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Influence of the large-scale climate variability on daily rainfall extremes over Argentina

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ABSTRACT: A singular value decomposition (SVD) analysis was performed jointly on the daily intensity of extreme rainfall (DIER) over Argentina and sea surface temperature (SST) anomalies from 17.5°N–90°S to describe and understand the influence of the large-scale variability of the SSTs on the regional extreme rainfall events for spring summer, autumn and winter. Three main leading modes were identified in agreement with previous works. Mode 1 activity is strongly related to El Niño-Southern Oscillation (ENSO). Warm anomalies in the central-eastern tropical Pacific and western Indian Ocean induce circulation anomalies extended along the South Pacific and the development of a continental-scale circulation gyre in South America promoting moisture convergence, and in turn favouring DIER positive anomalies, in eastern Argentina. The combined influence of SST anomalies in the tropical Atlantic and western tropical Pacific characterizes Mode 2 activity, which induces an anticyclonic (cyclonic) circulation gyre in southeastern South America promoting anomalous moisture convergence (divergence) and thus positive (negative) DIER anomalies in eastern Argentina in spring and fall (summer and winter). Finally, Mode 3 activity is also influenced by SST anomalies in tropical central-eastern Pacific from winter to summer. The associated teleconnections contribute to the development of a cyclonic circulation mainly influencing southeastern South America (SESA) circulation to the north of 30°S from summer to winter, and further south in spring.

KEY WORDS large-scale climate variability; tropical oceans; daily precipitation; Argentina

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1. Introduction

Previous studies have documented that seasonal precipitation variability in southern South America (SSA) is partially influenced by local and remote ocean conditions and in particular by those at the tropics. SSA is strongly affected by El Niño-Southern Oscillation (ENSO), especially in austral spring and autumn (e.g. Grimm *et al.*, 2000; Penalba *et al.*, 2005). Such influence is mainly exerted by Rossby wave trains, extended along arch trajectories from tropical Pacific towards South America (e.g. Kidson, 1999). During ENSO warm events, the large-scale circulation anomalies induce a cyclonic (anticyclonic) circulation anomaly at extratropical (tropical) regions of South America, favouring moisture convergence and upward conditions in southeastern South America (SESA) (e.g. Grimm *et al.*, 2000). Pacific Decadal Oscillation (PDO) modulates ENSO influence on precipitation anomalies in SSA, acting constructively (destructively) when ENSO and PDO are in the same (opposite) phase (Kayano *et al.*, 2009). In addition, sea surface temperature (SST) variability in both tropical Indian and Atlantic Oceans influences rainfall variability in SSA on interannual and decadal time scales. The equatorial Atlantic conditions during ENSO warm events can modulate its influence on austral summer rainfall over SSA, such that when the equatorial Atlantic is warmer than normal, ENSO influence is weaker (Barreiro and Tippmann, 2008). Doyle and Barros (2002) showed that in austral summer, positive SST anomalies over the southwestern Atlantic are related to positive seasonal precipitation anomalies over SSA and negative over the South Atlantic Convergence Zone (SACZ). Moreover, SST anomalies in the Indian Ocean associated with the so-called Indian Ocean dipole are associated with positive rainfall anomalies in SSA, particularly during austral spring (Chan *et al.*, 2008).

Besides the large interest that the scientific community has shown in describing and understanding the variability of seasonal precipitation in SSA (e.g. Vera *et al.*, 2006; Marengo *et al.*, 2010), research focusing on the variability associated with the occurrence of extreme daily rainfall events in SSA, and in particular in Argentina, has not received enough attention yet. Grimm and Tedeschi (2009) show that the ENSO influence on the frequency of precipitation extremes over South America seems to be generally coherent with that on monthly rainfall quantities, although the former exhibits a larger magnitude. In addition, Mo and Berbery (2011) found that circulation changes in South

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America in response to ENSO affect the moisture transport from the tropics to the extratropics through modulations of the low-level jet east of the Andes, which in turn favours or suppresses the occurrence of extreme precipitation events. Moreover, persistent wet spells are intensified over SESA in ENSO warm events associated with cold tropical Atlantic conditions (Mo and Berbery, 2011).

