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Mean atmospheric circulation leading to generalized frosts in central southern South America

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With 11 Figures

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Summary

The purpose of this study is to analyze the atmospheric circulation patterns associated to extreme frost episodes which affect the extensive region known as the Wet Pampas in the center-south of South America during the 1961–1990 period. The years with an extreme frequency of generalized frost are identified by selecting the cases beyond one standard deviation above and below the average of the corresponding period. Two groups were formed: one for the years with events above the average (+s) and the other with those below the average (−s). The years of generalized frosts were separated into the periods from May to September, June to August and individual months.

From the comparison between the composite of the two groups (+s and −s), it was possible to determine that the anomaly fields are opposite in almost all the periods studied. In the seasonal composites of generalized frosts below average, the circulation field presented a barotropic structure with an anomalous cyclonic persistence over the south-west of South America and a weak subtropical jet over the continent. On the other hand, the structure and evolution of the systems that produce generalized frosts in extremely cold winters were analyzed by calculating the composites of the daily fields from these episodes. The results showed that the incursion of cold air in the lower levels begins with a migratory anticyclone moving from the south-east Pacific to the south of the continent and a deepening of an anomalous low pressure center over the south-east of the Argentine Atlantic coast. Both systems cause cold, dry air advection from the south, with a reduction in temperature over the center and eastern parts of the country. The development of a mid-latitude wave was observed at higher levels with a large-amplitude trough over South America extending to tropical latitudes and a progressive amplification from another trough located upstream in the Pacific Ocean.

The analysis of the different periods confirmed the relationship between the intensification of the subtropical jet in South America and the higher frequency of generalized frosts. The intensification of the jet may be related to an amplification of the pressure gradient in the region due to the increase in Rossby wave activity.

1. Introduction

Among many meteorological parameters whose variability significantly affects human activities, frosts may be considered as one of the most important because of their impact on everyday life. The processes involved in producing these extremely cold conditions are associated with complex interaction mechanisms at different atmospheric scales. The combination of factors such as those related to atmospheric circulation, radiative balance, soil humidity and topographic features are an example of the multiple processes taking part to produce a marked drop in temperature.

In South America, the cold air outbreaks which come from the south–southwest of the continent in winter, occur with a weekly or biweekly frequency. Mid and upper level circulation over South America during these outbreaks have a mid-latitude wave with a ridge to the west of the Pacific coast and a trough extending towards the southeast from the subtropical region of the south Atlantic (Garreaud, 2000). Krishnamutri et al. (1999) showed that the large amplitude of the ridge-trough system during these episodes is the result of the overlap of the quick movement of the synoptic wave and quasi-stationary planetary waves. The largest amplification of the wave at upper levels during the mature stage of the cold surge is, in part, due to the baroclinic growth of the synoptic wave with cold air at the low levels moving northwards below the axis of the upper level trough (Marengo et al., 1997; Krishnamurti et al., 1999). As has been shown in the literature, the typical feature of these episodes is the presence of an anticyclonic surface disturbance over the coast of Chile, which enters South America to the south of 45° S, where the Andes are relatively low, and moves along the Andes following a continental path. The flow from the south, which is typical of these situations, and its relation to the channeling effect of the Andes, has been observed in climatological studies (Garreaud 1998, 1991) as well as during some case studies of frost events in the south and southeast of Brazil (Marengo et al., 1997; Krishnamurti et al., 1999).

In an analysis of frequencies, intensities and extension of frosts, Müller et al. (2000) classified these events into different groups according to their spatial occurrence over a large region of south-central South America known as the Wet Pampas. This region lies in a highly baroclinic area associated with the passage of transient systems. Small disturbances in the cyclone and anticyclone paths have a great impact on the occurrence of frosts in central and northeastern Argentina. However, not all of these have the same effect and questions have arisen such as how and why some of these waves are colder than others; why the propagation of one transient system is more able to penetrate even into tropical latitudes than others; and why the persistence of some systems is longer than others. The emphasis on generalized frosts in this paper attempts to answer these questions. These events have a spatial representativeness which in principle would make the sample homogeneous and specifically independent from the intensity of the cold wave which affects the region, its latitudinal penetration or its persistence. According to the spatial classification of Müller et al. (2000), the generalized frosts group is chosen for days when more than 75% of the Pampas meteorological stations registered temperatures less than or equal to 0°.

In a recent paper, Müller et al. (2003a) classified the patterns associated with generalized and partial frosts (0 °C from 25 to 75% of the meteorological stations) based on Principal Component (PC) Analysis. They made a synoptic-climatic classification of atmospheric circulation in order to obtain synoptic patterns related to frost in the Wet Pampas. They analyzed synoptic situations represented by surface pressure fields on days when partial or generalized frosts occurred. The different situations obtained, represented by the first six PCs, explained 94% of the total variance. The most important patterns were represented by the 1st (Pattern A), 2nd (Pattern B) and 3rd PCs (Pattern C). Pattern A showed a high pressure system north of 40° S. This is connected to radiative cooling rather than advection since it has weak gradients that give rise to light winds or calm conditions over the Wet Pampas. Pattern B consisted of a post-frontal high pressure system moving onto the continent towards the Pole at 40° S. This pattern generates south to southwest winds that cause a marked advection of very cold and dry polar air across the area, favoring advection and frosts. Pattern C represents a low pressure system to the east of the continent and a high pressure system entering from the Pacific, affecting the Wet Pampas from the west and producing a strong flow of cold and dry air from the south. This situation is also associated with a ridge in the middle troposphere that favors a drop in temperature due to clear skies and nocturnal radiation. The remaining patterns are connected to cold anticyclones which cause advective and/or radiative frosts.

In this paper, the seasonal and monthly circulation patterns of generalized frosts (Sects. 3.1 and 3.2 respectively) are analyzed through the composite of atmospheric fields in the years of extreme frequency of these episodes. The seasonal analysis was completed by making an analogy between the anomalous fields resulting from the composites of winters with generalized frosts above (below) average and those obtained for another group of cold (warm) anomalous winters. The evolution of circulation fields before and after the generalized frost, which took place during the winters of the years with a maximum frequency of these events, was also studied (Sect. 3.3).

2. Data and methodology

Following the spatial criterion applied by Müller et al. (2000), generalized frosts days are defined as days on which minimum temperatures below 0° were recorded at more than 75% of meteorological stations in the Pampas (see their Fig. 1 for stations location in the Argentine Pampas). Table 1 shows the number of generalized frosts for each year from 1961 to 1990. In order to facilitate the analysis, the events were separated in the following periods: from May to September (MJJAS), June to August (JJA) and each month of the frosts occurrence. Table 1 also indicates (in bold) the number of frosts above (+s) or below (−s) one standard deviation from the average. This criterion was used to separate the highest and lowest number of episodes in the period. Therefore, two groups were defined and composites were calculated for different meteorological variables. The anomalies of the following variables were considered: sea-level pressure, upper

