Influence of the Frontal Systems on the Day-to-Day Convection Variability over South America

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ABSTRACT

Cold cloud-top fractions derived from International Satellite Cloud Climatology Project images and latitude–time diagrams are used to study the interaction of frontal systems with tropical convection over South America (SA). An 11-yr climatology for three frequent types of frontal system–tropical convection interaction is built, and the associated day-to-day convection variability is described using satellite images, complex principal components, and wavelet transforms. Type 1 is frequent throughout the year, especially in austral summer, and is characterized by the penetration of a cold front in subtropical SA that interacts with tropical convection and moves with it into lower tropical latitudes. Type 2 is also more frequent in austral summer and is characterized by Amazon convection and enhancement of a quasi-stationary northwest–southeast-oriented band of convection extending from the Amazon basin to subtropical SA along the passage of a cold front in the subtropics. When the type 2 pattern remains longer than 4 days over SA, it often characterizes the South Atlantic convergence zone. Type 3, which is more frequent in austral winter, is represented by a quasi-stationary cold front in subtropical SA and midlatitudes without significant interaction with tropical convection. Predominant day-to-day fluctuation time scales of convection associated with the three types were identified, ranging from 5 to 7 days in the Tropics (types 1 and 2) and subtropics (type 3). By evaluating circulation patterns over SA using National Centers for Environmental Prediction analysis at 850 and 200 hPa, the northeastward propagation of a transient cyclonic vortex organized by a cold front in southeast SA and Amazon moisture flows is the main feature of the type 1 pattern at low levels. A cyclonic vortex similar to the one in type 1 but quasi-stationary in the subtropics is remarkable for the type 2 pattern, while upper-level cyclonic vortices in northeast Brazil and the existence of a subtropical jet seem to contribute to the blocking configuration of cold fronts in subtropical SA that characterizes the type 3 pattern.

1. Introduction

The day-to-day convection variability over South America (SA) modulates the precipitation regime in several regions of the continent throughout the year. The main sources for the day-to-day convection variability in SA are African easterly waves, upper-level cyclonic vortices in northeast Brazil, the South Atlantic convergence zone (SACZ), and the penetration of frontal systems into the subtropics and Tropics. The modulation of convection by African easterly waves has recently been studied by Diedhiou et al. (2003, manuscript submitted to *J. Climate*). This study has identified strong convection variability over north and northeast Brazil associated with African easterly waves. The Bolivia high is an upper-level circulation related to deep convection over the Amazon basin and was extensively studied. Gandu and Geisler (1991) observed a relationship between the formation of the Bolivia high and the release of latent heat over areas with deep convection over the Amazon basin. Several authors identified the existence of upper-level cyclonic vortices over northeast Brazil and oceanic adjacent areas, which organize convection over those regions mainly in January (Gan and Kousky 1986; Rao and Bonatti 1987). The penetration of frontal systems over SA largely contributes to the day-to-day convection variability in the Tropics. Some important studies have addressed the influences of these synoptic systems on the convective activity over several regions of the continent. The influence of frontal systems over northeast Brazil was studied by Kousky (1979) using precipitation data. Over north and central Brazil, the influence of frontal systems has recently been described by Marengo et al. (1997) and Machado et al.

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(1999). In both studies, fluctuations of cloudiness from 3 to 6 days over the Amazon basin were associated with penetrations of frontal systems. Machado et al. (1999) have also identified events of meridional propagation of convection from southeastern SA to the Amazon basin associated with frontal systems. The authors have considered these events as the most important pattern of the day-to-day convection variability observed in SA during austral spring. Satyamurty and Mattos (1989) noted frequent formation and propagation of frontal systems in south and southeast Brazil, while Oliveira and Nobre (1986) found a high frequency of frontal systems between 20° and 35°S interacting with tropical convection in SA throughout the year. The existence of blocking configurations of frontal systems over southeast SA has recently been documented by Marques and Rao (2001).

The goal of this paper is to understand the main patterns of convection variability over SA associated with frontal systems. A climatology of the most important types of frontal system–tropical convection interaction is elaborated, and their associated main spatial and temporal patterns of convection variability are extensively documented. An analysis of the main circulation patterns in SA during the penetrations of frontal systems and its interaction with tropical convection is also made. The main data sources used in this study consist of satellite composites provided by International Satellite Cloud Climatology Project (ISCCP) images and circulation fields from the National Centers for Environmental Prediction (NCEP) reanalyses.

The paper is organized as follows. The data, identification, classification, and description of the frontal system–tropical convection interactions over SA are presented in section 2. In section 3, the main spatial and temporal patterns of convective variability in SA associated with the frontal system–tropical convection interactions are described. In section 4, the circulation patterns in SA associated with these interactions are studied. Concluding remarks are presented in section 5.

2. Data and methodology

a. Data

The cold cloud-top fraction that is a definition of high cloud cover as the ratio between the number of cloudy pixels with top pressure lower than 560 hPa (top temperature lower than ≅ 270 K) and the total number of pixels in a grid, has been used to estimate the convective activity over SA. This analysis included 3-hourly data for July 1983–December 1993. A linear interpolation was performed to remove gaps due to missing values. The cold cloud-top fraction is provided by the C1 images of ISCCP. The C1 images consist of geostationary satellite infrared data and estimates of cloud properties at 2.5° latitude–longitude resolution (Schiffer and Rossow 1983). The advantage of using cold clouds is that they are primarily associated with convective processes in the Tropics. Mean daily analyses of horizontal wind and vertical velocity at 850 and 200 hPa and horizontal moisture flow vertically integrated from surface to 850 hPa from NCEP were used to study circulation features in SA, with 2.5° latitude–longitude resolution (Kalnay et al. 1996).

b. Classification of the frontal system–tropical convection interactions in SA

To identify and classify the most important types of frontal system–tropical convection interaction over SA in the period from July 1983 to December 1993, latitude–time diagrams were produced for the cold cloud-top fractions from the C1 images of ISCCP for the whole period. In order to eliminate the direct influence of the Andes mountains on the day-to-day convection variability and get a better defined organization of cold clouds by frontal systems over tropical SA before their crossing to the Atlantic Ocean, a 10° longitudinal window between 48.75° and 58.75°W was used for computing zonal averages of the cold cloud-top fractions for the latitude–time diagrams. The choice of a 10° longitudinal window was also important for removing the organization of cold clouds that is caused only by local processes. Figure 1 shows a latitude–time diagram for 0° to 40°S in October 1987, for every 3 h. Three important types of cold cloud organization related to frontal systems that interact differently with convection over tropical and subtropical SA are noted. Type 1 focuses on the frequent penetrations of frontal systems from the subtropics or midlatitudes organizing convective activity in the Tropics and moving northward with convection into lower tropical latitudes. The occurrence of four type 1 events is observed during the first 13 days of October. Type 2 is characterized by a cold cloud organization in the Tropics due to frontal systems in the subtropics associated with a southward enhancement of convection from the Tropics to the subtropics or midlatitudes. The occurrence of one type 2 event is observed between 10 and 15 October. The frontal systems in the subtropics and midlatitudes that have nearly no interaction with tropical convection are classified as type 3, with one type 3 event occurring between 17 and 20 October. This paper focuses on these three most frequent types of frontal system–tropical convection interaction that modulate strongly convection over SA.

