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Observational evidences on the modulation of the South American Low Level Jet east of the Andes according the ENSO variability

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Abstract. The differences on the phase and wavelength of the quasi-stationary waves over the South America generated by El Niño (EN) and La Niña (LN) events seem to affect the daily evolution of the South American Low Level Jet east of the Andes (SALLJ). For the austral summer period of 1977–2004 the SALLJ episodes detected according to Bonner criterion 1 show normal to above-normal frequency in EN years, and in LN years the episodes show normal to below-normal frequency.

During EN and LN years the SALLJ episodes were associated with positive rainfall anomalies over the La Plata Basin, but more intense during LN years. During EN years the increase in the SALLJ cases were associated to intensification of the Subtropical Jet (SJ) around 30° S and positive Sea Level Pressure (SLP) anomalies over the western equatorial Atlantic and tropical South America, particularly over central Brazil. This favored the intensification of the northeasterly trade winds over the northern continent and it channeled by the Andes mountain to the La Plata Basin region where negative SLP are found. The SALLJ cases identified during the LN events were weaker and less frequent when compared to those for EN years. In this case the SJ was weaker than in EN years and the negative SLP anomalies over the tropical continent contributed to the inversion of the northeasterly trade winds. Also a southerly flow anomaly was generated by the geostrophic balance due to the anomalous blocking over southeast Pacific and the intense cyclonic transient over the southern tip of South America. As result the warm tropical air brought by the SALLJ encounters the cold extratropical air from the southerly winds over the La Plata basin. This configuration can increase the conditional instability over the La Plata basin and may explain the more intense positive rainfall anomalies in SALLJ cases during LN years than in EN years.

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1 Introduction

The rainy season in Brazil (December–February) is related to monsoon system on the South American continent were higher rainfall values are found in Central Brazil. However, precipitation is observed in La Plata Basin (southeastern South America) throughout the year with values about 9 mm day^{-1} toward the northern boundary and about 5 mm day^{-1} over the central region of the basin (Fig. 6b of Berbery and Barros, 2002). This is in part due the low level northerly jet that develops along the eastern slopes of the Andes, here called South American Low-Level Jet east of the Andes (SALLJ). The SALLJ is responsible for transporting moist air from the Amazon region into central and southern South America mainly during austral summer (e.g. Nogués-Paegle and Mo, 1997; Saulo et al., 2000; Silva Dias, 2000; Marengo et al., 2004). It also generates turbulence through shear and participates actively as trigging mechanism for the formation of severe storm and Mesoscale Convective Systems over Paraguay, Northern Argentina and South of Brazil (e.g. Guedes and Silva Dias, 1985; Nicolini et al., 2002; Nieto Ferreira et al., 2003). Some studies using data from large field experiments such as the LBA WET AMC (Marengo et al., 2002; Silva Dias et al., 2002) and the SALLJEX (Vera et

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Table 1. El Niño, La Niña and neutral events selected according the Oceanic Niño Index (ONI)/NOAA criterion.

El Niños	La Niñas	Neutral events
1976/77, 1977/78, 1979/80, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03	1984/85, 1988/89, 1995/96, 1998/99, 1999/2000	1978/79, 1980/81, 1981/82, 1983/84, 1985/86, 1989/90, 1990/91, 1992/93, 1993/94, 1996/97, 2000/01, 2001/02, 2003/04

al., 2006), as well as the reanalysis from the National Center for Environmental Prediction – NCEP (Paegle, 1998; Douglas et al., 2000; Saulo et al., 2000; Marengo et al., 2004) have shown the occurrence of SALLJ in different seasons of the year. However, it is in the summer that most intense events seem to occur.

On diurnal timescales the presence of a boundary layer inversion is responsible to modulate the maximum wind profiles at low level (Marengo et al., 2004). Silva Dias (2000) has also suggested that the position of the jet, its intensity and diurnal cycle may be substantially altered by the impact of latent heating in the central Brazilian Amazon basin. On submonthly timescales the frontal passages and the South Atlantic Convergence Zone (SCAZ) activity (Saulo and Nicolini, 2000; Vera et al., 2002; Campetella and Vera, 2002) may modulate the SALLJ. For example, when moisture flux into southeastern South America via the low-level jet is strong, SACZ convection is weaker than normal (Sugahara et al., 1994; Liebmann et al., 1999). Moreover, Liebmann et al. (2004) have shown the relationship among the SALLJ and extreme precipitation events over subtropical South America during austral summer. Using lead and lag composites of circulation for rainfall anomalies associated with the jet, they suggested that on a daily time scale, a preference for rain (no rain) in the SACZ may agree with a weak (strong) jet and dry (wet) conditions downstream of it.

On interannual timescales, some study cases linking El Niño/Southern Oscillation (ENSO) and SALLJ have already been documented in the literature. For instance, Berbery and Barros (2002) suggested that during the austral summer of the three more relevant El Niños (EN) that occurred in the 1980–2000 period, the large-scale patterns showed increased southward component of moisture flux over La Plata Basin. Lau and Zhou (2003) observed a reduction of rainfall over the Amazon associated with a poleward shift of the South American monsoon circulation and rainfall system during the 1997/98 El Niño. They indicated that the Bolivian high was hydrostatically enhanced by the anomalous tropospheric warm ridge extending from the Niño-3 region to the Altiplano Plateau. They found a much stronger SALLJ penetrated deeply into the extratropics along the eastern side of the subtropical Andes, coinciding with the reinforcement of the upper tropospheric subtropical westerly and the local meridional overturning. Marengo et al. (2004), Lau and Zhou (2003) and Nieto Ferreira et al. (2003) have also indicated that the 1997/98 EN had more frequent and strong SALLJ episodes when compared to the 1999/2000 La Niña (LN) event. Silva and Ambrizzi (2006) verified that during the event of 1997/98 a low-level anomalous anticyclonic circulation over the central part of Brazil enhanced the wind in the core of the SALLJ and displaced the jet to the Northern Argentina and South of Brazil. On the other hand, during the weak EN 2002/03 the SALLJ was less intense and displaced towards the southeast of Brazil.

From the above discussion one can suggest that there are many different mechanisms to explain the formation of SALLJ. The goal of this paper is to investigate if El Niño and La Niña signal variability can modulate the frequency, position and intensity of the SALLJ activity during the austral summer. This study is organized as follows. Section 2 describes the data and the methodology. Section 3 summarizes the large-scale patterns found during the ENSO events of austral summer from 1977 to 2004 period. In Sect. 4 the interannual variability on the frequency of the SALLJ episodes during the same period is investigate. Some aspects related to the modulation of the SALLJ variability by EN and LN events are described in Sect. 5. Section 6 summarizes the main findings.

