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Influence of the intraseasonal variability on heat waves in subtropical South America

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Abstract The influence of the intraseasonal variability on heat wave development over subtropical South America during austral summer is analyzed. The role of the South Atlantic Convergence Zone (SACZ) on this development is documented. Results show that intraseasonal variability can explain on average at least 32% of summer temperature variance. Moreover, 73% of the heat waves in subtropical South America develop in association with an active SACZ. The analysis of pentad maps shows that warm conditions in the region under study develop in association with the strengthening of an anticyclonic anomaly, which is discernible over the subtropical regions at least 15 days before temperature peak occurrence. That circulation anomaly is embedded in a large-scale Rossby wave train extending along the South Pacific Ocean that is linked to convection anomalies at the equatorial western and central Pacific Ocean. In addition, the development of the anticyclonic circulation over subtropical South America appears to be strengthened by the subsidence conditions promoted by the active SACZ, which result in temperature rise in the subtropical region under relatively dry conditions. On the other hand, during the last 2 days of evolution, SACZ activity weakens and the progressive temperature rise in the region is dominated by warmer and moister air being anomalously advected from the north. Results confirm the important role that SACZ activity on intraseasonal time scales has in inducing persistent circulation anomalies at the subtropical regions that can result in the development of persistent heat waves, and very extreme daily temperature.

Keywords Intraseasonal variability · South America · Temperature · Heat waves · SACZ · Warm season

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1 Introduction

The analysis and prediction of warm temperature extremes is of major relevance since these events strongly affect human activity. Meteorological events in which air temperature is above a given threshold for more than 24 h, and sometimes associated with high moisture levels, are usually referred as heat waves (Lyon and Dole 1995; Rusticucci and Vargas 1995; Robinson 2001 among others). Katz and Brown (1992) demonstrated that heat wave frequency is relatively more dependent on any changes in the variability than in the mean. The occurrence of heat waves over subtropical South America has been generally related to the activity of synoptic-scale waves. Previous studies (e.g., Rusticucci and Vargas 1995; Campetella and Rusticucci 1998) and Alessandro and de Garín 2003 show that during heat wave events, northerly winds are present over the region encompassed by the eastern portions of Argentina and Paraguay, southern Brazil and Uruguay. Northerlies are promoted by the equatorward progression of a frontal system from higher latitudes along the region that contributes to temperature rises up to extreme values, mainly through advective processes (Rusticucci and Vargas 1995).

There is observational evidence, however, that positive temperature anomalies in subtropical regions may persist for periods longer than synoptic scale (e.g., Rusticucci 1995; Campetella and Rusticucci 1998; Norte et al. 2000). Recently, Cerne et al. (2007) studied the processes associated with a persistent heat wave that took place over southeastern South America during the summer 2002–2003, and found that the South Atlantic Convergence Zone (SACZ) had a significant influence on the evolution of the heat wave. During weeks preceding the development of the heat wave, an intensified SACZ was evident over tropical South America, which promoted temperature increase at the subtropics mainly through subsidence and diabatic processes. The latter are related to sensible heat transfer due to absorption of solar energy at the surface. Seluchi et al. (2006) performed numerical simulations, and confirmed that such processes were dominant during the beginning of that particular heat wave event, which was also associated to orographic forced subsidence over western central Argentina. On the other hand, by the end of the event when temperature over the region achieves its maximum values, SACZ related warming processes weakened, and horizontal temperature advection associated with the evolution of a middle-latitude synoptic wave, dominated. In addition, Schneider et al. (2006) suggested that the warm and drought environment that characterized the austral summers between 2003 and 2005 were reinforced by the influence of the semi-annual oscillation.

Previous studies (Vera et al. 2006 and references therein) reveal that regional circulation may exhibit considerable variability at intraseasonal scales (20–70 days). In particular, Nogués-Paegle and Mo (1997) show that the leading pattern of outgoing longwave radiation (OLR) anomaly variability at intraseasonal timescales is associated with a dipole-like pattern, with one of the centers located over the SACZ climatological position region and the second one of opposite sign located over the subtropical plains in southeastern South America. The dipole pattern activity has been associated with Rossby wave trains extending along the South Pacific between Australia and South America. In addition, Liebmann et al. (2004) showed that the activity of such dipole pattern influences the occurrence of extreme rainfall episodes.

Earlier research focusing on other continental regions of the world identified the combined influence of regional and large-scale circulation anomalies as relevant on heat wave occurrence. Lyon and Dole (1995) analyzed the role of remote and local circulation forcing in the development of the heat waves that occurred in the US in 1980 and 1988. They found that the initial stage of those extreme events was associated with a stationary wave that extended over the central Pacific while towards the event end, the remote effect weakened and local surface energy balance kept temperatures high. Lyvezey and Tinker (1996) and Palecki et al. (2001) arrived at similar conclusions when studying the 1995 and 1999 heat waves in the US. They observed the presence of a quasi-stationary ridge at the beginning of the event and an evapotranspiration rise in association with a temperature peak towards the heat wave end. In addition, the occurrence of a very intense heat wave in central-southern Europe in 2003 has been associated with a combined influence of both large-scale and local drivers. In particular, Wolter et al. (2005) associated the 2003 heat wave with the influence of an unusually active west African monsoon. Moreover, Cassou et al. (2005) indicated that such extreme heat wave was associated with atmospheric circulation patterns favored by anomalous tropical Atlantic heating related to wetter than-average conditions in both the Caribbean basin and the Sahel. Recently, Feudale and Shukla (2010a, b) showed that warm SST anomalies in the northern part of the North Atlantic Ocean, toward the Arctic Circle, affected the air temperature field at mid-high latitudes, leading to a reduction of the absolute value of the meridional gradient and a consequent decrease of the baroclinic activitiy in the European area. Also, it has been suggested that Indian Ocean Dipole events may play a role on the variability of air temperature over South America (Saji et al. 2005).

The objective of this paper is therefore to document the influence of intraseasonal variability over South America on the occurrence of extreme temperature events in subtropical regions. Special focus is given in determining to what extent the physical processes associated with the SACZ activity play a role in the development of heat waves.

The paper is organized as follows: Sect. 2 summarizes the datasets used and discussed the methodology to identify the heat wave events. Intraseasonal variability of surface temperature is discussed in Sect. 3. Dynamical processes associated with heat wave development are presented in Sect. 4, including a specific discussion about the heat waves associated with and without an active phase of the SACZ. Section 5 summarizes the results.