The three types of frontal system–tropical convection interaction identified in SA are defined according to the meridional evolution of the cold cloudiness (Fig. 1). The identification of the events corresponding to the three types was done objectively as follows: The main idea of the methodology applied was to capture a maximum value of cold cloud-top fraction associated with the frontal systems for a given latitude and try to find a similar maximum value in the neighbor latitude. Based on the time series for four individual latitudes in the latitude–

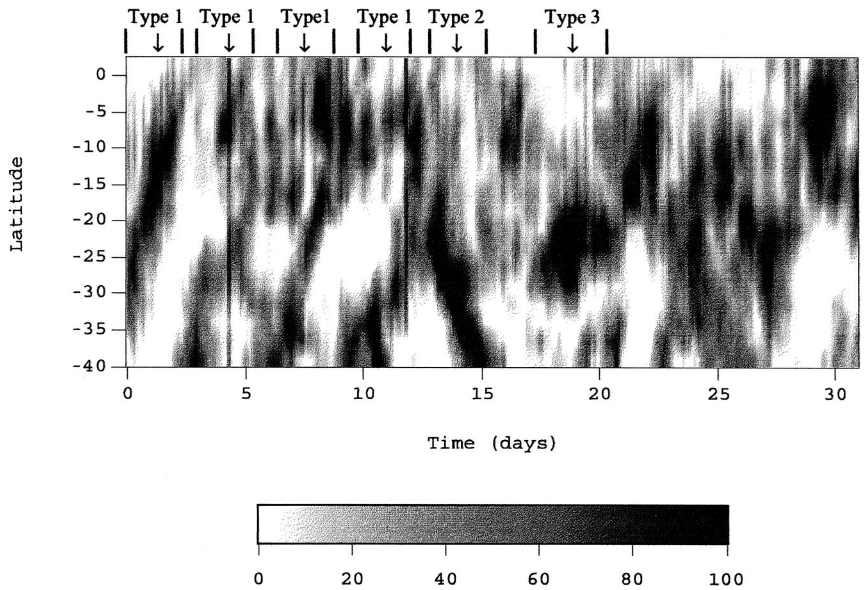

FIG. 1. Latitude–time diagram of cold cloud-top fractions for 48.75° to 58.75°W in Oct 1987, for every 3 h. Arrows point at central day of the type 1 to 3 events.

time diagram, we have first identified all the local maximums of cold cloud-top fractions and calculated their times of occurrence in the latitude–time diagram. The individual latitudes used were 6.25°, 16.25°, 26.25°, and 36.25°S. The second step was to compute the time lags between the local maximums of cold cloud-top fractions for each of the three 10° latitudinal bands between 6.25° and 36.25°S (6.25° and 16.25°S, 16.25° and 26.25°S, and 26.25° and 36.25°S). That was performed by subtracting each of the times of occurrence corresponding to the local maximums of cold cloud-top fractions identified for 36.25°S from each of those ones found for 26.25°S, and so on (in this order up to 6.25°S). In addition, the presence of convective activity inside each latitudinal band was confirmed by computing the magnitude of the cold cloud-top fractions over the average latitudinal position between each of the two individual latitudes. By examining the time lags estimated for each latitudinal band, results of interest were considered, as follows. If the time lags range from +0.5 to +2 days, a northward propagation of convection associated with the penetration of a frontal system over SA is characterized inside the latitudinal band (type 1). The extreme values established for the time lags correspond respectively to magnitudes of the meridional velocities of approximately 20 and 6 m s^{-1}, and they were defined by calculating the meridional velocity of some of these events in the latitude–time diagrams. The magnitude of the mean meridional velocities of synoptic systems of almost 10 m s^{-1} given by Houghton (1985) is intermediate to the estimated values. If the time lags range from −2 to −0.5 days, a southward enhancement of convection over SA associated with a frontal system is characterized (type 2). Finally, if the time lags range from −0.5 to +0.5 days, the latitudinal band is characterized by a quasi-stationary frontal system (here always referred to with respect to the meridional direction) moving with convection eastward and primarily inside the band (type 3). This case is considered only for latitudinal bands in the subtropics and midlatitudes, in which the quasi-stationary frontal systems are more likely to occur (Oliveira and Nobre 1986).

After describing the behavior of convection over SA associated with the frontal systems inside the three latitudinal bands defined previously, the third step was to classify the frontal system–tropical convection interactions over the total latitudinal band between 6.25° and 36.25°S (classification of events). The times and latitudinal bands in which northward propagation or southward enhancement of convection were observed in the time sequence were grouped, and the events were classified as type 1 or type 2, respectively. The initial (final) time of occurrence of each type 1 and type 2 event corresponds to the time of maximum cold cloud-top fraction at the initial (final) individual latitude of occurrence of each event, while the central time of occurrence (in integer days) is defined by the arithmetic mean of the initial and final times. For the times at which no northward propagation or southward enhancement of convection was identified inside the latitudinal band from 26.25° to 36.25°S but maximums of cloudiness were present, the events were classified as type 3. The initial and final time of occurrence of a type 3 event correspond to the times of the first and the last maximums of cold cloud-top fraction found inside the latitudinal band, respectively. It is important to point out that the definition used to classify the types 1 and 2 events considers only frontal systems that propagate

TABLE 1. Classification of the three types of frontal system–tropical convection interaction identified over SA between Jul 1983 and Dec 1993.

Type	Main pattern of convection variability	Subtype	Approx latitudinal band	Approx mean duration (days)	Mean meridional velocity (m s^{-1})	No. of events
1	Northward propagation of convection between 6° and 36°S	A	36°–6°S	3.5	9.8	87
		B	36°–16°S	2.3	9.9	67
		C	26°–6°S	2.5	9.2	142
		D	26°–16°S	1.2	9.7	146
2	Southward enhancement of convection between 6° and 36°S	A	6°–36°S	3.5	—	15
		B	16°–36°S	2.5	—	15
		C	6°–26°S	2.4	—	81
		D	16°–26°S	1.2	—	83
3	Quasi-stationary propagation of convection between 26° and 36°S	—	—	1.4	—	25

with meridional velocities between 6 and 20 m s^{-1} in magnitude. As the classification is performed using difference of times corresponding to the maximums of cloudiness and considers only the times inside a 10° longitudinal window, the initial and decay phases of the types 1 to 3 events are not necessarily considered and their actual durations may be higher than the value obtained using this method. Due to the criterion used for identifying quasi-stationary frontal systems without significant interaction with the Tropics that are mostly inside the latitudinal band from 26.25° to 36.25°S, the number of type 3 events identified may be low. Another important point concerns the possibility of overlapping with type 2 events, since some type 2 interactions can also exhibit either northward propagation of convection into the Tropics (type 1) or quasi-stationary propagation of convection in the subtropics (type 3) sometime along their life cycle.

