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On the variability of seasonal temperature in southern South America

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Abstract The aim of this paper is to investigate different aspects of the seasonal-to-interannual temperature variability in Eastern Patagonia, the southernmost area of South America, east of the Andes Cordillera. Homogenous regions of seasonal variability and the atmospheric circulation patterns associated with warm and cold conditions in each of them are described in this study. Relationships between temperature in Eastern Patagonia and that registered in other areas of southern South America are also addressed. Results show that the northern and southern areas of Eastern Patagonia have different temperature variability in summer and autumn whereas the temperature variability tends to be more homogeneous within the region during winter and spring. Warm (cold) conditions in the northern areas are associated with reinforced (weakened) westerlies in summer, winter and spring whereas northerly (southerly) advections of warm (cold) air toward the region produce such conditions in autumn. Temperature in the southern portion of Eastern Patagonia is affected by anticyclonic (cyclonic) anomalies that enhance (reduce) the incoming solar radiation and induce reinforced (weakened) westerlies promoting warm (cold) conditions in the region. Furthermore, cyclonic (anticyclonic) anomalies at subpolar latitudes hinder (favor) outbreaks of cold air increasing (decreasing) the temperature over areas of Eastern Patagonia. The circulation anomalies associated with warm (cold) conditions in Eastern Patagonia also promote cold (warm) conditions over areas of northern Argentina, Paraguay and southern Brazil. Consequently, a dipole of temperature is detected in southern South America with centers of opposite sign over these regions.

Keywords Patagonia region · South American temperature · Interannual variability · Southern Annular Mode · Pacific–South American modes

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1 Introduction

The area of southern South America south of 40°S is known as Patagonia (Fig. 1). This region is strongly influenced by the westerly flow extended throughout the entire troposphere and the transient anomalies typical at high latitudes of the Southern Hemisphere (e.g., Prohaska 1976; Satyamurti et al. 1998). At low levels, the westerly flow ascends on the western slope of the Andes Cordillera and descends on the Argentinean side east of the mountains (region hereafter referred to as Eastern Patagonia, EPAT) (e.g., Hoffman 1975). In summer, the temperature in EPAT shows a pronounced meridional gradient which is a consequence of the higher continental heating in the northern areas with respect to that registered farther to the south

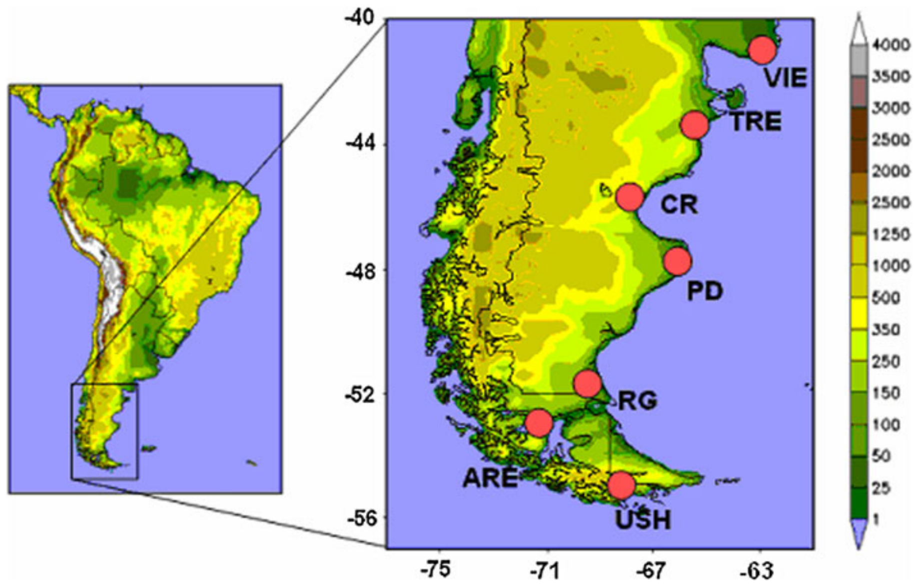


Fig. 1 Patagonia region (topography is *shaded*; units: meters). The *red points* indicate the location of the seven meteorological stations considered in the analysis (see the text for more details)

(e.g., Prohaska 1976). Such heterogeneous continental heating produces a north–south pattern of temperature variability. In winter, the meridional gradient of temperature is weak and the temperature variability within EPAT is more regionally homogeneous than in summer because the reduced incident solar radiation produces only small changes in the characteristics of the polar air masses moving to the north channeled by the Andes. In particular, high pressure transient systems that cross the Andes associated with a reinforced subtropical jet produce favorable conditions for intense southerly advections of cold air and frost over a large spatial extension of the continent to the east of the Andes (Müller et al. 2005). In consequence, the transient systems favor generalized cooling or frost in the south of the continent promoting homogeneous conditions of temperature variability within EPAT during winter.

Some aspects of temperature variability in the southern tip of South America have been described in previous studies. Pittock (1980) analyzed climatic variations in southern South America finding north–south structures of interannual temperature variability. A north–south pattern of interannual temperature variability within EPAT was also described by Coronato and Bisigato (1998). The study performed by Alessandro (2005) shows that outbreaks of cold air from polar latitudes reduce the temperature in EPAT and strong northerly flow produces warm conditions in the region. Furthermore, Alessandro (2008, 2011) shows that the westerly flow over subpolar latitudes of the Southern Hemisphere has important influence on the EPAT temperature because strong westerly winds are associated with warmer conditions due to the subsidence over the eastern Andes.

Different studies have connected the interannual temperature variability in areas of EPAT with atmospheric large-scale circulation patterns. In fact, significant influence of the Southern Oscillation on regional temperature during austral spring was showed by Aceituno (1988) whereas Garreaud (2009) found significant relationships with the Multivariate El Niño-Southern Oscillation Index during the four seasons. Furthermore, Rusticucci and Vargas (2002) described cold conditions in EPAT during El Niño events due to the persistence of masses of cold air over the region. Seasonal and annual mean temperatures in EPAT are also influenced by the Southern Annular Mode (SAM) (e.g., Gillett et al. 2006; Garreaud et al. 2008; Silvestri and Vera 2009).

Important trends and changes in the temperature registered in different areas of southern South America have been reported by different authors. In fact, Rosenblüth et al. (1997) described the occurrence of a cold period during 1950s–1970s followed by a persistent warming in the northwestern portion of EPAT near the Andes Cordillera whereas a mild warming period beginning in the 1950s is detected in central and southern areas of EPAT. Positive significant trends in EPAT during the second half of the 20th Century were also found by Boninsegna et al. (1989), Villalba et al. (2003), Vincent et al. (2005) and Collins et al. (2009). Furthermore, Rusticucci and Barrucand (2004) showed that the number of cold (warm) days in EPAT has decreased (increased) in summer and winter since the 1960s.

The previously mentioned bibliography describes important progress made in the knowledge of the temperature variability in southern South America. However, further research focused in the area of EPAT should be done in order to understand the physical processes affecting the climate of this remote region of the world. In particular, the analysis of homogeneous subregions of variability, the atmospheric circulation anomalies that produce warm and cold conditions in such subregions and the connections with the temperature registered in other areas of southern South America is addressed in this article.

Data and methodology used in this study are described in Sect. 2. Section 3 presents the homogeneous subregions of temperature variability in EPAT and the relationships with the anomalies of atmospheric circulation and South American temperature. The main conclusions are summarized in Sect. 4.

2 Data and methodology

Information of temperature in the area of EPAT is scarce. Although there are several meteorological stations located in this region, the information in most of them is incomplete or covers short periods of time. The National Meteorological Service of Argentina (NMSA) provides the time series of monthly mean temperature without missing values during 1979–2009 from six meteorological stations located in the area of EPAT. These stations are: Trelew (TRE), Viedma (VIE), Comodoro Rivadavia (CR), Puerto Deseado (PD), Río Gallegos (RG) and Ushuaia (USH) (Fig. 1). The information of the Chilean station Punta Arenas (ARE) is taken from the Global Historical Climatology Network-Monthly (GHCN-M, version 3). The monthly mean temperature of the University of Delaware (UDEL) dataset produced by Willmott and Matsuura (available online from http://climate.geog.udel.edu/∼climate) is also considered.