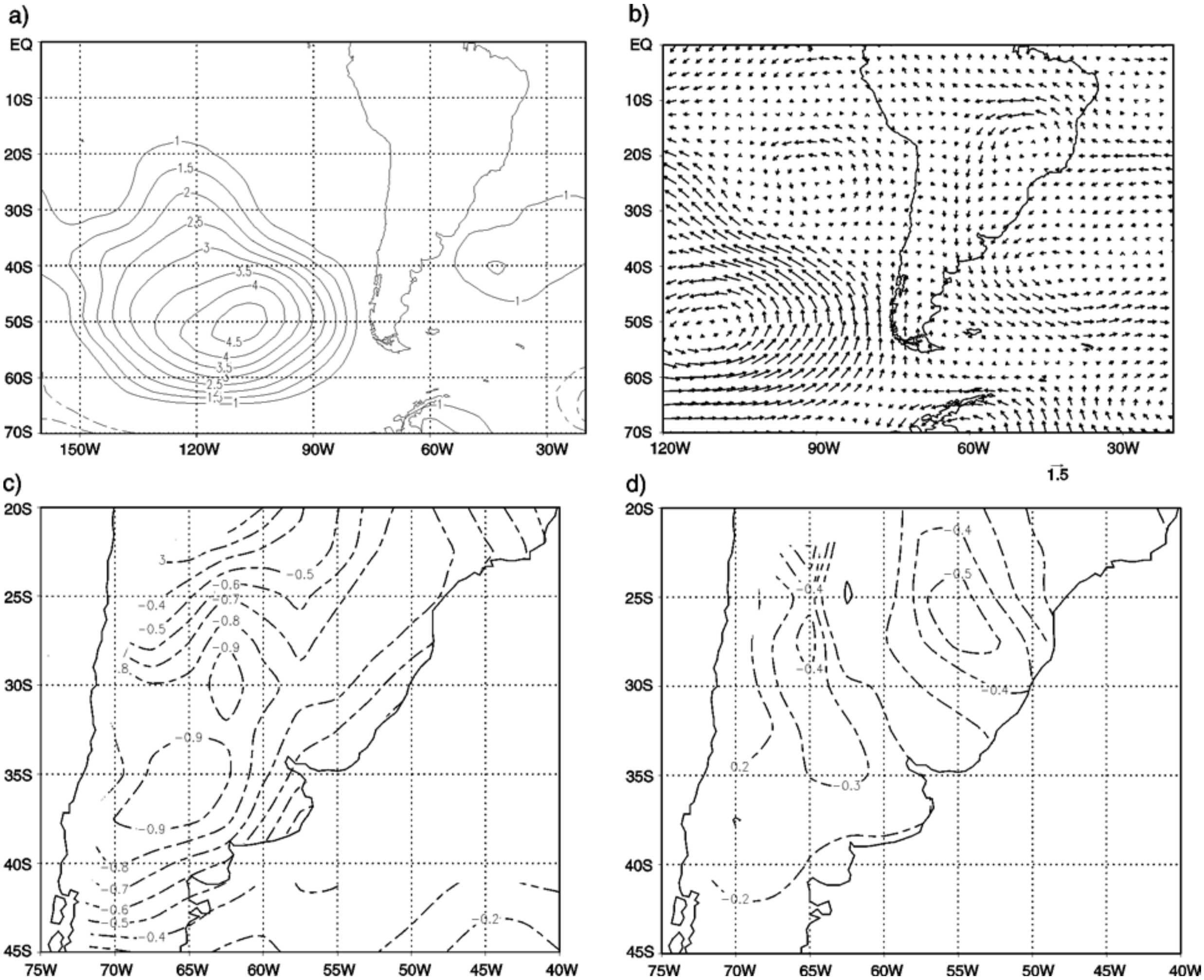

Fig. 1. Anomalies of (**a**) sea level pressure (hPa), (**b**) wind vector ($m\,s^{-1}$) at 850 hPa, (**c**) surface temperature (°C) and (**d**) specific humidity ($g\,kg^{-1}$) at 850 hPa, for composites of winters with generalized frosts above average ($+\sigma$). Positive (negative) contours in full (dotted) line

Table 1. Number of generalized frosts in the seasonal (MJJAS, JJA) and monthly periods. Bold (italics) indicate values with one standard deviation greater than (smaller than) average

Year	MJJAS	JJA	May	June	July	August	September
1961	3	3	0	3	0	0	0
1962	6	6	0	1	5	0	0
1963	3	3	0	1	0	2	0
1964	7	6	0	2	0	**4**	1
1965	6	6	0	*0*	5	1	0
1966	5	4	0	*0*	1	**3**	1
1967	8	8	0	**6**	1	1	0
1968	*2*	*1*	0	*0*	1	0	1
1969	7	7	0	**4**	0	**3**	0
1970	**11**	**11**	0	2	**7**	2	0
1971	9	6	**3**	**5**	0	1	0
1972	6	5	0	*0*	3	2	1
1973	*0*	*0*	0	*0*	0	0	0
1974	**10**	7	0	2	1	**4**	**3**
1975	4	4	0	*0*	4	0	0
1976	**14**	**14**	0	**5**	**8**	1	0
1977	5	3	**1**	1	1	1	1
1978	4	4	0	3	0	1	0
1979	5	5	0	3	2	0	0
1980	9	8	0	2	**6**	0	1
1981	6	6	0	2	4	0	0
1982	*2*	*2*	0	2	0	0	0
1983	7	6	0	2	2	2	1
1984	8	6	**2**	2	2	2	0
1985	4	4	0	1	3	0	0
1986	*0*	*0*	0	*0*	0	0	0
1987	5	5	0	**4**	1	0	0
1988	**13**	**13**	0	3	**9**	1	0
1989	4	4	0	*0*	4	0	0
1990	5	4	0	1	3	0	1
MEAN	6	5	0	2	2	1	0

and lower level geopotential height, surface temperature, humidity at 850 hPa, wind vector at 850 and 250 hPa, and zonal and meridional wind at 250 hPa. Anomalies were calculated with respect to the 1968–1996 climatology for each period analyzed. The NCEP reanalyses data were used with a horizontal resolution of 2.5° latitude and 2.5° longitude (Kalnay et al., 1996). For the SST composites COADS data were used (Woodruff, 1998).

The study of the patterns leading to generalized frost was based on the composite of individual events during the winter (JJA). The selection criterion considered the spatial distribution of the explained variance for events in the band of synoptic scale. According to Escobar (2001) this band is located between 3.7 and 6.6 days and

Table 2. Events selected from the winters (JJA) with generalized frosts with one standard deviation above average

Events
1970/06/24
1970/07/07
1970/08/08
1970/08/25
1976/06/11
1976/06/26
1976/07/04
1976/08/14
1988/06/01
1988/06/14
1988/06/24
1988/07/05
1988/07/24
1988/08/26

behaves fairly homogeneously across the whole region, covering south-central South America. A similar analysis was made for the longer waves between 7.1 and 13 days and showed that the largest variance is again in the same area, decreasing southward. Based on these results a minimum of 7 days of time interval in a sequence of days with generalized frosts will be considered along with the selected dates shown in Table 2. A comprehensive analysis of the evolution of mean and anomaly fields of atmospheric circulation was made on the basis of the composite of individual events which covers three days before the event (identified as day 0) and one day after.

In order to determine whether the winter circulation anomalies correspond to situations which favor extreme generalized frost or are simply conditions characteristic of very cold or very warm years, a selection of years with generalized frosts events above (below) average were obtained for a group of anomalously cold (warm) winters. The classification of extreme winters was based on the Barrucand and Rusticucci (2002) study. They defined extremely cold years as those with more than 65% of meteorological stations with cold minimum temperatures for many days and statistically significant. The extremely warm years correspond to those with less than 10% of the meteorological stations in which extremely cold minimum temperatures were registered for the winter. Table 3 shows the years selected by this criterion from 1961 to 1990. It should be noted that the respective years

Table 3. Anomalous cold and warm winters in the period 1961–1990, from the classification of Barrucand and Rusticucci (2002)

Anomalous cold winters	Anomalous warm winters
1961	1968
1962	1972
1964	1973
1967	1977
1970	1982
1976	1985
1983	1986
1988	1987
	1989

obtained using the extreme criterion of generalized frost frequency (Table 1) are within the above mentioned group of extreme winters (Table 3). Therefore, this comparative analysis includes all the years with anomalous winters with the exception of those with extreme generalized frosts (Table 2). The years of the anomalous cold winters (AC) are 1961, 1962, 1964, 1967, 1983 and the anomalous warm winters (AW) correspond to 1972, 1977, 1985, 1987 and 1989.

3. Analysis of results

3.1 Seasonal composites

The seasonal analysis will concentrate on the JJA period once the composites obtained for MJJAS show a similar atmospheric pattern structure, though with smaller amplitudes. Two winter groups, one formed by the years with a generalized frost frequency above average ($+\sigma$) and the other with a generalized frost frequency below average ($-\sigma$) will be discussed next.

3.1.1 $+\sigma$ winters

The results for the $+\sigma$ winters show a surface pressure field with a high pressure center in southwestern South America at approximately 110° W, 50° S with an anomaly greater than 4 hPa (Fig. 1a). Physically, this anomaly reflects a higher incidence of intense anticyclones which eventually enter the continent around 35° S where the Andes are lower (approx. 2,000 m) (Garreaud, 2000; Seluchi and Marengo, 2000, among others). From the 850 hPa wind field (Fig. 1b), one can see a meridional flow in across southwest Argentina, favoring the channeling of cold air towards the whole country, verified by the negative temperature anomalies observed during the three winters formed by the composite (Fig. 1c). From a climatic-synoptic point of view, the anticyclones cause advective and/or radiative cooling depending on their location over the continent. They are the most frequent events responsible for the frosts in the Wet Pampas region (Müller et al., 2003a). These extreme conditions are accompanied by low humidity all over Argentina, particularlly in the Pampas (Fig. 1d).

