SYNOPTICS CHARACTERISTICS ASSOCIATED WITH HEAVY RAINFALL EPISODES IN SOUTHEASTERN BRAZIL

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1. INTRODUCTION

The Southeastern of Brazil (SEB) is an important region to the country, due the economy to have the largest development among the five Brazilian regions, where is concentrated more of the half of the national production. It is also, the region with the largest demographic density and the highest urbanization index. During the austral summer the SEB is affected by heavy rainfall episodes which are associated mainly with the presence of the South Atlantic Convergence Zone (SACZ). This atmospheric system is considered as one of the main phenomena responsible for intra-seasonal variability during the summer in South America and the main mechanism responsible for prolonged periods of heavy rainfall on the SEB. It is known that this system suffers influences so much of remote factors as locale. Among the places, Andes intensify aiding the feeding of the convergence with the humid air of the Amazonian (Figueroa et al., 1995).

In SEB during the rainy season, 01 December through 31 March, the civil defense organization of Brazil adapts preventive measures and executes contingency plans to minimize the effects of intense 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. During the summer of 2008-2009, until January 23, 2009, 80 municipal districts were already affected by rains, leaving 29 wounded, 52 dead and 1912 homeless only in the state of São Paulo, the most populous state in Brazil (http://www.defesacivil.sp.gov.br). Whereas if an understanding of the occurrence of episodes of intense rain is relevant for a given region, it is all the more important for SEB because it is home for a large population and is responsible for 61.5% of the Gross National Product (GNP) of Brazil (http://www.ibge.gov.br).

The numeric forecast of time has been increasingly used as strategic information of planning for several areas of the economical and social activities. However, the forecast of the intensity and location of the rains is still one of the main challenges faced in the operational activities of the main world centers of forecast of time and climate (NCEP, ECMWF, JMA, CPTEC, among others). Therefore, accurate weather forecasts during intense precipitation episodes are a necessity. For improving the forecasts of the meteorologists must to understand the atmospheric conditions and mechanisms that produce such events.

The objective of this study is to identify characteristics of the synoptic-scale patterns that distinguish "Very heavy Rainfall Events (VRE)" from m "Nonheavy Rainfall Events (NRE)" in southeastern Brazil caused by cold frontal incursions (CF) and by South Atlantic Convergence Zone formation (SACZ).

2. DATA AND METHODS

2.1 Data

The daily rainfall data for the SEB used in this study is obtained from the *Agência Nacional das Águas* (ANA; National Water Agency) and available at the *Centro de Previsão de Tempo e Estudos Climáticos* (CPTEC; Center for Weather Forecasts and Climate Studies). The data consists of daily precipitation totals for the 45-year period 1960 – 2005 over SEB. The SEB has its rainy season extending from November through March (Rao and Hada, 1990) and, hence, this study is limited only to examine the heavy rainfall events in this season, NDJFM.

In order to study the characteristics of the atmosphere 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 used. The meteorological variables used are outgoing long-wave radiation (OLR – 1979-2005 period), zonal and meridional wind components at 250 and 850 hPa (u250, v850), omega and geopotencial height at 500 hPa (W500, Z500), for the 1960-2005 period with horizontal resolution of 2.5 ° latitude × 2.5 ° longitude.

2.2 Precipitation events

The definition of heavy rainfall chosen for this study is adapted from Liebmann et al. (2001). For a rain gauge station, an event of precipitation is considered "very heavy", when the precipitation in one day is equal to or greater than 20% of the seasonal climatological total (five-month period). Based on the rainy season (NDJFM) climatology for the SEB of the order of 850 mm (Rao and Hada, 1990), these threshold percentages are chosen to ensure that "very heavy rainfall events (VRE)" occur relatively rarely.

As the main objective of this study is to identify the characteristics that distinguish heavy rainfall events from "nonheavy" (or normal) rainfall events, we need to define "nonheavy rainfall events (NRE)" also. This definition is based on the average number of rainy days, N_R, in the season, and the area average

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seasonal rainfall climatology, P_R. If the rainfall were distributed equally on all the rainy days, the normal rainfall per rainy day would be $P_N = P_R/N_R$. Thus, a normal rainy day is defined as a day on which the precipitation at any station in the region, P, is within 0.1 mm from P_N, i. e., if P_N – 0,1 mm ≤ P ≤ P_N + 0,1 mm.