2 Data and methodology

In view of the poor observational data in the east Andes region, the NCEP-NCAR reanalysis (Kalnay et al., 1996) have been used in this study. They satisfactorily represent the large-scale atmospheric conditions associated to the SALLJ (Marengo et al., 2004; Silva and Ambrizzi, 2006 and references). The data for December-January-February (DJF) from 1977 to 2004 period are reported on a $2.5°\times2.5°$ grid every 6 h (00:00, 06:00, 12:00 and 18:00 UTC). The period of the study was chosen based on the shift toward warmer tropical Pacific Sea Surface Temperatures (SST) that occurred in 1976 (Zhang et al., 1997) and because the improvement of quality of the observational network. The meteorological variables used are: zonal and meridional winds (u, v) in 850 hPa; Sea Level Pressure (SLP) and 500-hPa geopotential height (Φ). Daily mean streamfunction (ψ) at the 0.21 sigma level (about 200 hPa) are also used. Daily gridded precipitation data from Liebmann and Allured (2005) on 1° grid for the same period was used. This dataset was generated from daily precipitation observations over the South American continent based on 7900 meteorological stations. The Oceanic Niño Index (ONI), which is the main index used by NOAA to identify ENSO events in the tropical Pacific

(NOAA Magazine, 23 February 2005, http://www.noaanews.noaa.gov/stories2005/s2394.htm) was used in the study. ONI is calculated using a 3-months running mean of NOAA's Extended Reconstruction SST (ERSST.v2) anomalies in the Niño 3.4 region (5° N–5° S, 120° W–170° W). The EN (LN) is defined as condition whereby the ONI is more (less) than or equal to 0.5° (−0.5°)C. On the basis of this classification, 28 cases were chosen for the study, where December represents the initial year (0) and February the following year (Table 1). The period of 1977–2004 was chosen due to the precipitation data limitations.

Seasonal composites anomalies of EN and LN years of atmospheric circulation variables considered in the study were constructed. This procedure was applied to help to understand links between the different frequencies of SALLJ cases (cases per event) and different evolution during ENSO events. For instance these seasonal composites anomalies were determined as the difference between the composite mean of the EN (LN) events and the composite mean of the neutral years.

The methodology of previous studies (Saulo et al., 2000; Marengo et al., 2002, 2004; Silva and Ambrizzi, 2006) was applied to wind data (u, v) to select the SALLJ episodes according to each ENSO event. It was assumed that the region of Santa Cruz in Bolivia (17.75° S; 63.06° W) is where the core of the jet is usually located and only the northerly wind was selected. Also, the maximum flow should be located around 850 hPa which is less restrictive than the 925 hPa generally used. The Bonner criterion 1 (Bonner, 1968) was applied to the selected wind fields and it is based on the following conditions: the level of maximum wind must be equal or exceed $12\,\mathrm{m\,s^{-1}}$ and must decrease by at least $6\,\mathrm{m\,s^{-1}}$ to the next higher minimum or to the 3-km level, whichever is lower.

Based on the SALLJ episodes detected the interannual variability on the frequency, positioning and intensity was analyzed. For this purpose, daily composite anomalies from day −1 to day +1, assuming day 0 where the SALLJ reaches it maximum intensity where constructed. For each ENSO event the day 0 composite anomaly was defined as the difference between the day average of the SALLJ maximum intensity and the composite mean of the neutral years. Day −1 and day +1 are defined as the anomalous fields during −1 (+1) day before (after) each original day 0.

In order to assess the statistical significance of all composites, a two-tailed Student t-test (Harrison and Larkin, 1998) was used. The composite anomalies were accepted with the confidence level at 95%. Only absolute anomalies equal or exceeding

$$\frac{Z_{95}(n) \times \sigma_c}{\sqrt{n}} \tag{1}$$

were accepted, where n is the number of values used in the composite, σ_c is the corresponding standard deviation and Z_{95} is the value of t-distribution for n degrees of freedom (number of events in each group) for 95% confidence level.

3 ENSO-related anomalies circulation during the austral summer (1977–2004)

The seasonal anomalies composites of EN and LN years during austral summer are illustrated in Fig. 1. The EN-related 200-hPa zonally asymmetric ψ anomaly composite shows anticyclones over the central-eastern tropical Pacific centered in the latitudinal bands of 20° of both hemispheres (Fig. 1a). This pattern is part of a Rossby wave train pattern stretching from the heating source in the equatorial eastern Pacific to northeastern Brazil through the Southern Hemisphere mid-latitudes. Cyclonic and anticyclonic centers over northeastern Brazil and southeast SA are observed. The LN events shows an opposite pattern mainly over the tropics where the most significant anomalies were found (Fig. 1d).

The 500-hPa Φ anomaly pattern in the EN composite shows positive values over the tropical and subtropical SA and negative ones in the extratropics (Fig. 1b). The gradient among these systems favor the intensification of the SJ around 30° S. During the LN events (Fig. 1e) negative anomalies dominate over the South American continent. In fact, the cyclonic center over 40° W–30° S contributes to the intensification of SJ though it is weaker than in Fig. 1b.

The 850 hPa winds and SLP anomalies for the EN and LN composites show many differences (Fig. 1c and f, respectively). For EN years the positive SLP anomalies over the eastern equatorial Atlantic and tropics contributes to intensify the northeasterly trade winds over northern SA (Fig. 1c). The positive SLP nucleus over central Brazil contributes to channel the wind to the southeast part of the continent bringing moisture over this region where there is negative SLP anomalies. In contrast, the LN composites show an inversion of the northeasterly trade winds over SA. A positive (negative) SLP nucleus centered over the southwestern Pacific (southern Atlantic) related to the anticyclonic (cyclonic) circulation are observed in high and mid-latitudes (Fig. 1d and e, respectively) and having a vertical equivalent barotropic structure. This configuration contributes to strong low level southerly winds which prevail over the subtropical SA favoring the southerly transport of moist air to the east of the Andes and weakening the northerly LLJ. Due to the extratropical cyclone anomaly, this flow can be accompanied by synoptic-scale bands of deep convection at the leading edge, frequently associated with SACZ intensification (e.g. Garreaud and Wallace 1998).