The characteristics of the three most important types of frontal system–tropical convection interaction identified over SA between July 1983 and December 1993, classified using the methodology described in the previous section are shown in Table 1. The subtypes of northward propagation of convection corresponding to type 1 and the subtypes of southward enhancement of convection corresponding to type 2, as well as the mean durations for the three types inside the Hovmöller longitudinal window, the mean meridional velocities of convection for type 1, and the distribution of events for the three types are shown. The subtypes 1A and 1C denote northward propagation of convection into the northernmost latitudes of the region of study, that is, the propagation from either the midlatitudes (1A) or the subtropics (1C) up to at least 6.25°S latitude. The subtypes 2A and 2B represent southward enhancement of convection from either the Amazon basin (2A) or central SA (2B) into the southernmost latitudes (at least 36.25°S). Similar mean durations can be noted between the subtypes of type 1 and type 2 that are defined for the same latitudinal ranges. In addition, the mean meridional velocities of propagation of cold clouds associated with type 1 are approximately equal to the synoptic systems given by Houghton (1985). From 442 type 1 events, subtypes 1A, 1B, 1C, and 1D were observed to occur in about 20%, 15%, 32%, and 33% of the total number, respectively. For type 2, subtypes 2A, 2B, 2C, and 2D were found in almost 8%, 8%, 41%, and 43% of the 194 type 2 events, respectively. A total number of only 25 events was found for type 3. These results reveal a high number of events of northward propagation and southward enhancement of convection associated with frontal systems over subtropical and tropical SA (types 1 and 2). Another relevant point is the high number of northwardmost propagation exhibited by the type 1 (subtypes 1A and 1C), which modulates convection up to over the Amazon basin. About 14% and 2% of the 194 type 2 events were overlapped with the types 1 and 3 events, respectively (same central day). This fraction represents only around 6% of the type 1 and 16% of the type 3 events overlapped with type 2, allowing an individual description of the three types of frontal system–tropical convection interaction using mean satellite and circulation composite images.

c. *Description of the frontal system–tropical convection interactions in SA*

The mean satellite composite images built to illustrate the life cycle of the three types of frontal system–tropical convection interaction over SA for 6.25° to 36.25°S are shown in Fig. 2. To eliminate the diurnal cycle of convection, mean cold cloud-top fractions are shown at 1800 UTC for 2 days before to 2 days after the central day of occurrence of types 1 and 2 events (day 0). For type 3 events, whose approximate mean duration is shorter than 2 days (see Table 1), mean cold cloud-top fractions are exhibited only for 1 day before to 1 day after the central day. The time at 1800 UTC was chosen because it corresponds to the time of day when convective activity is increasing over the continent. The mean pattern observed for the 442 type 1 events consists of the penetration of a cold front over southeast SA in day −2. During day −1, the cold front organizes convection over that region. In day 0 and day +1, the propagation and enhancement of convection with the cold front towards central SA, the Amazon basin, and

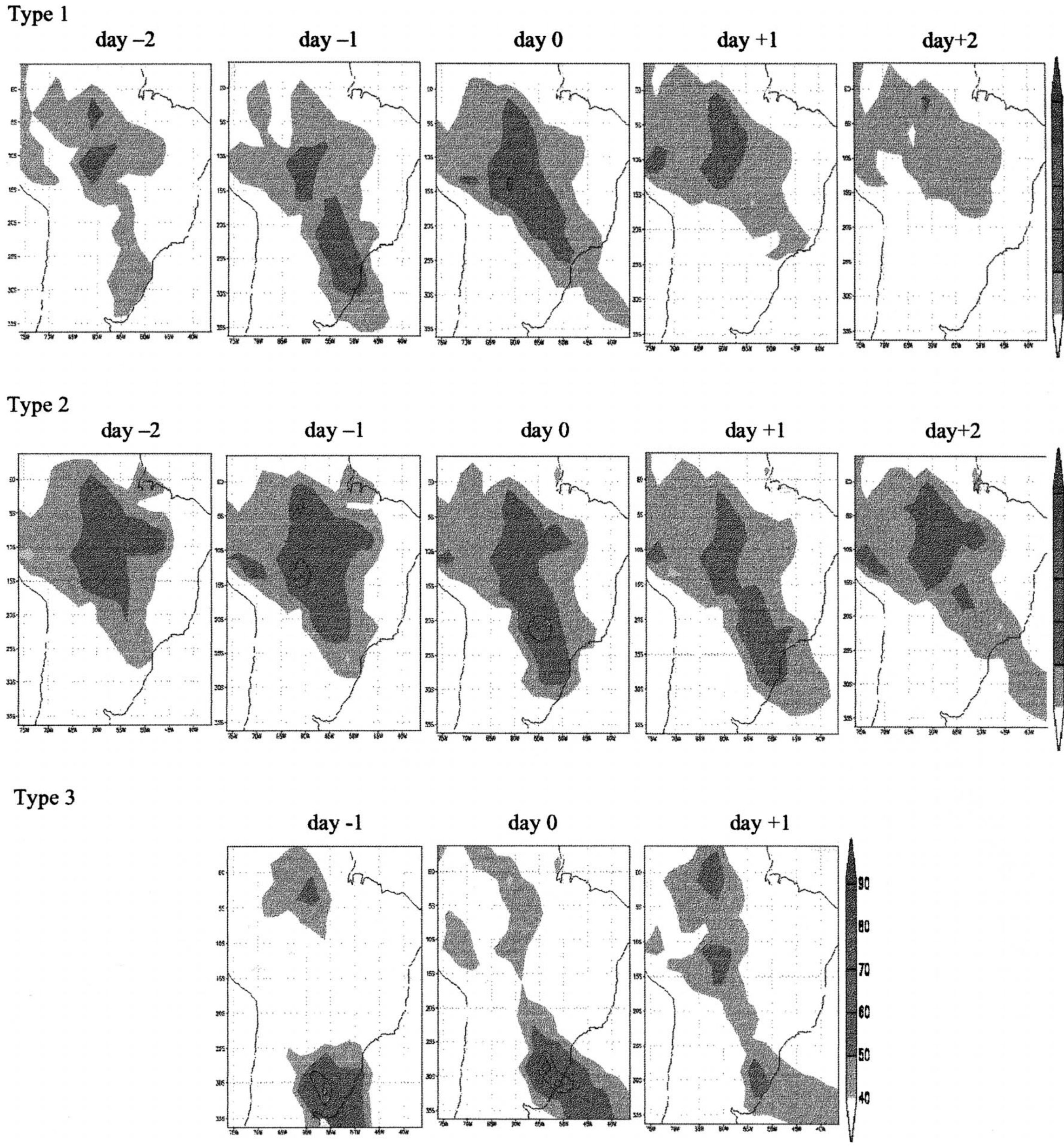

FIG. 2. Mean cold cloud-top fractions for day −2 to day +2 of occurrence of the 442 type 1 and 194 type 2 events. For the 25 type 3 events, only day −1 to day +1 are shown.

southern northeast SA are observed, followed by a weakening of the convective activity over southeast SA in day +2. This pattern is similar to the one found by Machado et al. (1999) using complex principal components and satellite images in austral spring.