2.3 Atmospheric Perturbations

First, the cases of NRE and VRE as defined in the last subsection are identified. These cases are separated according to the type of the atmospheric perurbation 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 VRE are separated according to the two types of meteorological systems responsible for the rains, SACZ and CF. The two perturbations are distinct in one respect, duration. The CF is a transient perturbation and affects a station 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 the cases of NRE and VRE into CF and SACZ situations is possible observing this characteristic. To achieve this objectively, lag correlations of the outgoing long-wave radiation OLR and 500-hPa vertical velocity, W500, fields are utilized. Arial correlation of the OLR and W500 fields between the day of the event D0 and two preceding days D-1 and D-2 and two succeeding days D+1 and D+2 are calculated over the space domain of 0°-40°S and 30°-70°W. Then, the following criteria are used to separate the cases into CF and SACZ:

A case of NRE or VRE is considered to be caused by SACZ if any one of the conditions below is satisfied:

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

(2) $[r_{W500}(D0, D\text{-}2) + r_{W500}(D0, D\text{+}2)]/2 \geq 0.20$

where: r_{OLR} and r_{W500} are the spatial autocorrelations of the OLR and W500 fields, respectively, 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.

A case of NRE or VRE is considered to be caused by CF if the following two conditions are satisfied:

(1) r_{OLR}(D0, D-2) ≤ 0,2 and

(2) r_{W500}(D0, D-2) and r_{W500}(D0, D+2) are of opposite signs.

where: r_{W500}(D0, D-2) and r_{W500}(D0, D+2) have meaning similar to those defined for r_{OLR}(D0, D-2).

Hereafter the categories of rain are defined as: NRE or VRE and the situations are CF or SACZ.

2.4 Composite anomaly charts

After the separation of the cases according to the associated atmospheric system, composite anomalies charts of atmospheric variables for the day of the episode and up to 2 days prior 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 months of NDJFM season and for each one of the types of the synoptic situation (CF and SACZ). The sequences of composites for D0, D-1 and D-2 are useful for tracking the evolution of the synoptic-scale systems responsible for the NRE or VRE.

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

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

where: $\bar{\Phi}$ 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 n^{th} day preceding the event, where n = 0, 1, 2.

We designate $\Phi_C(x,y,p)$ to represent the climatology of the variable Φ. The composite anomaly is defined as $\bar{\Phi}'(x,y,p,D-n)=\bar{\Phi}(x,y,p,D-n)-\Phi_C(x,y,p)$. 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:

$$\frac{\bar{\Phi}'\sqrt{n}}{\sigma}\geq t_{90\%} \quad (2)$$

where: $$\sigma=\sqrt{\left(\frac{\sum_{i=1}^{n}\left(\Phi_i-\bar{\Phi}\right)^2}{(N-1)}\right)} \quad (3)$$

where: $\bar{\Phi}'$ = composite of the anomaly, N = number of events used, σ = standard deviation of the composite, $t_{90\%}$ = tabulated value of Student-t at 90% significance level.

3. RESULTS

3.1 Outgoing long-wave radiation anomaly fields

The fields of the composite anomaly of OLR for NRE and VRE, associated with the CF synoptic situations are shown in **Figure 1**. These fields permit us to reaffirm the fact that OLR anomaly really serves as a proxy for rainfall, especially so for the very heavy rainfall situations. The NRE associated with CF does not show convective activity on the SEB two days before of the event, when only on the day of the event

(D0) an anomaly of -5 W/m^2 is observed. Differently, in the VRE the average OLR anomaly is –15 W/m^2 on D-2 and intensifies to –25 W/m^2 on D0. Another important feature is that there is a strong positive anomaly of OLR (+10 W/m^2) over southern Brazil and northern Argentina in the wake of the cold front on D-1 and D0, associated with a cold and dry air mass. The convective bands as inferred by the anomaly fields are oriented NW-SE over SEB. The difference in the OLR anomaly between NRE and VRE is very striking on all the three days D-2, D-1 and D0.

The OLR composite anomalies associated with SACZ situations are shown in **Figure 2**. In this situation even the NRE shows significant anomalies right from D-2 through D0. However, the anomalies for the VRE are stronger, intensifying from –20 W/m^2 on D-2 to –30 W/m^2 on D0. The convective bands in this situation are also slant as in the CF case except that they penetrate deeper into the continent in the case of SACZ. A high degree of similarity in the patterns associated with the two situations causes the distinction between CF and SACZ somewhat difficult.

3.2 500-hPa geopotential and omega anomaly fields

The fields of 500-hPa geopotential height anomaly composite are shown in **Figures 3 and 4**. In situations of CF, the negative height anomalies are of the order 10 m in the case of NRE and 25 m in the case of VRE in the sea adjoining SEB on D0. The high pressure center south of the region presents strong positive anomalies of the order of 40 m. Both the negative and positive anomalies of the height field intensify from D-2 to D0. In the SACZ situations we find 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 NW-SE orientation. In the CF situations they are more meridionally oriented. The height anomalies are stronger in the case of SACZ compared to CF situation. The propagation to the east of the anomaly centers is somewhat slower in the SACZ situations (13° longitude in 2 days) than in CF situation (26° in 2 days). This is due to the quasi-stationary nature of the SACZ.