In the next section, a detailed daily evolution of the SALLJ episodes during EN and LN years which will be compared to the seasonal anomalies of the atmospheric circulation patterns during ENSO events analyzed here. This analysis will help to strengthen the main ideas proposed in the study, i.e. how the EN and LN signal variability can modulate the

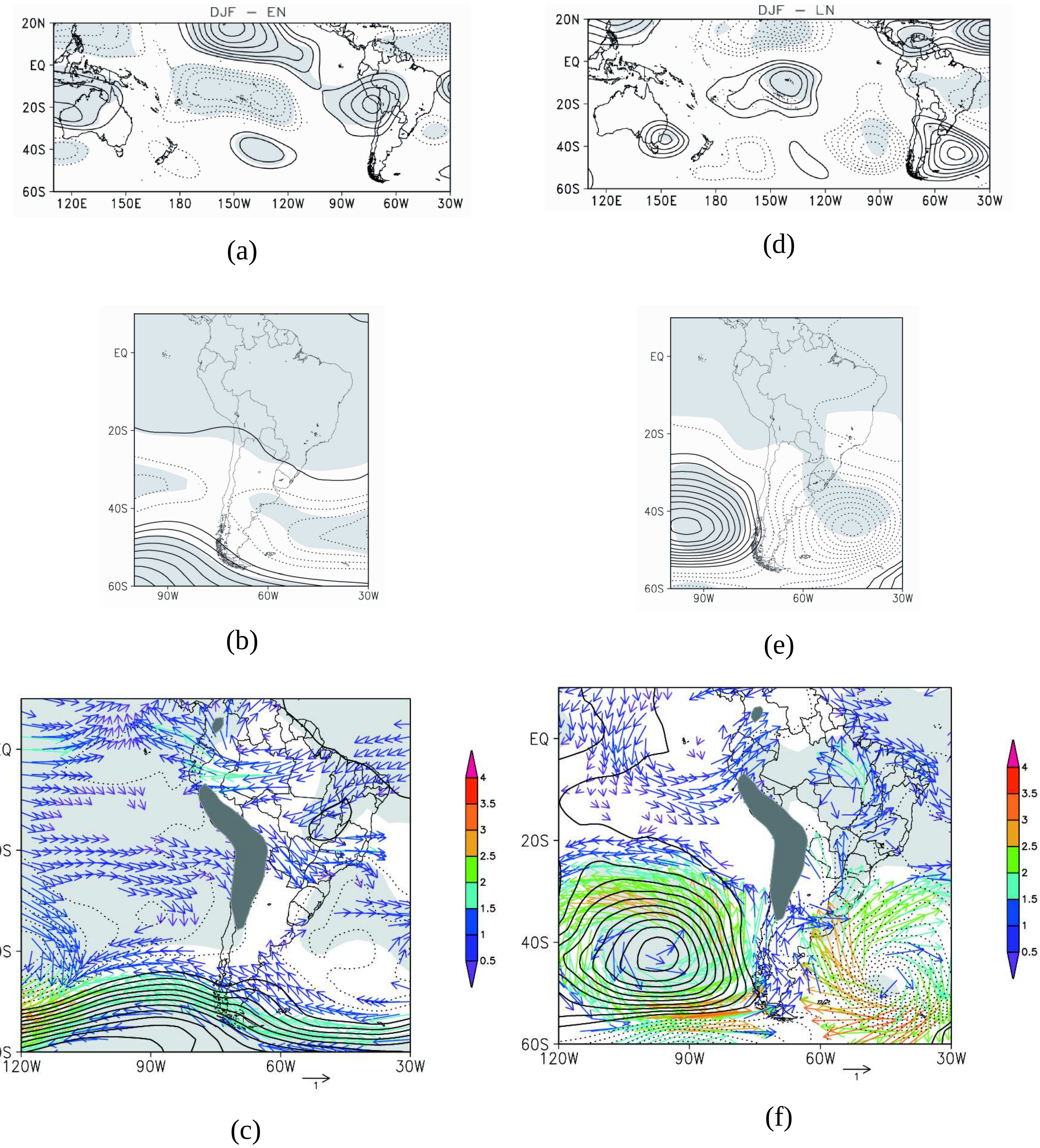

Fig. 1. Anomaly composites during austral summer from 1977–2004. On the left panel **(a)** 200 hPa zonally asymmetric streamfunction; **(b)** 500 hPa geopotential height and **(c)** 850 hPa wind and SLP for EN years; on the right panel the same as left panel but for LN years. Contour interval is $1\times10^{6}\,\mathrm{m}^2\,\mathrm{s}^{-1}$, 5 m, 1 hPa. A reference vector of $1\,\mathrm{m\,s}^{-1}$ is shown at the lower right-hand side of each panel. Negative contours are dashed and the zero contours are omitted. Areas where anomalies are statistically significant at the 95% level are shaded in gray.

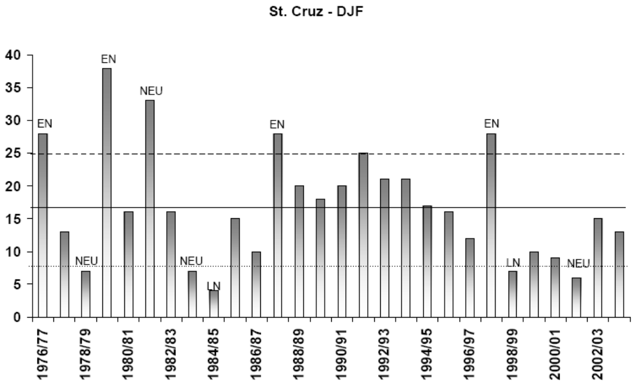

Fig. 2. Frequency of SALLJ detected according the Bonner criterion 1 during DJF season in Santa Cruz- Bolivia. The full, dashed and dotted lines represent the mean, one standard deviation above normal and one standard deviation below normal, respectively. The abbreviations EN, LN and NEU above of the bars indicate El Niño, La Niña and neutral years, respectively.

frequency, position and intensity of the SALLJ activity during the austral summer.

4 Interannual variability of SALLJ frequency

The interannual variability of the SALLJ episodes detected in Santa Cruz during DJF from 1977 to 2004 period is shown in Fig. 2, where December represents the initial year (0) of the ENSO event and February the following year. The full, dashed and dotted lines in the figure represent the mean, one standard deviation above normal and one standard deviation below normal, respectively. In the EN events of 1976/77, 1979/80, 1987/88 and 1997/98 it is observed above-normal SALLJ frequency, i.e. number of jets is one standard deviation above-normal (17 plus 8) and the other events the frequencies are normal. For the LN events of 1984/85 and 1998/99, the number of jets was one standard deviation below-normal (17 minus 8), being normal for the others events.

Marengo et al. (2004) showed that statistically significant positive correlations among SALLJ frequency and SST anomalies are observed in the Pacific Ocean implying that a low percentage about 20% of the SALLJ variance can be explained by the SST anomalies in the Equatorial Pacific during austral summer. Although in the period used here the number of EN events (10) is double of the LN (5) and the sum of them is almost equivalent to the neutral years (13) (see Table 1), the SALLJ cases during the warm ENSO phase is greater than in the cold phase (Table 2). This analysis clearly indicates that there is a tendency for more jets during EN events independently of their number.