2 Data and methodology

The determination of the heat wave events as well as their associated features was made considering the time series of 12 UTC surface temperature data measured at Rosario Aero station (32°55′S, 60°47′W, 25 masl) of the Argentina Meteorological Service, as representative of the study region. Atmospheric circulation anomalies were described using the NCEP–NCAR reanalysis (Kalnay et al. 1996) for the period 1979–2003, with spatial resolution of 2.5° × 2.5°. Daily averages of OLR provided by the National Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith 1996) for the period 1979–2003 were also used as a proxy for summer convection.

Summer season was defined from December 1 to February 28 without considering leap years. Daily temperature anomalies (T') at Rosario Aero station were obtained subtracting from each individual value, the corresponding climatological daily mean and the difference between the seasonal mean for that particular year and the long-term seasonal mean, effectively removing in this way both, the annual cycle and the interannual variability. The standard deviation of T' was computed using all 35 summers. Heat wave episodes were selected as those fulfilling that: (1) T' was positive for at least 5 consecutive days and (2) T' was larger than its own standard deviation, for at least 3 days. In this sense, the criterion restricts the identification to those heat waves that are not only anomalously warm but also persistent on intraseasonal scales. The humidity effect was not included in the heat wave determination. However, humidity conditions in the region were analyzed for selected cases.

Forty two heat wave episodes were identified during the 1968–2003 period, with an average occurrence of 1.2 episodes per summer. This result indicates that variability on time scales longer than synoptic scales could be present on average in more than one heat wave per year.

3 Temperature intraseasonal variability

In order to describe the temperature intraseasonal variability, T' was filtered retaining variability in the 10–90 day band by means of both harmonic analysis and Lanczos filter (Duchon 1979). Both methods gave similar results, with a correlation coefficient of 0.93 between both filtered series, in agreement with, Jones et al. (1998) among others. Therefore, hereafter the filter based on harmonic analysis was used.

Figure 1 shows the standardized time series of T' in Rosario (determined as departures from the long-term summer mean and divided by the standard deviation) and their corresponding filtered anomalies for three individual summers. Besides the typical and expected synoptic-scale variability, T' also exhibits considerable modulation by the intraseasonal variability, mainly characterized by periods of consecutive days with daily temperature anomalies of the same sign. In particular that behavior is clearly evident in the summers of 1982/1983 (Fig. 1a) and 2002/2003 (Fig. 1b), in which intraseasonal variability explains 43.2 and 45.4% of the corresponding summer variance, respectively. In fact, both summers are the only ones in the whole period in which intraseasonal variability explains a larger variance percentage than that associated with synoptic scales. On the other hand, the smallest intraseasonal variability contribution to variance was found for the summer 1975/1976 (Fig 1c), being of 11.7%. On average, intraseasonal variability represents more than 32% of the summer variance. While in 63% of the summers, intraseasonal

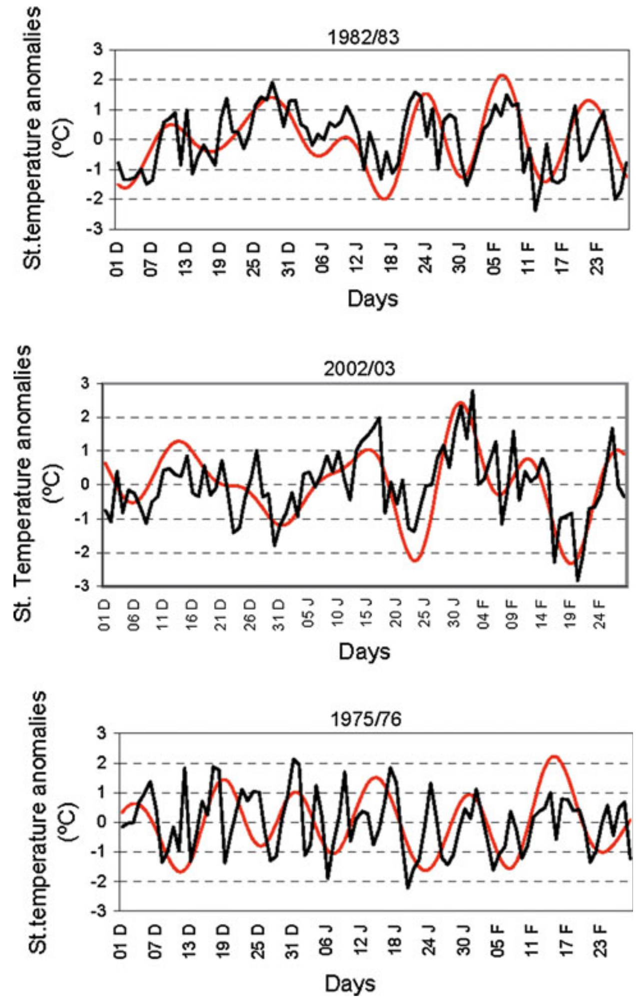

Fig. 1 Standardized time series of surface temperature anomalies in Rosario (°C) and their corresponding filtered anomalies (*red line*) for three individual summers

variability represents 30–40% of the variance; in 23% of them it explains 20–30%. Moreover, intraseasonal variability accounts for more than 40% of the variance in three individual summers, while its contribution is less than 20% for only two of the seasons.

The analysis of heat wave duration shows that the longest event took place in December 1982. That particular event was characterized by 20 consecutive days of positive T', with nine of them associated with values larger than one standard deviation and, being five of those days consecutive. In general, more than 50% of the heat wave events were associated with periods of at least 5 consecutive days with T' larger than one standard deviation.

The relationship between the occurrence of daily temperature extremes and the heat waves identified by means of the proposed criterion was particularly analyzed. It was found that 60% of the summer days with T' values larger than one standard deviation were associated with any of the identified heat wave events. Moreover, such events include at least 70% of the days associated with values larger than the 95th percentile.

The results described above then confirm the relevance of the intraseasonal variability influence on the occurrence and persistence of daily warm extremes over subtropical South America.

4 Dynamical processes associated with the heat waves

The spatial and temporal structure of the atmospheric circulation anomalies associated with the heat waves was analyzed for the period 1979–2003., in which 26 heat wave events were identified. Daily anomalies were determined for the variables under study, removing only the seasonal cycle defined by the corresponding daily climatological mean. Composite fields for pentads (5-day no-overlapping means) of OLR, geopotential height and temperature daily anomalies were constructed. For each heat wave, Pentad 0 is determined as the 5-day period ending on the day when T' peaks in the event. Previous and following Pentads are defined in relation to Pentad 0. In that sense, Pentad-1 is related to the 5-day period between 9 and 5 days before the daily warm extreme; Pentad-2 to that between 10 and 14 previous days, and Pentad-3 to that between 15 and 19 previous days.