The analysis of atmospheric circulation patterns associated with different conditions of temperature in areas of EPAT is performed considering monthly mean values of wind at 850 hPa and geopotential height at 850 hPa (Z850) and 200 hPa (Z200) extracted from the NCEP–NCAR reanalysis (Kalnay et al. 1996).

The analysis is restricted to 1979–2009 due to the availability of monthly mean temperature provided by the NMSA. During this period, the NCEP–NCAR reanalysis contains satellite data being one of the most complete datasets for high latitudes of the Southern Hemisphere. Seasonal means of monthly anomalies with respect to the entire 1979–2009 period are calculated for all dataset considering the Southern Hemisphere seasons (summer: December–January–February; autumn: March–April–May; winter: June–July–August; spring: September–October–November).

Correlations among the time series of temperature registered at the seven meteorological stations are computed in order to investigate the spatial homogeneity of this variable in EPAT. The atmospheric circulation anomalies associated with the temperature in each subregion and the relationships with temperature registered in other areas of southern South America are described in terms of linear correlations between the corresponding time series. The statistical significance of correlations is assessed using a two-tailed Student's t test (e.g., Brooks and Carruthers 1953) for 90, 95 and 99 % significant levels. In each of the seven considered meteorological stations, the seasonal averages of temperature are independent (i.e., the first-order autocorrelation coefficient is zero in each time series). The same characteristic is detected in the time series representing the temperature in the subregions NORTH and SOUTH. Therefore, the effective number of degrees of freedom in the Student's t test for the correlation coefficients is equal to the original sample size (e.g., Dawdy and Matalas 1964; Bretherton et al. 1999).

3 Results

3.1 Subregions of EPAT temperature

Seasonal correlations among the seven considered time series of temperature are shown in Table 1. In summer, the northern stations VIE and TRE are closely connected (the correlation is 0.76) whereas the southern stations RG, ARE and USH have significant correlations between them (correlations are 0.63–0.70) (Table 1a). However, there are not significant relationships among both groups because correlations between the stations VIE and TRE with RG, ARE or USH are lower than 0.22. The stations CR and PD, located in the center of EPAT (see Fig. 1), have significant relationships with both the northern and the southern stations. These summer correlations for the period 1979–2009 describe a north–south pattern similar to those suggested by Pittock (1980) for annual values in 1931–1960 and Coronato and Bisigato (1998) for monthly anomalies in 1977–1991. The north–south pattern is also detected in autumn. The northern stations VIE and TRE have significant correlation but both are not connected with the southern stations RG, ARE and USH which are significantly linked among them (Table 1b). Furthermore, the stations of the central area (CR and PD) have significant relationships with both groups, especially with the southern one.

During winter, all series of temperature have significant correlation among them (Table 1c). However, the values of correlations involving the northern stations VIE and TRE decrease toward the south. Coherently, the magnitudes of correlations involving the southern stations RG, ARE and USH decrease toward the north. It means that the north–south pattern is also detected but it has a weakened

Table 1 Correlations between the time series of seasonal temperature corresponding to the seven meteorological stations depicted in Fig. 1

	VIE	TRE	CR	PD	RG	ARE
(a) Summer						
TRE	0.76***					
CR	0.67***	0.85***				
PD	0.43**	0.59***	0.71***			
RG	0.22	0.16	0.43**	0.46**		
ARE	−0.11	−0.08	0.21	0.39**	0.68***	
USH	−0.06	−0.08	0.19	0.38**	0.70***	0.63***
(b) Autumn						
TRE	0.58***					
CR	0.36*	0.59***				
PD	0.41**	0.37**	0.65***			
RG	0.03	0.33*	0.70***	0.66***		
ARE	0.03	0.26	0.67***	0.68***	0.89***	
USH	0.11	0.11	0.54***	0.67***	0.67***	0.66***
(c) Winter						
TRE	0.88***					
CR	0.70***	0.85***				
PD	0.68***	0.75***	0.84***			
RG	0.60***	0.80***	0.87***	0.77***		
ARE	0.48***	0.58***	0.74***	0.81***	0.86***	
USH	0.42**	0.49***	0.67***	0.65***	0.67***	0.70***
(d) Spring						
TRE	0.78***					
CR	0.52***	0.84***				
PD	0.62***	0.76***	0.88***			
RG	0.33*	0.54***	0.76***	0.60***		
ARE	0.37**	0.51***	0.71***	0.57***	0.77***	
USH	0.28	0.49***	0.65***	0.50***	0.73***	0.70***

Correlations statistically significant at 90, 95 and 99 % level according to the Student's *t* test are indicated with one, two and three asterisk(s), respectively

structure relative to that observed in the previous seasons. The correlation pattern detected in winter persists during spring. In fact, all considered series have significant correlations among them, except VIE–USH, but the values of correlations show north–south changes (Table 1d).

The studies of Pittock (1980) and Coronato and Bisigato (1998) demonstrated a north–south separation in the variability of annual and monthly temperature in areas of EPAT. Although we also find a north–south pattern in the four seasons, our results show that such separation is more important in summer-autumn than in winter-spring. In other words, there are well defined differences in the temperature variability registered in the north and south of EPAT during summer and autumn whereas in winter and spring the temperature variability within EPAT tends to be more regionally homogeneous than in the two previous seasons. As was commented in Sect. 1, the north–south pattern of temperature variability during summer is a consequence of the higher continental heating in the north of the region with respect to that registered in the southern areas whereas the reduced incident solar radiation and the southerly cold-air outbreaks promote homogeneous conditions of temperature variability within EPAT during winter. The correlations for each season presented in Table 1 reveal that the north–south differences within EPAT observed in summer persist during autumn whereas the more homogeneous conditions during winter are also detected in spring.

In light of the previous correlation analysis, three well defined subregions of temperature can be defined in the area of EPAT. In fact, temperature from the seven considered meteorological stations can be averaged in the subregions NORTH (stations VIE and TRE), CENTRE (stations CR and PD) and SOUTH (stations RG, ARE and USH). These three groups represent the same relationships detected among the individual time series (Table 2): the subregions NORTH and SOUTH are independent during summer and autumn but both have significant relationships with the subregion CENTRE. In contrast, during winter and spring the three subregions have significant correlations among them describing a weaker structure of the north–south pattern of temperature. Considering these results, the

Table 2 As Table 1 but for the three subregions of EPAT depicted in the text

	(a) Summer		(b) Autumn		(c) Winter		(d) Spring	
	NORTH	CENTRE	NORTH	CENTRE	NORTH	CENTRE	NORTH	CENTRE
CENTRE	0.63***		0.52***		0.80***		0.81***	
SOUTH	−0.04	0.44**	0.15	0.83***	0.64***	0.87***	0.49***	0.68***

study of the atmospheric circulation anomalies that produce warm and cold conditions in EPAT and the possible relationships with temperature registered in other areas of southern South America can be simplified focusing the analysis on the three mentioned subregions.