While there are still many aspects that may be further explored the present study will only be focused in how different large-scale patterns associated with warm and cold phase of ENSO over South America may modulate the interannual SALLJ variability.

Table 2. Total number of observed SALLJ cases in Santa Cruz for EN, LN and neutral groups and the ratio between the SALLJ and the number of ENSO events during austral summer. The number of ENSO events is shown in the square bracket in the last column.

ENSO events	Total number of SALLJ	Ratio between number of SALLJ and ENSO events
El Niños	218	22 (10)
La Niñas	57	11 (5)
Neutral	198	15 (13)

5 El Niño and La Niña signal in the variability of the SALLJ during austral summer

Figure 3 displays the rainfall anomaly composites for the SALLJ maximum intensity at day 0. For EN years significant positive anomalies are found in Uruguay, Northern Argentina, Paraguay, Southern Brazil, in mostly of the La Plata basin and isolated points around 20° S over Brazil (Fig. 3a). In Fig. 3b for LN years, the La Plata basin region shows a similar pattern to the EN composites; however the anomalies are more intense in this case. Berbery and Barros (2002) have already suggested that the large rainfall anomalies over La Plata region are not limited to EN events, and according to Fig. 3b it also happens in LN years when SALLJ occurs.

Figures 4 to 6 show the evolution of the atmospheric circulation features associated with the rainfall anomalies described in Fig. 3. The 200-hPa zonally asymmetric ψ anomaly composite during EN and LN events from day -1 to +1 of SALLJ activity are shown in Fig. 4. The EN composites show a quasi-stationary wave pattern similar to the Pacific-South American 1 (PSA1) identified by Karoly (1989) and Mo and Paegle (2001): a wave train extending to southeast from the equatorial central Pacific turning to the northeast near the 60° S and reaching tropical latitudes over the Atlantic Ocean. Over southern South America near 35° S and adjacent ocean the cyclonic anomaly with the anticyclonic anomaly in the southern Brazil produce an enhancement of the SJ which generates a condition to increase rainfall over the region (Fig. 4a). This anomalous pattern is intensified on days 0 and +1 (Fig. 4b and c, respectively) and shows the same phase when compared to the seasonal anomalies (Fig. 1a), though with higher amplitude. For the LN (Fig. 4d) composites the wave train observed shows opposite phase over the most part of the tropical latitudes. On the southern tip of South America an anomalous cyclonic circulation similar with that for EN composite is established but with no statistic significance. The anomalous wave pattern is

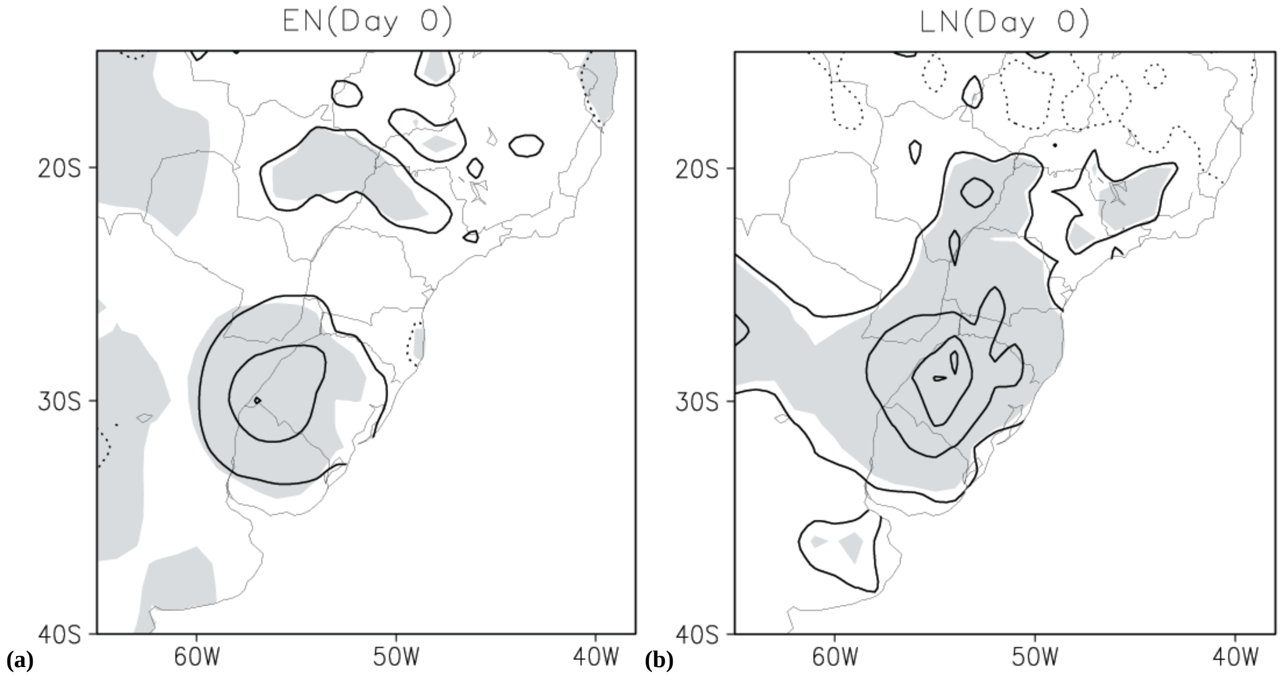

Fig. 3. Precipitation anomaly for DJF of SALLJ composites during their maximum intensity (day 0) for **(a)** EN and **(b)** LN years. Contour interval is 2 mm day^{-1}. Negative contours are dotted and the zero contours are omitted. Areas where the anomalies are statistically significant at the 95% level are shaded in gray.

intensified over the continent in the days 0 and +1 (Fig. 4e and f, respectively) having the same structure as observed in seasonal anomalies (Fig. 1d) but stronger.

From the 500-hPa Φ anomaly composite during EN and LN years for days −1, 0 and +1, we can see some important differences in the fields (Fig. 5). Although a negative geopotential height centered around (50° S; 70° W) is clearly observed in both composites at day 0 (Fig. 5a and d, respectively), being part of a wave train structure, their wavelength is quite different. In the EN composite the gradient between the positive values over the tropical SA and negative over the subtropics favors the intensification of the SJ around 30° S over the continent (Fig. 5a) which is maintained in the following days (Fig. 5b and c). It indicates more meridional wave propagation and resembles to the structure observed in Fig. 1b but intensified. From day −1 to day +1 of the LN composites (Fig. 5d–f) a more zonally propagation pattern and larger wavelength is seen over the mid-latitudes when compared to the EN years. Negative values dominates over the SA related to the cyclonic center positioned in 50° S; 70° W acting to produce a much weaker SJ over southeast South America when compared to the EN composites. This pattern resembles Fig. 1e with a shifted phase.

