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SYNOPTIC SCALE WAVES ASSOCIATED WITH HEAVY RAINFALL EPISODES IN SOUTHERN BRAZIL

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1. INTRODUCTION

Although the monthly distribution of rainfall in Southern Brazil is quite uniform (Rao and Hada 1990), day-to-day variability is high. The sources for rainfall in this region are mainly cold fronts and mesoscale convective complexes (MCC) (Velasco and Fritsch 1987). The extratropical cyclones approaching South America from the west move to east-southeast after crossing the Andes while the associated cold fronts move to north-northeast, producing convective activity in southern Brazil and further north (Kousky and Cavalcanti 1984).

MCC develop over Paraguay and northern Argentina preferentially in the spring season (SON). They form during early morning hours and have a life cycle of less than one day (Velasco and Fritsch 1987). Interactions between low-level jet east of the Andes and the upper-level jet provide the instability for triggering the explosive development of the MCC in a moist ambient (Uccellini and Johnson 1979). MCC move eastward from their source region reaching Uruguay and southern Brazil causing, often, heavy rainfall. Other possible synoptic-scale systems responsible for heavy rainfall are the comma-cloud systems in the Atlantic (Bonatti and Rao 1987) and the midtropospheric cut-off lows approaching from the Pacific (Ramirez et al. 2000).

Occasionally, the rainfall exceeds 100 mm day^{-1} in some episodes causing serious problems to this region. The major economic activity of the region is agriculture and heavy rainfall may destroy entire crops over millions of hectares. The floods associated with these episodes are the worst natural disasters of southern Brazil. During some episodes loss of livestock and human lives are also reported.

Heavy rainfall is a subjective term and its definition varies significantly. It is sometimes defined with reference to a single station rainfall and other times with reference to an average over a reasonably large area.

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However, it generally refers to a short period of time ranging from a few hours to one day. In many disastrously heavy rainfall episodes both intensity and duration of rain tend to be large. Harnack et al. (1999), for example, defined heavy rainfall episodes as those that had more than 51 mm of precipitation over an area of 10 000 km^2 in a period of 1 to 2 days.

As mentioned above, flood is one of the most dramatic consequences of heavy rainfall episodes both in the mountainous northeastern parts and in the southwestern pampas of southern Brazil. The possibility of a specific rainfall episode causing floods at a place is a function of many factors such as previous rainfall, regional topography, hydrological basin size, soil moisture saturation etc. But, the rainfall itself depends on convective instability, moisture convergence and its sustainability by synoptic-scale atmospheric conditions, which play a very important role in the maintenance of intense precipitation over sufficiently long intervals of time. Thus, the hypothesis we make here is that the small scale and mesoscale disturbances, which produce heavy rainfall over southern Brazil, develop when there is a favorable synoptic-scale situation over South America and the adjoining seas.

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 southern Brazil within the period of 3 days prior to the occurrence of the episodes.

2. DATA AND METHODOLOGY

2.1. *Data sets*

Daily precipitation data for the 11-year period 1991-2001 obtained from the Agência Nacional das Águas (ANA, National Water Agency), Brazil, and available at the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC, Center for Weather Forecasts and Climate Studies) are used. The rain gauge network consists of 401 meteorological stations distributed as shown in Fig. 1. As can be seen from this figure, the average density of the network is about 20 per 10 000 km^2, varying somewhat from one subregion to another.

The rainfall data are examined for spatial consistency and coding errors. Whenever a rainfall value greater than 50 mm day^{-1} is reported at a station, say S1, precipitation at the stations in its immediate neighborhood (8 nearest stations, one each in the 45º sectors around S1) is examined. If less than two stations in the neighborhood report rainfall of any value the data at S1 is not considered for rainfall analysis. Similarly, if a station, say S2, reports rainfall greater than 100 mm day^{-1} the requirement is that there must be at least four stations reporting rainfall in the immediate neighborhood of S2 and the average rainfall in the neighboring stations must be greater than 25% of the reported rainfall at S2. Moreover, the GOES satellite cloud pictures available at the CPTEC are examined for the presence of convective systems supporting the rainfall.