In the mean satellite composite images of the 194 type 2 events, enhanced Amazon convection in day −2 is the main feature observed initially. The amplification of convection in central SA is observed in day −1, while strong convective activity is also present over southeast SA in day 0. The existence of a quasi-stationary northwest–southeast-oriented band of convection extending from the Amazon basin to the subtropics and partially over the southern South Atlantic for a minimum period of 3 days starting from day 0 is evident, with maximum of cloudiness between day 0 and day +1. This pattern represents the synoptic configuration of the SACZ over SA. The SACZ, which is characterized by long periods of precipitation in southeast Brazil mainly in austral summer, is an important mode of convection variability over tropical SA. The fundamental role of enhanced Amazon convection on increasing convective activity over southeast SA and establishing the SACZ pattern has been emphasized in several studies describing the

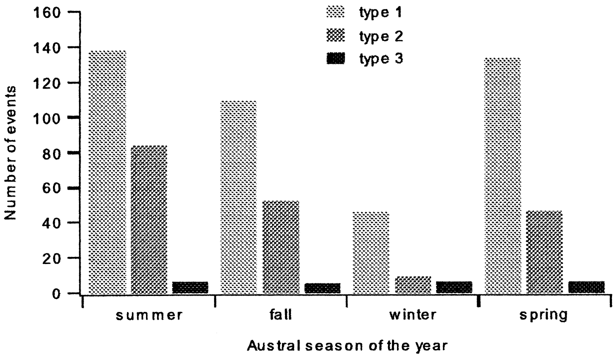

FIG. 3. Distribution of the number of type 1 to 3 events identified in SA from Dec 1983 to Nov 1993 in austral summer, fall, winter, and spring seasons.

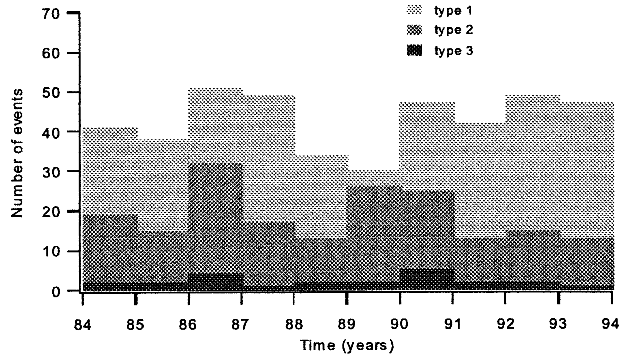

FIG. 4. Distribution of the number of type 1 to 3 events identified in SA for 1984–93.

synoptic formation of the SACZ (Kodama 1992; Figueroa et al. 1995; Liebmann et al. 1999). The existence of cold fronts over the subtropics was pointed out by Liebmann et al. (1999) as being necessary to characterize and maintain the SACZ pattern over SA. By examining several individual type 2 events in the latitude–time diagrams, we have also noted that Amazon convection is frequently stimulated by cold fronts (primarily belonging to type 1) at the onset of the type 2 events, consistent with that assumption (e.g., see Fig. 1).

Few objective methods exist for identification of SACZ episodes from the satellite images. Several authors describe the SACZ events by decomposing the data series into pentads (e.g., Paegle et al. 2000). An objective method that consists of establishing an approximate minimum period of 4 days for the quasi-stationary northwest–northeast band of convection over SA has been applied for monitoring SACZ episodes in the *Climanalise* monthly climate bulletin (Cavalcanti et al. 1988). By comparing the dates of the type 2 events estimated by the methodology described in section 2b with the *Climanalise* bulletins developed by Cavalcanti et al. (1988, 1991) for October, January, and April of 1988 and 1991, it was observed that SACZ episodes were present during 60% of the type 2 events that occurred during this period (not shown). This result reveals that the type 2 frontal system–tropical convection interactions may constitute the synoptic mechanism necessary for the formation of the SACZ, but they do not necessarily satisfy the 4-day criterion for the existence of the SACZ over SA.

For the 25 type 3 events, the mean pattern observed in the mean satellite composite images is represented by a quasi-stationary cold front in the subtropics and midlatitudes between day -1 and day $+1$. Some convective activity is also observed in central and north SA from day 0 to day $+1$, but less intense compared to the one found for the types 1 and 2. The blocking of cold fronts over southeast SA, well described by Marques and Rao (2001), is a mechanism frequently associated with the occurrence of the type 3 events mainly in austral winter.

The seasonal distribution of the number of events corresponding to the three types of frontal system–tropical convection interaction identified over SA for the period December 1983 to November 1993 is shown in Fig. 3. Type 1 exhibited higher fractions of events in austral summer (32%) and spring (31%), while the lowest fraction was observed in austral winter (11%). The subtypes 1A and 1C were predominantly present in around 24% and 42% of the number of type 1 events in austral summer and almost 26% and 35% in austral spring, respectively (not shown). This shows the important role of the cold fronts in organizing and moving with convection from the subtropics or the midlatitudes to lower tropical latitudes (6.25°S) in seasons in which the convective activity is intense, reaching the Amazon basin. The subtypes 1B and 1D were predominant among type 1 occurrences in austral winter, with about 30% and 60% of the number of type 1 events in austral winter, respectively (not shown). The distribution of the subtypes 1B and 1D suggests the inability of the cold fronts in organizing and displacing convection northward into lower tropical latitudes in cold seasons, reaching only central SA (16.25°S) in the majority of the cases. For type 2, the highest fraction of the 194 events was found in austral summer (44%), while the lowest fraction was observed in austral winter (5%). The subtype 2C was the most representative in austral summer (47% of the number of type 2 events in austral summer; not shown), while the subtype 2D was predominant in austral winter (66% of the number of type 2 events in austral winter; not shown). These results suggest an important role of Amazon convection on the southward enhancement of the convective activity and development of SACZ episodes in the Tropics and subtropics in austral summer, as well as its weakening in cold seasons. No significant seasonal variation was noted for type 3 due to the very low number of events found.

Figure 4 shows the interannual variability of the events corresponding to the types 1 to 3 frontal system–tropical convection interaction for the 1984–93 years.