3.2 Anomalies of atmospheric circulation and South American temperature associated with EPAT temperature

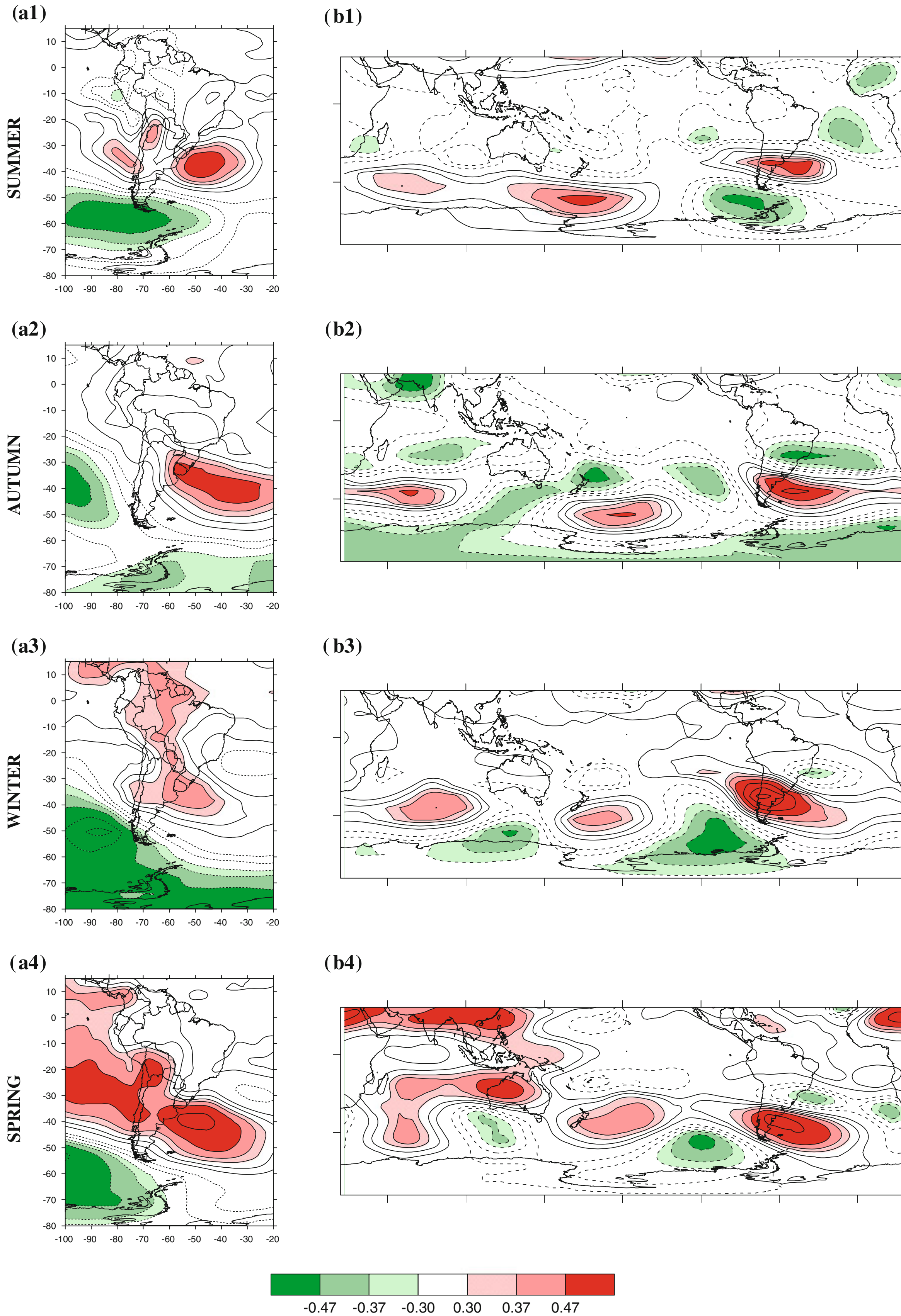
Patterns of Southern Hemisphere atmospheric circulation and South American temperature associated with temperature variability in the subregions NORTH and SOUTH are presented in this section. Those associated with the variability of temperature in the subregion CENTRE are not shown because such patterns are a combination of the features detected in the subregions NORTH and SOUTH. This characteristic is a consequence of the close relationships between temperature in the central area of EPAT with those registered in the northern and southern subregions (see the previous section).

Anomalies of Z850 and wind at 850 hPa represent the atmospheric circulation patterns at low levels. The upper-level atmospheric circulation is described considering anomalies of Z200 but the results are similar to those obtained with the streamfunction at 200 hPa extracted from the NCEP–NCAR reanalysis, even in tropical latitudes. In other words, the streamfunction does not detect additional structures to the anomalies described by the geopotential height.

3.2.1 Subregion NORTH

During summer, correlations between temperature in the subregion NORTH and Z850 are positive over southern South America and the adjacent oceans in 20°S–40°S with significant values in centers extended over the western Atlantic, northwestern Argentina and the eastern Pacific (Fig. 2-a1). Furthermore, significant negative correlations are observed over the Drake Passage and adjacent areas in Patagonia and the Atlantic and Pacific oceans. Significant positive correlations between temperature in the subregion NORTH and geopotential heights around southern South America and negative correlations at subpolar latitudes are detected throughout the entire troposphere with a structure similar to that observed at upper levels (Fig. 2-b1). This circulation pattern indicates that warm (cold) conditions in the north of EPAT are associated with anticyclonic (cyclonic) anomalies over southern South America and a cyclonic (anticyclonic) center farther to the south involving reinforced (weakened) westerly flow over the region. The relationship between temperature in the subregion NORTH and low-level winds is clearly described by the corresponding correlation pattern (Fig. 3a). In fact, significant positive correlations are observed between the temperature and the zonal component of the wind over the north of EPAT indicating that the occurrence of warm (cold) conditions is associated with reinforced (weakened) westerly component of the wind over the region. The cyclonic (anticyclonic) anomalies of circulation at subpolar latitudes contribute to reinforced (weakened) westerlies and also hinder (favor) outbreaks of cold air from polar areas to the south of South America increasing (decreasing) the temperature in the north of EPAT. Furthermore, the anticyclonic (cyclonic) anomalies over the north of EPAT reduce (increase) the cloud cover inducing warm (cold) conditions in the area due to the increment (reduction) of solar heating.

The significant positive correlations between temperature in the subregion NORTH and Z850 over the subtropical western Atlantic detected in summer persists during autumn with an elongated structure of northwest-southeast orientation throughout the entire troposphere that affects the low-level circulation over eastern areas of southern South America (Fig. 2-a2, -b2). The low-level flow associated with the anomaly developed over the western Atlantic is clearly described by the correlations between temperature in the subregion NORTH and winds at 850 hPa (Fig. 3b) showing that the north of EPAT is embedded in an area of purely meridional anomalies. It means that an anticyclonic (cyclonic) center developed over the western Atlantic involves northerly (southerly) flow of warm (cold) air toward the north of EPAT producing warm (cold) conditions in the region. Although negative correlations between temperature in the subregion NORTH and the geopotential heights are observed in the South Pacific and surroundings of the Antarctic continent, there is not a well defined negative correlation center as that observed during summer in the area of the Drake Passage.


(a1)
(b1)
SUMMER
(a2)
(b2)
AUTUMN
(a3)
(b3)
WINTER
(a4)
(b4)
SPRING
10 0 -10 -20 -30 -40 -50 -60 -70 -80
-100 -90 -80 -70 -60 -50 -40 -30 -20
-0.47 -0.37 -0.30 0.30 0.37 0.47

◀ **Fig. 2** Correlations of temperature in the subregion NORTH with Z850 (*left*) and Z200 (*right*). Areas with statistically significant positive (negative) values at 90, 95 and 99 % level according to the Student's *t* test are *shaded* in *light*, intermediate and *dark red* (*green*), respectively. *Solid* (*dashed*) *black lines* indicate positive (negative) correlations. Contours: ±0.1, ±0.2, ±0.3, ±0.37, ±0.47, ±0.60, ±0.70, ±0.80

During winter, correlations between temperature in the subregion NORTH and Z850 exhibit a center of significant positive values extended over the western Atlantic and the eastern portion of southern South America whereas significant negative correlations cover broad areas of the South Pacific and surroundings of Antarctica (Fig. 2-a3). The corresponding low-level flow is clearly described by the correlations between temperature in the subregion NORTH and winds at 850 hPa (Fig. 3c). This circulation pattern indicates that the cyclonic (anticyclonic) circulation detected over the southeastern Pacific promotes reinforced (weakened) westerly component of the wind and obstructs (favors) the southerly advection of polar air toward the north of EPAT producing warm (cold) conditions in the region. Furthermore, the anticyclonic (cyclonic) circulation over the western Atlantic induces northerly (southerly) advection of warm (cold) air toward the northeastern corner of EPAT (see Fig. 3c) increasing (decreasing) the temperature in such area. Significant positive correlations between temperature in the subregion NORTH and geopotential heights over the South American continent to the south of 20°S are observed throughout the entire troposphere (Fig. 2-b3) and the upper-level circulation shows a structure that resembles the Pacific-South America 1 (PSA1) pattern extending from the western tropical Pacific to South America and the Atlantic Ocean (e.g., Mo and Ghil 1987; Karoly 1989; Mo and Higgins 1998). A structure resembling wave trains extended into subtropical and subpolar latitudes from the Indian Ocean to southern South America and the adjacent Atlantic is also detected. The physical mechanisms associated with these atmospheric perturbations have been described by Müller and Ambrizzi (2007) suggesting that stationary Rossby waves excited over the tropical Indian Ocean propagate in subpolar latitudes through the entire Southern Hemisphere. The theoretical formulation of propagation of such disturbances can be found in Müller and Ambrizzi (2010) and references cited therein. The circulation pattern promoting cold conditions in the north of EPAT contains anticyclonic anomalies to the southwest of Patagonia and a cyclonic center over the western Atlantic strengthening the southerly advection of cold air in the lower troposphere (Figs. 2-a3, 3c) whereas a reinforced subtropical jet is observed in upper levels (Fig. 2-b3). These characteristics resemble those associated with persistent generalized frost in southern South America described by Müller and Berri (2007). Detailed description of the dynamic conditions that favor the frequency and duration of frost over southern South America can be found in Müller and Berri (2012) and references cited therein.

