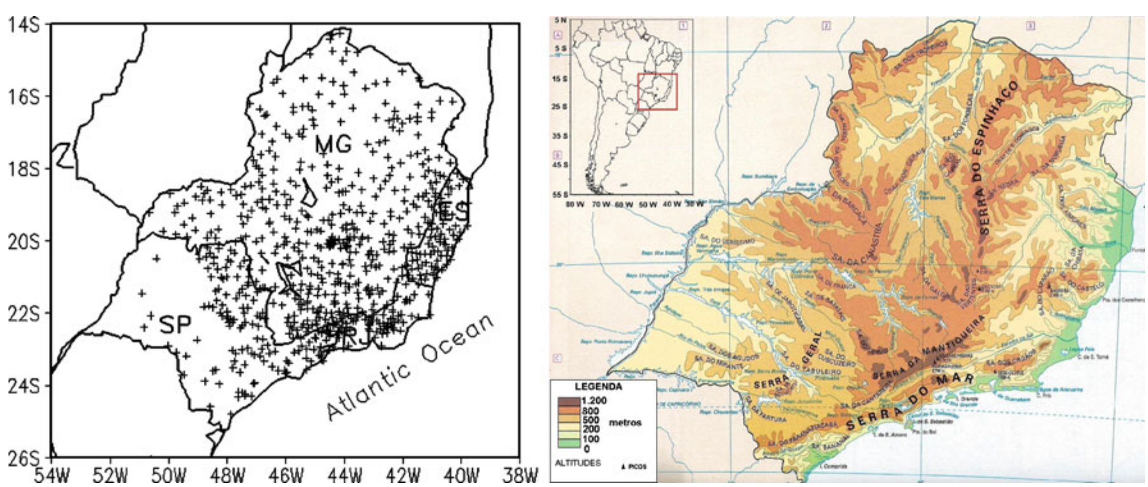


Fig. 1 Rain gage network in *SP* São Paulo, *MG* Minas Gerais, *RJ* Rio de Janeiro and *ES* Espírito Santo. Topography of the Southeast Brazil (*right panel*) region and its location within the South American continent (*inset*)

The synoptic patterns associated with landslide events in the Serra do Mar, in the southeast coastal mountain region in Brazil, during the summer season, were studied by Seluchi and Chou (2009). In the cases associated with both the SACZ and the CF, the composite fields showed that the 250-hPa mass divergence was strikingly more intense than the climatology and had a preferred location in the 24 h prior to landslide events. Anomalies of this 10-year event climatology showed above-normal moisture anomalies, which were more evident in the SACZ than in the frontal cases. Teixeira and Satyamurty (2007) studied the dynamical and synoptic characteristics that distinguish heavy rainfall episodes from nonheavy rainfall episodes in Southern Brazil. The mean flow patterns in the period of 1–3 days preceding the episodes showed some striking synoptic-scale features that may be considered forerunners of these episodes: a deepening mid-tropospheric trough in the eastern South Pacific approaches the continent three days before; a surface low-pressure center forms in northern Argentina 1 day before; a northerly low-level jet develops over Paraguay 2 days before; and a strong moisture flux convergence over southern Brazil becomes prominent 1 day before the episode. However, the features associated with heavy rainfall episodes in Southeast Brazil are not yet completely studied.

The objective of this study is to establish the characteristics of the synoptic-scale patterns in the middle and lower troposphere associated with heavy rainfall episodes in Southeast Brazil caused by cold frontal incursions and by South Atlantic Convergence Zone formation. These characteristics are compared with the normal rainfall episodes over the region.

The paper is organized as follows: Section 2 explains the datasets and methodology utilized, Section 3 describes the frequencies of heavy precipitation events, and Section 4 presents the synoptic analyses. A case study is shown in Section 5. Finally, the discussion and conclusions of the results are given in Section 6.

2 Data and methodology

2.1 Datasets

The daily rainfall data for the SEB used in this study is obtained from the National Water Agency of Brazil (Agência Nacional das Águas, ANA) and available at the Center for Weather Forecasts and Climate Studies (Centro de Previsão de Tempo e Estudos Climáticos, CPTEC). The data consists of daily precipitation totals for the 45-year period 1960–2005 over SEB. The numbers of rain gage stations in the region of study have increased steadily from around 300 in 1960 to 795 in 2005. The rain gage network in SEB in 2005 consisted of 85 stations in the state of ES, 86 in RJ, 135 in SP, and 489 in MG and is shown in Fig. 1. However, only 602 stations with 25 years of uninterrupted data are considered in this study. The datasets are considered to be of good quality, because the data has already gone through quality control by ANA. We did not carry out any interpolation to fill missing observations, because this may result in unreliable data, since the rainfall is a discontinuous variable both in space and time. The SEB has its rainy season extending from November through March, NDJFM (Rao and Hada 1990) and, hence, this study is limited only to examine the heavy rainfall events in this season.

In order to study the atmospheric characteristics associated with intense precipitation events daily gridded reanalysis meteorological data from National Centers for Environmental Prediction-National Center for Atmosphere Research (NCEP-NCAR; Kalnay et al. 1996) are utilized. The meteorological variables used are outgoing long-wave radiation (OLR 1976–2005 period), sea-level pressure (SLP), specific humidity and wind components at all the standard levels between 1,000 and 200 hPa (q, u, v), vertical velocity and geopotential height at 500 hPa (W500, Z500) for the 1960–2005 period with horizontal resolution of 2.5° latitude × 2.5° longitude.

ERA 40 reanalysis dataset with horizontal resolution of 1.125° latitude × 1.125° longitude for the days January 29 until February 2, 1988 over the domain 140°W−20°W; 0°−40°S is utilized for the synoptic analysis and energetics calculations of a heavy precipitation event.

2.2 Normal and heavy precipitation events

The basic idea of this work is to compare the differences in the structure of the atmospheric perturbations between heavy rainfall events (HRE) and normal rainfall events (NRE). The two types of rainfall events are identified with the aid of quantile or percentile analysis (Wilks 1995) of the daily precipitation series at 602 stations. A HRE is defined as a day when $P \geq q(0.99)$ at 10 or more stations in the whole region, where P is the daily precipitation registered at a given station and $q(r)$ is the value corresponding to $(100 \times r)$th quantile. That is, only the daily rainfalls in the highest 1% category were considered to identify HRE. This small percentage and the simultaneity of ten stations are used for limiting the study to extreme events. An NRE is defined when ten or more stations report rainfall around their median values: $q(0.45) \geq P \geq q(0.55)$. This narrow band of values is chosen so that the number of NRE during the 45 rainy seasons (NDJFM) in the period 1960–2005 is not enormously large.

2.3 Atmospheric perturbations

First, the NRE and HRE as defined in the last subsection are identified. Then, these events are separated according to the type of the atmospheric perturbation responsible for their occurrence. It is known that during the austral summer the quasi-stationary system dominant on the SEB is the SACZ. Another atmospheric perturbation that is frequent in this period is the CF (Satyamurty et al. 1998). The heavy precipitation events are mostly associated with these two meteorological systems (some events are caused by localized convective systems, but are rare).