The El Niño–Southern Oscillation (ENSO) variability in the number of events is investigated for two El Niño episodes (1986–87 and 1990–95) and two La Niña episodes (1984–85 and 1988–89) listed by Trenberth (1997) using sea surface temperatures (SSTs) in the region of Niño-3.4 (5°N–5°S, 120°–170°W). No linear relationship is observed between the occurrence of both climatic phenomena with respect to the frequency of type 1 and type 2 events. However, the subtype 1D was more frequent during some El Niño years (1986 and 1990), representing around 35% and 47% of the number of type 1 events in 1986 and in 1990, respectively (not shown). The main reason for that is the occurrence of intense blocking episodes of cold fronts over southeast SA during El Niño episodes, which hinder the northward advance of cold fronts and convection into the Tropics. The blocking episodes usually observed in El Niño years are characterized by an intensification of the Hadley circulation in the winter hemispheres that propitiates a high transport of angular momentum into higher latitudes and consequently a stronger subtropical jet stream than normal (Bjerkness 1966). This pattern contributes to intensifying the blocking episodes of cold fronts in the midlatitudes and subtropics, which are characterized by a bifurcation of air fluxes in upper levels that persist in those regions for several days (Marques and Rao 2001). In opposition to that, the subtype 1C was predominant in La Niña years for almost 37% and 41% of the number of type 1 events in 1985 and 1989, respectively (not shown). In this case, a better facility of the cold fronts in moving with convection northwardmost from the subtropics to lower latitudes was noted during La Niña episodes. These results reveal that the occurrence of El Niño or La Niña episodes apparently affects the northward advance of the cold front and associated convection towards the Tropics, but not the frequency of these events over SA (type 1). For the same reason, the intense blocking episodes of cold fronts over southeast SA characterized by the two El Niño episodes and observed by Marques and Rao (2001) seem to have favored a little increase in the number of type 3 events in 1986 and 1990, resulting in a higher number of quasi-stationary cold fronts in the subtropics. The few El Niño episodes observed during the 10-yr period analyzed do not allow a precise conclusion about the interannual variability mainly of the type 2 frontal system–tropical convection interactions.

3. Main oscillation patterns of convection in SA associated with frontal systems

a. Complex principal components and Morlet wavelet transform

Complex principal components (CPCs) analysis was applied to the time series of cold cloud-top fractions to investigate the impact of the day-to-day convective variability caused by the three types of frontal system–tropical convection interaction on the total day-to-day convective variability over SA. The CPCs analyses are based on eigenvalues and eigenvectors from a cross-spectral matrix and provide information about the amplitudes and phases produced by temporal fluctuations of a geophysical field inside a region (Goulet and Duvel 2000). The amplitude of the CPC (size of the vector) is directly proportional to the statistical variance of the field inside a region in time, while the phase (direction of the vector) is an angle associated with the temporal evolution of the field inside the region. To investigate the impact of the convective variability caused by each of the three types of frontal system–tropical convection interaction on the total day-to-day convective variability, we have first estimated the correspondent mean spatial pattern to the day-to-day convective variability produced by each of the three types. That was done by applying CPCs analysis to 3-hourly mean satellite composites for day -2 to day $+2$ of occurrence for each of the three types between July 1983 and December 1993. Subsequently, we have computed the correspondent spatial pattern to the total day-to-day convective variability present over SA during each season by applying CPCs analysis to 3-hourly satellite composites for each season of the 1984–93 years. The region is the same discussed in the mean satellite composite images (section 2c), but entire filtered, normalized time series of cold cloud-top fractions was used to retain fluctuations of convection between 2 and 10 days.

Another statistical tool used to describe the day-to-day oscillation patterns of convection in SA is the Morlet wavelet transform (MWT). The MWT decomposes a time series into time-frequency space and makes it possible to determine the dominant time scales of variability of geophysical fields in time (Torrence and Compo 1998). The main fluctuation time scales of convection associated with the three types of frontal system–tropical convection interaction from January 1984 to December 1993 were estimated by applying the MWT to filtered time series of cold cloud-top fractions for the individual latitudes in the latitude–time diagrams (6.25° to 36.25°S, with a lag of 2.5°), for every 3 h. The MWT was applied once over the whole period, and the fluctuation time scales corresponding to the strongest amplitudes of the MWT coefficients in central days of each event were extracted. Results are discussed for the Amazon region (6.25°S, $-58.75°$ to $-48.75°$W) only for types 1 and 2 since type 3 has reduced interaction with tropical convection. For central (16.25°S, $-58.75°$ to $-48.75°$W) and subtropical (26.25°S, $-58.75°$ to $-48.75°$W) SA, results are discussed for the three types.

b. Type 1 frontal system–tropical convection interactions

The amplitudes and phases of the first CPC were computed using mean satellite composites for each of the three types of frontal system–tropical convection inter-

TABLE 2. Predominant types of frontal system–tropical convection interaction found in the correspondent spatial pattern to the total day-to-day convective variability expressed by the first and second CPCs obtained using filtered time series of cold cloud-top fractions over SA for each season of the 1984–93 years. The percentage of the total day-to-day variance of the time series explained by the first and second CPCs is also shown.

Austral season	Predominant types of frontal system–tropical convection interaction/ Percentage of the total day-to-day variance explained by the CPCs				Total percentage of the day-to-day variance
	Type	First CPC	Type	Second CPC	
Summer	1	Variance explained = 32%	2	Variance explained = 16%	48%
Fall	1	Variance explained = 33%	2	Variance explained = 17%	50%
Winter	1 and 3	Variance explained = 34%	3	Variance explained = 16%	50%
Spring	1	Variance explained = 37%	3	Variance explained = 17%	54%

action (types 1 to 3 first CPC) and represent the correspondent spatial pattern to the day-to-day convective variability over SA caused by each of the three types. Similarly, the amplitudes and phases of the first and second CPC were computed using satellite composites for each season of 10 yr and represent the correspondent spatial pattern to the total day-to-day convective variability over SA during each season (first and second CPC estimated for each season). The next analysis step was to verify whether the day-to-day convective variability over SA caused by types 1 to 3 correspond to the total day-to-day convective variability during each season and estimate possible contributions of the day-to-day convective variability produced by types 1 to 3 on the total day-to-day convective variability over SA during each season. That was done by comparing objectively the spatial pattern of the types 1 to 3 first CPC with the spatial patterns of the first and second CPC estimated for each season and by identifying types of frontal system–tropical convection interaction whose spatial patterns of their first CPC are similar to the spatial patterns of the first and/or the second CPC estimated for each season (predominant types). The contribution of the day-to-day convective variability produced by the predominant types on the total day-to-day convective variability was known by extracting the percentage of the total day-to-day variance of convection explained by the first and second CPC estimated for each season. Table 2 shows the predominant types of frontal system–tropical convection interaction found in the first and/or the second CPC estimated for each season and the percentage of the total day-to-day variance of convection explained by them. The correspondent spatial pattern to the day-to-day convective variability produced by type 1 (type 1 first CPC) was identified in the spatial pattern of the first CPC estimated for the four seasons, explaining almost 37% of the total day-to-day variance of convection in austral spring, followed by austral fall, summer, and winter with around 33%, 32%, and 34%, respectively.