During spring, correlations between temperature in the subregion NORTH and Z850 show significant positive values in a wide area extended over the South American continent between 20°S and 45°S, approximately, and the western Atlantic and eastern Pacific oceans whereas significant negative values cover the Bellingshausen Sea (Fig. 2-a4). Similar features are observed in the upper troposphere being part of anomalies that resemble a PSA1 pattern (Fig. 2-b4). The low-level flow affecting the north of EPAT is clearly described by the correlations between temperature in the subregion NORTH and winds at 850 hPa (Fig. 3d). The anticyclonic (cyclonic) center over the eastern Pacific and the cyclonic (anticyclonic) circulation at subpolar latitudes reinforce (reduce) the westerlies and obstruct (favor) the advection of polar air toward the north of EPAT promoting warm (cold) conditions in the region. As in winter, the anticyclonic (cyclonic) circulation developed over the western Atlantic favors the increment (reduction) of temperature in the northeastern corner of EPAT around 40°S because it promotes northerly (southerly) advection of warm (cold) air toward such specific area.

The atmospheric circulation patterns associated with temperature variability in the north of EPAT also affect the temperature in other areas of southern South America. Consequently, temperature in the subregion NORTH has significant correlations with temperature registered in different regions east of the Andes during the four seasons. In fact, significant positive correlations with temperature of a broad area extended over Argentina and Uruguay are detected during summer (Fig. 4a). These relationships are consistent with the circulation patterns previously described (see Fig. 2-a1, -b1) because the anticyclonic anomalies associated with warm conditions in the north of EPAT extend throughout the entire troposphere over the area of South America between 30°S and 45°S with a structure similar to that detected at upper levels. The subsidence associated with these anticyclonic anomalies reduces the cloud cover increasing the solar heating that promotes warm conditions in most of Argentina and Uruguay. Opposite features are associated with cyclonic anomalies producing cold conditions in the same area. Moreover, temperature in the subregion NORTH has negative correlation significant at the 90 % level with that registered in small areas of southern Brazil (Fig. 4a). Although correlations between temperature in the subregion NORTH and the low-level winds over these specific Brazilian zones are non-significant (see Fig. 3a), advection and convergence of moisture detected in the northerly anomalous flow increase

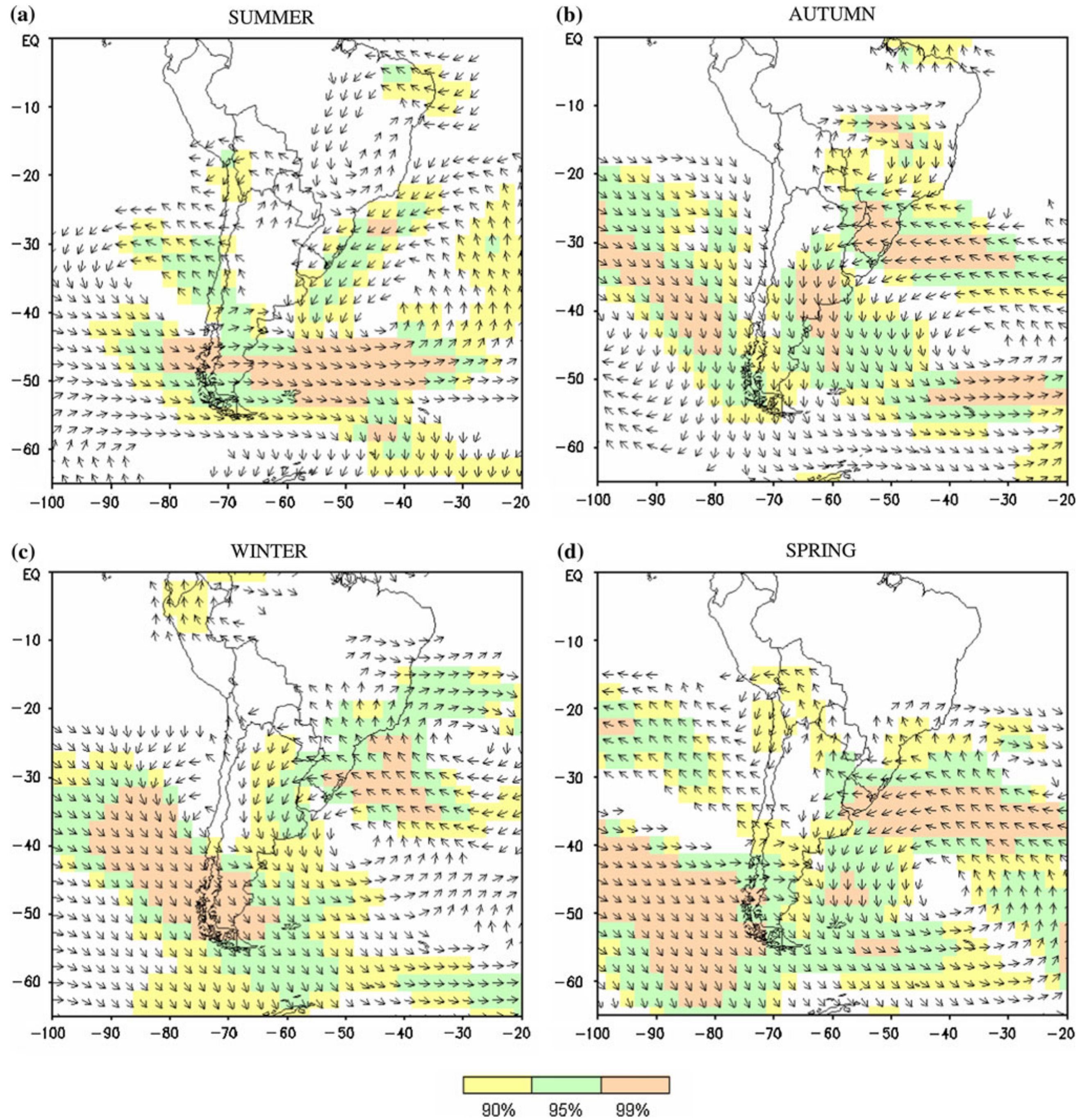


Fig. 3 Correlations between temperature in the subregion NORTH and wind at 850 hPa. Areas where correlations with at least one of the wind components (zonal or meridional) are statistically significant at 90, 95 and 99 % level according to the Student's *t* test are *shaded* in *yellow*, *green* and *orange*, respectively. *Vectors* indicate the corresponding wind directions

the cloud cover and produce precipitation over such small areas (figures not shown) inducing cold conditions when temperature in the north of EPAT increases. Inverse processes explain the occurrence of warm conditions in the small Brazilian areas when temperature in the north of EPAT decreases. The north–south separation in the EPAT temperature previously described (see Table 2a) is clearly distinguished in the correlation pattern (Fig. 4a) because there is a lack of significant correlations in the southernmost portion of EPAT.