Thus, the NRE and HRE cases are separated according to the two types of meteorological systems responsible for the rains, SACZ and CF. The two perturbations are distinct in one aspect: duration. The CF is a transient perturbation and affects the region for a day or two, whereas the SACZ is a quasi-stationary system and stays over SEB for more than three days, on the average. The separation of NRE and HRE into CF and SACZ situations is possible, observing this characteristic. To achieve this objectively, lag spatial correlations of the OLR fields are utilized for the events after 1976. Spatial correlation of the OLR between the day of the event, D0 and D−2, and D0 and D+2 are calculated over the space domain of 0°–40°S and 30°–70°W, that encompasses SEB. Then, the following criterion is used to separate the cases into CF and SACZ. A case of NRE or HRE is considered to be caused by SACZ if the condition below is satisfied:

$$[r_{\mathrm{OLR}}(\mathrm{D0}, \mathrm{D}-2) + r_{\mathrm{OLR}}(\mathrm{D0}, \mathrm{D}+2)]/2 \geq 0.35. \qquad (1)$$

where: r_{OLR} is the spatial correlation of the OLR fields on the two days in the parentheses. For example, r_{OLR}(D0, D−2) is the spatial correlation between the OLR fields on D0 and D−2. The rest of the cases is considered to be caused by CF. This threshold correlation value is the mean of the correlation values obtained in all the selected cases. Before 1976, OLR observations were not available and therefore the fields of 500-hPa vertical velocity (W500), instead of OLR, are used for obtaining the spatial correlations. In this case, the threshold value of correlation is 0.25.

Hereafter, the categories of rainfall are NRE and HRE and the situations are CF and SACZ. To confirm the synoptic situation (SACZ or CF) associated with the rainfall events, the Climanálise Journal (Revista Climanálise) is consulted, for cases after 1986. The Journal includes a description of the major events of the month, especially the occurrences of SACZ and CF, based on the satellite imagery. This bulletin is edited by the Brazilian Institute for Space Research (Instituto Nacional de Pesquisas Espaciais, INPE) since 1986. The agreement between the categorization obtained objectively and the Climanálise information found is satisfactory.

Although small-scale and mesoscale atmospheric perturbations are very important for heavy rainfall episodes, we suppose that a favorable synoptic-scale environment is essential for such events. The resolution of the datasets (2.5° latitude×2.5° longitude) allows us to identify the essential synoptic-scale features.

2.4 Composite charts

After the separation of the NRE and HRE according to the associated atmospheric perturbation, composite anomaly charts of atmospheric variables mentioned in section 2.1 for the day of the episode (D0) and 2 days before the event (D−1) and (D−2) are calculated, in order to identify the dynamical and synoptic features associated with such episodes. Composite anomalies are constructed in the spatial domain of 0°–65°S and 140°–20°W for Z500, and 0°–40°S and 80°–20°W domain for the others variables. A larger domain for Z500 field allows us to verify the propagation and evolution of the mid-tropospheric synoptic waves. The composite anomalies are prepared for the period of NDJFM (rainy season) and for each one of the types of the synoptic situation (CF and SACZ). The composites for D0, D−1 and D−2 are useful for tracking the evolution of the synoptic-scale systems responsible for the NRE or HRE.

The seasonal composite chart of a general variable is obtained in the following manner:

$$\overline{\Phi}(x, y, p, D-n) = \frac{1}{N}\sum_{j=1}^{N} \overline{\Phi}(x, y, p, j, D-n) \qquad (2)$$

where $\overline{\Phi}$ is the composite variable, (x, y, p) indicates the spatial position in the field, N is the number of cases identified during the season in the period of study, D−n is the nth day preceding the event, where n=0, 1, 2 and the suffix j refers to the jth event.

We designate Φ_C (x, y, p) to represent the climatology of the variable Φ. The composite anomaly is defined as:

$$\overline{\Phi}'(x, y, p, D-n) = \overline{\Phi}(x, y, p, D-n) - \overline{\Phi}_C(x, y, p) \qquad (3)$$

The anomalies are tested for statistical significance using the Student t at 90% significance level (Harrison and Larkin 1998). Thus, the anomaly is considered significant if:

$$\frac{\overline{\Phi}'\sqrt{n}}{\sigma} \geq t_{90\%} \qquad (4)$$

where: the standard deviation σ at a location (x, y, p) is given by:

$$\sigma = \sqrt{\left(\frac{\sum_{i=1}^{n} \left(\overline{\Phi}_i - \overline{\Phi} \right)^2}{(N-1)} \right)} \quad (5)$$

where $\overline{\Phi}'$ is the anomaly of the composite at (x, y, p), N is the number of events used, and $t_{90\%}$ is the tabulated value of Student t at 90% significance level.

2.5 Water vapor (H_2O) transport

A rectangular target area between 14°S–26°S and 38°W–54°W, encompassing SEB, is considered for studying the transport of H_2O inward and outward of the area. The vertically and laterally integrated values of H_2O flux across the four walls of the target area are calculated for each HRE and NRE and then composites of both categories are constructed. The composites are constructed for SACZ and CF separately in order to find the differences, if any, between the two types of meteorological perturbations. The mean convergence of H_2O flux over the target area is obtained by adding the inward transports and subtracting the outward transports.

2.6 Energetics

Daily data from ERA 40 model analysis (1.125°×1.125° resolution) were used for the energetic calculations of the heavy rainfall case that occurred on February 1, 1988 over SEB. The zonal and eddy components of atmospheric available potential energy (AZ and AE, respectively) and kinetic energy (KZ and KE, respectively) are obtained for the period January 29 until February 2. The conversion between the various energy forms is given by (AZ–AE), (AE–KE), (KE–KZ), and (AZ–KZ). Mathematical expressions for the components of the energetics are taken from Krishnamurti and Lahouari (1995). Horizontal integrations in the present study are performed over the area bounded by 38.25°W–60.75°W and 14.625°S–25.875°S that roughly contains SEB. The vertical integrations are performed from 1,000 to 100 hPa.

3 Frequency of heavy precipitation events in SEB

Using the methodology and criteria described above, precipitation events during the period 1960−2005 are identified, for the 5-month rainy season considered, i.e., NDJFM. Over SEB, in the 45-year period, 1981 NRE are identified, of which 1,089 (55%) cases are associated with CF and 892 (45%) are associated with SACZ. In the same period, the number of HRE identified are 157, of which 83 (53%) are associated with CF and 74 (47%) with SACZ. That is, the CF situations are responsible for slightly more rainy and heavy rainy events than the SACZ situations, although the SACZ persists much longer than CF. The reason is the high frequency of CF over SEB, about five per month (Oliveira 1986), compared with only one or two SACZ situations per month.

In the geographical distribution of the HRE (not shown) there are higher concentrations of HRE near the Atlantic coast. This is perhaps partly due to the higher density of stations along the coastal belt. However, this result indicates that the HRE are associated with strong advection of moisture from the Atlantic Ocean. In addition, the area has a complex terrain with the Serra do Mar and the Mantiqueira mountain ranges (see Fig. 1). These topographic features are likely to influence the formation and intensification of stationary convective systems (Smith et al. 1996), which can cause occasional large daily totals of rainfall.

It is interesting to take note of the two extreme values (or highest values) of single-day precipitation registered at any station in SEB by the ANA rain gage network during the 45-year period: 375.2 mm on February 1, 1988 at Angra dos Reis/RJ (23°S−44°W; 6 m) and 308.5 mm on March 6, 1983 at Cananéia/SP (24°S−47°W; 8 m). Possible causes for those high values of rainfall are that 1983 was a strong El Niño year and 1988 was a moderate El Niño year (www.cptec.inpe.br/enos) and that SACZ persisted over RJ in February 1988, with duration of 14 days.