4.1 OLR anomalies

Figure 2 shows the composite fields of OLR anomalies (OLR′) from Pentad-3 to Pentad 0. It is known that the use of OLR at mid-latitudes as proxy of convection is questionable. In that sense, the analysis and discussion of OLR′ fields depicted in this figure, as well as in similar figures of the next sections are restricted to tropical regions. Nevertheless, Gonzalez et al. (2008) shows that OLR is able to reproduce the main features of intraseasonal precipitation variability over subtropical South America. At Pentad -3, negative OLR′ values are observed along a band located over southeastern South America slightly north of the climatological position of the SACZ, and over the western portion of Argentina (Fig. 2a). On Pentad-2 (Fig. 2b), negative anomalies become stronger over the center of the subtropical continental region while they progress northeastwards on Pentad-1 (Fig. 2c). At Pentad 0 (Fig. 2d), a well organized band of negative values is observed over southeastern Brazil, while an area of positive anomalies over central-eastern Argentina is also discernible at Pentad 0. The presence of an active SACZ in association with the occurrence of heat waves at the subtropical areas of South America, agrees with the results obtained by Cerne et al. (2007). In that sense, the role of SACZ dynamics on the

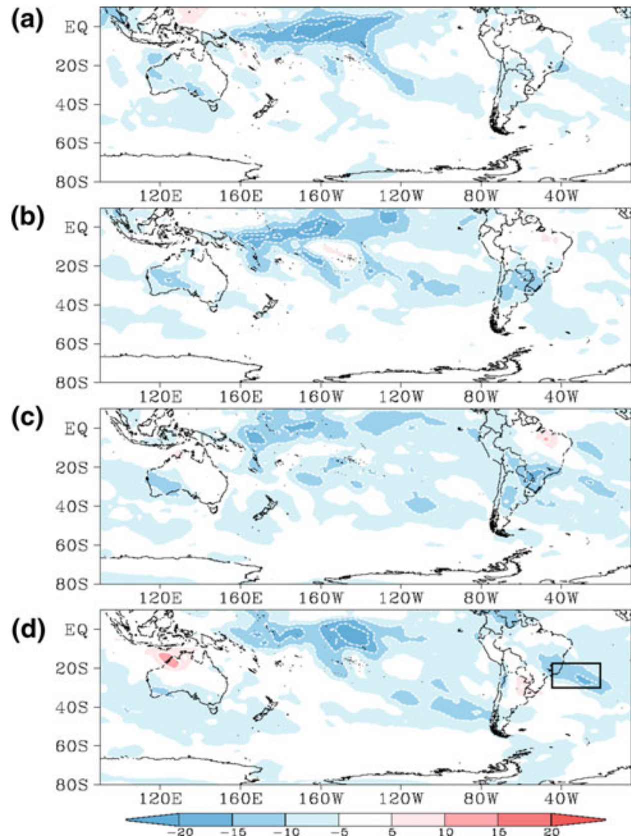

Fig. 2 Composite fields of OLR anomalies from **a** Pentad-3 **b** Pentad-2, **c** Pentad-1 and **d** Pentad 0. The region where the SACZ index was defined is shown in (**d**). *Shaded*/contours level is 5 W m^{-2}. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

persistence of heat waves in subtropical South America is further explored in the following sections.

The 4-pentad OLR′ evolution (Fig. 2) also shows the persistence of a zonally elongated band of negative values along the equatorial Pacific which will be discussed in the next sections.

4.2 Heat waves related with active SACZ

The SACZ activity was described through the analysis of an index defined as the spatial average of OLR′ between 30°S–17°S and 45°W–20°W (Fig. 2d). Positive (negative) index values represent inhibited (active) SACZ conditions. The index was used to classify heat waves occurrence in the region under study, depending on their association to intense or inhibited SACZ conditions. It was found that 19 of the 26 heat wave cases identified in the 1979–2003 period were associated with active SACZ in Pentad 0. On the other hand, the rest of the heat wave events identified in the period (7), were not associated with active SACZ.

Figure 3a–d shows OLR′ composite fields for heat waves associated with active SACZ. At Pentad-3, an area

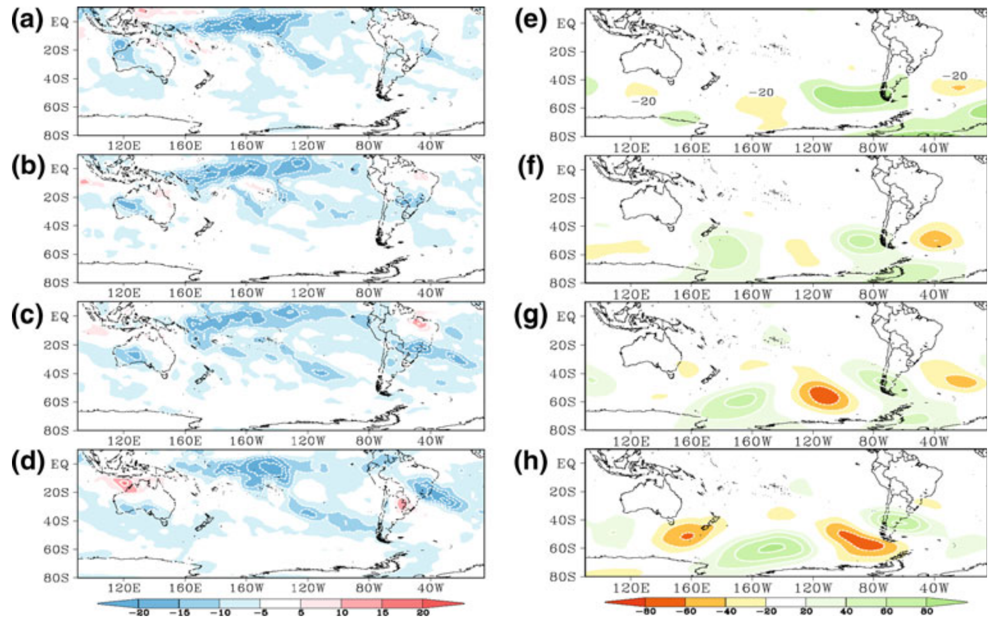

Fig. 3 Composite fields of: OLR anomalies for **a** Pentad-3, **b** Pentad-2, **c** Pentad-1 and **d** Pentad 0 and 300-hPa geopotential height anomalies for **e** Pentad-3, **f** Pentad-2, **g** Pentad-1 and **h** Pentad 0 during active SACZ conditions. *Shaded*/contours level is 5 W m^{-2} in **a**–**d** and 20 m in **e**–**h**. The zero contour is omitted. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