For the VRE, the anomalous cyclone is located mainly over the southern and southeastern regions of Brazil. It stands out that the anomalous anticyclone over southern Argentina for NRE weaken with the time, while they intensify in the case of HRE. These geopotential height positive anomalies suggest a pattern of circulation characteristic of blocking (Marques and Rao, 1999), which is characterized by a persistent high-pressure center that impedes the propagation of transient systems. The large difference in the intensity of the anomalies between NRE and VRE is very useful for the identification of severe events.

Figures 5 and 6 shows 500-hPa omega composite anomaly fields. In both the situations there are significant differences between NRE and VRE. In the case of NRE the vertical motion is weak with an average of 1 Pa s-1, whereas in the case of VRE it is 3 Pa s^{-1} and 5 Pa s^{-1}, respectively in the CF and SACZ situations. The reason why the upward motion anomalies in the SACZ composites are stronger than in CF situation irrespective of the NRE or VRE is as follows. As the frontal situation is highly transient and the horizontal location of the maxima and minima in the vertical motion fields are not fixed, the compositing process reduces the intensity of the vertical motion. The reduction in the case of SACZ situation is less because SACZ is a quasi-stationary situation (it has to be remembered that only the negative anomalies are plotted in these figures for clarity. So the region without vertical motion contours is under the influence of subsidence). It is interesting to note that the upward motion area extends northward over the continent into Northeast Brazil in all the situations.

3.3 850 hPa and 250-hPa wind anomaly fields

The wind anomaly composites are presented in **Figures 7 and 8** for the CF and SACZ situations, respectively. In both the figures top two rows show the composites of wind anomalies at 850 hPa level representing the lower troposphere and the bottom two rows show the same at 200 hPa representing upper troposphere. For the CF situation (**Figure 7**) in the NRE composites at 850 hPa (top row) the wind anomaly composites do not show appreciable cyclonic and anticyclonic centers, except for a slightly stronger subtropical high region in the eastern pacific off the Chile coast. The NRE composite in the upper troposphere show an anticyclonic wind anomaly off the SEB coast.

It is interesting to note that the VRE composites distinguish themselves by showing much stronger anomalies. In the lower troposphere there is an anomalous cyclonic center in the Atlantic adjacent to southern Brazil. This center moves east-southeastward from D-2 to D0. The northwestward projecting trough associated with the cold front moves over the SEB. In the upper troposphere a strong ridge in the wind anomaly over the SEB indicates warmer-than-normal troposphere. The cyclonic center over Argentina, Uruguay and southernmost Brazil in the troposphere is indicative of a colder-than-normal air mass south of the frontal region. The wind anomalies are seen to indicate more clearly the intensity of the frontal system associated with VRE as compared to NRE.

The lower tropospheric wind anomaly composites in the SACZ situation are very characteristic, showing very clearly a convergence line between the northeasterly anomalies to its north and the southwesterly anomalies to its south. The convergence line on D0 is oriented NW-SE from 10S, 60W over the continent to 34°S, 35°W in the South Atlantic. A clear picture of the anomalous wind field associated with SACZ composites as shown here is illustrative of the anomalous convergence zone. The upper tropospheric flow anomaly fields in the events of VRE associated with SACZ (Fig. 18 last row) are very similar to the ones in the VRE case associated with CF. That is, in the midlatitudes a cyclonic center gradually intensifies from D-2 to D0. 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 track near the east coast of Brazil around 20°S and an upper cyclone in the equatorial South Atlantic off the Northeast Brazil coast remain quasistationary. The ridge and the Northeast cyclone are part of the SACZ structure. The anomalies in the NRE case (**Figure 8** third row) also look similar to the VRE case with one exception: The anomalous cyclones and the ridge are less intense in this case (compare the size of the wind vectors). One clear difference between the VRE events in the CF and SACZ situations is the eastward movement of the extratropical upper cyclone in the case of CF.

4. CONCLUSIONS

The purpose of this study was to identify characteristics of the synoptic-scale patterns that distinguish "Very heavy Rainfall Events (VRE)" from "Nonheavy Rainfall Events (NRE)" in Southeastern Brazil (SEB) caused by Cold Front (CF) and South Atlantic Convergence Zone (SACZ). So, the mean features associated with 1238 NRE and 150 VRE were presented. Based in the composite anomalies for up to 2 days prior to the episodes the results showed as different are the synoptic characteristics between NRE and VRE.