The frequency distribution of the main fluctuation time scales of convection in the central day of the events corresponding to each of the three types of frontal system–tropical convection interaction was determined by applying the MWT in the filtered time series in subtropical SA to retain oscillations of the cold cloud-top fractions from 2 to 50 days over that region (Table 3). The day-to-day fluctuation time scales of convection from 2 to 10 days were found predominant in around 45% of the type 1 events, followed by the intraseasonal modes of 22–28 days and 30–50 days, with almost 12% and 9%, respectively. By applying the MWT in the filtered time series to retain only the day-to-day variability of convection, mean fluctuation time scales from 5.7 to 6.3 days were observed during the type 1 events in subtropical SA, central SA, and the Amazon basin during austral summer, falling to 5 to 5.8 days in austral spring and fall (Table 4). These day-to-day time scales

TABLE 3. Frequency distribution of the number of type 1 to 3 events according to the predominant fluctuation time scales exhibited by convection over subtropical SA (26.25°S) during central days of events. Predominant time scales were estimated by applying MWT to cold cloud-top fractions.

Type	Frequency distribution		
	Band: 2–10 days	Band: 22–28 days	Band: 30–50 days
1	45%	12%	9%
2	38%	16%	5%
3	50%	17%	<1%

TABLE 4. Mean seasonal predominant day-to-day time scales of convection in central days of type 1 to 3 events over central (16.25°S) and subtropical SA estimated by applying MWT to cold cloud-top fractions. The Amazon basin (6.25°S) is shown for types 1 and 2.

Type	Austral season	Mean predominant day-to-day time scales (days)		
		Amazon region	Central region	Subtropics
1	Summer	5.7	6.3	5.9
	Fall	5.0	5.6	5.6
	Winter	6.3	5.3	6.5
	Spring	5.0	5.7	5.4
2	Summer	5.7	6.5	6.1
	Fall	5.1	5.7	6.0
	Winter	5.6	4.5	5.6
	Spring	4.8	6.3	5.5
3	Summer	—	5.7	6.8
	Fall	—	5.6	6.0
	Winter	—	6.9	6.2
	Spring	—	6.2	5.6

are the main exhibited by convection that moves northward with cold fronts from the subtropics or midlatitudes into lower tropical latitudes, and are intermediate to values found by Machado et al. (1999) for convection variability in the Amazon basin in austral spring (3 to 6 days).

c. Type 2 frontal system–tropical convection interactions

The spatial pattern of the type-2 first CPC was identified only in the spatial pattern of the second CPC for austral summer and fall, contributing almost 16% of the total day-to-day convection variability over SA in both seasons (Table 2). These results are consistent with the highest frequency of SACZ episodes in austral summer. By examining the main fluctuation time scales of convection along type 2 occurrences, the day-to-day and the intraseasonal mode of 22–28 days were predominant in around 38% and 16% of type 2 events, respectively (Table 3). By restricting analysis to day-to-day fluctuation time scales, mean values from 5.7 to 6.5 days were found in subtropical SA, central SA, and the Amazon in austral summer, falling to 4.8 to 6.3 days in austral fall and spring (Table 4). These time scales, which are related to the SACZ episodes in tropical and subtropical SA, are consistent with SACZ time scales found in literature (Liebmann et al. 1999).

d. Type 3 frontal system–tropical convection interactions

The spatial pattern of the type 3 first CPC was identified in the spatial pattern of the first and second CPC for austral winter, contributing almost 50% (in total) of the total day-to-day convection variability over SA in that season (Table 2). A secondary contribution around 17% was found in the second CPC for austral spring. These results are consistent with the highest frequency of blocking episodes of cold fronts over southeast SA in austral winter found by Marques and Rao (2001). The day-to-day time scales and the intraseasonal mode of 22–28 days were the dominant fluctuation time scales of convection associated with the type 3 interactions in SA, present in around 50% and 17% of the type 3 events, respectively (Table 3). By examining the fluctuation time scales, mean values from 5.6 to 6.9 days were identified in subtropical and central SA in austral winter and summer, decreasing to 5.6–6.2 days in austral fall and spring (Table 4). These values show that the day-to-day fluctuation time scales of convection in the subtropics and Tropics associated with quasi-stationary cold fronts in the subtropics (type 3) are a little higher than that produced by cold fronts that advance northward with convection into tropical SA (type 1) in austral winter and summer.

4. Main circulation features in SA associated with the frontal system–tropical convection interactions

The most important circulation patterns in SA associated with the events corresponding to the three types of frontal system–tropical convection interaction identified between January 1984 and December 1993 are investigated in this section. The horizontal wind, horizontal moisture transport, and omega fields from NCEP were used to prepare a composite analysis describing the mean and the transient daily fields for day −2 to day +2 of occurrence of types 1 and 2 and day −1 to day +1 of occurrence of type 3 frontal system–tropical convection interactions. The mean daily fields were calculated by averaging the daily fields of all events corresponding to each type of frontal system–tropical convection interaction, while the transient daily fields were estimated by subtracting the daily fields from their respective mean seasonal fields and averaging them over all the events corresponding to each type. Figures 5 and 6 show the mean composites of the transient daily fields of horizontal wind at 850 and 200 hPa, respectively, for the three types of frontal system–tropical convection interaction. The structure initially found for type 1 at low levels is the strengthening and northward advance of a transient cyclonic vortex from southeastern to northeastern SA. The convergence zone moves northeastward from around 23°S in day −2 to at least 15°S in day 0, and its main feature is the weakening of anomalous winds from the Amazon basin and the strengthening of anomalous winds from the midlatitudes. This circulation pattern, similar to the one found by Machado et al. (1999) in austral spring, is indicative of the penetration of a cold front over subtropical SA that moves towards northeast SA. Enhanced moisture transport from the Amazon basin to central and southeastern SA was also confirmed in the mean and the transient daily moisture transport vertically integrated between the surface and 850 hPa (not shown). The wave train configuration in the midlatitudes and anomalous southerly winds characterize the presence of a cold front over southeast SA moving northeastward and a cold air incursion in the Tropics. A wave train configuration at upper levels is observed in the subtropics, coherent with the low-level circulation pattern observed.