of negative anomalies locates approximately over the climatological position of the SACZ, as well as a weaker negative anomaly band is discernible over the southern part of the continent (Fig. 3a). On Pentad-2 (Fig. 3b), large negative anomalies locate over southeastern Brazil and Paraguay, preceding the strengthening of the SACZ which starts in Pentad-1 accompanied by positive anomalies in the north of Brazil (Fig. 3c). On Pentad 0, a well organized band of large negative OLR′ in the SACZ region is clearly evident as well as a region of strong positive anomalies over center-northern Argentina. The latter might be associated with subsidence anomalous conditions promoted by intensified SACZ. In agreement, Gandu and Silva Dias (1998) showed performing numerical experiments, that the SACZ related subsidence effect is more intense on the subtropical side. Accordingly, Cerne et al. (2007) identified that effect as dominating during the development of the extreme heat wave occurred in the summer 2002/2003.

A zonally elongated band of negative anomalies in the equatorial Pacific Ocean can also be observed in Fig. 3a–d. That band exhibits evidences of an eastward progression, particularly between Pentads-1 and 0, towards the center of the Basin, and accompanied by a progressive eastward movement of a positive anomaly core from the Indian Ocean towards the north of Australia. This pattern resembles that typically associated with the evolution of the Madden-Julian Oscillation (Madden and Julian 1994), and that has been previously related in previous studies with the intraseasonal variability in South America (e.g., Nogués-Paegle et al. 2000). Also apparent in the OLR′ evolution is the development of a negative anomaly band which was previously evident in Fig. 2. The band has been associated with the intensification of the South Pacific Convergence Zone (SPCZ) over the subtropical central Pacific. Kiladis and Weickmann (1992); Grimm and Silva Dias (1995) among others linked the SPCZ and SACZ convection through southeastwardly Rossby waves that curved toward the northeast over South America.

The analysis of the composite fields for 300 hPa geopotential height anomalies (Fig. 3g–h) shows along the whole evolution, the presence of a wave train extended from southern Australia towards South America with very slow eastward propagation. In particular, the equatorward movement of an anticyclonic anomaly over the South American continent stands out between Pentad-2 (Fig. 3f) and Pentad 0 (Fig. 3h). Those regional circulation anomaly centers embedded in wavetrain-like structures have been described in previous works. In particular, Liebmann et al. 2004 showed that after crossing the Andes, the wave train curves towards the equator with opposite phases depending on whether the SACZ is active or inhibited. Figure 3h shows that on Pentad 0, the strong positive circulation anomaly covers the center of Argentina while a weak negative anomaly center is located to the northeast, in association to the intensified SACZ (Fig. 3d).

Composite fields for 925 hPa temperature anomalies show positive anomalies over the South American continent on Pentad-3 (Fig. 4a). Quasi-normal conditions dominate the subtropical region on Pentad-1 (Fig. 4c), while a warm anomaly center develops at the extratropical regions. On Pentad 0 such anomaly intensifies and it is centered at about 38°S, 62°W, while a weak negative anomaly center is observed to the northeast (Fig. 4d).

The analysis of OLR′ at regional scales (Fig. 4e–h) shows the progressive intensification of convection anomalies in the SACZ region, while positive OLR′ develop