Significant positive correlations between temperature in the subregion NORTH and temperature over Argentina and Uruguay are observed during autumn whereas negative correlations are detected in a wide area of southeastern

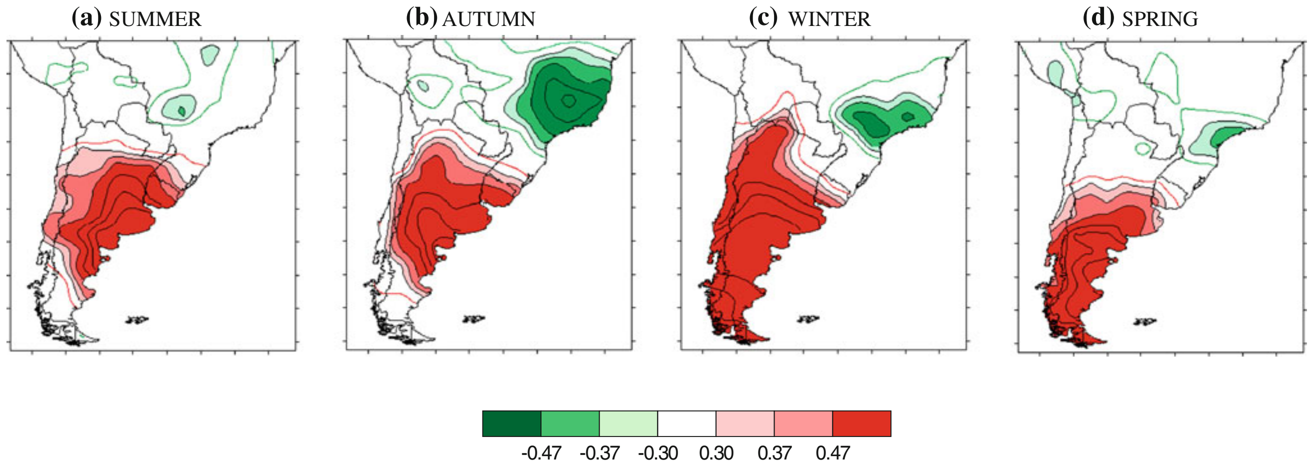


Fig. 4 Correlations between temperature in the subregion NORTH and UDEL temperature. Areas with statistically significant positive (negative) values at 90, 95 and 99 % level according to the Student's *t* test are *shaded* in *light*, intermediate and *dark red* (*green*), respectively. Contours: ±0.2, ±0.3, ±0.37, ±0.47, ±0.60, ±0.70, ±0.80

Brazil describing a dipolar pattern of temperature (Fig. 4b). These relationships are a consequence of the corresponding circulation anomalies. In fact, the anticyclonic center over the western Atlantic that induces warm conditions in the north of EPAT (Figs. 2-a2, -b2, 3b) favors the continental solar heating and enhances the northerly advection of warm air toward the centre-north of Argentina and Uruguay producing warm conditions in the region. Moreover, the cold anomalies over southeastern Brazil take place over the same area where upward vertical motion, reduced Outgoing Longwave Radiation and occurrence of precipitation are detected (figures not shown). Such characteristics promoting the reduction of temperature in the southeast of Brazil are associated with the cyclonic anomaly centered at 17°S–54°W clearly observed in the correlations between temperature in the subregion NORTH and the low-level winds (Fig. 3b). Opposite features occur with a cyclonic center over the western Atlantic and anticyclonic anomalies centered over southern Brazil. Consequently, temperature variability in areas of southern South America to the east of the Andes have inverse relationships describing a dipolar pattern with one center over the north of EPAT, centre-north of Argentina and Uruguay and the opposite center extended over southeastern Brazil. The lack of significant correlations between temperature in the subregion NORTH and those registered in the southernmost portion of Patagonia (Fig. 4b) shows the north–south pattern within EPAT previously described (see Table 2b).

During winter, a dipole of temperature is also detected over southern South America but with some characteristics different to that observed in autumn (Fig. 4c). Temperature in the subregion NORTH has significant positive correlation with temperature over most of Argentina and southern Uruguay. These relationships are consistent with the anticyclonic (cyclonic) circulation extended over the western Atlantic and eastern South America (Figs. 2-a3, 3c) that induce northerly (southerly) advection of warm (cold) air promoting warm (cold) conditions over a wide area of Argentina and Uruguay. Moreover, temperature in the subregion NORTH has significant negative correlation with temperature registered over southeastern Brazil. The cyclonic (anticyclonic) circulation centered over the western Atlantic at 25°S–30°W and the anticyclonic (cyclonic) center located farther to the southwest (Fig. 3c) induce weakened (reinforced) northwesterly advection of warm air or promote (obstruct) southeasterly advection of cold air producing cold (warm) conditions in the southeastern corner of Brazil. This pattern of atmospheric circulation that explains the significant inverse relationships between temperature in the north of EPAT and temperature registered in southeastern Brazil is different to the pattern described in autumn and, consequently, the anomalies of temperature in each season extend over different portions of southeastern Brazil (see Fig. 4b, c). In fact, the area where the temperature is affected by the anomalous circulation covers a small portion of the southeastern corner of Brazil during winter compared to the area affected by the processes described in the previous season. Although significant positive correlations cover the entire EPAT, the corresponding magnitudes decrease toward the south. This feature is consistent with results previously showed describing a weakened north–south separation during winter compared to the characteristics detected in summer and autumn (see Table 2c).

During spring, temperature in the subregion NORTH has significant positive correlations with those registered in the centre and south of Argentina and Chile whereas negative correlations are detected over a small area of southeastern Brazil near the Atlantic coast (Fig. 4d). The anticyclonic (cyclonic) anomalies extended throughout the entire troposphere over southern South America and the adjacent oceans that produce warm (cold) conditions in areas of EPAT (Fig. 2-a4, -b4) also promote warm (cold) conditions in central Argentina because affect the cloud cover increasing (reducing) the solar heating in the region. Moreover, the cyclonic (anticyclonic) circulation centered at 30°S–25°W over the western Atlantic (Fig. 3d) promotes (obstructs) southeasterly advection of cold air toward the southeastern corner of Brazil inducing cold (warm) conditions in such continental area. The correlation patterns between temperature in the subregion NORTH and the low-level winds show that the circulation anomalies over the Atlantic during spring are shifted to the southeast with respect to the positions observed in the previous winter (see Fig. 3c, d). Consequently, the area in southeastern Brazil where the temperature is influenced by the circulation pattern and it has inverse relationship with the temperature registered in the north of EPAT during spring is smaller than the area observed in winter (see Fig. 4c, d). In fact, temperature in the subregion NORTH during spring has significant negative correlation with temperature in a narrow area of southeastern Brazil (Fig. 4d) where the correlations with low-level winds are significant at the 90 % level (Fig. 3d). The significant positive correlations extended over the entire EPAT (Fig. 4d) are consistent with the weak north–south separation during spring previously described (see Table 2d).

3.2.2 Subregion SOUTH

During summer, correlations between temperature in the subregion SOUTH and Z850 show significant positive values over South America to the south of 20°S and the adjacent Atlantic and Pacific oceans (Fig. 5-a1). This correlation pattern indicates that warm (cold) conditions in the south of EPAT are associated with an anticyclonic (cyclonic) center extended over the region. Correlations between temperature in the subregion SOUTH and low-level winds (Fig. 6a) clearly display that warm (cold) conditions are associated with an anticyclonic (cyclonic) circulation center extended over southern South America and the adjacent oceans. The increased (reduced) solar radiation received at low levels due to the effect of this anticyclonic (cyclonic) anomaly induces high (low) continental heating producing warm (cold) conditions in the south of EPAT. The circulation pattern at upper levels shows that the strong anomalies over the south of South America extend throughout the entire troposphere (Fig. 5-b1).

The significant positive correlations between temperature in the subregion SOUTH and Z850 over southern South America and the adjacent Atlantic and Pacific oceans detected in summer persist during autumn (Fig. 5-a2). As was previously mentioned, anticyclonic (cyclonic) anomalies promote warm (cold) conditions over the south of EPAT. Correlations between temperature in the subregion SOUTH and low-level winds (Fig. 6b) display the anticyclonic (cyclonic) circulation center around southern South America associated with warm (cold) conditions in the south of EPAT and also detect a northwesterly (southeasterly) flow over the southernmost tip of the continent. Important differences with respect to the anomalies observed in summer are detected in the upper troposphere because the circulation pattern shows the typical structure of the SAM (Fig. 5-b2). This characteristic is a consequence of the particular configuration of the SAM during autumn which contains a strong anomalous center over southern South America of opposite sign to the anomalies developed over the Antarctic continent (e.g., Vera and Silvestri 2009). Anomalies resembling the PSA1 wave train extending from the tropical Pacific are also distinguished at upper levels.