For the type 2 frontal system–tropical convection interactions, the presence of a transient cyclonic vortex at low levels over subtropical SA and strong transient winds from the Amazon basin to central and southeastern SA are found before day 0. Moisture fluxes from the Amazon basin are also observed throughout the type 2 mean life cycle in the mean daily fields (not shown), and constitute an important mechanism for maintaining the transient cyclonic vortex and supporting convection over central and southeastern SA during type 2 events. Northerly transient winds and moisture fluxes in day +1 seem also to contribute to convection over central

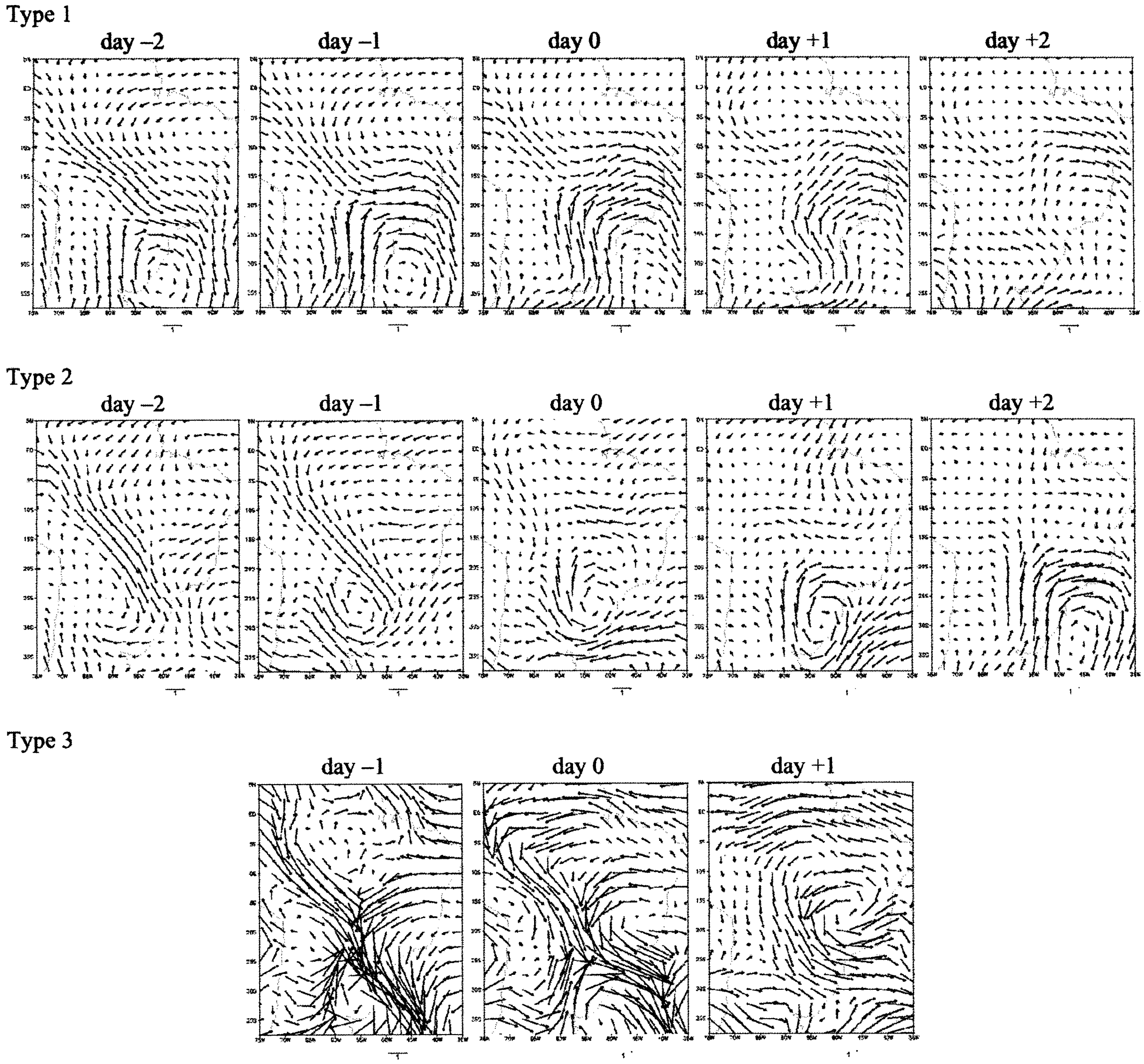

FIG. 5. Mean 850-hPa transient component of the horizontal wind for day −2 to day +2 of occurrence of the type 1 and type 2 events, for Jan 1984 to Dec 1993. For the 25 type 3 events, only day −1 to day +1 are shown.

SA, while a slow enhancement of the northerly moisture fluxes was noted along the Andes as the event progresses (not shown). Anomalous southerly winds and a transient anticyclone at low levels in the subtropics before day −1 indicate the presence of a cold front that remains quasi-stationary during the type 2 mean life cycle and contributes to the maintenance of the transient cyclonic vortex and convection over southeastern SA for several days. This circulation pattern favors SACZ formation during the majority of type 2 events. The SACZ synoptic configuration during the type 2 mean life cycle is also evidenced by an enhanced meridional northwest–southeast tilt at upper levels over tropical SA. Another important feature at upper levels is the existence of a transient upper-level cyclonic vortex over northeastern SA that migrates westward from day −2 to day 0, which can probably be related to the upper-level cyclonic vortices in northeast Brazil described in literature (Gan and Kousky 1986; Rao and Bonatti 1987).

During the type 3 mean life cycle, the presence of a quasi-stationary transient anticyclone in southeastern SA apparently strengthening the South Atlantic subtropical high constitutes an important feature of the circulation at low levels, besides anomalous winds and moisture fluxes from the Amazon basin before day 0 (also confirmed in the mean fields; not shown). The existence of a quasi-stationary cold front in the subtropics and midlatitudes is evident throughout the type 3 mean life cycle. In upper levels, an enhanced quasi-stationary westerly jet stream in the midlatitudes possibly associated with the subtropical jet and a transient anticyclone related to a cold front are noted until day 0, characterizing the blocking of the cold front in the subtropics and midlatitudes. The penetration of an ex-