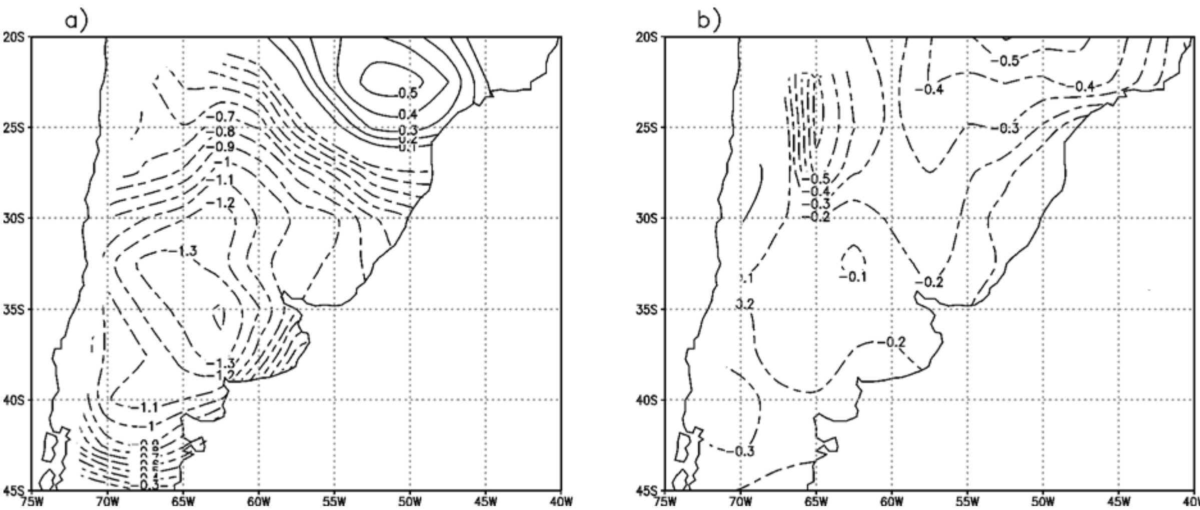

Fig. 2. (**a**) Surface temperature anomalies (°C) and (**b**) specific humidity (g kg^{-1}) at 850 hPa, for the anomalous cold winters (AC) composites. Positive (negative) contours are in full (dotted) line

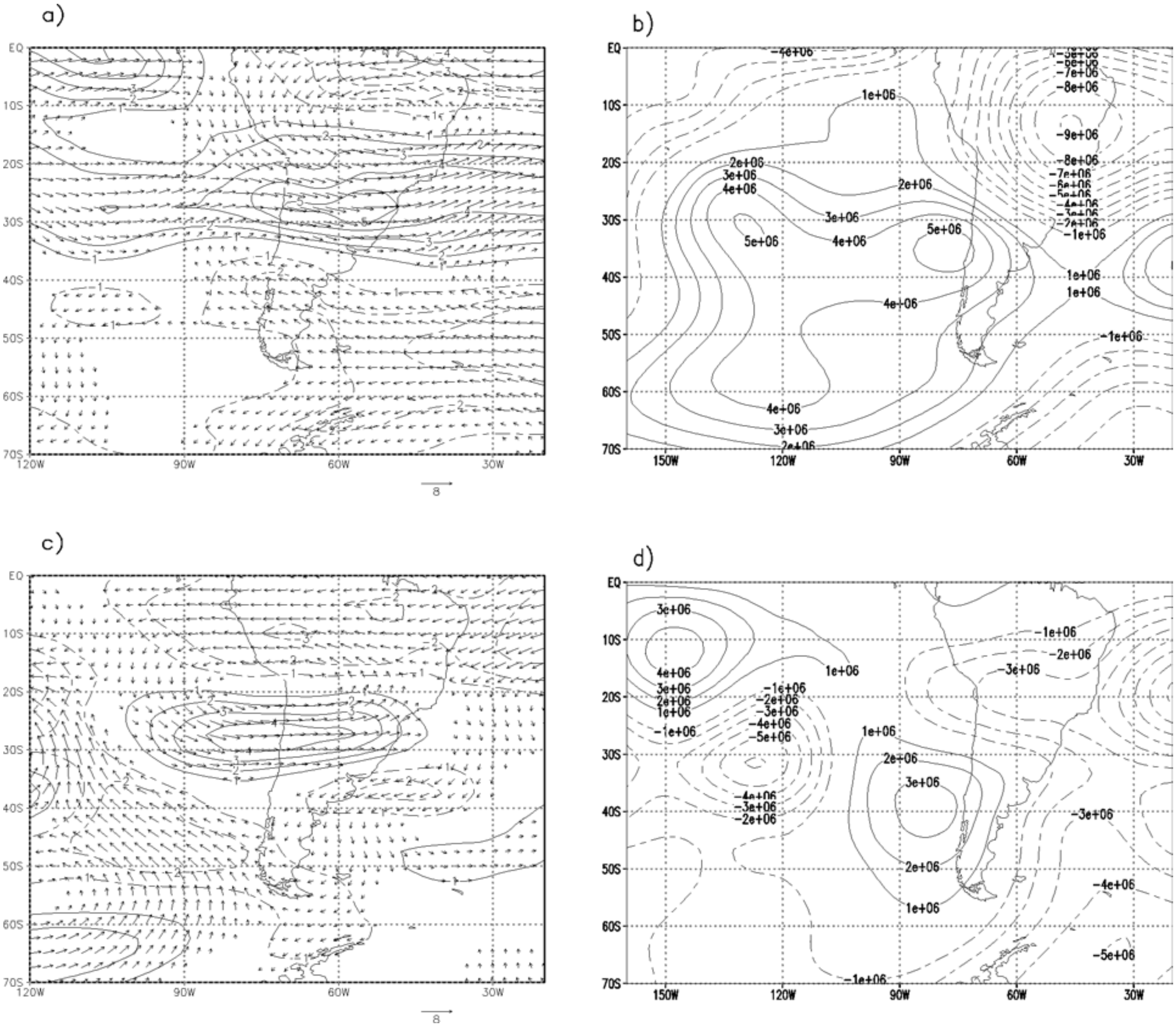

Fig. 3. (**a**) Zonal wind and wind vector anomalies ($m\,s^{-1}$) at 250 hPa, (**b**) stream function ($\times 10^{-6}\,m^2\,s^{-1}$) at 250 hPa, for the composites of anomalous cold winters (AC); (**c**) zonal wind and wind vector anomalies ($m\,s^{-1}$) at 250 hPa, and (**d**) stream function ($g\,kg^{-1}$) at 250 hPa, for the composites of winters with generalized frosts above average ($+\sigma$). Positive (negative) contours are in full (dotted) line

Comparing the $+\sigma$ fields with those obtained for the composites of anomalous cold (AC) winters, some differences appear. In particular, in the region under study, the anomalies of the temperature fields (Fig. 2a) and the humidity fields (Fig. 2b) for the case of AC are smaller. If we analyze the upper-level fields, it is interesting to note that the maximum wind anomaly at 250 hPa for AC composites is in the north–northeastern part of Argentina and in southern Brazil (Fig. 3a), precisely at the interphase of an intense anticyclonic anomaly towards the north over the continent and a cyclonic anomaly in the south extending over the Pacific (Fig. 3b). This situation is contrary to the configuration observed for the $+\sigma$ winters where the maximum wind occurs in the west of the continent, to the north of Chile and Argentina (Fig. 3c). Figure 3d shows that the maximum pressure gradient is located at this latitude with a cyclonic anomaly over the southwest of the continent and an anticyclone to the north-northeast. These maximum winds correspond to the subtropical jet over South America which reaches its extreme to the north, at approximately 26.8° S, during the winter months (Antico and Berri, 1999).

The anomalies observed in the jet for both $+\sigma$ and AC may be related to the tropical Pacific Sea Surface Temperature (SST) anomalies. Grimm and Silva Dias (1995) suggested the existence of a link between SST in the eastern region of the tropical Pacific and an upper-level circulation anomaly which affects the jet. During a warm ENSO phase, Karoly (1989) found a global scale zonal wind pattern at 200 hPa associated with the intensification of the subtropical jet. An anomalous warming in the tropical ocean can intensify the convection and therefore the Hadley cell. The hypothesis of an anomalous meridional direct circulation in the east Pacific which affects the subtropical jet over South America during the EI Niño and La Niña events has already been proposed by Ropelewski and Halpert (1987 and 1989) and Souza and Ambrizzi (2002), among others.

Mean meridional Hadley-type circulation is responsible for the transport of momentum from the Equatorial latitudes to the subtropics, causing an increase in zonal wind at the level of the subtropical jet over South America (Fig. 3a). In this case the composite of AC winters shows a positive SST anomaly in the EI Niño $1+2$ zone (Fig. 4a). The existence of a connection between the positive $1+2$ EI Niño index and the intensification of the subtropical jet over South America was shown by Antico and Berri (1999). This result seems to be in agreement with that shown here.