Recently, Robledo *et al.* (2013) described the main patterns of co-variability between monthly means of daily intensity of extreme rainfall (hereafter called DIER) in Argentina and global SST anomalies for spring, summer and autumn. They show that positive SST anomalies in the tropical Pacific, mainly related to ENSO activity, are associated with increased extreme daily rainfall in central and northeastern Argentina. In addition, they found significant relationship between DIER anomalies and SST anomalies in other tropical oceans such as tropical Indian and Atlantic Oceans. Their results motivate us to better understand the dynamical processes explaining the relationship between large-scale SST anomaly variability and that of DIER in Argentina. Therefore, the general goal of this work is to analyse the atmospheric circulation anomalies at large and regional scales that link changes in the SST conditions with those of DIER in Argentina. Robledo *et al.* (2013) focused only on three seasons: spring, summer and autumn. This study encompasses the four seasons (spring, summer, autumn and winter),

The variance of seasonal circulation anomalies in the Southern Hemisphere (SH) is largely explained by the activity of three principal patterns (e.g. Kidson, 1999; Mo, 2000). The leading pattern, generally known as the Southern Annular Mode (SAM), is characterized by an anomaly centre of geopotential heights or surface pressure centred over the Antarctica and anomaly centres of opposite signs at middle latitudes with a 3-wave structure. SAM is mainly maintained by internal atmospheric variability. The second and third leading patterns of circulation variability (known as 'Pacific – South American' or PSA patterns) are related to Rossby wave trains forced by tropical convection and extended along the South Indian-South Pacific Oceans. The second leading pattern, known as PSA1 pattern (e.g. Mo, 2000), emanates from central equatorial Pacific towards the high latitudes and is strongly influenced by ENSO. On the other hand, the third leading pattern, known as PSA2 pattern, is characterized by a wavetrain extended from Australia-Indian Ocean sector towards South America, and is mainly influenced by the SST variability in the tropical Indian Ocean and the Maritime continent (Mo, 2000). The hypothesis underpinning the present study considers that the activity of the three leading patterns influences the climate variability in South America. In that sense, the relevance of the development of teleconnection patterns in the SH onto DIER variability in Argentina is also assessed.

The paper is organized as follows: Section 2 describes data sources and methodology, Section 3 discusses for each leading singular value decomposition (SVD) pattern between DIER in Argentina and SST anomalies, the associated anomalies of both SST and circulation in the SH with a special focus on the regional circulation features in SSA; Section 4 presents the conclusions.

2. Data and methodology

Daily rainfall data available from surface stations of the National Weather Service of Argentina distributed throughout the country are used. The period of study is 1962–2005, and the austral seasons are considered: December-January-February (DJF) as summer, March-April-May (MAM) as autumn, June-July-August (JJA) as winter and September-October-November (SON) as spring. An index of DIER is defined as the quotient between the monthly accumulated extreme daily rainfall (AE) and the number of days with extreme daily precipitation events per month (PE),

$$\mathrm{DIER}_{i,j} = \frac{\mathrm{AE}_{i,j}}{\mathrm{PE}_{i,j}} \quad (1)$$

where i represents months (i.e. from 1 to 12) and j represents years (Robledo and Penalba, 2008). It can be mentioned that the climatology presented in Figure 1 includes 43 rain gauges available in this region for the period 1960–2000 (Robledo and Penalba, 2008). However, the analysis of the leading modes of extreme rainfall variability described below includes only 35 of them, as they cover the longest possible periods, have less than 10% of missing data and have passed the quality control tests (Penalba and Robledo, 2010).

Following Robledo and Penalba (2008), the extreme daily rainfall values considered are those daily amounts larger than 75th daily percentile. This threshold is based on the 75th daily percentile which is determined empirically calculated on all the daily rainfall for each meteorological station. This daily percentile series is clarified by smoothing the data using a 7-day running average.

As Robledo and Penalba (2008) described, for all seasons, maximum mean DIER values are locate over northeastern Argentina and decrease westward and southward (Figure 1), in agreement with Penalba and Robledo (2010). Largest values are observed in autumn and summer while they are smaller during winter (Figure 1).

SST fields defined over a 5° grid are used from Kaplan SST V2 dataset (Kaplan *et al.*, 1998). Circulation and moisture fields correspond to the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis I project (Kalnay *et al.*, 1996), on a 2.5° grid. All gridded datasets are for the period 1962–2005, provided by the National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research/Earth System Research Laboratory Physical Sciences Division (NOAA/OAR/ESRL PSD), Boulder, Colorado, USA, through their web site at http://www.esrl.noaa.gov/psd/.