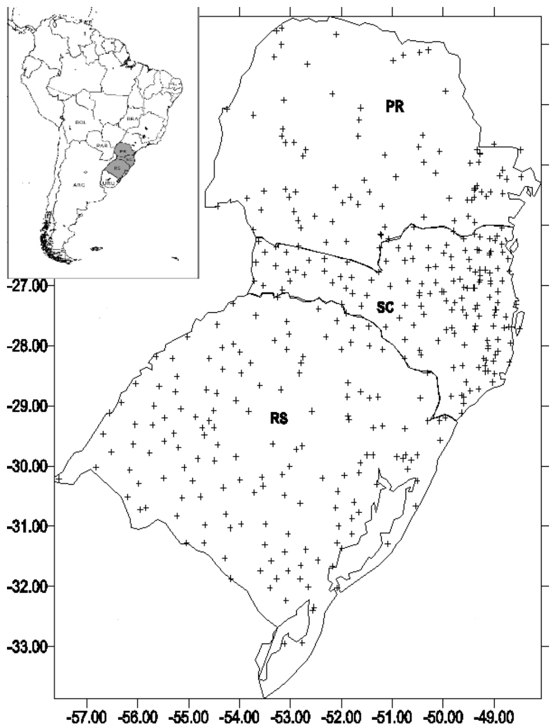

Figure 1: Rain gauge network in southern Brazil and the position of southern Brazil within the South American continent (top left corner).

Daily 12 UTC gridded meteorological data are obtained from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al. 1996), from their website. The meteorological variables used are the zonal and meridional wind components at 250-hPa (u250, v250), 500-hPa geopotential height (Z500), 850-hPa zonal and meridional wind components, temperature and specific humidity (u850, v850, T850, q850), 700-hPa wind components and specific humidity (u700, v700, q700), and sea-level pressure (SLP). The data has a spatial resolution of 2.5º x 2.5º latitude x longitude. The 12 UTC data sets are chosen because of greater density of observations over South American continent at this time of the day and therefore the analysis is expected to be more accurate.

2.2. *Definition of a heavy rainfall episode*

The definition of heavy rainfall varies from study to study depending on their objectives (Zhu and Thot 2001) and the availability and density of rainfall data. Some studies used only a precipitation threshold and duration to select their episodes. Konrad II (1997) in his study of flash floods over the plains of the USA selected rainfall episodes that presented precipitation greater than or equal to 50 mm in 6 hours. Carvalho et al. (2002) defined as extreme rainfall episodes those in which the precipitation in 24 hours is greater than 20% of the seasonal climatological total precipitation for one station. Other studies used additional conditions to select heavy rainfall episodes. Junker et al. (1999) selected episodes based on the size of the 75 mm isohyet. Whenever the area enclosed by 75 mm isohyet is equal to or greater than 17,000 km^2 it is considered as a heavy rainfall episode. Harnack et al. (1999) considered all episodes that presented precipitation above 51 mm in an area greater than or equal to 10 000 km^2 (represented by 4 contiguous grid points), in one or two days, as heavy rainfall episodes.

The major concern of this study is with the synoptic-scale features associated with heavy rainfall episodes, so an adequate definition should discard intense local rainfall episodes caused by isolated small-scale atmospheric perturbations. Following previous studies mentioned above and based on rain gauge network of southern Brazil, a rainfall episode is classified as heavy when it presents a minimum area of 10 000 km^2 of the 50 mm isohyet in 24 hours in the domain of southern Brazil shown in Fig. 1. The isohyet analysis of a typical heavy rainfall episode is shown in Fig. 2. On 12 April 1992 there was heavy and widespread rainfall over the southern portions of the state of Rio Grande do Sul (RS in Fig. 1). The rainfall exceeded 50 mm day^{-1} over a large area and even the 100 mm day^{-1} isohyet occupied an area larger than 10 000 km^2.

If a rainfall episode persists for more than one day in the domain, only the first day is considered, even the system intensifies later. That is, the present study is interested in the atmospheric patterns associated with the beginning of a heavy rainfall episode and not with its persistence or subsequent intensification. This procedure assures that only non-sequential days will be considered as separate episodes.

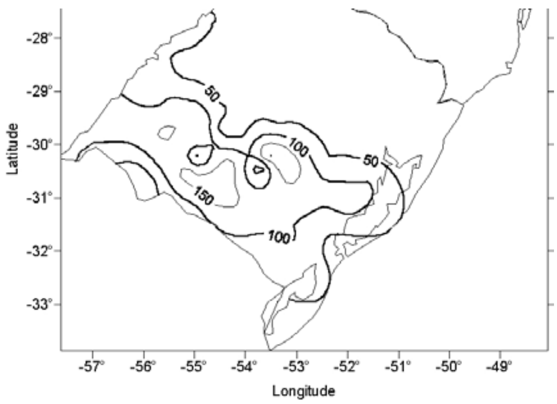

Figure 2: Isohyet analysis of a typical heavy rainfall episode. This episode occurred on 12 april 1992 in which there was heavy and widesread rainfall.