Thus, the VRE in SEB on average, were associated with -25 W/m^2 more intense OLR anomaly on event day (D0) in CF situations than those associated with NRE. On the other hand, in SACZ situations in NRE where there was predominance of convective activity on the D0 in VRE presented -15 W/m^2 of larger intensity than NRE.

In situations of CF, the 500-hPa geopotential height anomaly composite was of the order 10 m in case de NRE and 25 m in the case of VRE in the adjoining SEB on D0. The height anomalies were stronger in case of SACZ compared to CF situations. The 500-hPa omega composite anomaly, in both the situations, there was significant differences between NRE and VRE. In case of NRE the vertical motion is weak with an average of 1 Pa s^{-1}, whereas in the case of VRE it is 3 Pa s^{-1} and 5 Pa s^{-1}, respectively, in case of CF and SACZ situations.

The wind anomalies was seen to indicate more clearly the intensity of the frontal system associated with VRE as compared to NRE. The lower troposphere wind anomaly composites in the SACZ situation were very characteristic, showing very clearly the convergence line between the northeasterly anomalies to its north and south westerly anomalies to its south.

5. ACKNOWLEDGMENTS

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7. ILUSTRATIONS

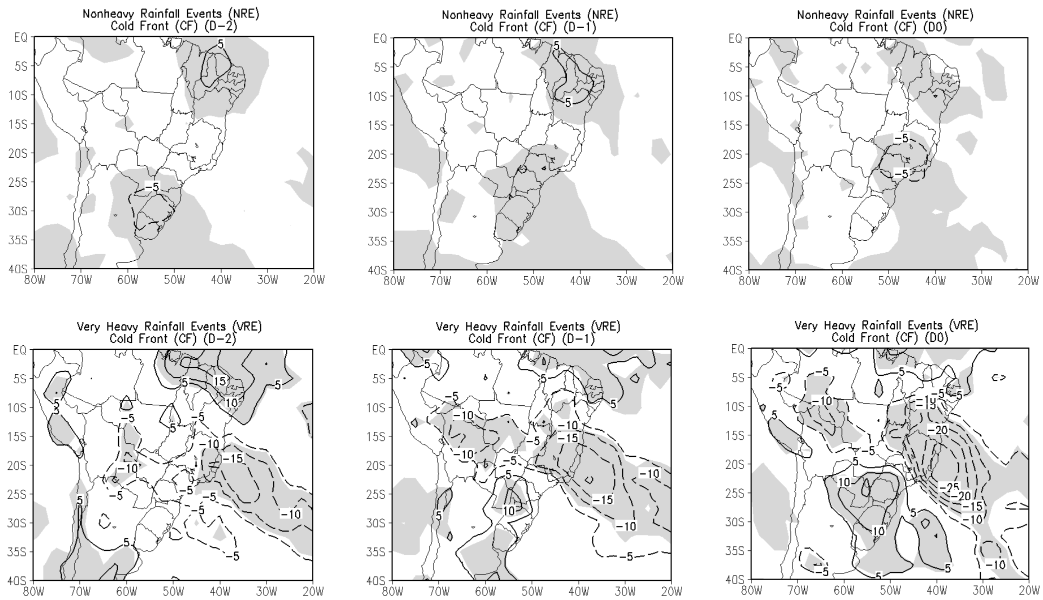

Figure 1 - Outgoing long-wave radiation composite anomaly, negative (dashed lines) and positive (continuous lines), for NRE (upper row) and VRE (lower row) in Cold Front (CF) situations over southeastern Brazil. D-*d* above each panel refers to the *d*th day prior to the day of the event. Contour interval is 5 W/m^2. Shaded areas are significant at 90% level.