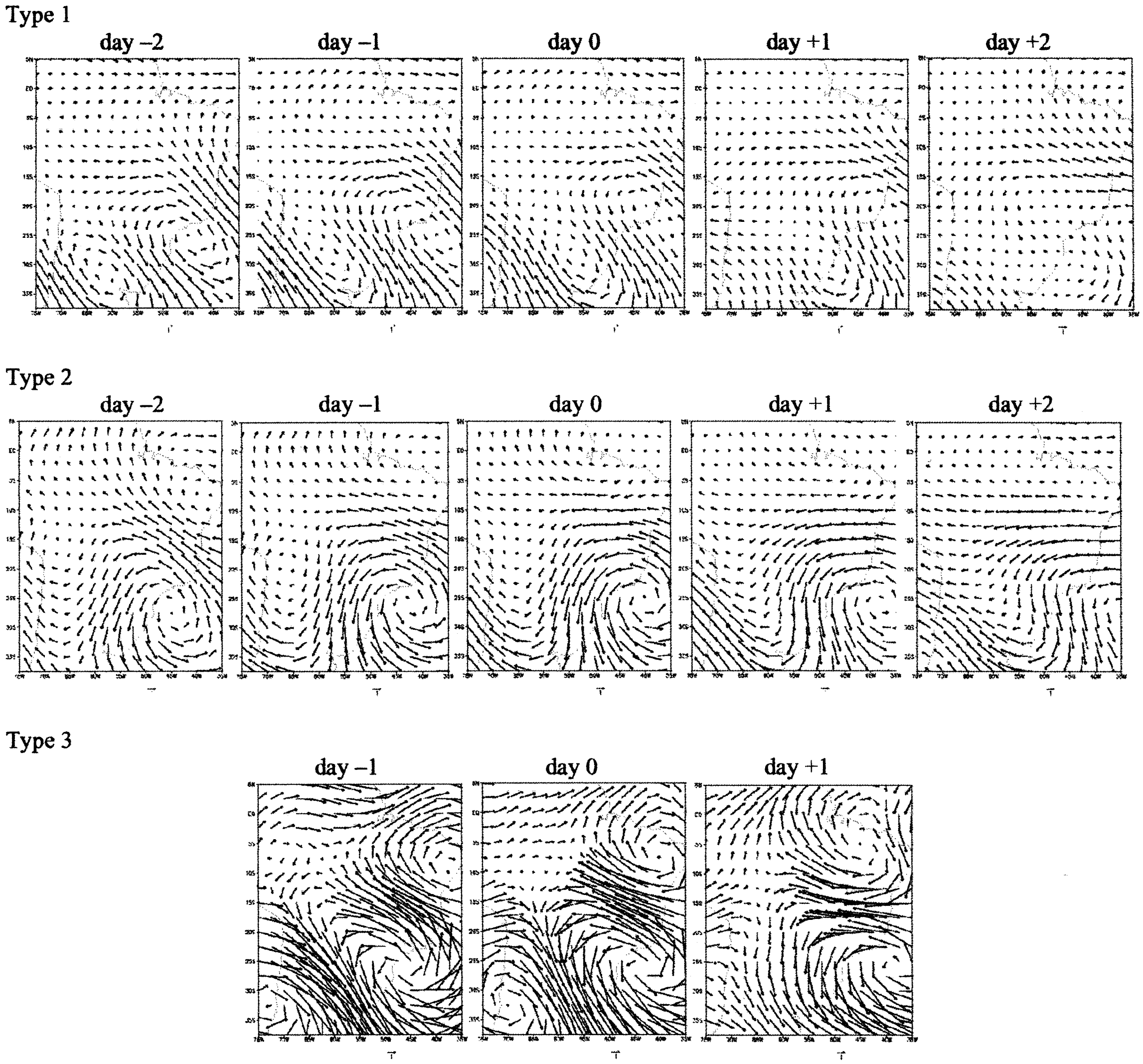

FIG. 6. The same as in Fig. 5 but for the 200-hPa level.

tended transient upper-level cyclonic vortex over northeastern SA that migrates westward throughout the type 3 mean life cycle is another relevant mechanism for the type 3 circulation pattern, and may also be related to the upper-level cyclonic vortices in northeast Brazil described in literature. According to Kousky (1979), the upper-level cyclonic vortices over northeast Brazil appears to be an important mechanism for the weaker northward advances of cold fronts and their associated convection into that region.

5. Concluding remarks

The interactions of frontal systems with tropical convection in SA were studied using ISCCP satellite composites, statistical tools, and circulation composites from NCEP. Three important types of frontal system–tropical convection interaction were identified in the latitude–time diagrams produced to the satellite composites. Type 1 consists of frontal systems from the subtropics or midlatitudes that interact with tropical convection over SA and move with it northward into lower tropical latitudes. The passage of a cold front over southeastern SA that advances northward with convection into central SA, southern northeast SA, and the Amazon basin is the main spatial pattern of convection variability expressed by the satellite composites for type 1. Type 1 is more frequent in austral summer and spring, and contributed almost 32% and 37% of the total day-to-day convection variability in those seasons, respectively. Type 2 consists of frontal systems in the subtropics or midlatitudes along which a southward enhancement of the tropical convection from lower tropical latitudes to the subtropics occurs. The existence of a cold front over southeastern SA at the first days of occurrence of the events accompanied by a quasi-stationary northwest–southeast band of convection extended from the Amazon basin to the South Atlantic for periods longer than

3 days is the main spatial pattern of convection variability found for type 2. Type 2 is associated with SACZ formation, such that SACZ episodes correspond to the type 2 synoptic pattern that remains over SA for more than 4 days. Type 2 has the highest frequency of occurrence in austral summer, and contributes about 16% of the total day-to-day convection variability in that season. The quasi-stationary frontal systems over the subtropics and midlatitudes that exhibit reduced interaction with tropical convection were classified as type 3. No significant seasonal variability was found for type 3 due to the low number of events found. Type 3 contributed 50% and 17% of the total day-to-day convection variability over SA in austral winter and spring, respectively.

Day-to-day fluctuation time scales dominated the convective variability associated with the three types of frontal system–tropical convection interaction observed in subtropical SA, followed by intraseasonal modes of 22–28 and 30–50 days. Convection that moves northward with cold fronts in the Tropics (type 1) and is enhanced southward along the cold fronts in the subtropics (type 2) exhibited coherent day-to-day time scales from 5 to 7 days in the Amazon basin, central and subtropical SA. A similar range of values was estimated for convection in the subtropics that is modulated by quasi-stationary cold fronts over that region (type 3).

Important circulation features in SA associated with the three types of frontal system–tropical convection interaction were documented using dynamical composites from NCEP. The advance of a low-level transient cyclonic vortex from southeastern to northeastern SA maintained by the convergence of moisture flows from the Amazon basin and southerly winds from the midlatitudes (cold front) constitutes the main type 1 circulation pattern. A similar pattern is observed for type 2, except for the quasi-stationary behavior presented by the low-level transient cyclone in southeastern SA which favors SACZ formation during type 2 events. A slow enhancement of the northerly moisture fluxes along the Andes is also observed during the type 2 life cycle. The existence of a quasi-stationary low-level transient anticyclone over southeast SA, accompanied by a low-level transient cyclone located southernmost and strong westerly winds possibly associated with the subtropical jet is the main type 3 circulation pattern, and represents the blocking of a cold front over that region. An upper-level transient cyclonic vortex over northeastern SA that migrates westward seems to contribute to the type 3 circulation pattern, what suggests a role of the upper-level cyclonic vortices over northeastern SA described in literature for the type 3 blocking configurations.

This paper has shown that frontal systems often interact with tropical convection over SA throughout the year, primarily in day-to-day time scales of convection variability. Types 1 and 2 frontal system–tropical convection interactions contribute together more than 48% of the total day-to-day convection variability over a large portion of SA during austral summer. The subtropical jet and upper-level cyclonic vortices in northeast Brazil are mechanisms noted to weaken the frontal system–tropical convection interactions over SA, establishing interactions similar to type 3. In addition to knowing the influence of these mechanisms on the frequent patterns of convection variability observed throughout the year, the knowledge about the structural characteristics of different events concerning types of clouds and rainfall rates is also extremely important. We hope to address some of these topics in future work.

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