In the 11-year period 1991-2001, 170 rainfall episodes are classified as heavy. For all these episodes the areas enclosed by 50 mm day^{-1} and 100 mm day^{-1} isohyets (A50 and A100) are calculated. The area-averaged rainfall within the 50 mm day^{-1} isohyet (R50) is also obtained by taking a simple mean of all the valid rainfall reports within that area in the domain of southern Brazil.

A frequency diagram of A50 for the 170 episodes is presented in Fig. 3. It can be seen that large majority of the episodes (70%) have 80 000 km^2 $\leq$ A50 $\leq$ 15 000 km^2. The mean spatial coverage of the heavy rainfall episodes considered in this study is about 65 000 km^2 which means that the episodes chosen are fairly extensive.

To analyze the dynamical and synoptic features associated with the heavy rainfall episodes, composites of the atmospheric variables mentioned in subsection 2.1 are calculated for the day of the episode and up to 3 days prior. The composites are prepared for each season, thus permitting to examine the seasonal differences, if any, of the heavy rainfall episodes.

Composite fields are constructed in the spatial domain of 120ºW-20ºW and 10ºS-60ºS for Z500, and in the domain 80ºW-30ºW and 10ºS-60ºS for the others variables. The composites are obtained for the four seasons, winter (JJA), spring (SON), summer (DJF) and autumn (MAM) separately by taking an average of all the episodes observed in each of those seasons, for lags of 0, 1, 2, and 3 days. Lag 0 corresponds to the starting day of the rainy episode. The sequences of composites are useful for tracking the evolution of synoptic-scale systems responsible for the heavy rainfall episodes in southern Brazil. In order to understand which synoptic scale ingredients make the difference between a heavy rainfall episode and a non-heavy rainfall episode the anomalies of the heavy rainfall composites with respect to the mean of all the rest of the rainy episodes are obtained. These anomaly fields provide useful information for the operational meteorologists for forecasting activities.

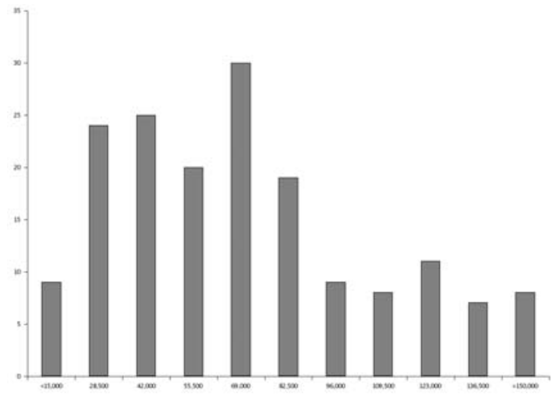

Figure 3: Frequency distribution of heavy rainfall episodes in southern Brazil based on the area enclosed by 50-mm day^{-1} isohyet (A50) in the 1991-2001 period. The ordinate shows the frequency of heavy rainfall episodes in each 50-mm day^{-1} class indicated in the abscissa on km^2.

3. MEAN CHARACTERISTICS ASSOCIATED WITH HEAVY RAINFALL EPISODES

The seasonal distribution of heavy rainfall episodes in the 11-year period is shown in Table 1. The episodes are almost uniformly distributed over the year with the autumn season having the largest mean A50 value. Therefore, for the sake of brevity, the composites for autumn season are presented in more detail and the other seasons are mentioned wherever there is a noticeable difference from the autumn case.

3.1. *500-hPa geopotential anomaly*

The 500-hPa geopotential anomaly composites of the 41 heavy rainfall episodes for the autumn season are shown in Fig. 4. On D-2 a 60 m significant negative anomaly over south of South America indicates the beginning of the deepening of a midtropospheric trough. On D-1 the anomaly deepens as it moves into Chile and Argentina. On the day of heavy rainfall occurrence (D0), the anomaly region is above Central Argentina with a value of -90 m. The sequence shows the intensification and its eastward movement at a speed of 5º longitude per day of the anomalous trough.

Table 1: Seasonal distribution of the heavy rainfall episodes in southern Brazil and mean values for the parameters presented in methodology: A100 and A50 are the areas (10^4 km^2) enclosed by the isohyets of 50 mm day^{-1} and 100 mm day^{-1}, respectively, and R50 is the average rainfall in A50.