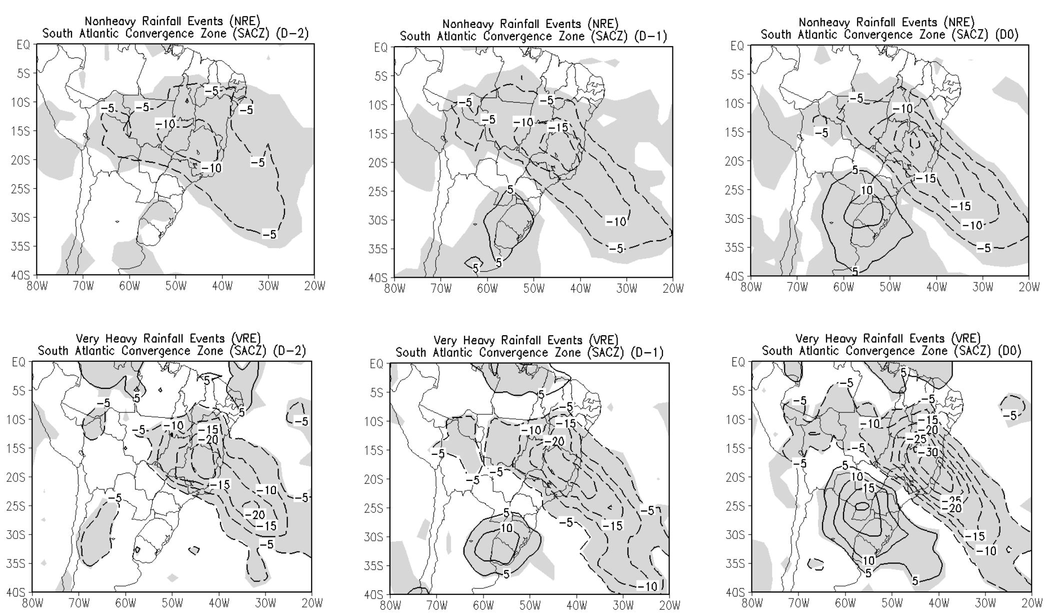

Figure 2 - Same as Figure 1, but for South Atlantic Convergence Zone (SACZ) situations.

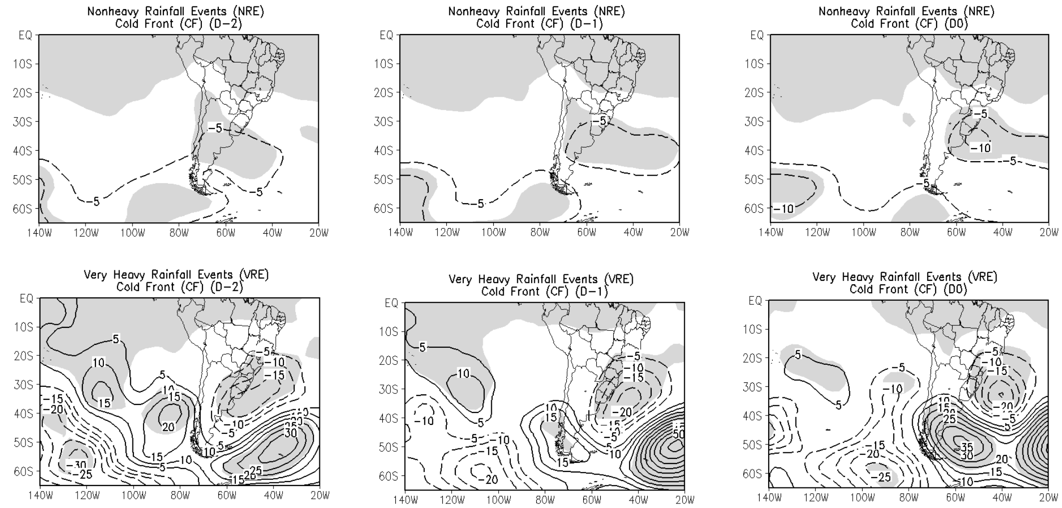

Figure 3 - 500-hPa geopotential height (m) composite anomaly, negative (dashed lines) and positive (continuous lines), for NRE (upper row) and VRE (lower row) in CF situations over southeastern Brazil for D-2 to D0. Contour interval is 5 m. Shaded areas are significant at 90% level.