The interannual and monthly variations of the frequencies of HRE are shown in Fig. 2. Figure 2a shows the 5-year running means of HRE frequencies in SEB. The most striking aspect is the interdecadal variability of the HRE frequency over the 45-year period. The precipitation over SEB presents interdecadal oscillations associated with the Pacific decadal oscillation (PDO, Grimm and Canestraro 2003). The period 1979−1989 registered the highest frequency and the period 1974–1976 registered the lowest frequency. In particular, the frequencies were very low around 1975–76 and very high around 1981–82. The former is due to a strong El Niño and the latter is due to a La Niña. Presently, the frequencies are showing a rising trend since the year 1999. Great floods and higher-than-normal temperatures in SEB are often results of the El Niño phenomenon (Silva Dias and Marengo 1999).

The monthly distribution of the HRE (Fig. 2b) shows an increase in the frequency from November through January that is, peaking in the middle of the rainy season. In March, there is a small rise in the frequency compared to February, although the monthly rainfall climatology decreases. That

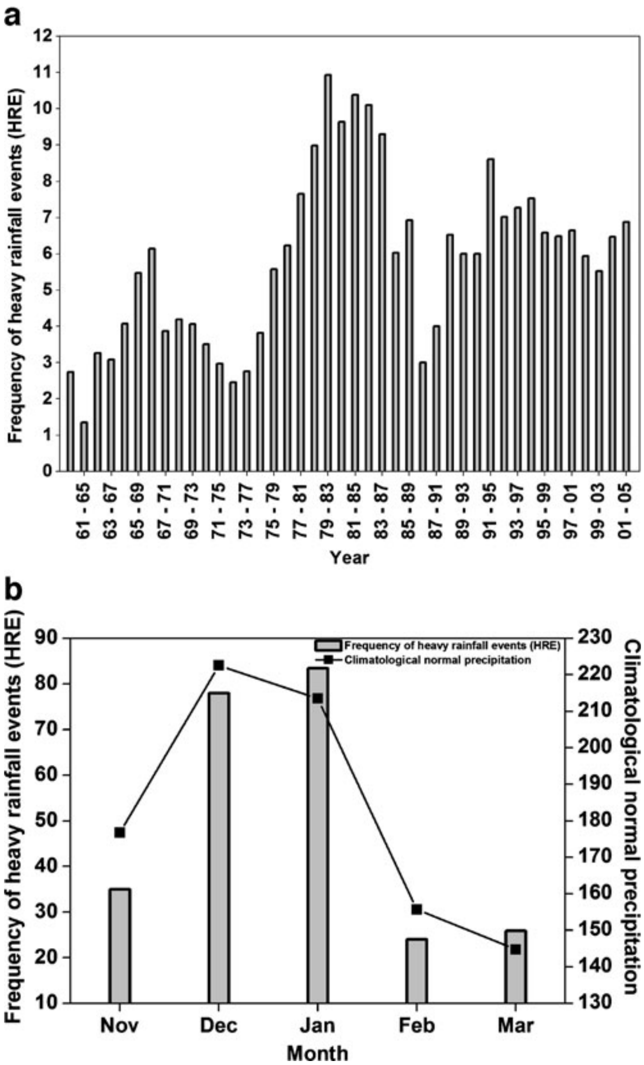


Fig. 2 **a** Interannual distribution of the number of heavy rainfall events per year. **b** Monthly distribution of heavy rainfall events, in Southeast Brazil during the season November through March for the period 1960 to 2005. The continuous line in panel (**b**) is climatological monthly rainfall (mm)

is, the March rains in SEB are more concentrated in heavy rainfall events, and these rains are known in the state of São Paulo as "waters of March" (*águas de Março*).

4 Large-scale atmospheric features associated with NRE and HRE

The fields of the composite anomalies of OLR associated with HREs for both the CF and the SACZ situations are prepared for the period 1976−2005 (we must remember that the OLR datasets are available only since 1976). They (not given here) show large bands of negative anomalies of the order of −40 and −45 W m^{-2}, for CF and SACZ respectively, while for the NREs the values are −20 and −25 W m^{-2} over SEB. These fields permit us to reaffirm the fact that OLR anomaly really serves as a proxy for rainfall over SEB, especially so for the very heavy rainfall situations. The negative anomaly in the NRE composites intensifies from –5 W m^{-2} on D−2 to –25 W m^{-2} on D0, whereas in the situation of HRE associated with SACZ the value is –35 W m^{-2} even on D−2. Another important feature is that there is a strong positive anomaly of OLR (+25 W m^{-2}) on D0 over southern Brazil and northern Argentina, south of the SACZ, indicative of dry air mass.

The sea-level pressure (SLP) composite anomalies for NRE and HRE for the CF and SACZ situations on days D0 and D–2 are shown in Fig. 3. For NRE situation the SLP anomaly is very small whereas in the HRE the average negative anomaly over SEB is of the order of 2.0 to 2.5 hPa on D0. The difference between the NRE and HRE composites are very striking. The HRE composites associated SACZ and CF show one obvious difference. In the case of CF, the low-pressure anomaly on D−2 is weak and intensifies to double its value on D0. In the case of SACZ, the intensity of the low-pressure anomaly over SEB is almost the same on both D−2 and D0. In both the cases, a high-pressure anomaly south of SEB, indicative of cold air mass over Argentina, builds from D−2 to D0.

The fields of 500-hPa geopotential height anomaly composites are presented in Fig. 4. In the NRE, the negative height anomalies over SEB are of the order −10 m. The high-pressure center south of SEB presents strong positive anomalies of the order of 40 m over Argentina on D0. Both the negative and positive anomalies of the height field intensify from D−2 to D0. In the HRE composites, we find a well-defined wave train in the South Pacific and over the South American continent, with a strong ridge over Argentina and a strong trough or a low over SEB. The troughs and ridges in the wave train have northwest–southeast orientation. The height anomalies are somewhat stronger in the case of CF compared to SACZ situation. The eastward propagation of the high-pressure anomaly center is somewhat slower in the SACZ situations (15° longitude in 2 days) than in CF situation (26° in 2 days). This is due to the quasi-stationary nature of the SACZ. These positive and negative anomalies of geopotential over South America suggest a blocking pattern of circulation (Seluchi and Chou 2009) in the SACZ case, which are characterized by a persistent high-pressure center that impedes the propagation of transient systems. The large difference found in the intensity of the anomalies between NRE and HRE is useful for the identification of severe events.