In winter, correlations between temperature in the subregion SOUTH and Z850 reveal that warm (cold) conditions in the south of EPAT are associated with an anticyclonic (cyclonic) center extended over the south of South America and the adjacent oceans and cyclonic (anticyclonic) anomalies at subpolar latitudes (Fig. 5-a3). Correlations between temperature in the subregion SOUTH and low-level winds (Fig. 6c) clearly show that such circulation anomalies promote reinforced (weakened) westerlies and obstruct (favor) the advection of polar air toward the south of EPAT producing warm (cold) conditions in the region. The circulation centers detected at low levels are also observed in the upper troposphere being part of a structure that resembles the PSA1 pattern with alternating negative and positive nucleus of correlation extended over the Pacific, the southern portion of South America and the western Atlantic (Fig. 5-b3). Some characteristics of the circulation patterns at both low and upper levels are also observed in the anomalies associated with temperature in the north of EPAT (see Fig. 2-a3, -b3). The occurrence of some similar features is consistent with the significant correlation between temperature registered in both subregions during this season (correlation = 0.64, see Table 2c). However, the corresponding low-level winds show a clear difference over the area of South America to the south of 25°S. In fact, it was described that temperature in the north of EPAT is associated with a well defined anomalous center of circulation located over the western Atlantic that produces meridional flow over central Argentina (Fig. 3c). Such meridional flow is absent in the pattern associated with temperature in the south of EPAT which is characterized by a circulation center extended over the southern portion of the continent and the adjacent oceanic regions (Fig. 6c).