On the other hand, an intensified subtropical jet was also observed in $+\sigma$ winters (Fig. 3c) although smaller than in the AC (Fig. 3a). This does not correspond, however, to a warming of the tropical Pacific; on the contrary, a cooling was observed in the SST composites for $+\sigma$ (Fig. 4b). This will weaken the Hadley cell and consequently the subtropical jet. Therefore, another mechanism could be responsible for the positive wind anomaly observed in $+\sigma$ composites. A review of the literature identifies other mechanisms which could affect the subtropical jet (e.g. Berbery and Nogues-Peagle, 1993; Vincent et al., 1997). Recently, Antico and Berri (2003) proposed an alternative mechanism for the intensification of the subtropical jet in South America: the excitation of Rossby waves caused by the differential warming of the western tropical Pacific. The large scale stationary wave can propagate along the Pacific Ocean up to the subtropical region to the east of South America. According to this study, the configuration of the

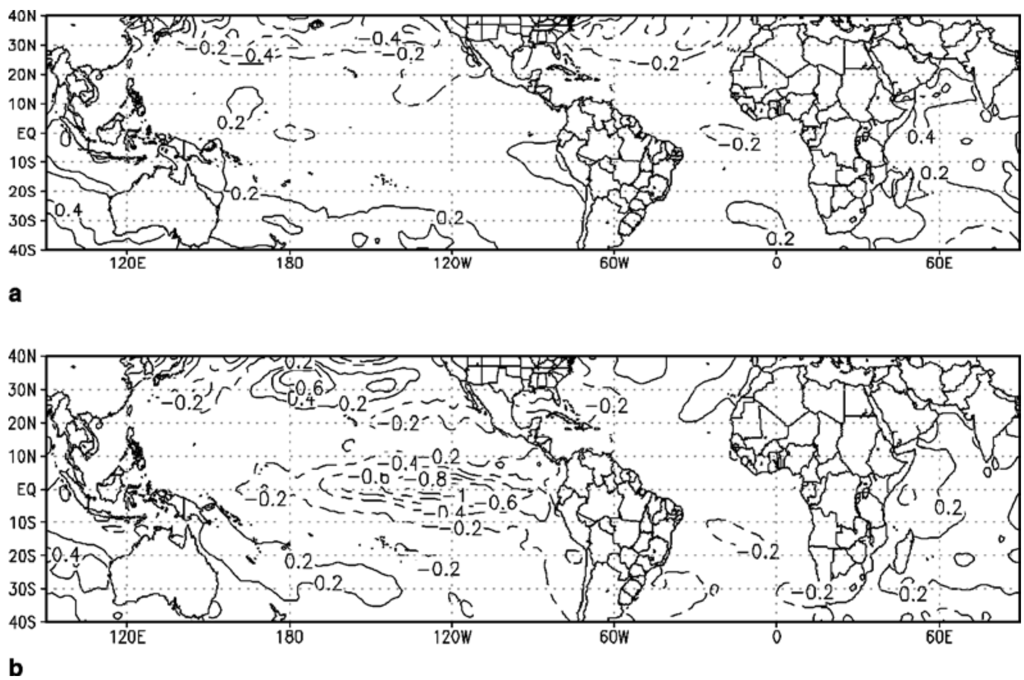

Fig. 4. Sea surface temperature anomalies (°C) for (**a**) composites of anomalous cold winters (AC) and (**b**) the winter composites for generalized frosts above average ($+\sigma$). Positive (negative) contours are in full (dotted) line

anomaly pattern generates a pressure gradient that strengthens the western circulation in the region of the jet.

The interaction between tropical convection and global circulation may occur through the dispersion of the extratropical Rossby waves, which

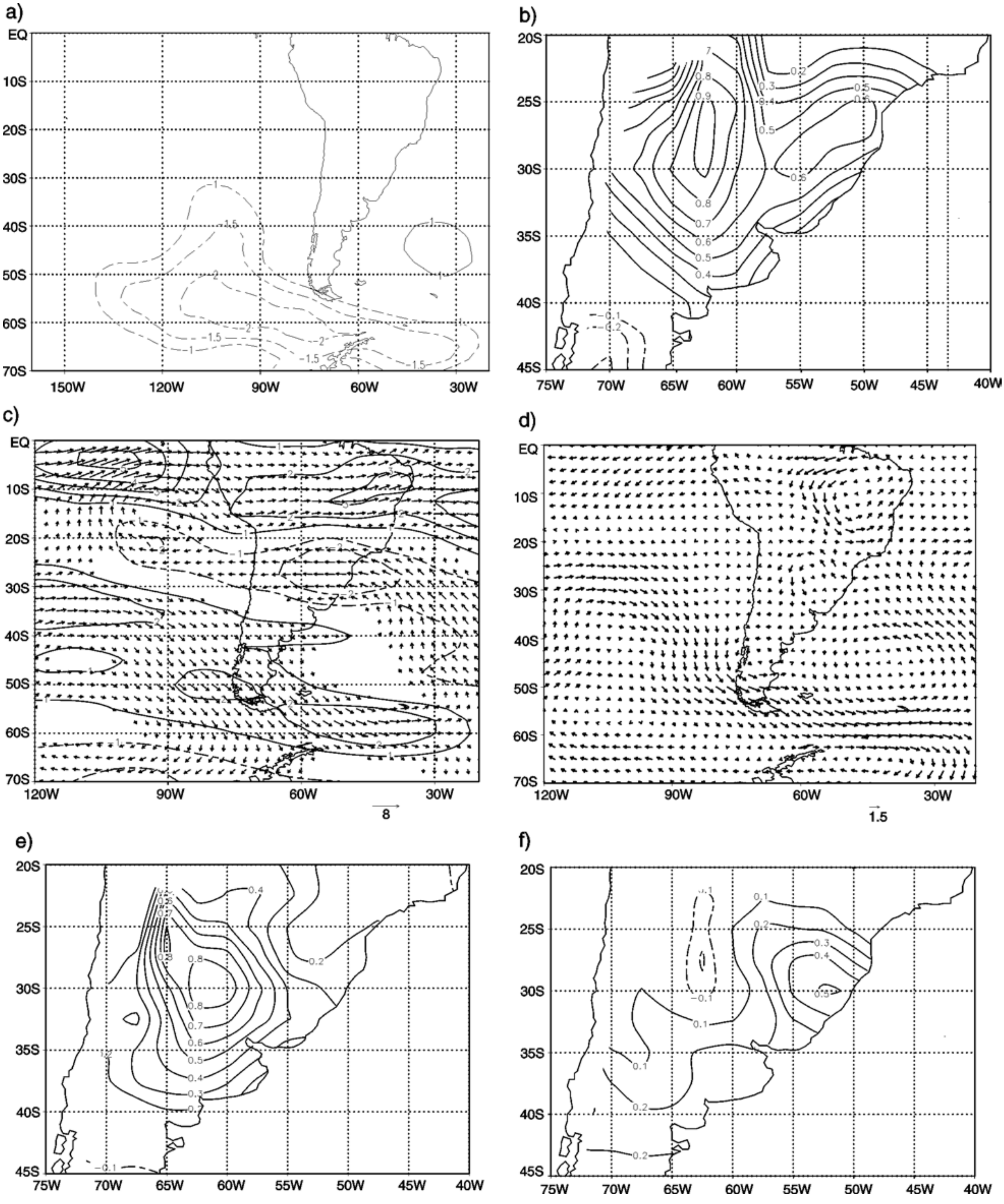

Fig. 5. Anomalies of (**a**) sea level pressure (hPa), (**b**) surface temperature (°C), (**c**) zonal wind and wind vector ($m\,s^{-1}$) at 250 hPa, (**d**) vector wind anomalies ($m\,s^{-1}$) at 850 hPa, (**e**) specific humidity ($g\,kg^{-1}$) at 850 hPa, for the composites winters with generalized frosts below average ($-\sigma$); anomalies of (**f**) specific humidity anomalies ($g\,kg^{-1}$) at 850 hPa, for the composites of anomalous warm winters (AW). Positive (negative) contours are in full (dotted) line

move towards the Equator. On the other hand, wave propagation essentially depends on the structure of the basic state and the source of heat (Ambrizzi et al., 1995). With a basic state formed by the $+\sigma$ winters, Müller et al. (2003b) showed the tropical-extratropical interaction through a numerical study. According to them, the differential warming observed in the western tropical Pacific acts as a Rossby wavemaker, which propagate to the South American continent. As a result, the anomalies in the fields of stream function, shown in Fig. 3d, are the result of Rossby wave action, generating a pressure gradient that intensifies the subtropical jet in South America (Fig. 3c).

3.1.2 $-\sigma$ winters

The surface field in Fig. 5a shows the prevalence of a negative pressure anomaly in southwest South America, blocking the flow towards the continent. Physically consistent with what has been said about the $+\sigma$ group, these anomalies indicate a lower than normal recurrence of cold migratory anticyclones in the region, which agrees with the smaller number of frosts in the Wet Pampas. This explains the high temperatures observed in Argentina during these winters and even the absence of generalized frosts in the Wet Pampas during 1973 and 1986 (see Table 1). This evidence is corroborated by the composites of temperature anomaly fields for $-\sigma$ winters with a prevalence of positive anomalies in the whole central and northern part of the country (Fig. 5b).

The wind composites in Fig. 5c show the weakening of the subtropical jet around 25° S. This pattern favors the occurrence of positive temperature anomalies in the Wet Pampas as this allows a quick passage of frontal systems to the north of 30° S and the re-establishment of the circulation with a northern component over most of Argentina (Fig. 5d). This explains the high humidity values observed in the north and central parts of the country (Fig. 5e).

Comparing these results with those obtained for the warm anomalous (AW) winters, differences appear mainly in the values of the anomalies rather than the configuration of the fields, as occurred in the AC winters. The temperature and humidity fields for AW show anomalies of the same sign but much less intense than in $-\sigma$. The example is given for the composite of the humidity field (Fig. 5f) indicating small negative values in the Wet Pampas region. The AW composites also show a weak subtropical jet (figure not shown) similar to $-\sigma$ winters (Fig. 5c).