The 500-hPa vertical velocity composite anomaly fields (no shown), in both the situations, there are significant differences between NRE and HRE. In the case of NRE, the upward motion (negative W500) with an average of

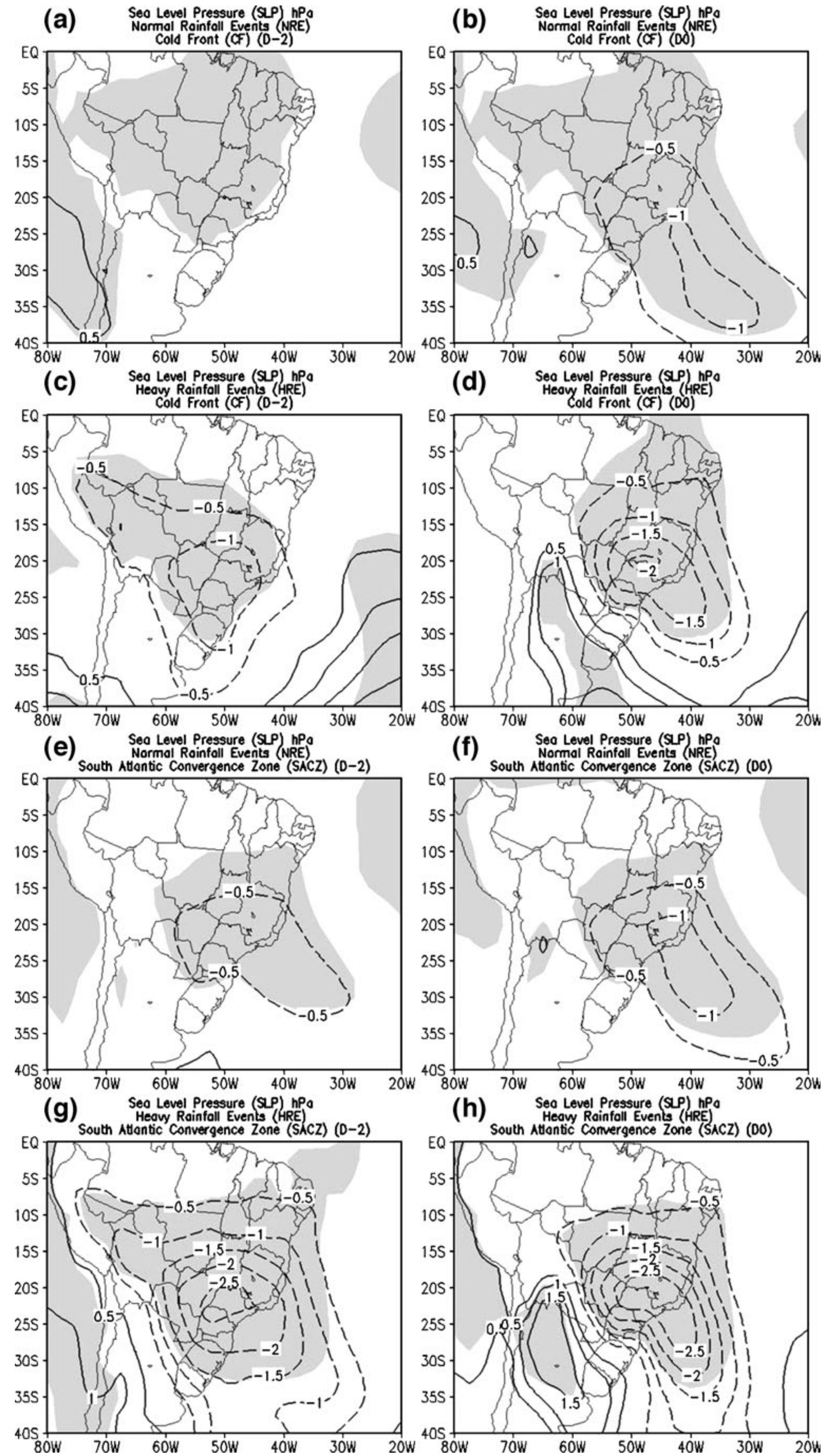
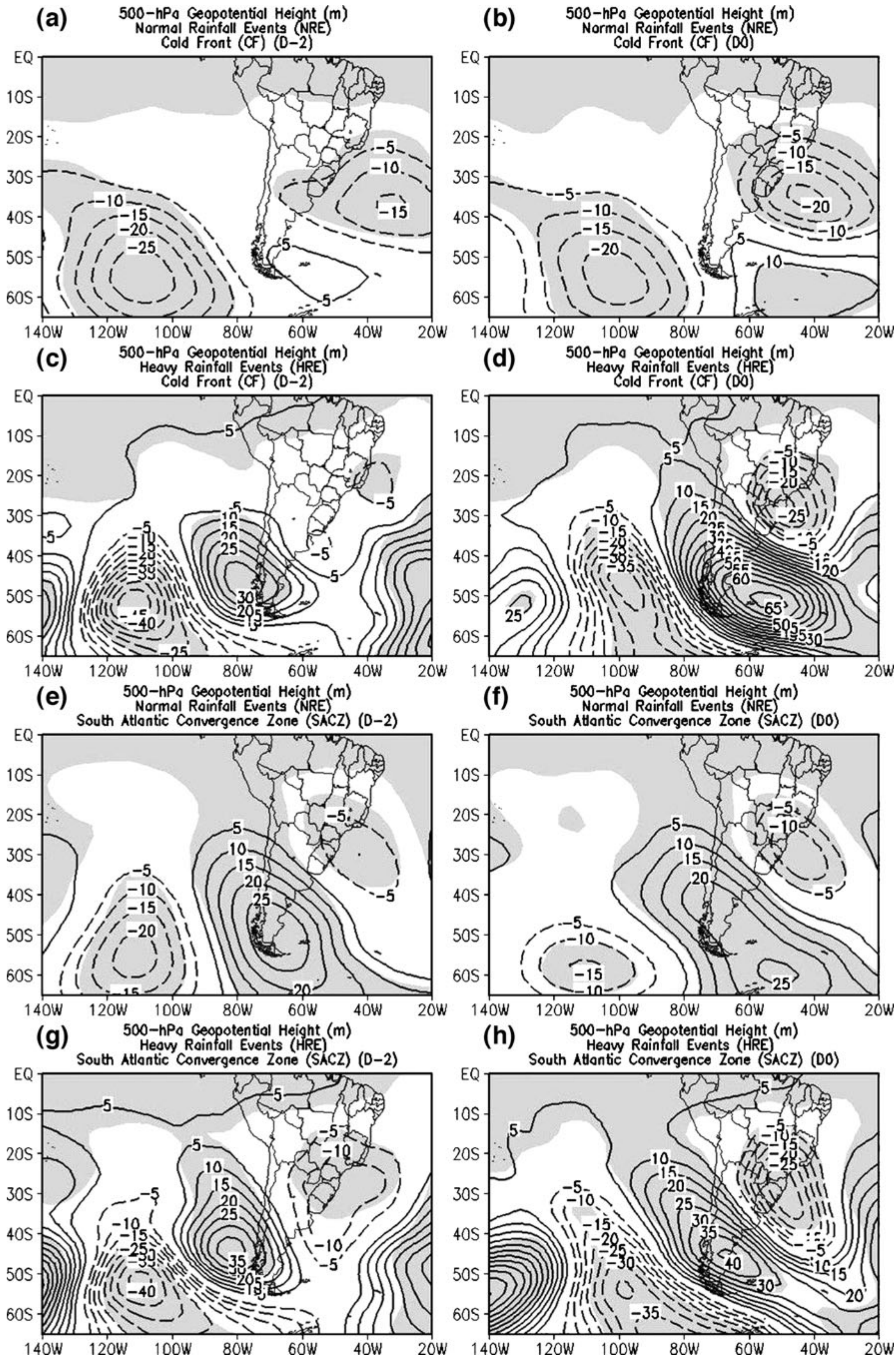