Figure 6 shows the 850 hPa winds and SLP anomalies during EN and LN years from day −1 to +1 of SALLJ activity maximum. The high pressure over the Tropical Atlantic Ocean and tropical Brazil at day −1 for EN composites contributes to intensify the northeasterly trade winds over northern SA (Fig. 6a). These winds are channeled to the southeast SA (northern Argentina, Uruguay, South and part of southeast Brazil) along the east of the Andes Mountain. Negative SLP anomalies cross the Andes during this period causing an elongation of its maximum on the lee side. At day 0 (Fig. 6b), a high pressure anomaly favor the anticyclonic circulation over the central Brazil that helps to the maximum intensity of the SALLJ core with 9 m s^{-1} winds intensity. The low pressure mentioned acquire a cyclonic curvature over 40° S; 55° W and when compared to the 500-hPa Φ anomaly composite (Fig. 5b) indicates a westward inclination in the vertical and therefore the presence of a baroclinic structure. There is here a coupled among the SALLJ and the SJ shown in upper and mid-levels (Figs. 4b and 5b). The presence of anomalous upper level SJ associated to the PSA1 wave-like may contribute to the formation and maintenance of the SALLJ trough mass adjustment by transversal circulations in the exit and entrance of the SJ. According to Uccellini and Johnson (1979) the flow accelerates in the jet entrance region of the SJ, the transverse ageostrophic flow generates a direct secondary circulation cell in the plane normal to the jet axis. The SALLJ located beneath the exit region of the upper tropospheric jet streak, was embedded within the lower branch of the indirect circulation cell. Convergence (divergence) regions in low levels, caused by divergence (convergence) mass pattern on equatorial (polar)

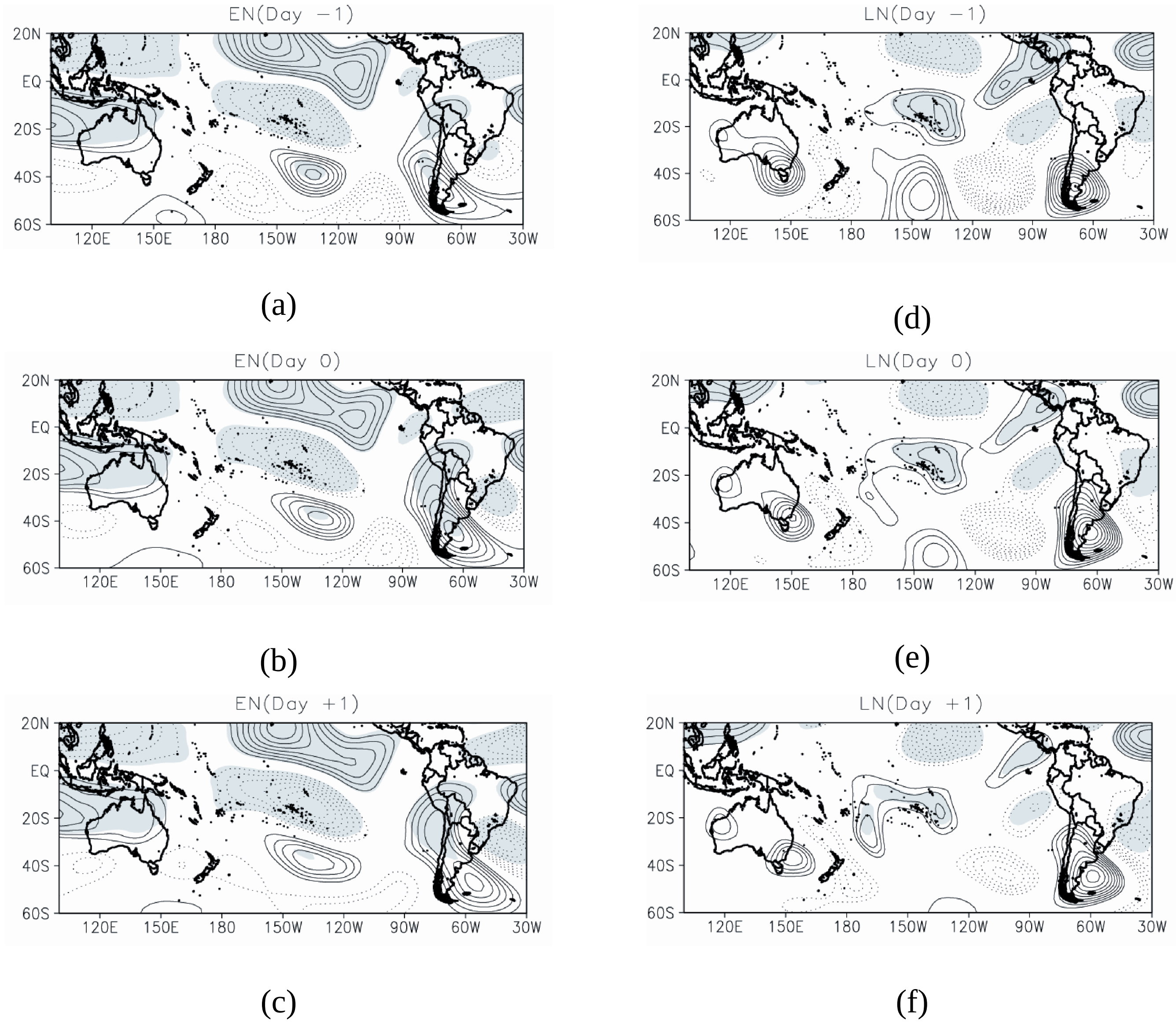

Fig. 4. 200 hPa zonally asymmetric streamfunction anomaly for SALLJ composites. Left panels: EN years of **(a)** day −1; **(b)** day 0 and **(c)** day +1 of the maximum SALLJ intensity. Right panels similar to the left but for: LN years of **(d)** day −1; **(e)** day 0 and **(f)** day +1. Contour interval is $1\times10^6\,m^2\,s^{-1}$. Negative contours are dotted and the zero contours are omitted. Areas where anomalies are statistically significant at the 95% level are shaded in gray.

side of the jet entrance and polar (equatorial) side of the jet exit produce negative (positive) tendency of SLP. The negative tendency of SLP favors more intense isallobaric wind component of the SALLJ. These conditions are favorable for the development of positive rainfall anomalies over La Plata Basin observed in Fig. 3a. In the following day, the anomalous anticyclonic pressure over the continent is maintained and the displacement of the cyclonic disturbance towards the South Atlantic Ocean coincides with the slight weakening of the SALLJ magnitude and its position is slight displaced to the north (Fig. 6c). The low level wind and SLP anomalies mainly observed in Fig. 6b shows the same structure as compared to the Fig. 1c. However, in the first there is a more pronounced channeled southward wind of the northwesterly flow because the Bonner criterion 1 has been applied to wind data to select the SALLJ cases.