3.2 Monthly composites

In the monthly composites from May to September, June is the only month presenting a below average number of frosts following the criterion used (see item 2). The years which form the composite for the different months, are not necessarily the same (see Table 1) and so the circulation anomaly fields may differ. August is a good example of this. The surface pressure field configuration obtained for this month shows an important cyclonic anomaly located to the south–east of the continent and an anticyclone in the south Pacific, which is much more intense than that observed in Fig. 1a for JJA. This configuration affects the south and the coast of Argentina (Fig. 6a). As Fig. 6b suggests, this situation generates a flow from the southwest to 40° S approximately. The circulation anomaly and low temperatures over the whole of Argentina (Fig. 6c) characterize a synoptic condition which favors frosts in the Wet Pampas. This configuration may be associated with to the most frequent frost pattern in the Pampas region following Müller et al. (2003a) synoptic-climatic classification. This is represented by the presence of cyclonic circulation towards the south of the continent and anticyclonic to the north of 40° S, favoring subsidence conditions, weak surface winds, low humidity and clear skies, all of which cause nocturnal radiative cooling.

Surface circulation in July is basically represented by the same structure as that obtained for the $+\sigma$ seasonal composite (see Fig. 1a). In this case the positive pressure anomaly is more intense, affecting the northeast of Argentina and southeast of Brazil (Fig. 6d). This configuration is represented by the pattern of the 4^{th} PC in the classification of Müller et al. (2003a) and corresponds to an anticyclone which favors radiative loss in its region of influence. Frost formation, in this case, is favored by the anticyclonic anomaly in the southwest of the continent, mentioned previously in the $+\sigma$ composites once a succession of anticyclones in the same region enhances frost formation.

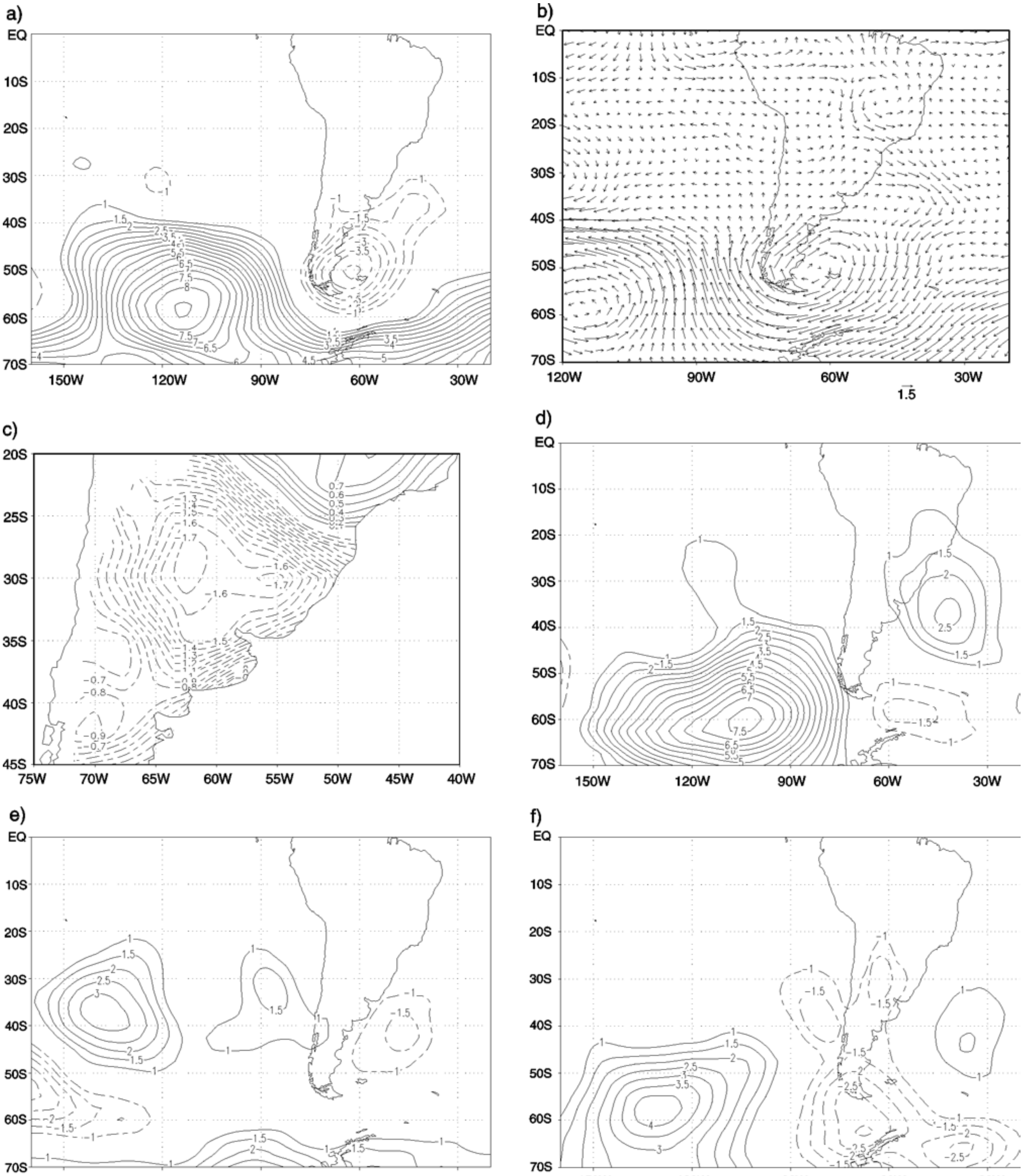

Fig. 6. Anomalies of (**a**) sea level pressure anomalies (hPa), (**b**) wind vector at 850 hPa (m s^{-1}), (**c**) surface temperature (°C), for the August composites; and anomalies of sea level pressure (hPa) for (**d**) the July composites; and the above (**e**) and (**f**) below average June composites. Positive (negative) contours are in full (dotted) line

A surface pressure field, similar to the one described for August, is seen in the May, June and September composites, with some changes in anomaly position and intensity. For instance, June is the month with the lowest values. In this case, the cyclonic surface anomaly is southeast of the Argentine coast while the anticyclonic anomaly is near the continent in the east Pacific (Fig. 6e). This pattern coincides with the 3rd PC, according to the decreasing order of explained variance in the classification of synoptic events causing frosts in the Wet Pampas (Müller et al., 2003a).

The only month that presented below average frost occurrence was June, and its composite shows a cyclonic anomaly dominating most of Argentina (Fig. 6f). This feature is different to the one obtained for the $-\sigma$ winters which only occupies the south of the continent and spreads to the east Pacific (Fig. 5a). The prevalence of this configuration does not favor surface temperature drops which explains the absence of generalized frosts during the years of the June composites (Table 1).

The analyses of upper-level maximum zonal winds over the continent show that the results for monthly composites are similar to the seasonal composites, with an intensification (weakening) in the case of frost above (below) average. This is evident in the June composites (Fig. 7a and b respectively). There is, however, a change in the position of the core maximum associated with the subtropical jet with respect to the JJA composites. For July in particular (Fig. 7c), a shift of the jet core is observed towards the east of the continent due to an anticyclonic anomaly in the mass field in southeast Brazil (Figure not shown). This maximum appears strengthened in the June composites and is located further east than the JJA average position, over northeast Argentina and southern Brazil (Fig. 7a). These results were also obtained