Season	Freq.	A50	A100	R50
DJF	37	5.0	0.3	78
MAM	41	7.4	0.6	77
JJA	44	5.3	0.5	72
SON	48	5.0	0.3	72

Since these anomalies are constructed with respect to the rainy days that are not classified as heavy episodes, these fields show the ingredients that make the difference. So, the heavy rainfall episodes in southern Brazil are related with troughs 90 m deeper than troughs associated with ordinary or non-heavy rainfall episodes. The latter are associated with troughs about 15 m deep only (fields not shown), on the average, with respect to the climatology.

3.2. *Sea-level pressure anomaly*

The sea-level pressure anomaly composites for the autumn season are shown in Fig. 5. From the day D-2, an anomalous surface low can be seen west of the South American continent. In the following days, this anomalous surface low loses its strength and another anomalous surface low appears over the central part of the continent. From D-1 to D0 the second low deepens from an anomaly of -2 hPa to -4 hPa over Paraguay and northern Argentina. The low-pressure anomaly area is significant on D-1 and D0. The surface low development has the dynamical forcing of the midtropospheric cyclonic vorticity advection. The sea-level pressure composites (not included) show that a strong west-to-east pressure gradient builds up east of the surface low center. The field for D0 shows a positive anomaly in western Atlantic Ocean, showing that this dipole of anomalies (negative anomaly over northern Argentina and this positive anomaly) is responsible for building the strong west-to-east pressure gradient. This situation supports stronger than normal surface northerlies (as shown in the next subsection) from south of Amazon forest to southern Brazil.

3.3. *850-hPa meridional wind component, divergence of the water vapor flux and thermal advection anomalies*

The lower tropospheric winds over central parts of South America are predominantly northwesterlies and northerlies in the autumn season (Satyamurty et al. 1998). The vertical wind profiles often show a belt of maximum north-northwesterly component with magnitude greater than 12 m s^{-1} around 850 hPa that has a sufficiently narrow zonal extent, with enough vertical shear to constitute a low-level jet (Marengo et al. 2004). The jet transports water vapor southward from the humid Amazon forest. The convergence of the water vapor flux over southern Brazil is an important factor for the rainfall there.

The composites for meridional wind component anomaly at 850 hPa are shown in Fig. 6. It can be seen that since day D-3 a significant anomalous area with northerly winds is located over Paraguay and adjacent areas. This anomaly persists during days D-2 and D-1, gaining strength gradually, consistent with the deepening of the surface low pressure (Fig. 5). The northerly anomaly on D0 has an intensity of more than 8 m s^{-1} over Paraguay and western sections of southern Brazil.

As a consequence of the stronger than normal meridional winds, anomalous convergence of the water vapor flux occurs over northern Argentina (Fig. 7) on D-3. This region moves east-southeastward, maintaining its strength between days D-2 and D-1. The convergence area increases both in size and in strength on the day of heavy rainfall episode (D0), covering almost the entire southern Brazil region and the northeastern parts of Argentina.

It is interesting to observe that there is significant water vapor flux divergence over southeastern Brazil and the adjoining South Atlantic on D0, which shows that this region may act as a source for the water vapor flux convergence in southern Brazil. More investigation should be made in order to certify that it is truly an additional source of moisture for rainfall episodes in Southern Brazil and is not only a result composite procedure.