Fig. 3 Sea-level pressure composite anomaly, negative (*dashed lines*) and positive (*continuous lines*), for (**a**–**d**) Cold Front and (**e**–**h**) South Atlantic Convergence Zone situations over Southeast Brazil for D–2and D0. Contour interval is 0.5 hPa. Panels (**a**, **b**, **e**, **f**) are for normal rainfall events and (**c**, **d**, **g**, **h**) for heavy rainfall events. *Shaded areas* are significant at 90% level


(a)
500-hPa Geopotential Height (m)
Normal Rainfall Events (NRE)
Cold Front (CF) (D-2)
(b)
500-hPa Geopotential Height (m)
Normal Rainfall Events (NRE)
Cold Front (CF) (D0)
(c)
500-hPa Geopotential Height (m)
Heavy Rainfall Events (HRE)
Cold Front (CF) (D-2)
(d)
500-hPa Geopotential Height (m)
Heavy Rainfall Events (HRE)
Cold Front (CF) (D0)
(e)
500-hPa Geopotential Height (m)
Normal Rainfall Events (NRE)
South Atlantic Convergence Zone (SACZ) (D-2)
(f)
500-hPa Geopotential Height (m)
Normal Rainfall Events (NRE)
South Atlantic Convergence Zone (SACZ) (D0)
(g)
500-hPa Geopotential Height (m)
Heavy Rainfall Events (HRE)
South Atlantic Convergence Zone (SACZ) (D-2)
(h)
500-hPa Geopotential Height (m)
Heavy Rainfall Events (HRE)
South Atlantic Convergence Zone (SACZ) (D0)
EQ
10S
20S
30S
40S
50S
60S
140W 120W 100W 80W 60W 40W 20W

◀ **Fig. 4** Same as in Fig. 3, but for 500-hPa geopotential height. Contour interval is 5 m

−3 Pa s^{-1} is quite weaker than −8 Pa s^{-1} for the HRE. The reason why the upward motion anomalies in the SACZ composites are stronger than in CF situation, both in NRE and HRE, could be as follows: the frontal situation is transient, and so is the horizontal locations of the maxima and minima in the vertical motion fields, and the compositing process smooths its intensity. In the case of SACZ situation, the smoothing is less because SACZ is a quasi-stationary situation. The upward motion area extends northward over the continent into Northeast Brazil in all the situations.

The wind anomaly composites for the events associated with SACZ are presented in Fig. 5. It is interesting to verify that the lower tropospheric cyclonic vortex with the center over SEB is several times stronger in the case of HRE (second row) compared to the NRE situation (first row). The southerly wind anomalies over southern Brazil, Paraguay, eastern Bolivia, and central-western Brazil are very strong (of the order of 10 m s^{-1}) indicating that the South American low-level-jet (LLJ) is completely weakened in the HRE. It is known that the LLJ east of the Andes becomes either weak or absent in the SACZ situations (Herdies et al. 2002). In the HRE, this characteristic becomes more evident and must serve as a good indicator of heavy rains over SEB. When the LLJ is strong, the moisture is transported to southern Brazil and Argentina, and when the jet is weak or absent, the moisture from the Atlantic and southern Amazon region converges over SEB.

The upper tropospheric wind anomalies also show stronger circulation centers in HRE composites than in NRE composites. The presence of a closed upper tropospheric vortex off the Northeast Brazil coast and the ridge over SEB are very conspicuous. This indicates that the air mass over SEB is warm and so the cyclone in the lower levels weakens with height and becomes a ridge at 200 hPa level. The upper wind anomalies around Bolivia show anticyclonic circulation and therefore the Bolivian High (Satyamurty et al. 1998) in the HRE associated with SACZ is slightly stronger than normal, indicating that the convective activity over the subtropics and tropics of the continent is stronger. A cyclonic center gradually intensifies from D−2 to D0 in the middle latitudes with zonally oriented subtropical jet intensification around 20°S over South America. This shows that the cold air mass south of the SACZ becomes colder, thus intensifying the upper cyclone. A huge ridge to the north of the cyclone near the east coast of Brazil around 20°S and an upper cyclone in the equatorial South Atlantic off the Northeast Brazil coast remain quasi-stationary. The ridge and the Northeast cyclone are part of the SACZ structure (Kodama 1992). The anomalies in the NRE also look similar to the HRE with one exception: the anomalous cyclones and the ridge are less intense in this case (compare the sizes of the wind vectors). One difference between the HRE in the CF (not shown) and SACZ situations is the eastward movement of the extratropical upper cyclone in the case of CF.

Figure 6 presents composites of the vertically integrated water vapor transport into the SEB region. In general, the transport of water vapor is more expressive across the eastern boundary, that is, from the Atlantic into the SEB region. In the situation of NRE, the flux convergence is about 7×10^{8}kg s^{-1} whereas in the HRE the convergence exceeds 10×10^{8}kg s^{-1}. The SACZ situation presents slightly more convergence than in the CF situation. This difference is due to widespread rains in SACZ situations compared to narrow-banded rain in the CF situation. We can also observe that the convergence increases from around 9×10^{8}kg s^{-1} on D–2to 12×10^{8}kg s^{-1} on D0 in the SACZ situation. The moisture convergence in HRE associated with SACZ is 60 % larger than NRE. This is yet another indicator of heavy rainfall possibility.

5 A case study

5.1 Synoptic situation

The composite fields express the mean conditions and patterns of the atmospheric anomaly fields. Due to the differences in the individual cases that are used to obtain the composites, the averaging procedure smooths the fields, reducing the intensity of the features such as pressure centers, cyclonic and anticyclonic circulations, and divergence. Therefore, to fully appreciate the intensity of the anomaly fields in the events of heavy rainfall, it is profitable to look into at least one individual case. Thus, we present some anomaly fields observed in the case of February 1, 1988 HRE mentioned in Section 3, in Fig. 7. We recall that, on this day, the rainfall at Angra dos Reis/RJ (23°S−44°W; 6 m) amounted to 375.2 mm.

The top two panels (Fig. 7a and b) show the observed rainfall total in the period from 09:00 LT on 31 January to 09:00 LT on 2 February 1988. The Revista Climanálise categorized the situation as SACZ. Here, we can see that the major rainfall band runs northwestward from Southeast Brazil. Panel (b) is a zoom of panel (a). Over the Rio de Janeiro state, the rainfall was very heavy. The IR satellite cloud picture on 1 February 21:00 UTC is shown in panel (c) in which we can see the convective area with a northwest to southeast orientation from the Amazon basin to Southeast Brazil. The lower tropospheric wind anomaly (panel d) shows a confluence line running from the ocean into the continent over Southeast Brazil. The 500-hPa