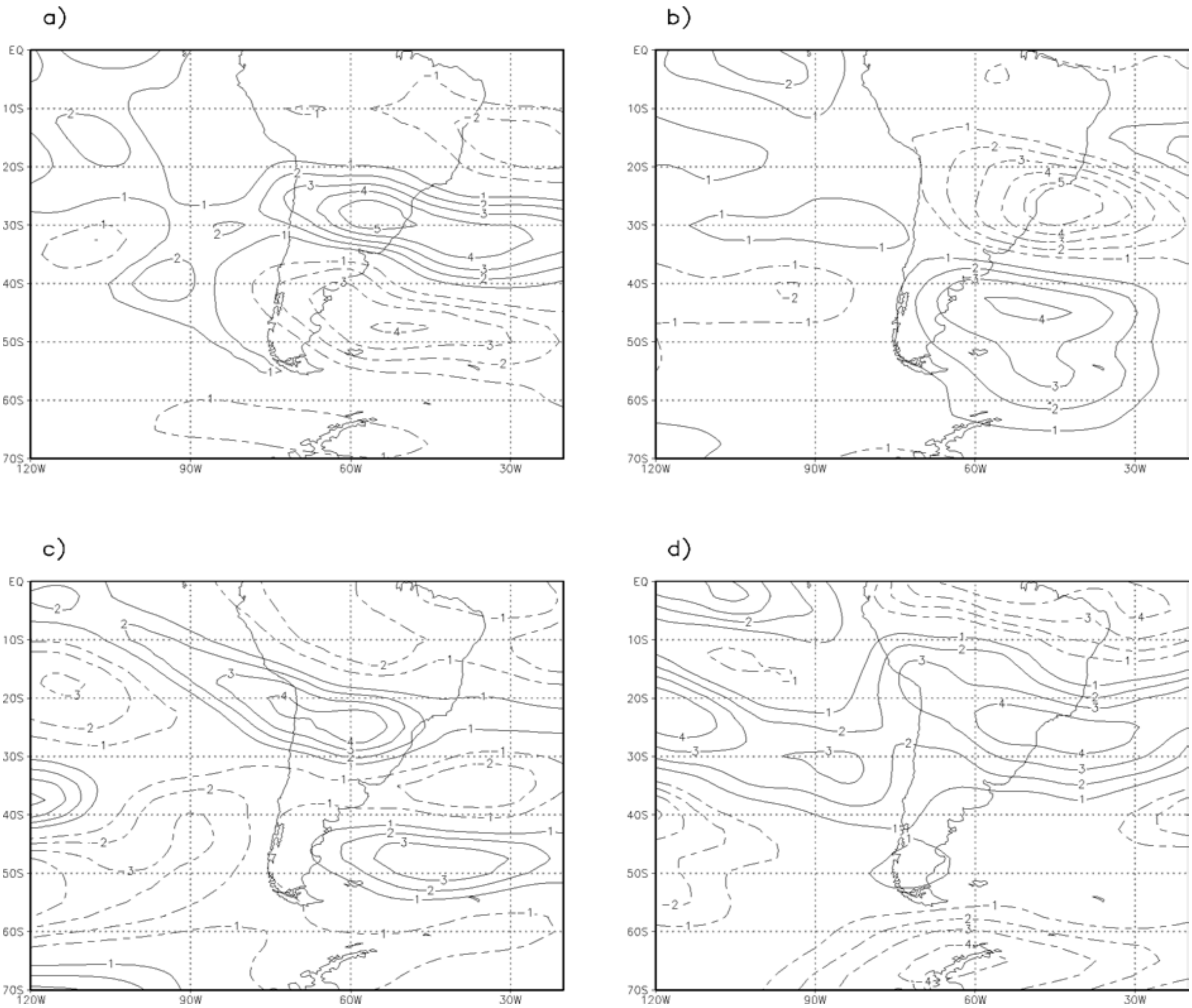

Fig. 7. Zonal wind anomalies ($m\,s^{-1}$) at 250 hPa for the months of June (**a**) above and (**b**) below average; and (**c**) above average for July (**c**) and (**d**) August. Positive (negative) contours are in full (dotted) line

by Antico and Berri (1999) who showed an increase in the mean intensity of the subtropical jet over South America in June compared to July. The composites of the years with frosts above average in August show a large positive zonal wind anomaly which extends along the Pacific with one of its main cores to the east of the continent over southern Brazil (Fig. 7d).

3.3 Daily composites

Large scale circulation at lower and upper levels over the south of South America, during generalized frosts, shows a characteristic mid-latitude wave. A ridge is located to the west of the continent over the Pacific Ocean, and a trough along the Atlantic coast extends from subtropical latitudes to the south (Fig. 8, left). The wave is amplified before and during the mature stage of the cold surge (Fig. 8b–d). The NW–SE direction of the ridge and trough axes is characteristic of transient extratropical waves when they move leeward from the Andes (Gan and Rao, 1994; Berbery and Vera, 1996; Seluchi et al., 1998; Vera et al., 2002). Such a configuration produces

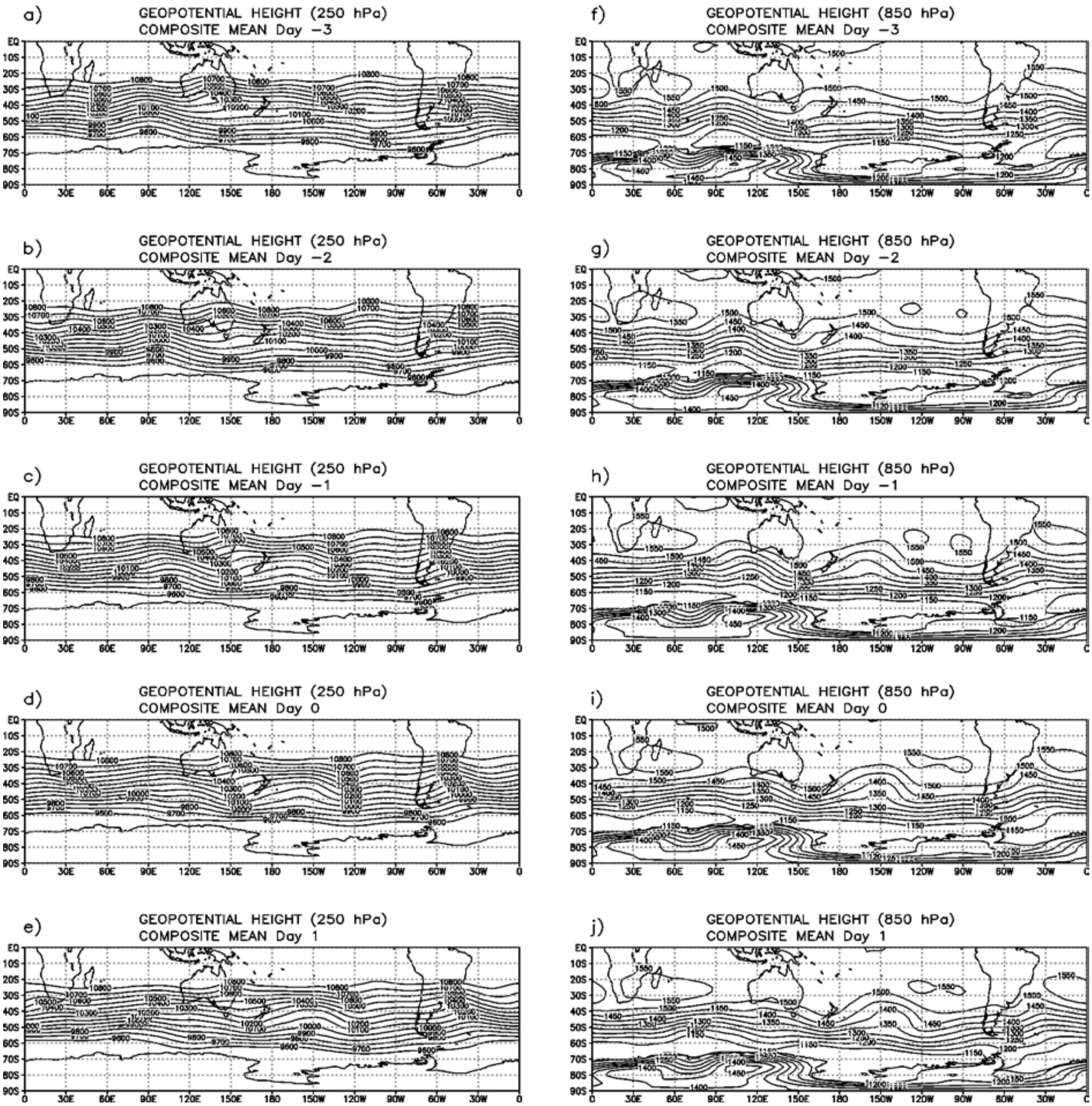

Fig. 8. Composites of mean geopotential height fields from day -3 to day 1 at 250 hPa (**a–e**) and 850 hPa (**f–j**). The contour intervals is 100 m at 250 hPa and 25 m at 850 hPa

strong anticyclonic vorticity advection to the east of the Andes between 30° S and 40° S (Garreaud, 2000), latitudes that include the Wet Pampas region. In addition, the amplification of a trough to the east of 180° W is impressive at lower levels (Fig. 8, right). Krishnamurti et al. (1999) showed that a downstream amplification mechanism of waves propagating along the Pacific on days prior to the event, could be a precursor of the stronger frosts in southeast Brazil. It manifests itself by ridges and troughs that propagate to the east. In an analysis of these events, they suggested that the growth of long stationary waves may be due to scale interaction between the components of the wave.