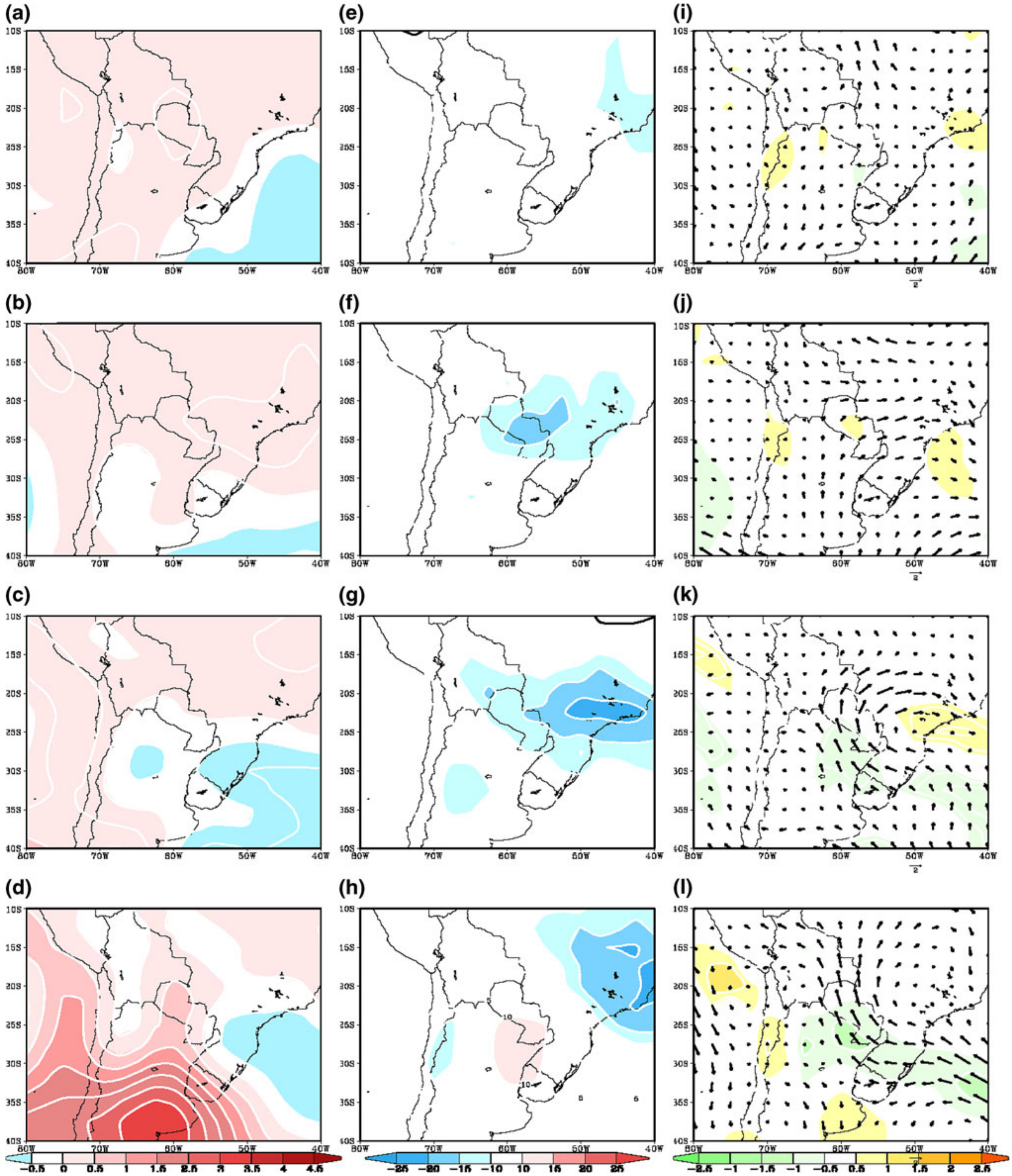

Fig. 4 Composites at Pentad-3, -2, -1 and 0, of: **a–d** 925 hPa temperature anomalies, **e–h** OLR anomalies and **i–l** wind vector and specific humidity anomalies at 850 hPa, during active SACZ conditions. *Shaded*/contours level is 0.5°C for temperature, 5 W m^{-2} for OLR, 0.5×10^3 g kg^{-1} for specific humidity and vector reference 2 m s^{-1}. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

over northeastern Argentina, particularly on Pentad 0. That OLR′ structure with opposite signs at tropical and subtropical regions is similar to that associated with the leading pattern of OLR′ intraseasonal variability (Nogués-Paegle and Mo 1997).

The anomaly evolution of both low-level wind vectors and specific humidity at 850 hPa (Fig. 4i–l) indicates the presence of quasi-normal winds on Pentad-3, while from Pentad-2, wind anomalies from the south develop over the center of the region. Negative humidity anomalies in the subtropical region particularly between Pentads-1 and 0 (Fig. 4k, l), are observed, which confirms that intensified SACZ induces drier than normal conditions over the subtropical region.

The analysis of the pentad maps, displayed in Fig. 4, then essentially shows that warm temperature anomalies in the study region develop in association with the strengthening of an anticyclonic circulation anomaly, which is discernible at least 15 days before the T' peak occurrence. That circulation anomaly is embedded in a large-scale Rossby wave train extended along the South Pacific Ocean. In addition, such circulation anomaly seems to be strengthened by the subsidence conditions promoted by an active SACZ, which results in temperature rise in the subtropical region under relatively dry conditions.

The analysis was complemented with the study of the daily evolution of the atmospheric conditions accompanying the temperature peak by the end of the heat wave event. In this case, for each heat wave, the day associated with T' daily maximum is defined as Day 0. Figure 5a shows between Day −4 and Day −3, the southwest–northeast displacement of a low-level center of positive daily 925 hPa temperature anomalies within an environment that is already anomalously warm. The center enhances on Day −2, peaks on Day 0 and decays on Day +1. The corresponding OLR′ daily composite fields indicate that the SACZ intensifies on Day −4 over southeastern Brazil, while on the following days it slowly moves northeastwards (Figs. not shown). Accordingly, between day −4 and -2, 850 hPa wind anomalies converge over the SACZ region while southeasterly wind anomalies dominate over the subtropical region jointly with negative humidity anomalies (Fig. 5b). Those conditions remain until about Day −1 when weak northerly wind anomalies start to strengthen over the center and east of Argentina. Between Day −1 and Day 0 those wind anomalies become stronger and are accompanied by increased positive humidity anomalies in the region.

The daily evolution of the heat waves associated with active SACZ shows then that the progressive temperature rise in the subtropical region, is due to subsidence conditions associated to an anticyclonic anomaly that remain in the region until Day −2. However, from Day −1, temperature rise seems to be mainly dominated by warmer and moister air being anomalously advected from the north into the region of interest.

4.3 Heat waves not related with active SACZ

Composite fields were determined to analyze the atmospheric conditions associated with the group of seven heat waves not associated with active SACZ. Besides the low number of cases, the composites provided relevant information about the mechanisms associated with this type of heat waves.

Figure 6a–d show the composite fields of OLR′ pentads for the heat waves not related to active SACZ. A positive OLR′ area is observed in the SACZ region during the whole evolution. In addition large negative OLR′ are extended over southern South America, and linked to an elongated band of negative anomalies located over southeastern Pacific. Furthermore, the links between the SPCZ and South America regions observed for heat waves associated with active SACZ, are not evident here. The exploration about whether the last result is due to the small number of cases considered, or whether it physically means that SPCZ only influences active SACZ which in turn has an impact on heat waves, is out of the scope of this paper. On Pentad 0, the center of positive anomalies in the SACZ area is somewhat displaced to the north while normal OLR conditions prevail in central-northern Argentina.

Between Pentad-3 and Pentad-2, an area of positive (negative) 300 hPa geopotential height anomalies expands zonally between 60°S and 80°S (40°S–60°S) (Fig. 6e–h). Between Pentad-1 and Pentad 0, circulation anomaly centers exhibit a wavetrain-like structure along the South Pacific Ocean extended from Australia to southern South America. In particular, the composite field on Pentad-1 is similar to the circulation anomaly pattern identified by Liebmann et al. (2004)for the cases of inhibited SACZ. On Pentad 0, a strong negative anomaly center locates at 50°S–90°W, while a positive anomaly center is evident over the continent. However, how those two circulation anomaly centers develop from the circulation anomalies present in the previous Pentads is not clear.