At day −1 for LN composites there is an inversion of the northeasterly trade winds over the continent due the predominance of low pressure over the tropics and in the most part of the western Tropical Atlantic Ocean (Fig. 6d). This is

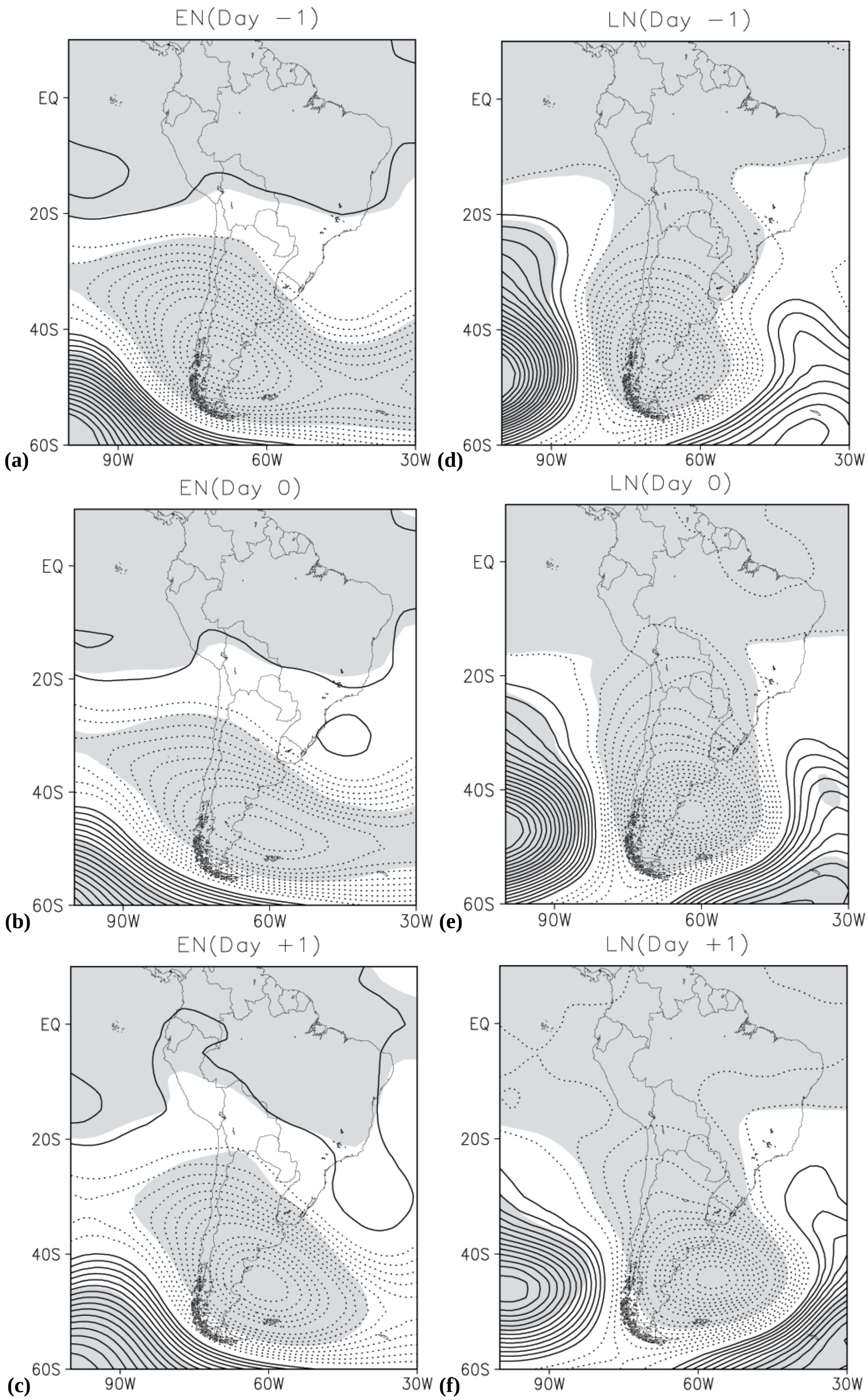

Fig. 5. Same as Fig. 4 but for the 500 hPa geopotential height anomaly. Contour interval is 5 m. Negative contours are dotted and the zero contours are omitted. Areas where anomalies are statistically significant at the 95% level are shaded in gray.