The temporal evolution of geopotential height anomaly fields at 250 hPa and 850 hPa, associated with generalized frost episodes, is shown

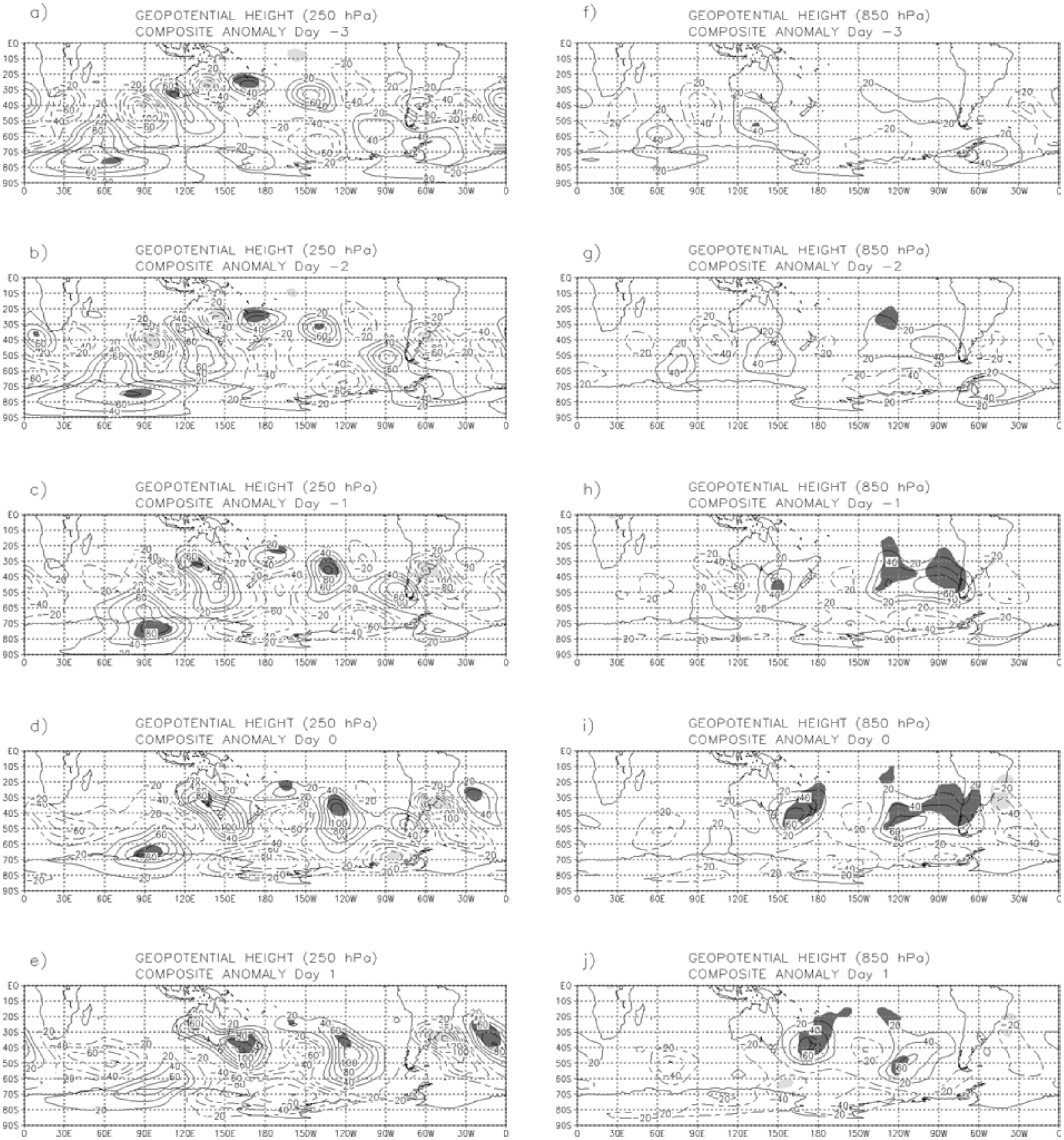

Fig. 9. Composites of the geopotential height fields anomaly from day -3 to day 1 at 250 hPa (**a–e**) and 850 hPa (**f–j**). Positive (negative) contours are in full (dotted) line at 20 m intervals. The shaded areas are significant at the 99% level according to the Student's t-test

in Fig. 9. At upper levels, the anomalies over southern South America show wave propagation towards the Equator three days before the event (Fig. 9a–d) with a progressive deepening and intensification of a significant negative anomaly followed by a positive anomaly to the southwest of the continent. The position of both vortices determines the leading movement observed at low levels, where a positive anomaly associated with an anticyclone from day 2 starts to penetrate through the high latitudes of South America at the lowest part of the Andes (Fig. 9g–h). Then, the rapid propagation leeward of the Andes is caused by the effect this has on the systems (Marengo, 1997; Garreaud, 2000; Seluchi and Marengo, 2000). On day 0 (Fig. 9i), the anomaly has spread over the whole country. Vera and Vigliarolo (2000) showed that the intensification of the leeward anticyclonic disturbance is produced by a strong meridional ageostrophic circulation on the polar side of the frontal surface which accompanies the advection of cold air which affect South America. These authors also observed a cyclonic disturbance entering the east of the continent from subpolar latitudes. Figure 9, on the right, shows a negative anomaly located to the east of the positive anomaly over the South Atlantic 2 days prior to the event, intensifying towards day 0 which is statistically significant at the 99% level. In this way, the cold air advection coming from the south, due to the surface anticyclone, is reinforced by this cyclonic anomaly and together they cause an extensive cooling over the region. The type of configuration described here is one of the most frequent patterns responsible for frosts in the Wet Pampas, according to Müller et al. (2003a) climatic-synoptic classification, representing their 2^{nd} and 3^{rd} PCs.

An analysis of the wind field (Fig. 10) shows how the NW–SE orientation of the ridge-trough situation causes advection with the southern component in the whole region up to 25° S where the winds turn to the east in the jet entrance region over the subtropical part of the continent. If the zonal wind components are analyzed separately, it can be seen that the anomaly associated to the subtropical jet is very intense and significant, which agrees with the studies of cold air outbreaks in South America (Garreaud 1999, 2000; Vera and Vigliarolo, 2000; Marengo et al., 2002). The maximum located in the central-eastern part of Argentina on day -2 is associated with the strong gradient between the anticyclonic anomaly in the extreme southwest of the country and the cyclonic anomaly to the north (Fig. 9b). Two days later, the jet core becomes more intense as the system advances to the east (Fig. 10b) and is located over the Atlantic on the day after the event (figure not shown).

The same figure also shows a positive zonal wind anomaly in the south-southwestern region

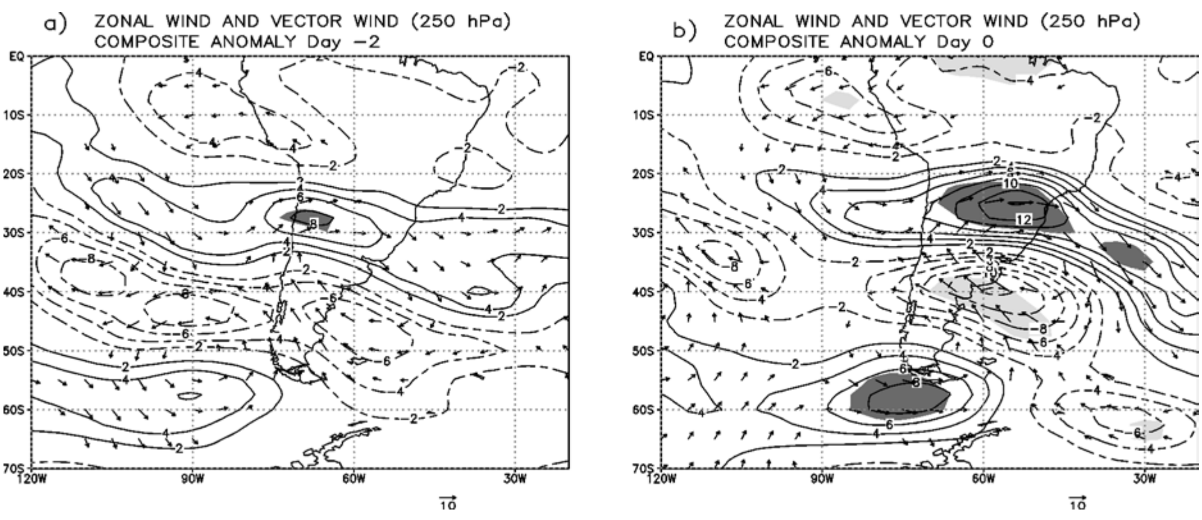

Fig. 10. Composite of wind vector and zonal wind anomaly fields at 250 hPa for day -2 (**a**) and 0 (**b**). Positive (negative) contours are in full (dotted) line at 2 m s^{-1} intervals. The shaded area is significant at the 99% level according to the Student's t-test

of South America which could be associated with the subpolar jet. In the Southern Hemisphere, the main wave activity occurs along the subtropical and Polar jets which act as a wave guide (Ambrizzi et al., 1995; Ambrizzi and Hoskins, 1997). During the southern winter, the synoptic scale waves spread over the South Pacific along two main paths: the subpolar and the subtropical jets (Berbery and Vera, 1996). This behavior is clearly observed in the days before the event (Fig. 11, left). When the waves come closer to the Andes they lengthen meridionally and form an arc with a NW–SE orientation (Fig. 11c), shifting progressively towards the north-east, leeward to the Andes where the positive anomaly reaches more than 12 m/s (Fig. 11d), which