At regional scales, 925 hPa temperature anomaly composite fields present between Pentad-3 and Pentad-1 the northeast progression of an area of weak positive anomalies (Fig. 7a–c). On Pentad 0 (Fig. 7d), the fast development of a large positive anomaly center is clear. In addition, between Pentad-3 and Pentad-1, inhibited SACZ conditions over southeastern Brazil and convection enhancement at northern and center Argentina are depicted in OLR′ composite fields (Fig. 7e–g). Between Pentad-2 and Pentad 0, both humidity and wind anomalies at 850 hPa (Fig. 7i–l) show the progressive incoming of

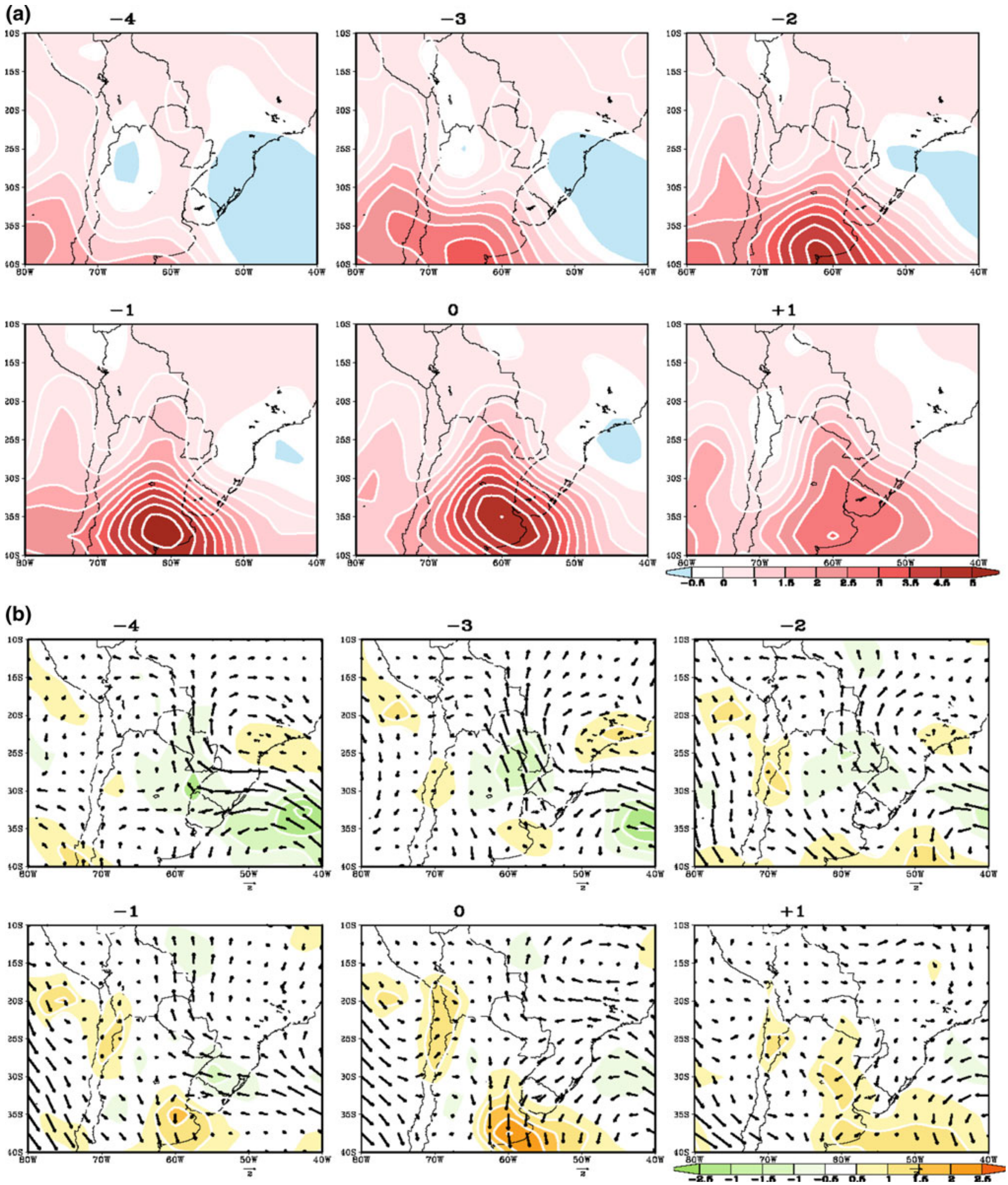

Fig. 5 Daily composites at days −4, −3, −2, −1, 0 and +1, of: **a** 925 hPa temperature anomalies, **b** wind vector and specific humidity anomalies, during active SACZ conditions. *Shaded*/contours level is 0.5°C for temperature, 0.5×10^3 g kg^{-1} for specific humidity and vector reference 2 m s^{-1}. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

moisture from the tropical to extratropical regions, associated with an intensification of northerly winds well into middle latitudes on Pentad 0.

The analysis of the temporal evolution of circulation anomalies associated with heat waves that occurred under inhibited SACZ conditions essentially shows that

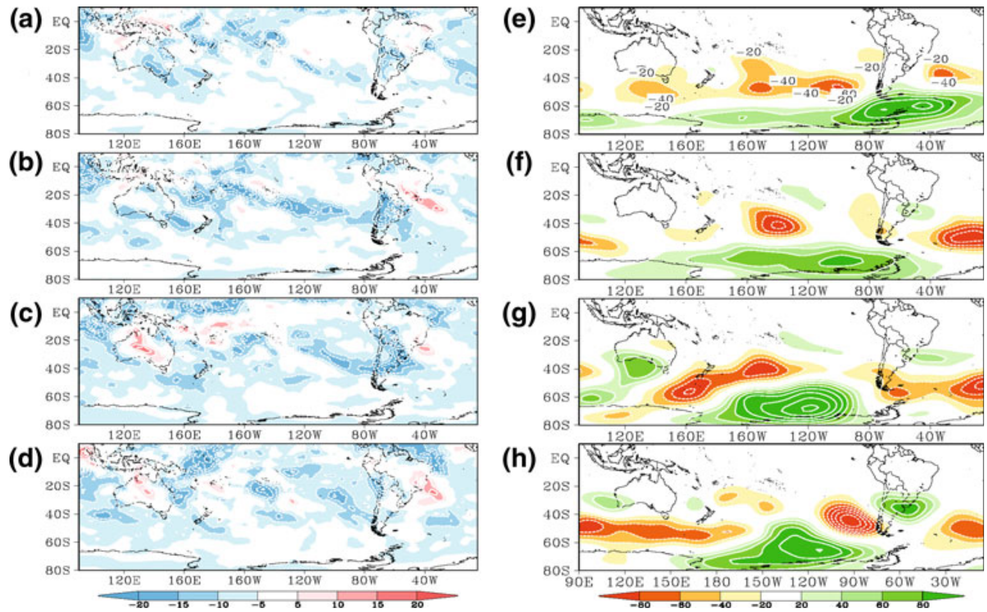

Fig. 6 Composite fields of: OLR anomalies for **a** Pentad-3, **b** Pentad-2, **c** Pentad-1 and **d** Pentad 0 and 300-hPa geopotential height anomalies for **e** Pentad-3, **f** Pentad-2, **g** Pentad-1 and **h** Pentad 0 during non-active SACZ conditions. *Shaded*/contours level is 5 W m^{-2} in **a**–**d** and 20 m in **e**–**h**. The zero contour is omitted. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

temperature anomaly peak in the region under study is preceded by at least 10 days of anomalously warm and moist air advection from the north.