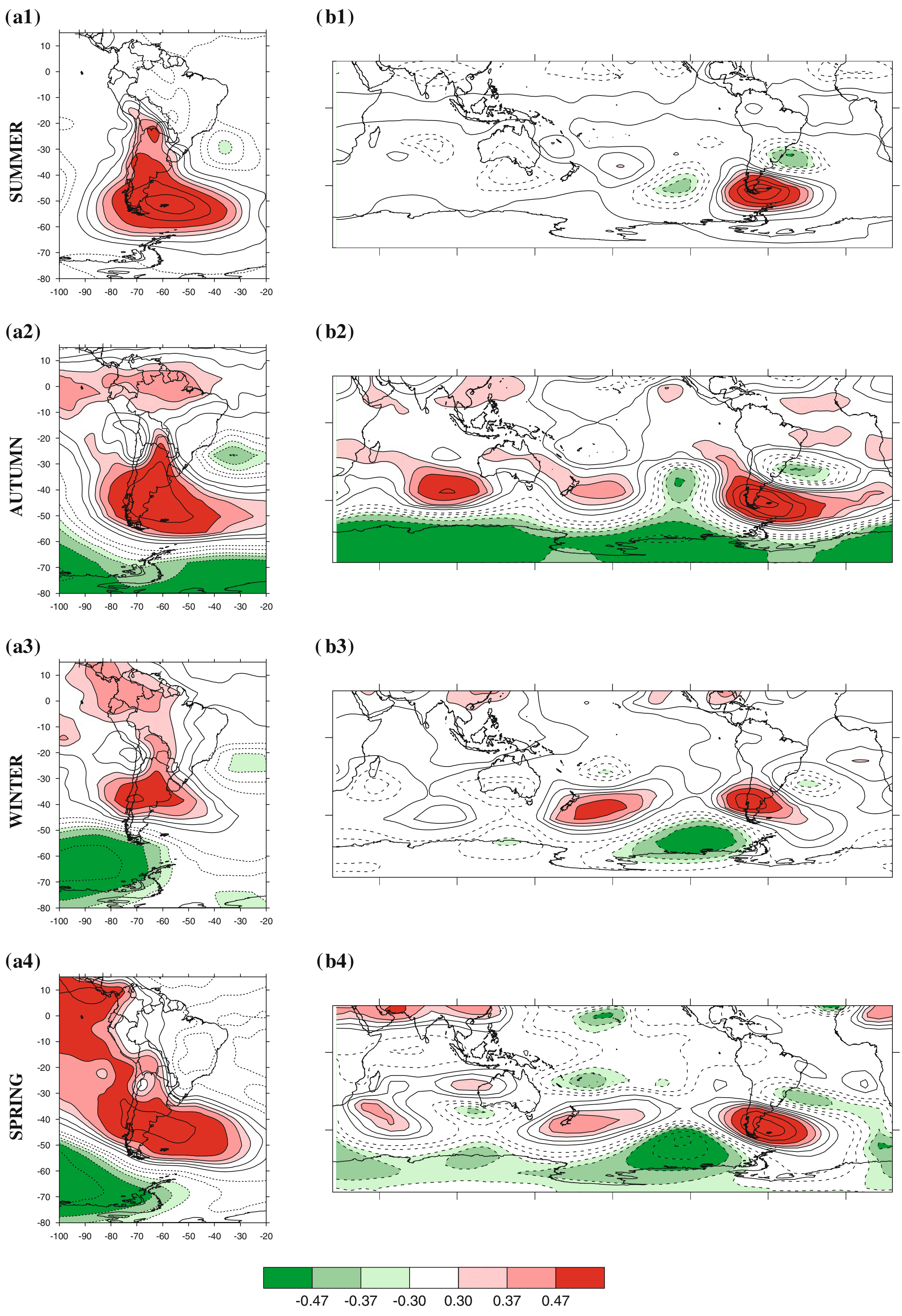


Fig. 5 As Fig. 2 but for the subregion SOUTH

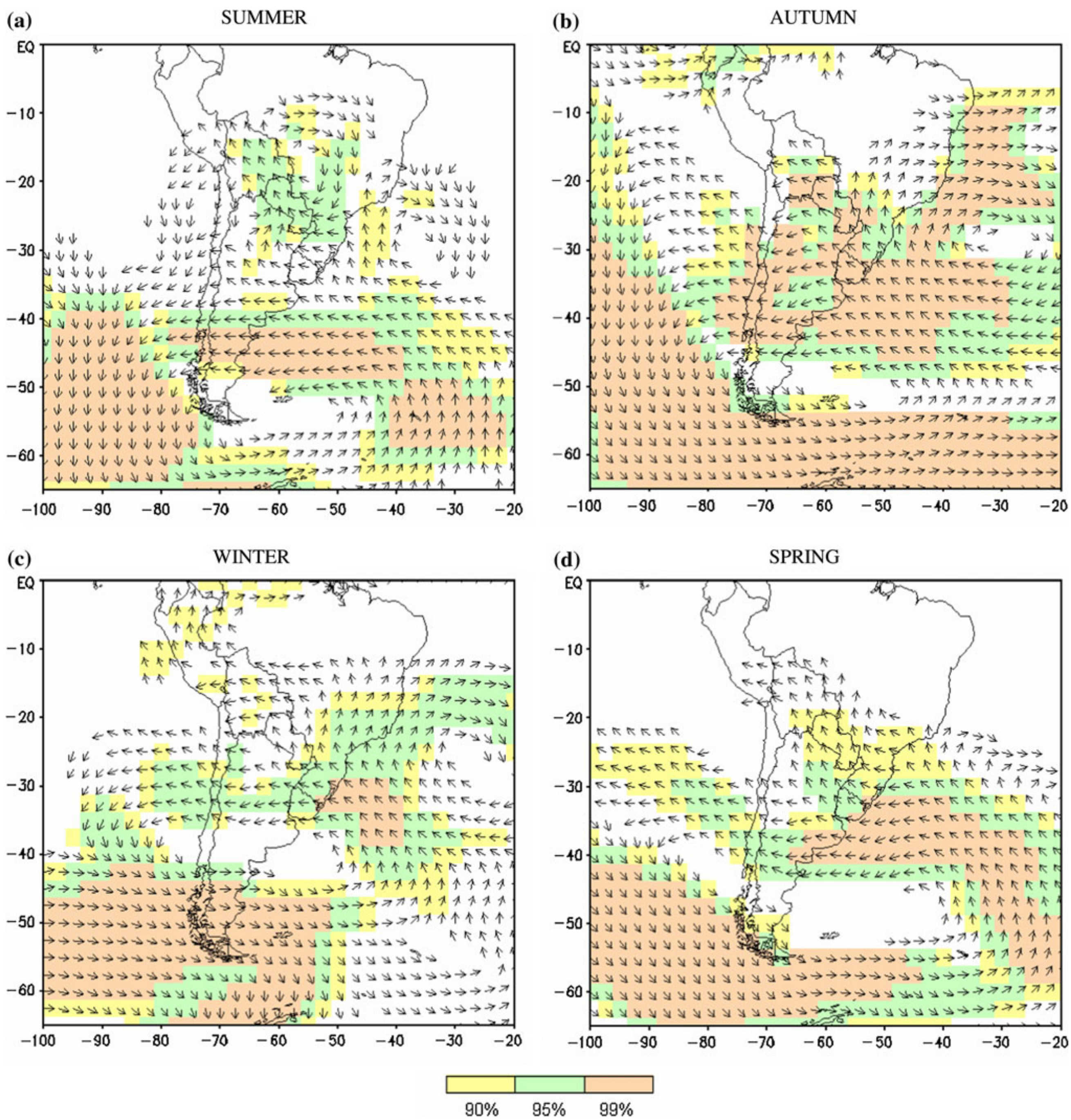


Fig. 6 As Fig. 3 but for the subregion SOUTH

Correlations between temperature in the subregion SOUTH and Z850 during spring exhibit significant positive values over the western Atlantic in 35°S–55°S, the South American continent to the south of 20°S and the eastern Pacific whereas significant negative values are detected at subpolar latitudes (Fig. 5-a4). As was described in summer and autumn, this correlation pattern indicates that warm (cold) conditions in the south of EPAT are promoted by anticyclonic (cyclonic) anomalies that reduce (increase) the cloud cover increasing (reducing) the continental heating in the region. Correlations between temperature in the subregion SOUTH and low-level winds clearly display the anticyclonic (cyclonic) circulation center over southern South America and the adjacent oceans associated with warm (cold) conditions in the south of EPAT (Fig. 6d). The northwesterly (southeasterly) low-level flow over the southern tip of the continent associated with the anticyclonic (cyclonic) circulation (Fig. 6d) also contribute to warm (cold) conditions in the area. The structure of the SAM is detected at upper levels (Fig. 5-b4) being a consequence of the spatial structure of this atmospheric pattern during spring over southern South America (e.g., Vera and Silvestri 2009). Anomalies resembling the PSA1 wave train extended southeastward from the western tropical Pacific are also detected at upper levels. As in winter, the low and upper-troposphere circulation anomalies associated with temperature variability in the subregion SOUTH during spring have some features similar to those observed in the anomalies affecting the temperature in the north of EPAT (see Fig. 2-a4, -b4). The occurrence of some similar characteristics is consistent with the significant positive correlation between temperature registered in both areas (correlation = 0.49, see Table 2d). However, the low-level winds over areas of South America to the south of 30°S associated with temperature in the subregion SOUTH describe a circulation center extended over the southern portion of the continent and the adjacent oceans (Fig. 6d) whereas two separated centers, one over the western Atlantic and the other over the eastern Pacific, are observed in the circulation pattern corresponding to the temperature in the north of EPAT (Fig. 3d).

Temperature in the subregion SOUTH depicts a dipolar pattern with temperature registered in subtropical areas of the continent east of the Andes (Fig. 7). Although this dipole is detected during the four seasons, the subtropical anomalies in winter and spring extend over areas smaller than those observed in summer and autumn. These differences are closely related to the structure of the atmospheric circulation pattern associated with the temperature over the south of EPAT in each season that promotes inverse anomalies at lower latitudes. In fact, correlations between temperature in the subregion SOUTH and Z850 during summer show that the low-level circulation pattern associated with warm (cold) conditions in southern EPAT contains an anticyclonic (cyclonic) anomaly extended over the South American continent to the south of 20°S and the adjacent oceans and a cyclonic (anticyclonic) anomaly centered at 17°S–57°W over Brazil (Fig. 5-a1). Correlations between temperature in the subregion SOUTH and low-level winds (Fig. 6a) clearly show that this circulation pattern associated with warm (cold) conditions in the south of EPAT induces weakened (reinforced) northwesterly advection of warm air from the Amazon promoting cold (warm) conditions over southern Brazil, Paraguay, northern Argentina and Uruguay (Fig. 7a).

In autumn, the anticyclonic (cyclonic) anomaly extended over the south of South America and the adjacent oceans associated with warm (cold) conditions in southern EPAT (Fig. 5-a2) also promotes weakened (enhanced) advection of warm air from the Amazon region toward subtropical areas. In fact, correlations between temperature in the subregion SOUTH and low-level winds (Fig. 6b) clearly show that the circulation pattern associated with increased (decreased) temperature in southern EPAT induces weakened (enhanced) northwesterly flow over a wide area comprising southern Brazil, eastern Bolivia, Paraguay and northern Argentina. Furthermore, the cyclonic (anticyclonic) circulation centered at 30°S–30°W over the western Atlantic (Fig. 6b) promotes anomalous southerly (northerly) winds over southeastern Brazil. These anomalies of atmospheric circulation induce cold (warm) conditions over the subtropical area explaining the occurrence of inverse relationships with the temperature registered in the south of EPAT (Fig. 7b).

The circulation pattern associated with warm (cold) conditions in the south of EPAT during winter exhibits anticyclonic (cyclonic) anomalies over a wide area of South America to the north of 45°S and a cyclonic (anticyclonic) anomaly centered at 25°S–25°W over the subtropical western Atlantic (Fig. 5-a3). Correlations between

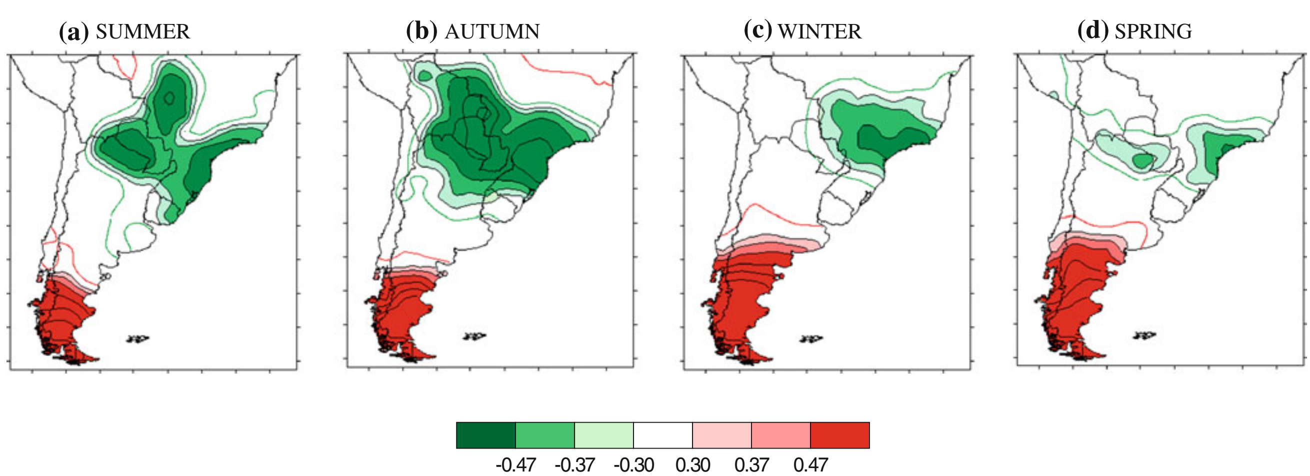


Fig. 7 As Fig. 4 but for the subregion SOUTH

temperature in the subregion SOUTH and low-level winds (Fig. 6c) show that this configuration leads to weakened (reinforced) northwesterly-northerly flow of warm air or induces (obstructs) southerly advection of cold air toward southeastern Brazil favoring the occurrence of cold (warm) conditions in this region (Fig. 7c). During winter, there is a lack of the strong correlations between temperature in the south of EPAT and low-level winds over Paraguay, northern Argentina and eastern Bolivia detected in the previous summer and autumn (see Fig. 6a–c). Coherently, the subtropical area where the temperature has inverse relationship with that registered in the subregion SOUTH extends only over a portion of southern Brazil during winter whereas it covers a wider region that include Paraguay, the north of Argentina and areas of eastern Bolivia in the previous seasons (see Fig. 7a–c).