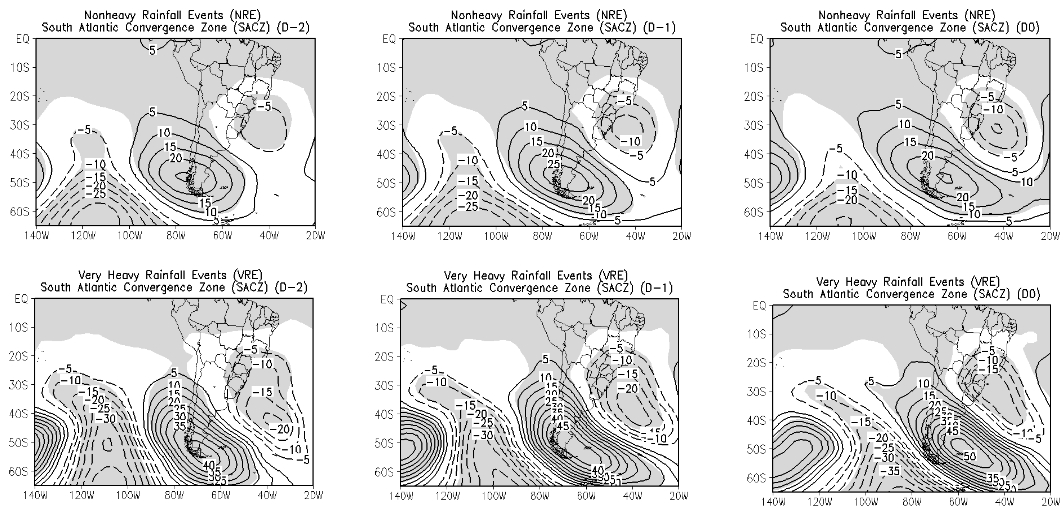

Figure 4- Same as Figure 3, but for SACZ situations.

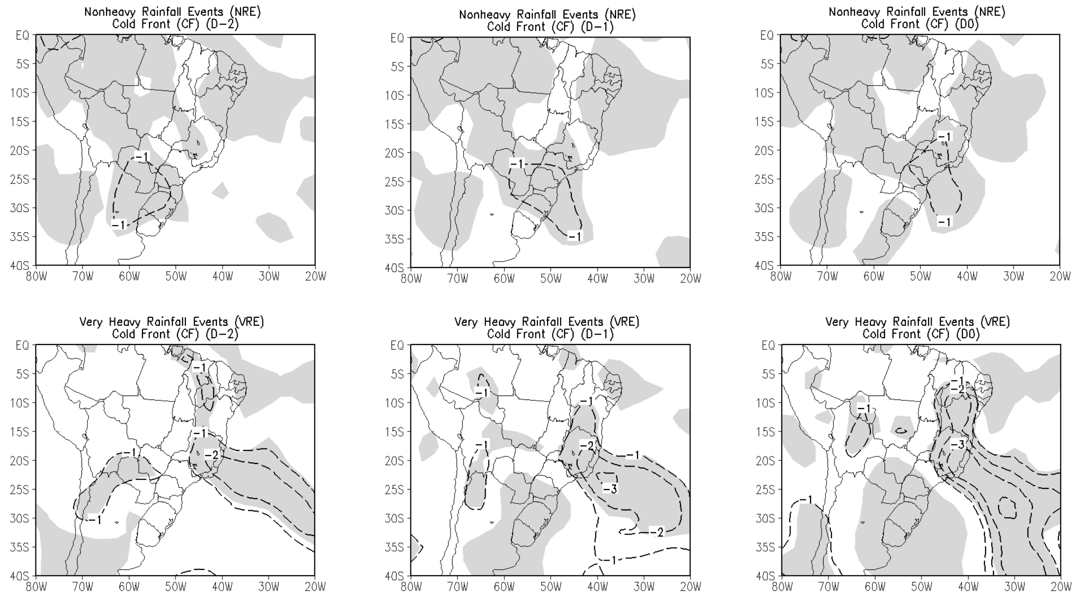

Figure 5 - 500-hPa vertical velocity (10^{-2} Pa s^{-1}) composite anomaly for NRE (upper row) and VRE (lower row) in CF situations over southeastern Brazil for D-2 to D0. Only the negative contours are shown. Contour interval is 1×10^{-2} Pa s^{-1}. Shaded areas are significant at 90% level.