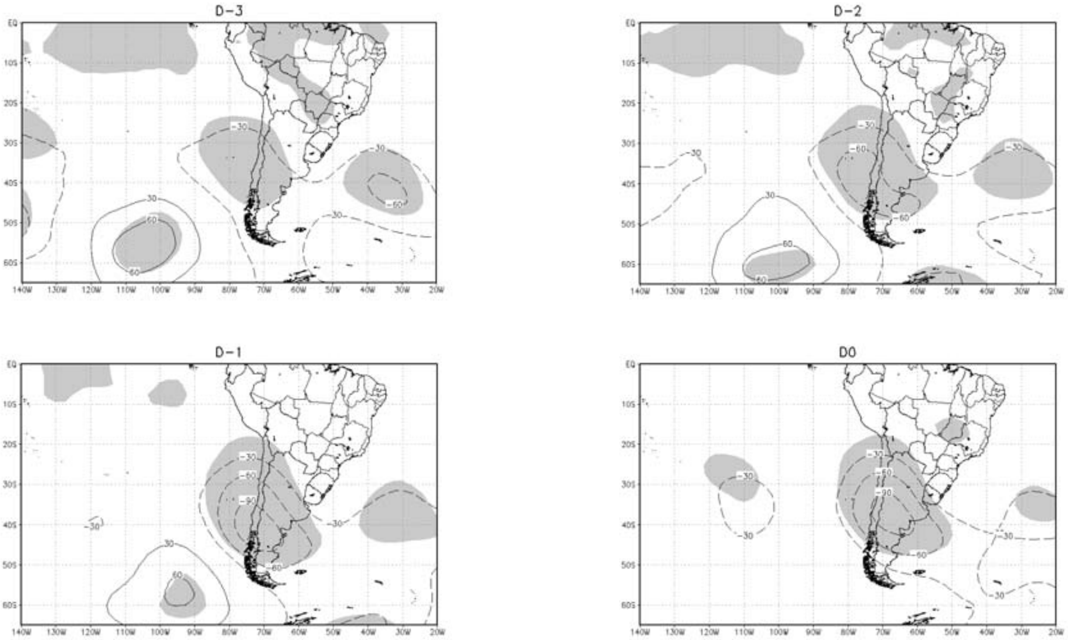

Figure 4: 500-hPa geopotential height (m) anomaly composites for the 41 heavy rainfall episodes in autumn season (MAM), in southern Brazil. The shaded areas show significance at the 95% level.

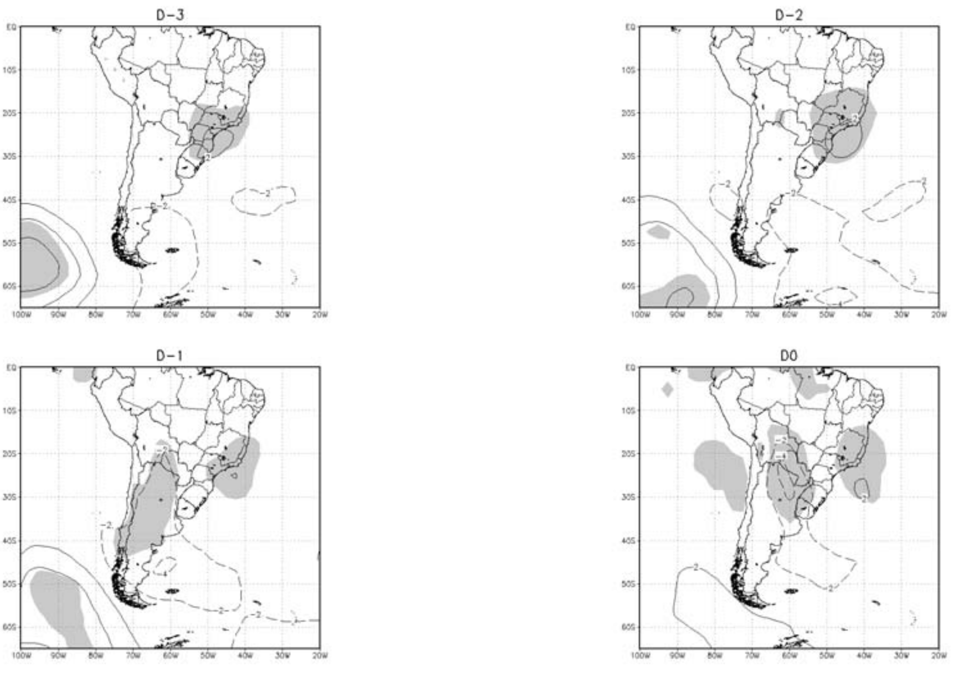

Figure 5: Same as in Fig. 4, except for the sea-level pressure anomaly (hPa).

The anomalously strong northerly winds bring not only humidity but also warm air to southern Brazil, contributing to enhance even more the low-pressure system development. As can be seen from Fig. 8, from day D-3, an anomalous warm advection region is located over the western parts of southern Brazil. This area broadens between days D-2 and D-1, and gets stronger between days D-1 and D0.

Even though the meteorologists know the sequence of a baroclinic short wave development, it is important to emphasize that the anomalies presented here are with respect to all the rainfall episodes that are not classified as heavy episodes.

This shows how anomalous the heavy rainfall episodes are and that this information can be significant for the forecasters.