In spring, the anticyclonic (cyclonic) anomaly extended over southern South America and the adjacent oceans associated with warm (cold) conditions in the south of EPAT (Fig. 5-a4) also induces weakened (reinforced) northwesterly warm flow from the Amazon toward subtropical regions (Fig. 6d) producing cold (warm) conditions in areas of Paraguay, northern Argentina and the southeastern corner of Brazil (Fig. 7d). Significant correlations between temperature in the subregion SOUTH and low-level winds over Paraguay, northern Argentina, eastern Bolivia and southern Brazil are also detected during summer and autumn (see Fig. 6a, b). However, the values of those correlations during spring are lower than in the other two seasons. This characteristic is clearly displayed by the fact that correlations over such subtropical areas are significant at the 90 % level in spring whereas they are significant at the 95 and 99 % levels in summer and autumn. It means that the connection between temperature in the subregion SOUTH and the low-level circulation affecting the subtropical areas during spring is weaker than in summer and autumn. Coherently, the inverse link between temperature in the south of EPAT and temperature registered at lower latitudes during spring is weaker than in the other two seasons. In fact, the subtropical region where the temperature has significant negative correlation with the temperature registered in the south of EPAT during spring (Fig. 7d) is small compared to those observed in summer and autumn (Fig. 7a, b). Furthermore, the magnitudes of the negative correlations over the southeastern corner of Brazil, Paraguay and northern Argentina during spring are lower than in the other two seasons.

4 Summary and conclusions

Characteristics of seasonal-to-interannual temperature variability during the last 30 years in the southernmost areas of South America east of the Andes have been presented in this paper providing a new insight about the climatic variability in this remote region of the world. The analysis describes homogeneous regions of temporal variability and the atmospheric circulation anomalies associated with warm and cold conditions in each of them. Relationships with temperature registered in other areas of southern South America are also depicted.

Previous studies found a north–south pattern of variability in annual and monthly temperature registered in Patagonia. Although we also show a separation among the northern and southern regions of EPAT, our analysis demonstrates that this separation is more evident in summer and autumn than in winter and spring. In other words, temperature variability within EPAT has a clear separation north–south in summer and autumn whereas it tends to be spatially more homogeneous in winter and spring. The differences north–south during summer are consistent with the fact that the incident solar radiation produces continental heating in the north of EPAT higher than that registered in the southern regions. In winter, the reduced solar radiation produces only small changes in the characteristics of the polar air masses moving to the north channeled by the Andes promoting homogeneous temperature variability within EPAT. Results presented in this paper show that the north–south difference observed in summer persists in autumn whereas the more homogeneous conditions during winter are also detected in spring.

The study of the atmospheric circulation pattern connected with temperature variability in the north of EPAT during summer shows that anticyclonic (cyclonic) anomalies extended over southern South America and the adjacent western Atlantic and eastern Pacific reinforce (reduce) the westerlies producing warm (cold) conditions in the region. Cyclonic (anticyclonic) anomalies at subpolar latitudes contribute to reinforced (weakened) westerlies and hinder (favor) outbreaks of polar air increasing (decreasing) the temperature. These circulation anomalies also affect other areas of southern South America inducing significant positive correlations between temperature in the north of EPAT and that registered over the centre-north of Argentina and Uruguay.

During autumn, an anticyclonic (cyclonic) center over the western Atlantic promotes northerly (southerly) advection of warm (cold) air producing warm (cold) conditions in the north of EPAT. The anticyclonic (cyclonic) anomaly over the western Atlantic also induces warm (cold) conditions in the centre-north of Argentina and Uruguay whereas a cyclonic (anticyclonic) center located farther to the north over the continent promotes cold (warm) conditions in a wide area of southeastern Brazil. Consequently, a dipole of temperature characterized by anomalies extended over northern Patagonia, centre-north of Argentina and Uruguay and anomalies of opposite sign located over southeastern Brazil is detected during this season.

Reinforced (weakened) westerlies and weakened (reinforced) southerly advection of polar air produce the warm (cold) conditions in the north of EPAT during winter. Anticyclonic (cyclonic) anomalies over the western Atlantic and a cyclonic (anticyclonic) center developed farther to the northeast inducing warm (cold) conditions over most of Argentina and southern Uruguay and cold (warm) conditions in the southeastern corner of Brazil are associated with the circulation pattern that produce warm (cold) conditions in the north of EPAT. Therefore, a dipole of temperature is also detected during this season in southern South America.

Anticyclonic (cyclonic) anomalies over the southern portion of South America and the adjacent oceans and a cyclonic (anticyclonic) center at subpolar latitudes produce reinforced (weakened) westerlies and hinder (favor) outbreaks of polar air promoting warm (cold) conditions in the north of EPAT during spring. The anticyclonic (cyclonic) anomalies extended over southern South America also induce warm (cold) conditions in central Argentina whereas a cyclonic (anticyclonic) center developed over the subtropical Atlantic promote cold (warm) conditions over a small area in the southeastern corner of Brazil. Therefore, the circulation anomalies explain the positive correlations between temperature in the north of EPAT with that registered over the centre of Argentina and the negative correlations with temperature in the southeastern corner of Brazil.

Temperature variability in the south of EPAT is strongly influenced by circulation anomalies extended over southern South America and the adjacent oceans. During summer, anticyclonic (cyclonic) anomalies developed over this region enhance (reduce) the incoming solar radiation producing warm (cold) conditions in the south of EPAT. The circulation pattern associated with warm (cold) conditions in southern areas of EPAT also contains a cyclonic (anticyclonic) center developed over the centre-south of Brazil. This circulation pattern induce weakened (reinforced) northwesterly advection of warm air from the Amazon producing cold (warm) conditions in a wide area of southern Brazil, Paraguay, northern Argentina and Uruguay. Consequently, inverse relationships are detected between temperature in southern EPAT and that registered at lower latitudes describing a dipole over southern South America.

During autumn, anticyclonic (cyclonic) anomalies over southern South America enhance (reduce) the continental heating and induce northwesterly (southeasterly) low-level winds over the south of EPAT producing warm (cold) conditions in the region. These anticyclonic (cyclonic) anomalies extended over the southern portion of the continent and adjacent oceans and a cyclonic (anticyclonic) circulation center located farther to the northeast over the western Atlantic produce weakened (reinforced) northwesterly flow from the Amazon and induce (obstruct) southerly advection of cold air promoting cold (warm) conditions in a broad subtropical area comprising southern Brazil, eastern Bolivia, Paraguay and northern Argentina. Therefore, a strong dipolar structure of temperature with opposed centers over Patagonia and the mentioned subtropical region is detected during this season.

The warm (cold) conditions in the south of EPAT during winter are associated with an anticyclonic (cyclonic) center developed over the south of South America and the adjacent oceans and cyclonic (anticyclonic) anomalies at subpolar latitudes that induce reinforced (weakened) westerlies and obstruct (favor) the advection of polar air toward Patagonia. The anticyclonic (cyclonic) anomalies over the continent and a cyclonic (anticyclonic) center developed over the subtropical western Atlantic promote cold (warm) conditions in southeastern Brazil. Consequently, the circulation pattern affecting the temperature in southern EPAT induces inverse conditions at lower latitudes promoting a dipolar pattern of temperature over southern South America.

During spring, warm (cold) conditions in the south of EPAT are associated with anticyclonic (cyclonic) anomalies over southern South America and the adjacent oceans that enhance (reduce) the incoming solar radiation and induce northwesterly (southeasterly) flow over southern Patagonia. These anticyclonic (cyclonic) anomalies also induce weakened (reinforced) northwesterly flow over subtropical areas promoting cold (warm) conditions in Paraguay, northern Argentina and southeastern Brazil.

The relationships between temperature in EPAT and temperature registered in other regions of southern South America showed throughout this paper describe a dipolar pattern characterized by one center over EPAT and the center of opposite sign extended in lower latitudes. The spatial configurations of this dipole in each season considering separately the northern and southern areas of EPAT were not previously addressed in the scientific bibliography. These characteristics and the anomalies of atmospheric circulation associated with temperature variability in the subregions of EPAT are new results relative to previous studies that investigated the climate variability in southern South America.

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