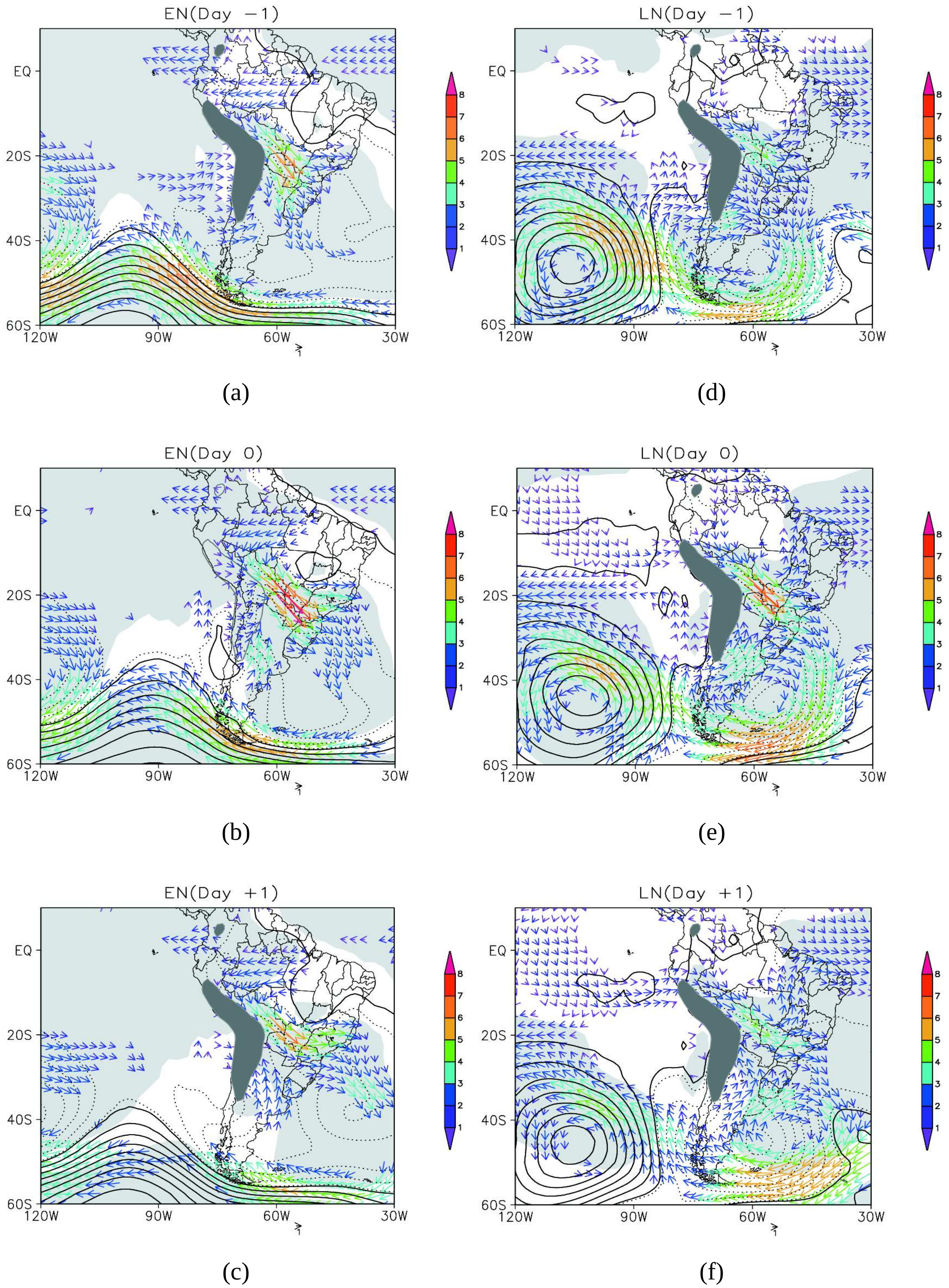

Fig. 6. Same as Fig. 4 but for the 850 hPa wind and SLP anomalies. Contour interval is 1 hPa. Negative contours are dashed and the zero contours are omitted. A reference vector of 1 m s^{-1} is shown at the lower right-hand side of each panel. The vector wind plotted and areas where anomalies are statistically significant at the 95% level are shaded in gray.

possibly associated to the zonally oriented high-low pressure configuration in mid-latitudes that configure a cyclonic transient centered at 45° S; 60° W. The wind magnitude on the core of SALLJ is up to 5 m s^{-1} and its exit is positioned over the central SA, not affecting the South of Brazil and Northern Argentina as observed in Fig. 6a. Despite of the importance of the Andes Mountain to channel the flow towards southeast of continent and the northern tropical Atlantic trade winds to trigger the whole process, Fig. 6d also suggests that the most important wind component (statistically significant) comes from the north Tropical Atlantic.

The zonally oriented high-low pressure configuration observed in mid-latitudes is intensified at day 0 when the SALLJ reaches around 7 m s^{-1} in the core (Fig. 6e). The stronger southwesterly flow over the southern sector of the continent due the gradient among the high-low pressure mentioned above maintain the SALLJ exit slightly positioned to the north when compared to Fig. 6b. These features are also very similar to those shown by Garreaud and Wallace (1998) and Mendes et al. (2007) related to the peaking at the time of extratropical cyclogeneses over SA during austral season. It creates a confluence region around 25° S; 58° W that can contribute with advection of warm air from the north by the SALLJ and cold advection from the south due to the cyclone position near the east coast of Argentina. This configuration generates an increase in conditional instability and therefore enhanced precipitation over the region that can explain the more intense positive anomalies over La Plata basin observed in Fig. 3b. In the day after, the high-low pressure structure decays, the cyclone slightly moves to the east over the South Atlantic, the intensity of the SALLJ decreases and the southerly flow acquires a more meridional component (Fig. 6f). Compared to the EN composites, the SALLJ in this case is less intense (about 7 m s^{-1} in its core) and its exit is slightly positioned to the north due the absence of the high pressure and inversion of the trade winds. The configuration of southwesterly flux in mid-latitudes mentioned above was also observed in Fig. 6b but weaker and with less statistic significance. The low level wind and SLP anomalies mainly observed at day 0 of LN years have a similar structure in mid-latitudes when compared to the Fig. 1f.

In general, it was observed that significant differences in frequency, amplitude and positioning of SALLJ depend on the ENSO phase. The frequency of normal to above normal in SALLJ cases during EN events and of normal to below normal during LN events can be explain by the differences in low level atmospheric circulation anomalies forced by the different high level wave pattern. This is agreement with results of Magaña and Ambrizzi (2005) that had already indicated that depending on the phase and trajectory followed by the wave generated on the tropical heating forcing during ENOS events the impact on the regional precipitation over the continent can be quite different. In the present study it was observed that this feature have impact on the daily evolution of the SALLJ follow by changes on the SLP anomaly over mid-latitudes. Also, the extratropical transients in SALLJ composites during LN years are more displaced to the south and more intense when compared to EN years. This is in accordance with Solman and Menéndez (2002) and Beu and Ambrizzi (2006) results who analyzed seasonal extratropical cyclones trajectories over the Southern Hemisphere during ENSO years.

6 Summary and discussion

The goal of this study was to investigate if EN and LN events can really affect the frequency, intensity, position and rainfall associated with the SALLJ cases during austral summer. Seasonal composites anomalies from EN and LN of atmospheric circulation variables and daily SALLJ composite anomalies were analyzed.

The differences on the phase and position of the quasi-stationary waves over the SA generated by the tropical heating source seem to affect the daily evolution of the SALLJ. With regard the ENSO-related circulations anomalies it was noted that during EN years the regional circulation anomalies over SA shows an intensification of the SJ around 30° S and the positive SLP anomalies over the western equatorial Atlantic and tropical SA helped to intensify the northeasterly trade winds over northern continent which were channeled by the Andes Mountain to the southeast region where negative SLP are found. It should be mentioned that a criterion was applied to identify what portion of this northwesterly flow east of the Andes is really related to the SALLJ circulation.

However, during LN years cyclonic anomalies prevailed at high level over the tropics associated to the cyclonic center over 40° W–30° S that contributes to the intensification of SJ though it is weaker than in EN years. The barotropic structured observed in this case also help to intensify the low level southerly winds over the subtropical SA. This favors the southerly transport of moist air to the east of the Andes and weakening the northwesterly flow east of the Andes.

The Bonner criterion 1 was applied to the NCEP reanalysis for the period 1977–2004 to identify the SALLJ episodes during austral summer period. It was found that the EN (LN) years tend to present normal to above-normal (below-normal) SALLJ frequency. The precipitation anomalies showed positive values over the La Plata Basin in both cases, but more intense during LN years. The daily evolution of the atmospheric circulation anomalies during the SALLJ maximum for EN and LN events were constructed and compared to the ENSO-related seasonal anomalies to explain the differences in the SALLJ frequency and rainfall anomalies associated.