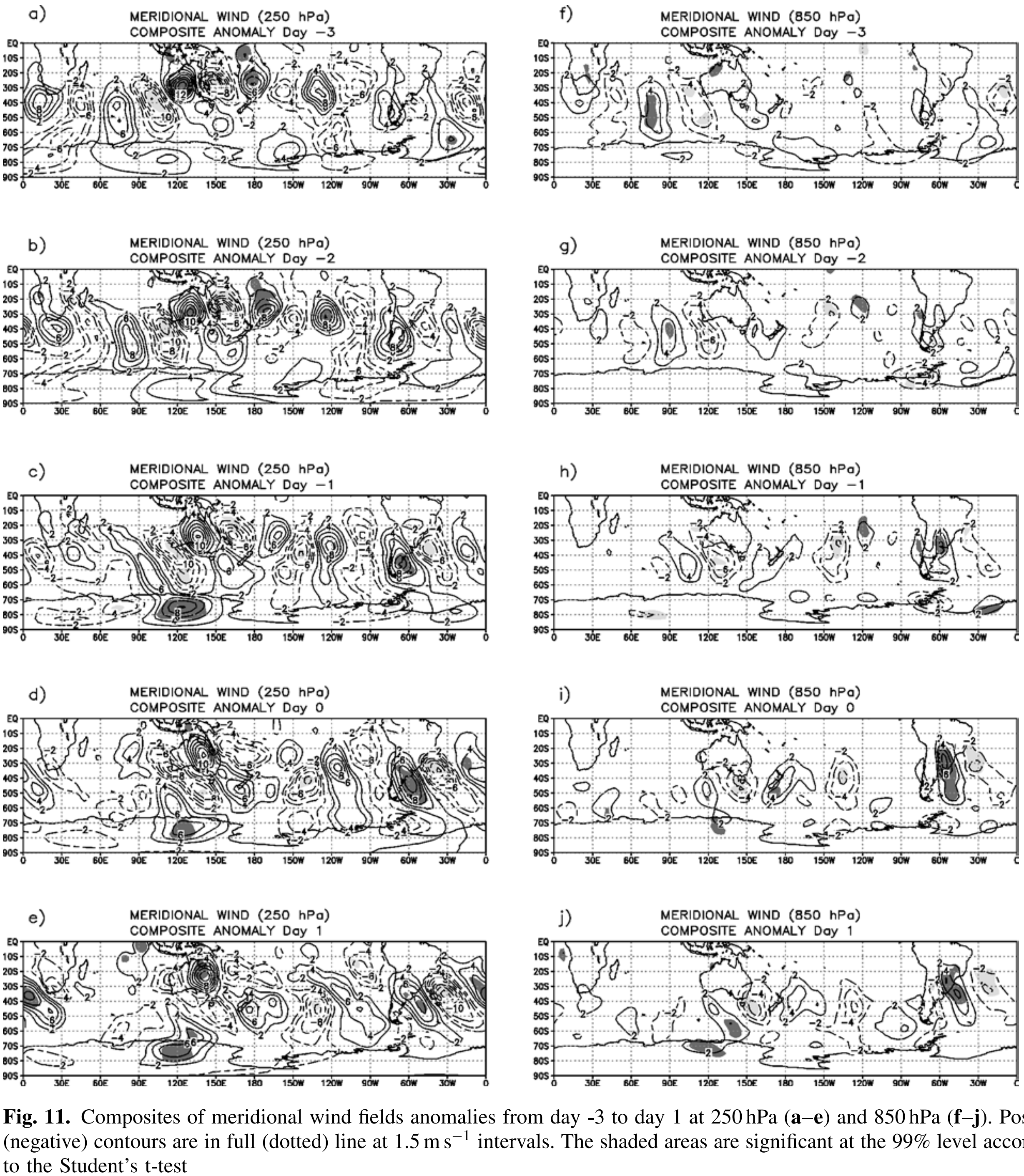

Fig. 11. Composites of meridional wind fields anomalies from day -3 to day 1 at 250 hPa (**a–e**) and 850 hPa (**f–j**). Positive (negative) contours are in full (dotted) line at 1.5 m s^{-1} intervals. The shaded areas are significant at the 99% level according to the Student's t-test

agrees with other studies (Berbery and Vera, 1996; Vera and Vigliarolo, 2000). Once the waves have crossed the Andes, they spread towards the north developing in a way which is consistent with the concept of Rossby wave dispersion on a sphere (Hsu, 1987). Comparing the surface meridional wind (on the right) with the upper levels (on the left, Fig. 11) the typical structure of a synoptic scale wave can be seen with a significant meridional wind anomaly which reaches its peak at upper levels and leans towards the south-west with height. On the surface, the train of shorter waves appears less intense and organized than at upper levels except on days 0 and 1 when there is a strong flow towards the Equator, leeward of the Andes, even reaching subtropical latitudes, with a 99% significance level.

4. Conclusions

The analysis of atmospheric field composites of generalized frost periods with an extreme occurrence frequency indicate that these episodes are related to large scale patterns characterized by well-defined wind and pressure fields.

The anomalous anticyclonic circulation observed in the composites of periods with a number of frost episodes above the average ($+\sigma$), suggests a greater anticyclonic activity allowing the entrance of cold air into the South American continent. The prevalence of this situation explains the low temperatures identified during the winters with a maximum number of generalized frosts. A similar configuration is observed in the composites for July, where a strong positive anomaly located to the north-east of Argentina and south of Brazil is observed. In the May, June and September composites, a cyclonic anomaly over south-east Argentina is coupled with the positive anomaly in the east Pacific. The mean surface fields obtained from the monthly composites were able to reproduce the most frequent situations which result in frosts in the Wet Pampas. According to the Müller et al. (2003a) synoptic-climatic classification, there are six patterns which explain 94% of the variance and therefore represent the most frequent synoptic conditions responsible for frosts in the area under study. The first four patterns have been linked to generalized frosts according to the results of the composites for each of the months analyzed.

The surface circulation observed for the winter composites with a number of events below average ($-\sigma$), reflects a decrease in the passage of anticyclones on the continent. The opposite pattern between the two groups, $+\sigma$ and $-\sigma$, was observed in all the variables analyzed. The positive values in surface temperature anomalies and in the humidity field are characteristic of the $-\sigma$ winter composites, responding to the prevalence of the northern flow showed in the low level wind anomaly field which affects the whole of the Wet Pampas region. For the monthly analysis, the prevalent surface situation corresponds to a negative pressure anomaly affecting the extreme south of the continent, explaining the absence of generalized frosts during the period.

To determine whether the winter circulation anomalies correspond to situations which favor extreme generalized frosts or are simply characteristic of colder or warmer years, the results obtained for the $+\sigma$ and $-\sigma$ winters were compared with a group of unusually cold and warm years (AC and AW), respectively. All the years having higher (smaller) number of generalized frosts in the Wet Pampas correspond to winters which were extremely cold (warm) in central Argentina. This implies that, even though these years had anomalous temperatures, there are features of the atmospheric circulation which favor or inhibit conditions of extensive frosts in the Pampas, causing an extreme occurrence of such events.

The results presented here show differences between the $+\sigma$ winter composites and those obtained for AC winters and between the $-\sigma$ winter composites and those of AW winters. Differences in the humidity and temperature fields in particular, are associated with the circulation in each case, characterized by a similar structure in the groups compared, but with differences in the anomaly values. The intense positive anomaly in the pressure field located to the south-west of the continent for $+\sigma$ composites, is considerably greater than in AC. The upper-level field is also different in the two pressure fields. The major consequence can be seen in the subtropical jet in South America. Although both the $+\sigma$ winter composites and the AC present an intensification of the subtropical jet over South America, the mechanism causing this anomaly could be different in each case. During the AC winters the intensification of the Hadley cell due to a warming in the east of the tropical Pacific may be the most important contributor, while in the $+\sigma$ a differential warming in the west tropical Pacific can act as a Rossby wavemaker, which propagates beyond the tropics. Thus, the mass field configuration may result in an increased pressure gradient and a more intense subtropical jet in South America. These results support Müller et al.'s (2003b) hypothesis that a teleconnection mechanism would be the precursor of generalized frosts in the Wet Pampas.

Both the AW and the $-\sigma$ winters have a negative wind anomaly in the South American subtropical jet region, indicating a prevalence of flow from the east. The weakening of the jet during the winter may suggest some dynamic process changes in the maintenance of the jet and which could be associated with the reduction of extensive frosts in southern South America or even a complete absence during some winters, as occurred in 1973 and 1986.

The monthly composites of the subtropical jet in South America show similar results as the seasonal composites, with an intensification (weakening) in the case of frosts above (below) average and some changes in position and intensity of the anomalies during the months.

The analysis of daily composites of generalized frosts which occurred during the winters with events above average, shows a large-amplitude trough in middle latitudes which extends over the continent towards the tropical regions and a progressive amplification from another trough located in the Pacific to the east of 180° W. Ahead of this trough, the associated geopotential field positive anomaly presents statistically significant values (99% level) from days prior to and even after the event. A significant upper-level cyclonic disturbance to the east of the Andes at subtropical latitudes can be seen on days preceding event. At the surface there is a progressive deepening of a significant cyclonic anomaly located over the Atlantic. This extends towards South America from subpolar latitudes together with an anticyclonic anomaly which enters from the south-west of the southern cone. Both cause the prevalence of cold air advection from the south which causes generalized frosts.

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