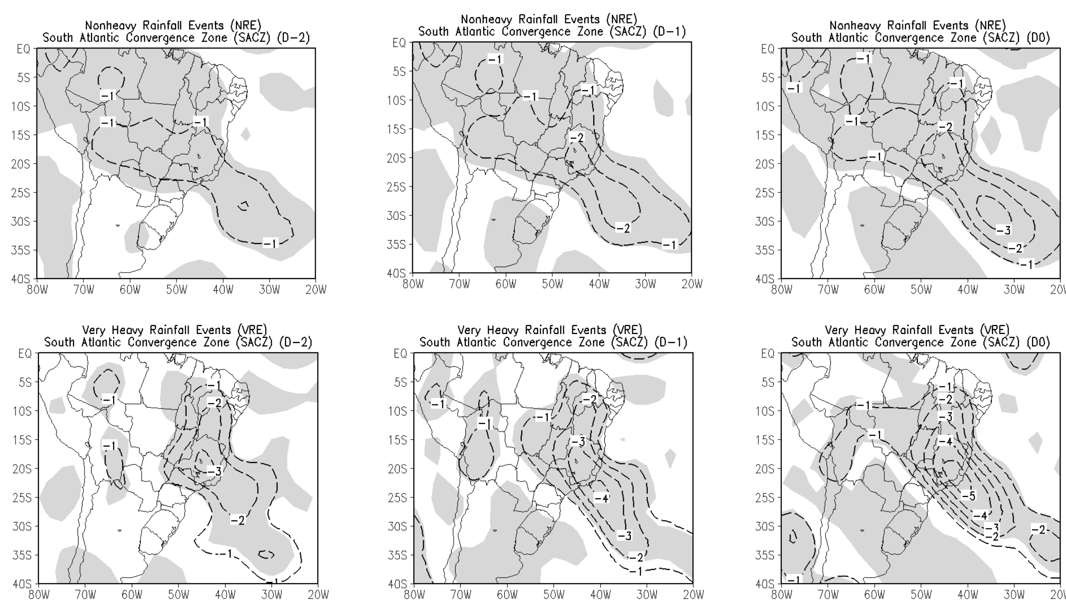

Figure 6 - Same as Figure 5, but for SACZ situations.

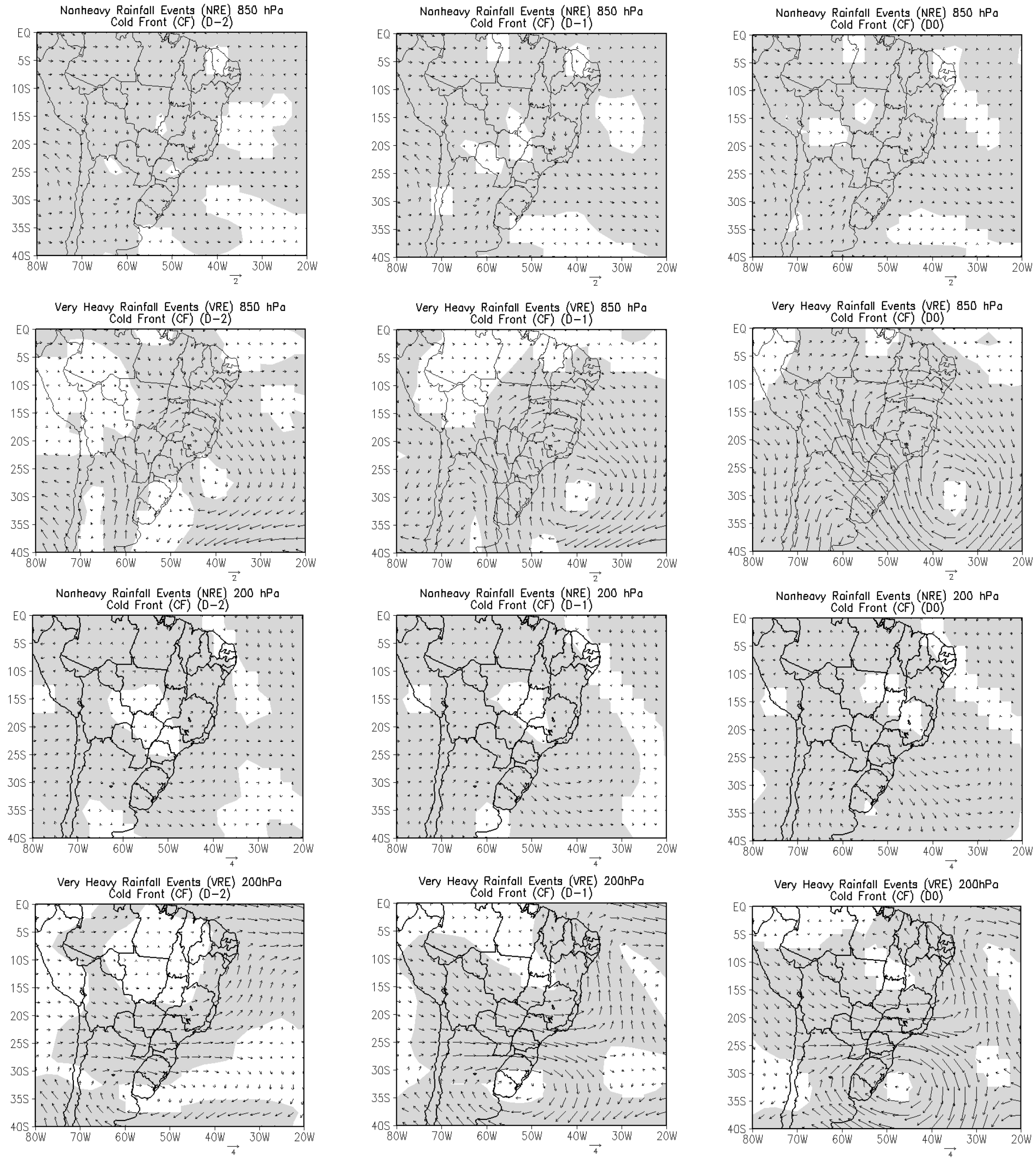

Figure 7 - 850 hPa (upper six panels) and 200 hPa (lower six panels) wind (ms^{-1}) composite anomaly for NRE (first and third rows) and VRE (second and fourth rows) in CF situations over southeastern Brazil for D-2 to D0. Contour interval for 850 hPa is 2 ms^{-1} and for 200 hPa is 4 ms^{-1}. Shaded areas are significant at 90% level.