In order to clarify the results found in the analysis, a conceptual diagram was constructed (Fig. 7) suggesting a possible physical mechanism to explain the modulation of the SALLJ by ENSO during austral summer. Figure 7a for the

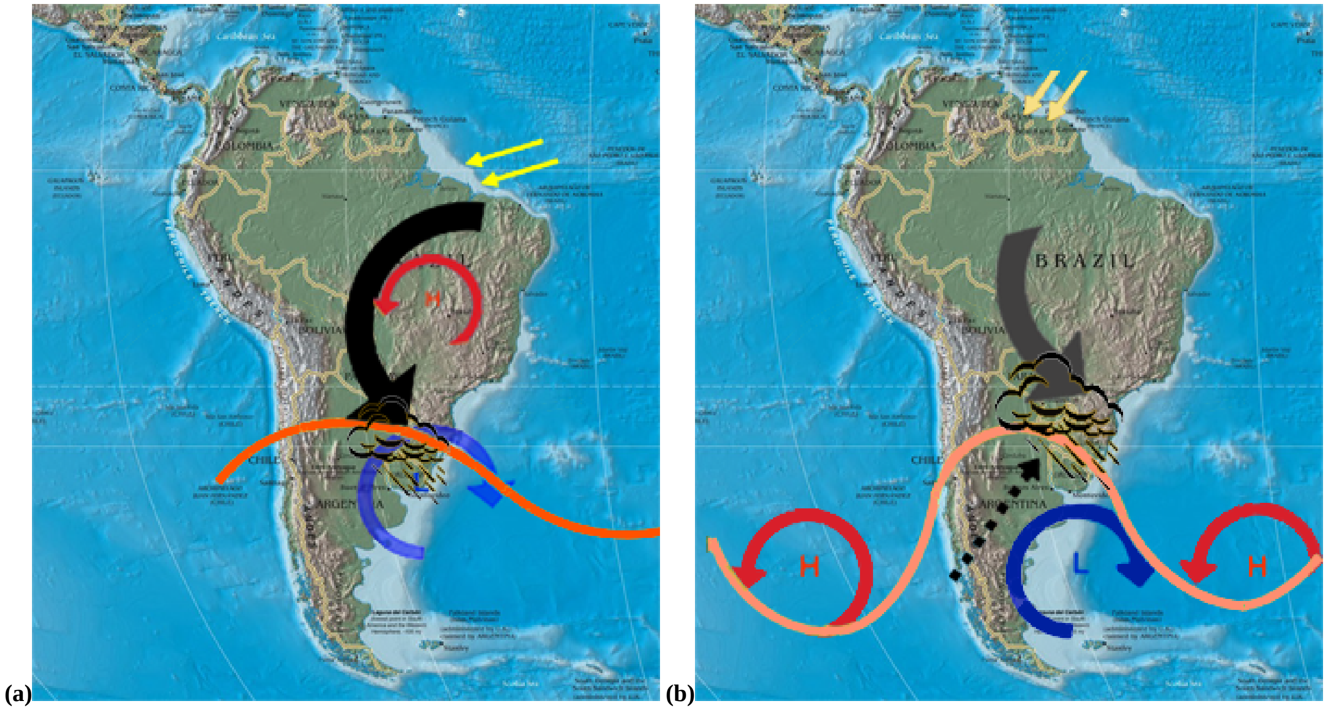

Fig. 7. Conceptual diagram on the physical mechanisms that may modulate the spatial and temporal variability of the SALLJ during the austral summer of **(a)** El Niño and **(b)** La Niña events. The yellow and black arrows indicate the trade winds and the SALLJ circulation that are more intense (darker arrow) in (a) than in (b). The H (red narrow) and the L (blue arrow) represents high and low pressures at 850 hPa. In (b) the dotted black arrow indicates the southerly flow associated with the high and low pressures at 850 hPa. The orange line shows the SJ at 200 hPa where the dark color in (a) indicates a much stronger intensity than in (b). The cloud represents the main precipitation region.

SALLJ cases detected during EN years indicates that the northeasterly trade winds are intensified (yellow dark arrows), enter through the eastern equatorial part of the continent and are channeled by the Andes Mountain toward La Plata Basin due the anticyclonic anomalies over central Brazil (red dark arrow). The large baroclinicity of the basic flow associated with the intensification of the SJ (orange dark line) over the continent around 30° S is important to maintain the SALLJ (black dark arrow). Convergence (divergence) regions at low levels, caused by divergence (convergence) mass pattern on the equatorial (polar) side of the jet entrance and polar (equatorial) side of the jet exit produce negative (positive) SLP tendency. This negative tendency (blue clear arrow) increases the isallobaric wind component of the SALLJ. All these conditions contribute to the development of positive rainfall anomalies over La Plata Basin as observed in Fig. 3a and above-normal frequency of SALLJ episodes.

For the SALLJ cases detected during LN years (Fig. 7b) it was observed that the negative SLP anomalies over the tropical SA contributes to the inversion of the northeasterly trade winds into the continent and consequently SALLJ cases becomes weaker and less frequent than in EN years. There is a weak but significant contribution of the flow coming from the northern tropical Atlantic (yellow clear arrows) on the SALLJ genesis. At mid-latitudes an equivalent barotropic environment modulates the SALLJ magnitude. A southerly flow anomaly (dotted black arrow) is generated as a result of the geostrophic balance between an anomalous southeast Pacific high (red dark arrow) and a cyclone over southeast South America (blue dark arrow). This configuration generates a cold air advection which encounters the warm northwesterly flow associated to the SALLJ (black clear arrow) which may explain the larger rainfall anomalies, particularly over Southern Brazil (Fig. 3b) when compared to the EN cases.

The interaction between the SALLJ and transient activity seem to be more pronounced during LN years, probably because the increase on the transient activity over midlatitude during this period which is in agreement with previous studies (Solman and Menéndez, 2002; Beu and Ambrizzi, 2006). This configuration helps to intensify the precipitation over the La Plata Basin though the subtropical jet is less intense when compared to the warm ENSO phase.

The regional atmospheric circulation observed in daily SALLJ anomalies composites during EN and LN years resembles that observed in the seasonal anomalies composites. This result suggests that the moisture transported by the SALLJ, besides the climatological flow due to the relationship among Amazon Basin – Andes Mountain – Brazilian Plateau – La Plata Basin, appears to depend also on the large-scale patterns of the atmospheric circulation generated during ENSO. Of course, one should notice that in daily composites the northwesterly flow related to the SALLJ is more evident than that obtained from the seasonal anomalies composites because a specific criterion to select the events was applied. Future work is still needed to understand how different scale forcings modulate the SALLJ variability.

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