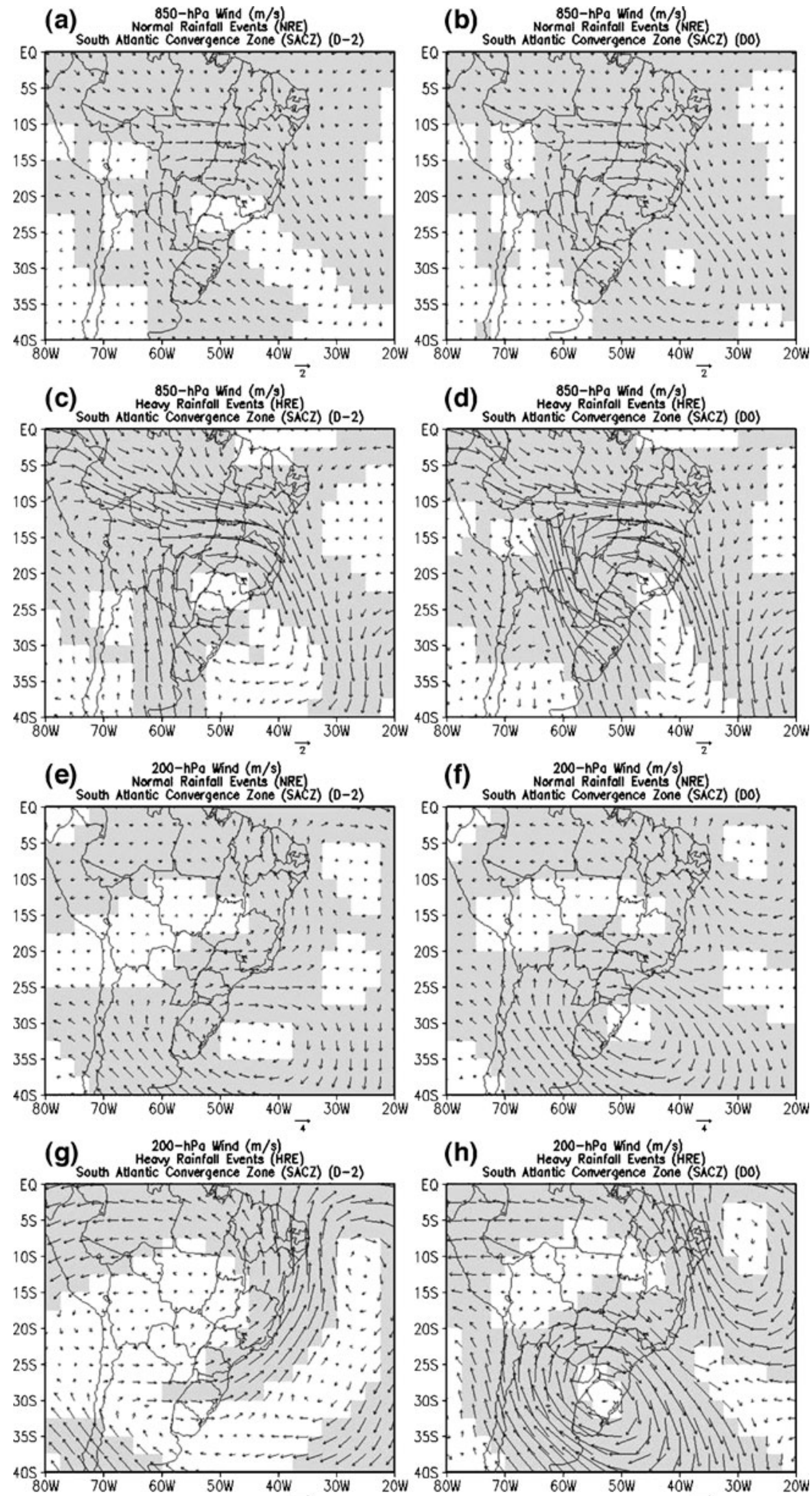


Fig. 5 Wind composite anomaly **a**–**d** 850 hPa and (**e**–**h**) 200 hPa in South Atlantic Convergence Zone situations over Southeast Brazil for D–2 and D0. Vector size for 850 hPa is 2 m s^{-1} and for 200 hPa is 4 m s^{-1}. Panels (**a**, **b**, **e**, **f**) are for normal rainfall events and (**c**, **d**, **g**, **h**) for heavy rainfall events. *Shaded areas* are significant at 90% level

geopotential anomaly presented in panel (e) shows a trough extending into southern Brazil from the Atlantic Ocean. The value of the height anomaly over SEB is −200 m, and is an order of magnitude larger than in the composites. The sea-level pressure anomaly (not presented) shows a trough over the Southeastern Brazil. That is, the trough is inclined in the vertical to the south indicating a strong cold air mass south of the SEB. The vertical velocity negative anomaly

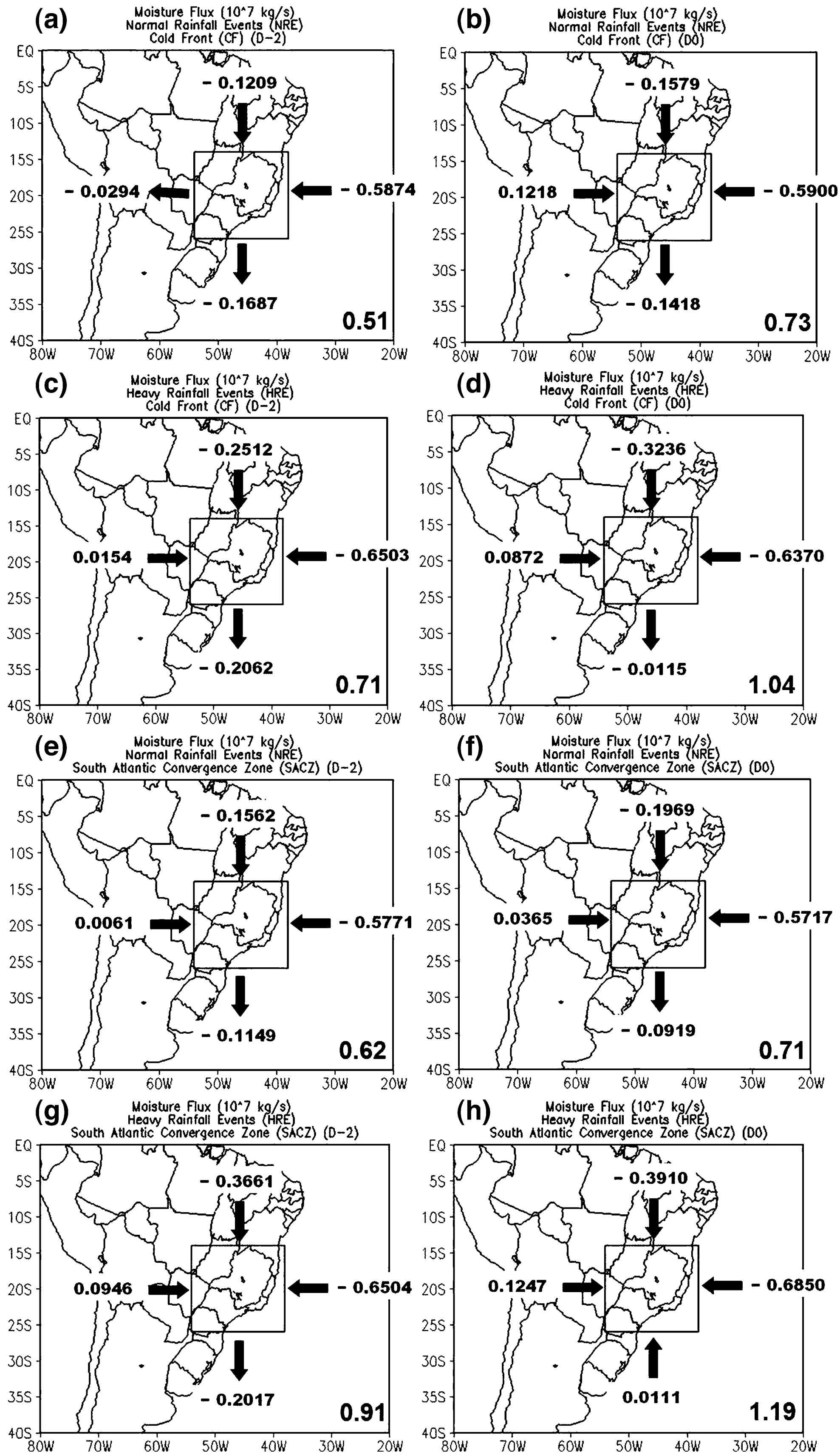


Fig. 6 Vertically integrated moisture flux composites across the lateral boundaries of the box around Southeast Brazil, for (**a**–**d**) Cold Front and (**e**–**h**) South Atlantic Convergence Zone situations for D–2 and D0. Panels (**a**, **b**, **e**, **f**) are for normal rainfall events and (**c**, **d**, **g**, **h**) for heavy rainfall events. *Number in the bottom right corner* of a panel is moisture flux convergence over the rectangular area. Units are 10^9kg s^{-1}