3.4. *Interseasonal differences*

The most striking difference between autumn and winter seasons is found in the geopotential fields. The winter anomalies are the largest among all the seasons; two times stronger than in autumn episodes. Obviously, the meridional gradients of 500-hPa geopotential heights are stronger and are responsible for stronger zonal upper winds south of 25ºS. In winter the meridional thermal gradients in the lower troposphere are stronger (fields not shown). However, the anomaly of thermal advection is not greater than in autumn. This can explain why, despite the higher baroclinity in winter, most of the heavy rainfall episodes in winter are not more intense than in the other seasons, contrary to the expectation.

For the spring season, the episodes presented largest values of convergence of the water vapor flux in 700-hPa level (field not shown). In other seasons, this variable presents values less than half of that observed in 850 hPa. In spring, this variable is almost as strong as that observed at the 850-hPa level. These characteristics show that the northerly jet responsible for the transports of water vapor and sensible heat to southern Brazil is deeper in spring. The other variables have almost the same values as in autumn.

In summer, the absolute value of the meridional wind is the largest, but its anomaly is not. Moreover, the axis of the maximum winds has an orientation not so meridional as in autumn and spring season (field not shown). An orientation of northwest-to-southeast is more evident. The region of anomalous convergence of water vapor flux also changes its position in summer to southern Brazil coast (field not shown), different from spring and autumn seasons, which present convergence maximum west of southern Brazil. The other variables are similar to those in autumn.

The above description shows that there are some basic ingredients of the synoptic wave common to all seasons, such as deepening migratory trough at 500 hPa and the formation of a surface low in the central parts of the continent in the three-day period preceding the heavy rainfall episodes in southern Brazil. However, there are some significant seasonal differences, which are important for forecasters.

4. CONCLUDING REMARKS

One of the purposes of this study is to provide to the operational meteorologist some forerunning synoptic-scale features of the heavy rainfall episodes in southern Brazil. The results shown here may, actually, encourage the meteorologist to develop strategies to improve the forecasts of the heavy rainfall episodes in southern Brazil.

For the occurrence of a heavy rainfall episode suitable atmospheric conditions, which provide enough moisture convergence, are necessary. Doswell III et al. (1996) showed that many factors act together to achieve the necessary moisture convergence. High content of moisture, slow motion of the synoptic or subsynoptic system, and system size, are among the most important factors for heavy rainfall.

The present study shows the mean features associated with 170 heavy rainfall episodes in southern Brazil as distinct from the non-heavy rainfall episodes. The definition used here may not be taking into account all the factors that make a rainfall episode a heavy one, but it considers the most important aspects of precipitation, the spatial extent and the intensity, that can be inferred from surface observations.

Based in the composites for up to 3 days prior to the heavy rainfall episodes the results show how anomalous are these episodes. The features observed here, (a) a middle-level trough moving to South American continent, (b) the formation of a surface thermal low-pressure center in northern Argentina, and (c) a northerly low-level jet that brings warm moist air to southern Brazil, may be not be entirely new. But, the results presented show how anomalous these features are in relation to ordinary rainfall episodes. So, the authors believe that this information can help the meteorologists in the forecast activity.

It should be emphasized that the moisture convergence question is very important for the heavy rainfall episodes. The majority of the studies about rainfall in this region and its