The daily evolution of the regional circulation anomalies during the last development stage of this group of heat waves exhibits the intensification of a positive 925 hPa temperature anomaly center over eastern Argentina from Day −4 to Day 0 (Fig. 8a). On Day +1 it weakens considerably and moves northward. Daily OLR′ (not shown) suggest inactive SACZ conditions during the whole period, while enhancement convection is observed at northern Argentina and south of Brazil between Day −4 and Day −2. On Pentad 0 anomalous convection is also observed south of 35°S, which moves towards the northeast on the following day. The evolution of both humidity and wind anomalies at 850 hPa (Fig. 8b) confirms the day-to-day moisture increase due to strong northerly wind anomalies. These anomalies penetrate up to 40°S at Day 0 and move eastwards on the following day, resembling the features associated with the typical progression of a frontal system over the region.

5 Summary and conclusions

This study concentrates on the analysis of the influence of the intraseasonal variability on heat wave development over subtropical South America during austral summer, and the particular influence of SACZ activity on that development. An exploratory analysis of the features associated with the variability of daily surface temperature anomalies in central Argentina; shows that intraseasonal variability can explain in average at least 32% of summer temperature variance and thus plays a significant role in the summer circulation dynamics over this particular region. Such variability induces periods of consecutive days of anomalies of the same sign in which the synoptic-scale variability is embedded.

Heat waves were determined requiring that positive daily temperature anomalies persist for at least 5 consecutive days during which T' must be larger than its own standard deviation for at least 3 days. It was found that more than 50% of the heat wave events were associated with at least 5 consecutive days with T' larger than its own standard deviation. Moreover, a clear relationship was found between the development of persistent heat waves and the occurrence of daily temperature extremes. More than 70% of the days associated with surface temperature extreme values larger than 95th percentile were embedded in a persistent heat wave event.

The analysis of the persistent heat wave development and SACZ activity at tropical regions shows that 73% of the heat waves in subtropical South America develop in association with an active SACZ. The analysis of the atmospheric conditions promoting the development of such heat waves shows that temperature anomalies develop in association with the strengthening of an anticyclonic anomaly over the subtropical region, which is discernible at least 15 days before the T' peak occurrence. That circulation anomaly is embedded in a large-scale Rossby wave train extended along the South Pacific Ocean that seems to be linked with intraseasonal changes of the convection at the equatorial western and central Pacific Ocean. Such conclusion agrees with previous publications that link SACZ intraseasonal activity with that associated with the MJO over the Indian Ocean and western Pacific Ocean. In

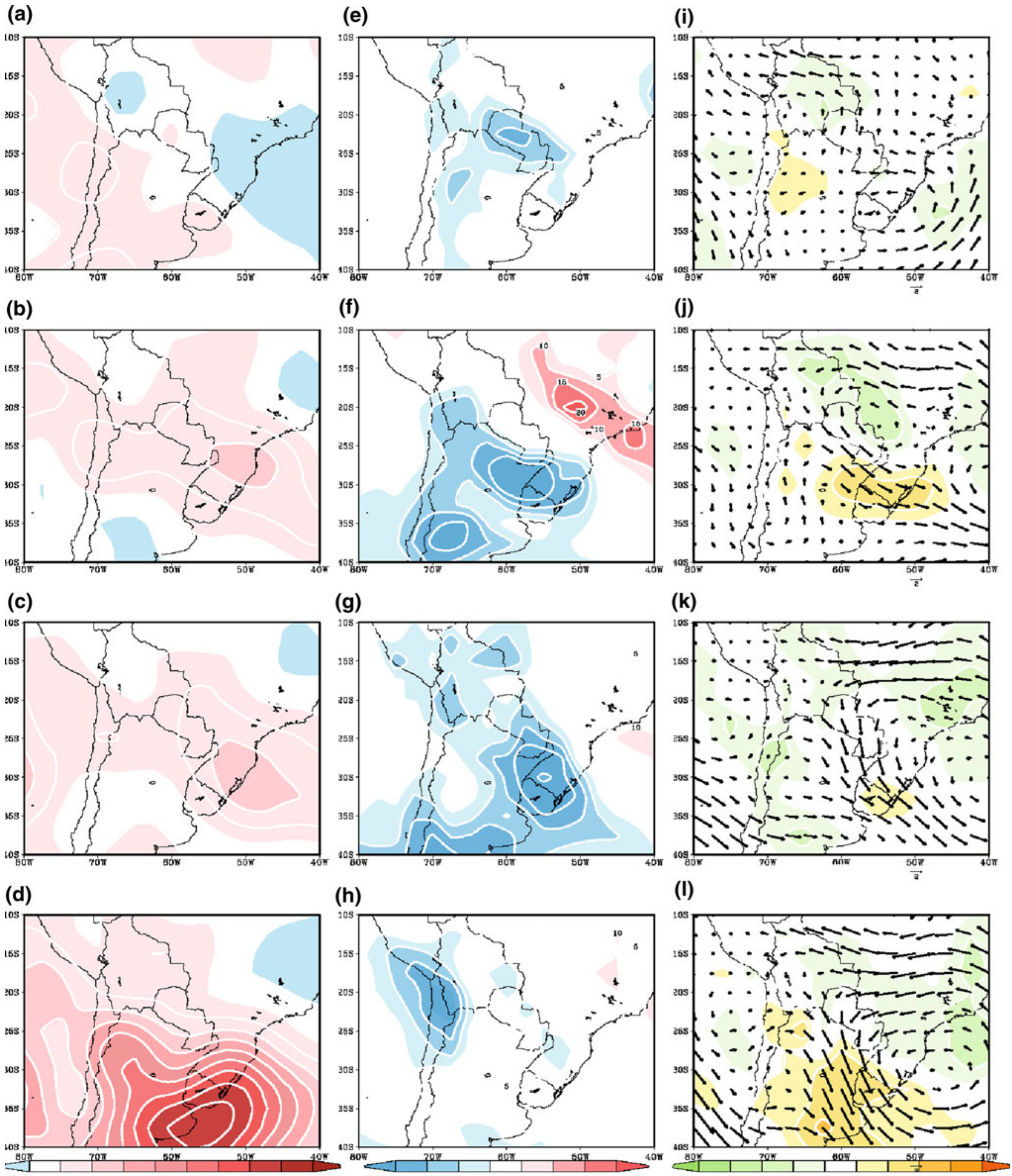

Fig. 7 Composites at Pentad-3, -2, -1 and 0, of: **a–d** 925 hPa temperature anomalies, **e–h** OLR anomalies and **i–l** wind vector and specific humidity anomalies at 850 hPa, during non-active SACZ conditions. *Shaded*/contours level is 0.5°C for temperature, 5 W m^{-2} for OLR, 0.5 × 10^{3} g kg^{-1} for specific humidity and vector reference 2 m s^{-1}. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