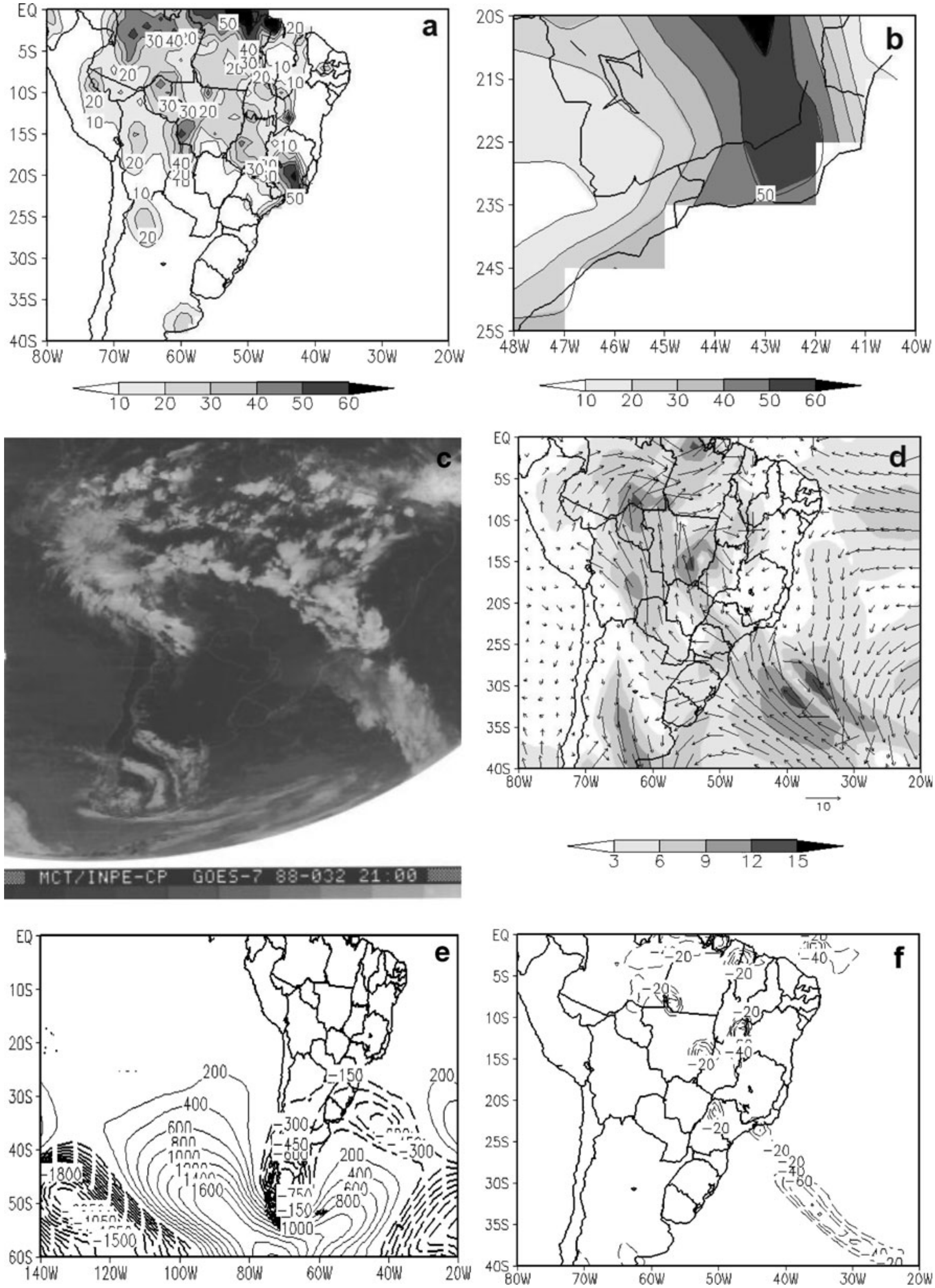


Fig. 7 Results of a case study. **a** Accumulated precipitation in the period January 31 until February 2, 1988 over South America (mm). **b** Zoom of the precipitation over and around the state of Rio de Janeiro. **c** IR satellite imagery at 21:00 UTC on 01 February. **d** Outgoing long-wave radiation anomaly (W m^{-2}); **e** 500-hPa geopotential height (m) anomaly, **f** 850-hPa vector wind anomaly (m s^{-1})

(panel f), with values of up to -60×10^{-2} Pa s^{-1}, extend well into South Atlantic Ocean which is characteristic of SACZ.

5.2 Energetics

The evolution of various components of the atmospheric energetic over the South American region during the period 00 UTC on 29 January through 00 UTC on 2 February at intervals of 6 h are shown in Fig. 8. We can identify the evolution of the components over the 5-day period. The zonal potential energy runs low till 31 January and increases after the HRE, indicating that the north–south thermal contrast over the region increased after 31 January. The eddy potential energy increased from 29 January until 1 February and decreases afterwards. The zonal kinetic energy showed a decrease from 29 January till 31 January and increased later and the eddy kinetic energy ran low till 30 January and increased later. These evolutions show that both the baroclinic instability and barotropic instability were responsible for the growth of the perturbation, which attained its maximum intensity on 1 February, both in terms of eddy potential energy and eddy kinetic energy (see KE, AE curves in Fig. 8a). The conversion of AZ to AE was intense at 18:00 UTC on 30 January while the conversion of KZ to KE was strong over the 2 days, from 18:00 UTC on 29 through 18:00 UTC on 1 February. The generation of AE and conversion from AE to KE also reached their peak intensities at 18:00 UTC on 29 January. These calculations show, surprisingly, the importance of the barotropic instability over SEB for producing the very heavy rainfall event studied. The slant orientation of the troughs and ridges in Fig. 4 and the barotropic instability are related.

6 Discussion and Conclusions

Regional or local extreme or severe meteorological events in the world are drawing attention of the public and the governments, because they are the major cause of the natural disasters. Examples are the Katrina tropical cyclone in the Caribbean in 2004 and the recent floods in the state of Santa Catarina in Brazil in 2008. The quality of the weather service is usually judged in terms of how well severe events are forecasted. The worst natural disasters in Southeast Brazil (SEB) are caused by heavy rainfall events.