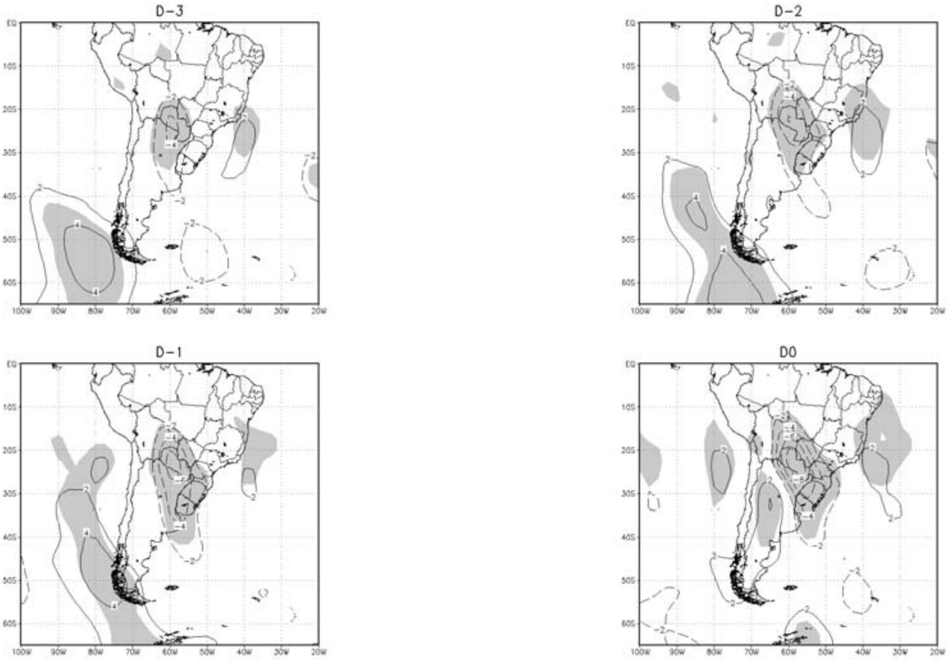

Figure 6: Same as in Fig. 4, except for the 850-hPa meridional wind component (m s^{-1}).

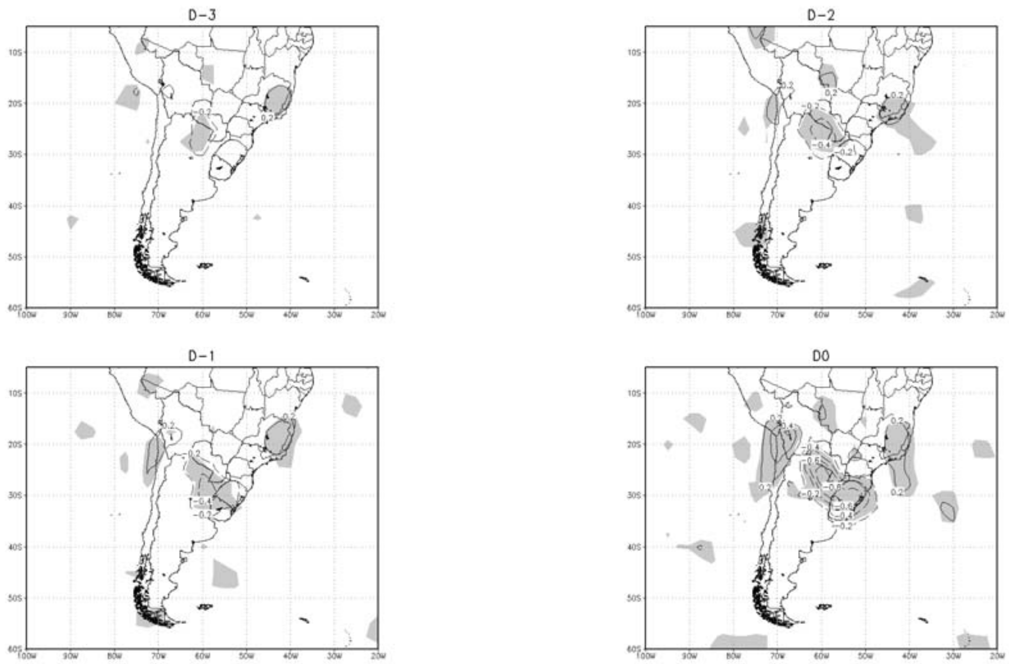

Figure 7: Same as in Fig. 4, expcept for the 850-hPa divergence of water vapor flux (10^{-7} s^{-1}).