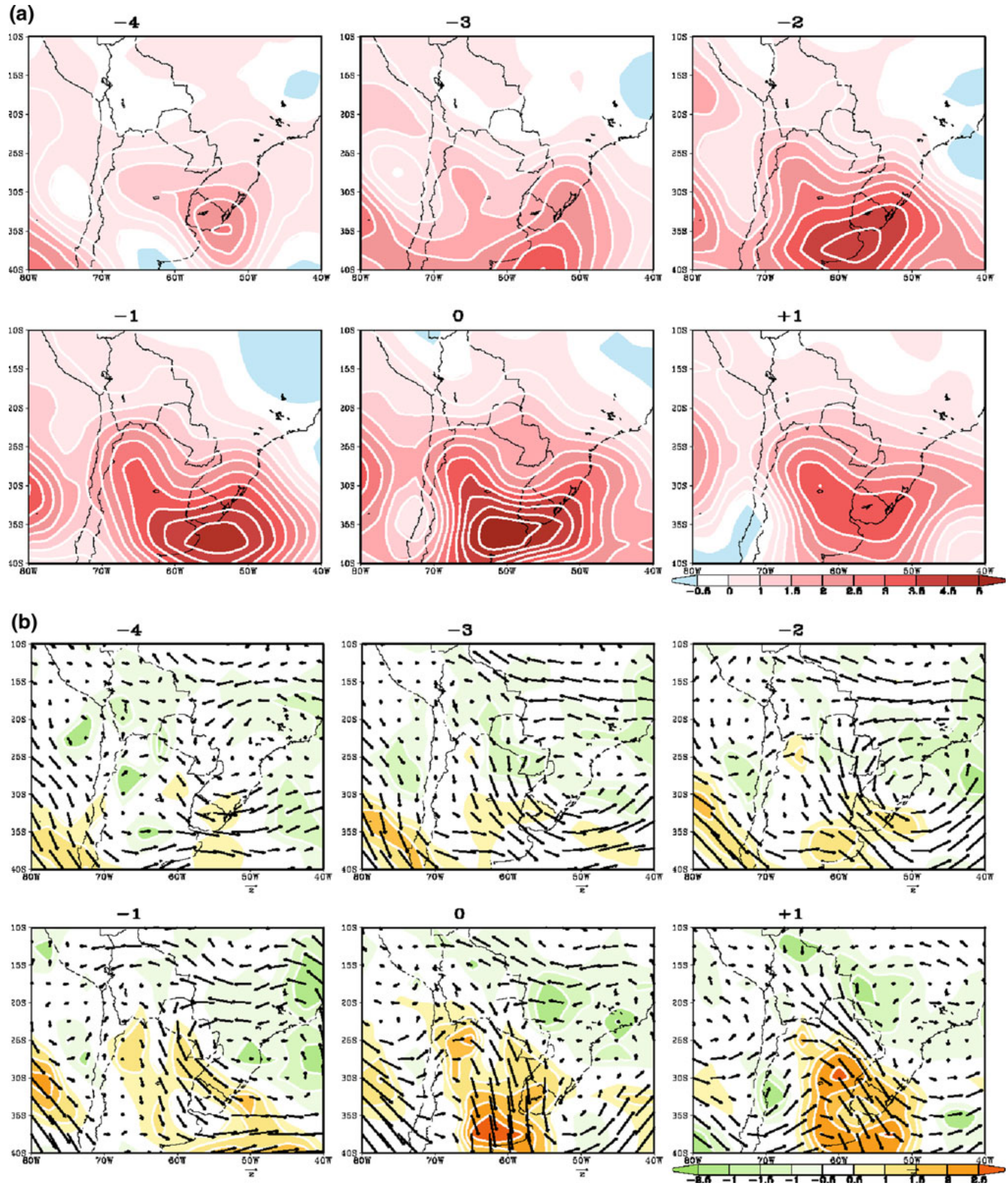

Fig. 8 Daily composites at days −4, −3, −2, −1, 0 and +1, of: **a** 925 hPa temperature anomalies, **b** wind vector and specific humidity anomalies, during non-active SACZ conditions. *Shaded/* contours level is 0.5°C for temperature, 0.5 × 10^3 g kg^{-1} for specific humidity and vector reference 2 m s^{-1}. Contours associated with statistically significant values at the 90% level of Student's *t* test are displayed

addition, the development of the anticyclonic circulation over subtropical South America during the early stage of the heat wave seems to be strengthened by the subsidence conditions promoted by active SACZ, which promotes temperature rise in the subtropical region under relatively dry conditions. On the other hand, during the last 2 days of the heat wave evolution, SACZ activity weakens and the progressive temperature rise in the subtropical region seems to be mainly dominated by warmer and moister air being anomalously advected from the north into the region of interest.

Therefore, the results derived from this analysis confirm the important role that SACZ intraseasonal activity has in inducing persistent circulation anomalies at the subtropical regions with may result in the development of persistence heat waves that in turn can induce the occurrence of very extreme daily events of surface temperature.

Finally, it should be pointed out that 7 of the 26 heat wave events identified in the 1979–2003 period were not associated with active SACZ. The analysis of the corresponding circulation anomalies show that during the development of this type of heat waves, warmer than normal conditions prevail over the subtropical regions for at least 10 days before the surface temperature peak. Such temperature conditions are favored by the persistence of advection processes of anomalous warm and moist air promoted into the region. Circulation anomalies resembling that associated with a quasi-stationary frontal system located at the southern tip of South America seems to promote such advection processes. Considering, however, the low number of heat wave events associated with inactive SACZ considered, the last conclusions should be taken cautiously.

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