One way to define a heavy rainfall event (HRE) is by considering a large-enough value of 24-h rainfall, based on Liebmann et al. (2001). This method does not take into account the different station characteristics and is not very appealing to the statisticians. The criterion used in this study to define a HRE, based on the percentile analysis, supposes that an extreme rainfall event is also a heavy rainfall event. We included a second criterion restricting the events to those in which at least ten stations reported extreme rainfall on the day of the event. The number looks somewhat arbitrary, but it is obtained after several trials, so

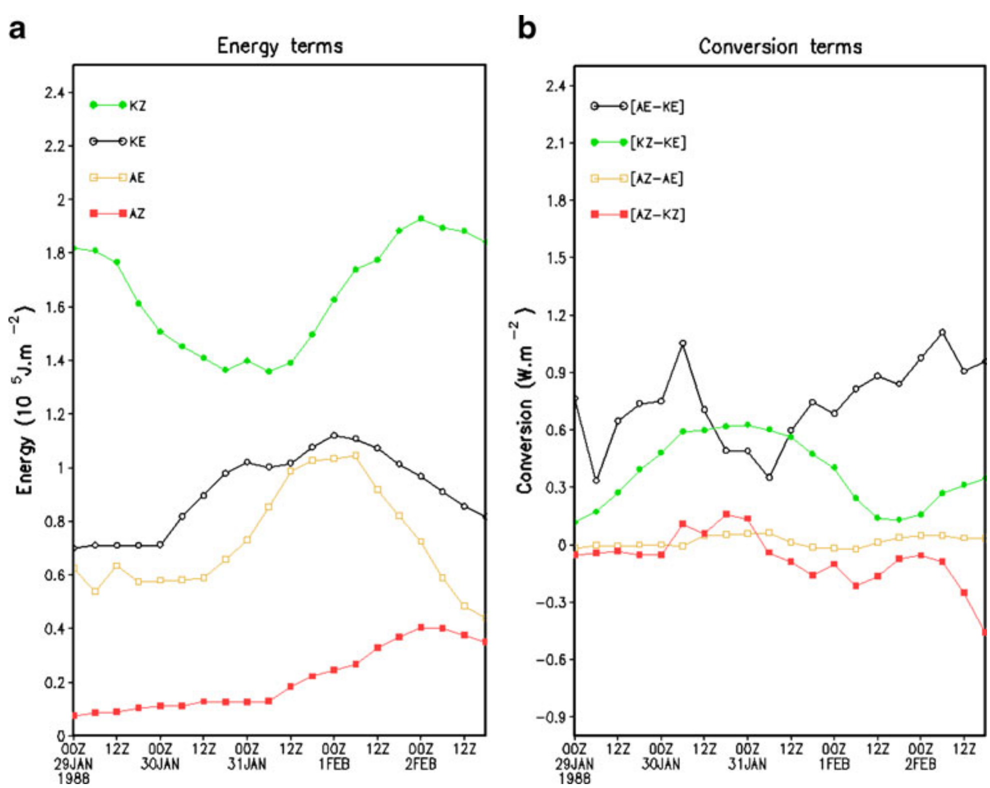


Fig. 8 Evolution of vertically integrated energy (100–1000 hPa). **a** AE, AZ, KE, and KZ terms. **b** Conversion terms for the period 29 January though 02 February 1988. Units are in **a** 10^5J m^{-2} and (**b**) W m^{-2}

that the numbers of HRE are neither too many nor too few. The advantage is that each station's frequency distribution characteristics are considered. We might have missed a few HREs due to lack of data or gaps in data sets, but the cases identified are truly extraordinary.

The anomalies of the composites with respect to the climatology, of the meteorological variables for the HREs tell us about the strength of the atmospheric perturbations responsible for the event. However, it is more revealing if a comparison is made between the anomalies of the HREs and the NRE. For this purpose, the NRE are chosen in such a way that the rainfall during these events is close to the median rainfall value, $q(50)$. The window used to consider the NREs is between 45% and 55% quantiles. This interval, although again looks arbitrary, is adjusted so that the events are not too many. With the window used, we obtained around 2,000 NRE in 45 rainy seasons. It is reasonable to believe that these cases represent fairly well the rainy days with normal rainfall, i.e., neither light rain nor heavy rain.

We find that the frequency of HRE associated with CF is slightly larger than the frequency associated with SACZ, but not in proportion to the frequency of CFs compared to SACZ. That is, although SACZ events are very few they quite often produce HREs. The reason for this is that the CFs are transient perturbations and the convective bands associated with them move away rapidly, producing short spells of rain, while the SACZ is a quasi-stationary system and the associated convective cloud bands reside over SEB for days. Carvalho et al. (2002) concluded that 35% of HRE over the state of São Paulo are due to SACZ. We verified that 47% cases are due to SACZ, for the whole SEB. The discrepancy is perhaps due to the length of the period studied and the definition used for HRE.

It is very common to come across studies analyzing the meteorological conditions associated with extraordinary weather events, where the anomalies with respect to the climatological conditions are discussed. In the present study, the extraordinary event is HRE and a comparison is made between the anomalies associated with these special events and normal rainfall situations. The results give the meteorologist the capability of distinguishing a normal event from an extraordinary event. For the scientific community, the results are useful to know what ingredients make a heavy rainy event.

The OLR composites over SEB for HREs in SACZ situations show more elongated patterns of negative anomalies than in the case of CF situations, as is expected. The positive OLR anomaly region over Argentina and southern Brazil on D–2 and D0, a cloud-free subsidence region, is associated with the high-pressure anomaly (Fig. 3). In the SACZ situations, the high-pressure anomaly is also three times stronger for HREs than for NREs. The Z500 composites show elongated troughs and ridges for HREs in SACZ situations showing a wave train from the East Pacific to SEB, with a rather slow progression. In the CF situations, the progression is faster, as is expected. The anomalies for the HREs are much stronger than for NREs in both situations. That is, the amplitude of the synoptic wave disturbance is important for the HREs. This validates our assumption that a suitable synoptic-scale environment is congenial for the occurrence of HREs associated with CF and SACZ perturbations. The lower tropospheric thermal advections (not shown) are very weak for HREs associated with SACZ situations. The vertical motion composites show strong rising motion over SEB for HREs associated with SACZ and these are caused mechanically by lower tropospheric convergence (not shown). In CF situations, the rising motion over SEB is caused by thermal advections (warm advection ahead and cold advection behind the cold frontal position). In general, the wind anomalies (Fig. 5) show stronger cyclonic and anticyclonic centers for HREs. The lower tropospheric anomalous cyclonic center for HREs in CF situations (figure not shown) shows an eastward progression that is absent in SACZ situations (Fig. 5c, d).

The analysis of the HRE of February 1, 1988 (Fig. 7) shows stronger anomalies than the composites. The evolution of the four components of energy and the conversions thereof (Fig. 8) shows that the KZ decreased as KE increased in the 3-day period prior to the HRE. Surprisingly, the conversion from AZ to AE over SEB remained very low. This indicates that the barotropic instability mechanism was important for the perturbation to grow.

It is important to identify the features associated with severe meteorological conditions with a potential for causing a disaster. The differences between very heavy rainfall events and normal rainfall events in terms of the associated synoptic-scale features are useful for the forecasters of the Southeast Brazil region that is the most populous and has the largest industrial base in Brazil. High amplitude perturbation with a high-pressure center over Argentina and low-pressure center over SEB, absence of LLJ and higher values of moisture convergence are some the important ingredients for HRE over SEB.

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