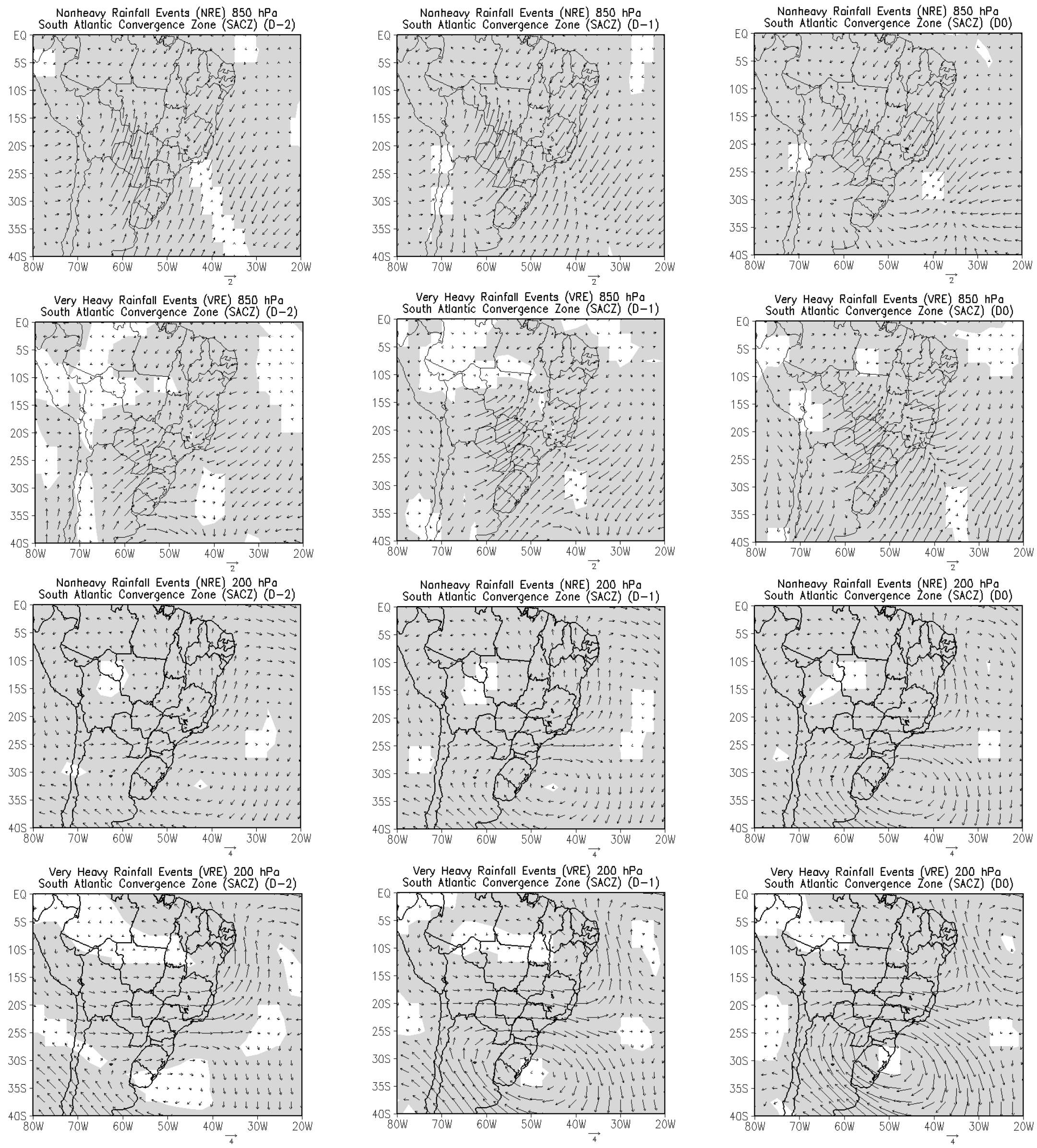

Figure 8 - Same as Figure 7, but for SACZ situations.