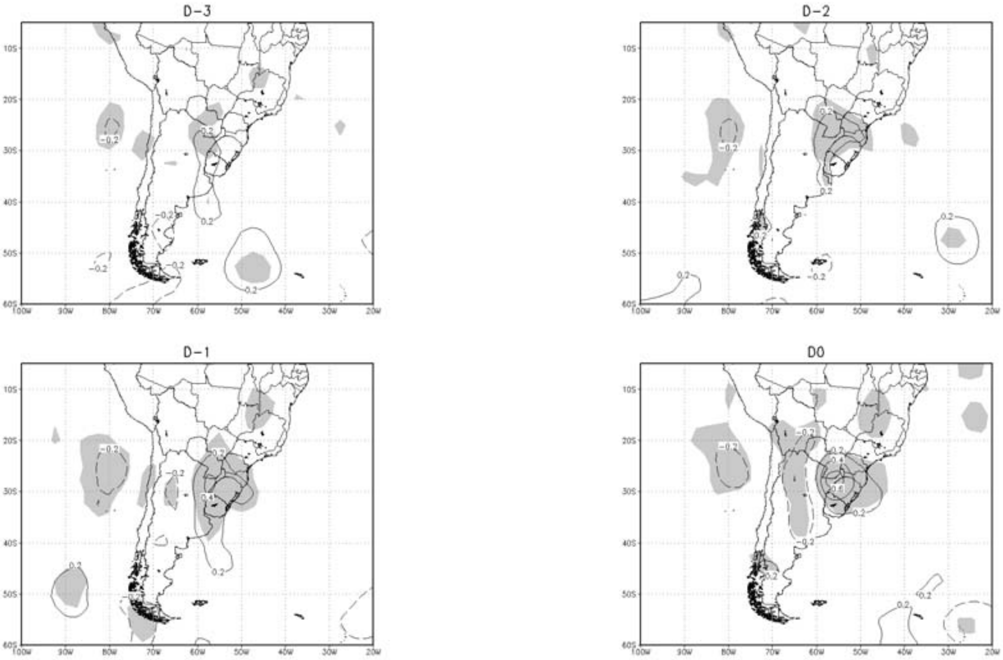

Figure 8: Same as in Fig. 4, except for the 850-hPa horizontal thermal advection (10^{-4} K s^{-1}).

neighborhood make the assumption that the low-level jet is the foremost contributor for moisture transport to these regions (Saulo et al. 2004, Marengo et al. 2004). The results here suggest that the low-level jet is an important transporter of moisture, but not the only one. Most extreme episodes are associated with two cores of moisture convergence maximum. One is connected with the low-level jet and the other is connected with the winds associated with the subtropical high-pressure center in the Atlantic Ocean.

As seen in the composites, the heavy rainfall episodes are also associated with these two cores, but to a lesser extent. In the non-heavy episodes, only one core is observed. As said previously, this may be an artifact of composite procedure, so more investigation should be made on this issue.

In the autumn season, all analyzed variables present significant anomalies two days prior the heavy rainfall, except the sea-level pressure. This suggests that the sea-level pressure is a consequence of the other variables, so we do not recommend using this variable as a heavy rainfall indicator. This characteristic is presented in all seasons and in many non-heavy rainfall episodes also.

Some interesting seasonal differences are observed. The anomalies of winter season are higher than in autumn, but they are not more significant. This is because the variability of the atmospheric flow parameters in this season is strong. In winter, there are frequent passages of the cold fronts over southern Brazil; the total rainfall quantity associated with a cold front may be distributed over a few days. The persistence of rainfall, but not necessarily higher intensity of rainfall, may also cause problems to the society. But the emphasis of the present study is on the episodes with higher quantity of precipitation spread over a sufficiently wide area.

Summer season episodes do not present high anomaly values for the variables analyzed. Once again, this is due to the low variability of the atmospheric parameters in summer. This is interesting and shows that small deviations from the features associated with ordinary rainfall episodes may result in a heavy one. As in spring, in the summer season large values of the convergence of water vapor flux at 700 hPa is a significant feature associated with heavy rainfall. In spring this parameter presents anomalies as high as at 850 hPa.

The results here suggest the meteorologists what variables they should analyze in order to detect the possibility of a heavy rainfall episode within two to three days. In the autumn season all variables mentioned, except the sea-level pressure, are important and should be analyzed for the anomalies with respect to the non-heavy rainfall conditions. Two-day forecasts may be improved with this information. In winter season, even if the anomalies are large, a heavy rainfall episode may not occur. But the thermal advection can possibly distinguish the heavy rainfall episodes. Further analysis for the winter season should be made, taking into account the persistence question. For the spring season, the differential feature may be the 700-hPa convergence of water vapor flux, in addition to the 850-hPa convergence. In this season this variable shows a large anomaly. In summer, the heavy rainfall forecast may be more complicated than in winter. Small deviations cause large differences in summer. Moreover, the small-scale convection or local summer rains are frequent and it is somewhat difficult to separate the large-scale effects from the small scale and local effects.

The results shown here suggest that the forecasters may gain improved reliability in heavy rainfall forecasts in southern Brazil. Since the analysis takes into account synoptic-scale characteristics associated with these episodes, the results may not be useful to forecast the exact quantity and exact location of heavy rainfall episodes. Also, it should be emphasized that others variables may present significant and important indications of the heavy rainfall so that, future investigation will be taken on this direction. But, using the special features of the heavy rainfall events shown here along with the numerical model outputs, meteorologists may be able to decide if a heavy rainfall episode is in the making.

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