SVD analyses are performed jointly on the anomalies of DIER in Argentina and SST between 17.5°N and 90°S for spring, summer, autumn and winter. Monthly anomalies are computed by first subtracting the climatological

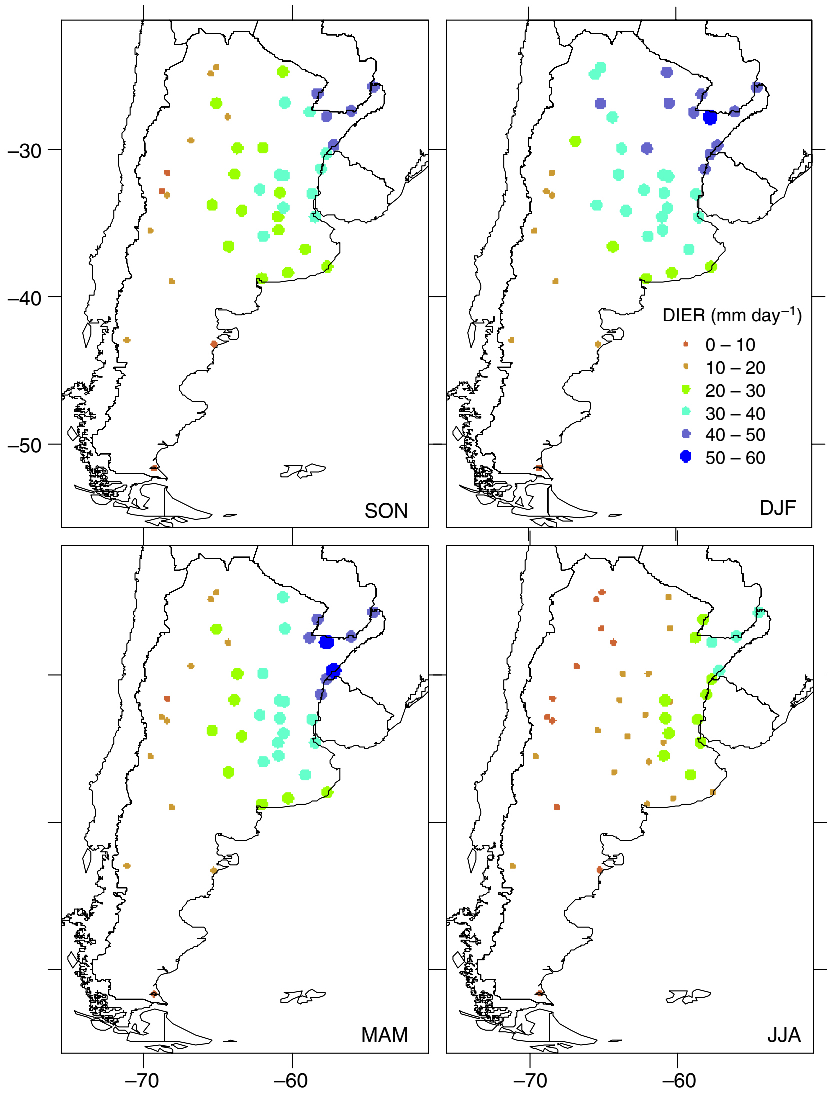

Figure 1. Climatological mean values of DIER75 for each season. Period 1961–2000. September, October and November (SON), December, January and February (DJF), March, April and May (MAM) and June, July and August (JJA). Values in mm day^{-1}.

monthly means from the original data and then removing the linear trends. The expansion coefficient time series (hereinafter SVD time series) for both variables are used to describe the temporal evolution of the leading patterns of co-variability. The dynamical conditions at both large and regional scales associated with the leading SVD patterns are analysed through the computation of linear regression maps between SVD time series of DIER and seasonal anomalies of different atmospheric fields (200-hPa streamfunction, moisture fluxes vertically integrated between 1000 and 500 hPa). Zonal means are also removed from 200-hPa streamfunction anomalies in order to better describe circulation zonal asymmetries (e.g. Vera *et al.*, 2004). Regressed values are only displayed if they are significant at the 90% level (Student's *t*-test).

3. Results

This section describes for each leading SVD mode, the general characteristics of the associated global and regional circulation anomalies resulted from the linear regression maps based on the SVD time series of DIER. SST regression maps based on the corresponding SVD SST time series are also included. To facilitate the description of the physical mechanisms involved, the anomalies represented in the regression maps are considered as associated with the positive phase of each SVD mode. However, it becomes obvious that also the opposite relationship holds.

3.1. Mode 1

Regressed DIER anomalies related to Mode 1 activity are presented in Figure 2(a). For all seasons, positive DIER anomalies are evident in eastern Argentina with an increase of around 20% with respect to the long-term mean values, depending the season (Figure 1). The largest values are found in autumn and winter. Robledo *et al.* (2013) show that Mode 1 displays dominant variability at around 4 years. In agreement, regressed SST anomalies related to this mode (Figure 3) exhibit for all seasons,

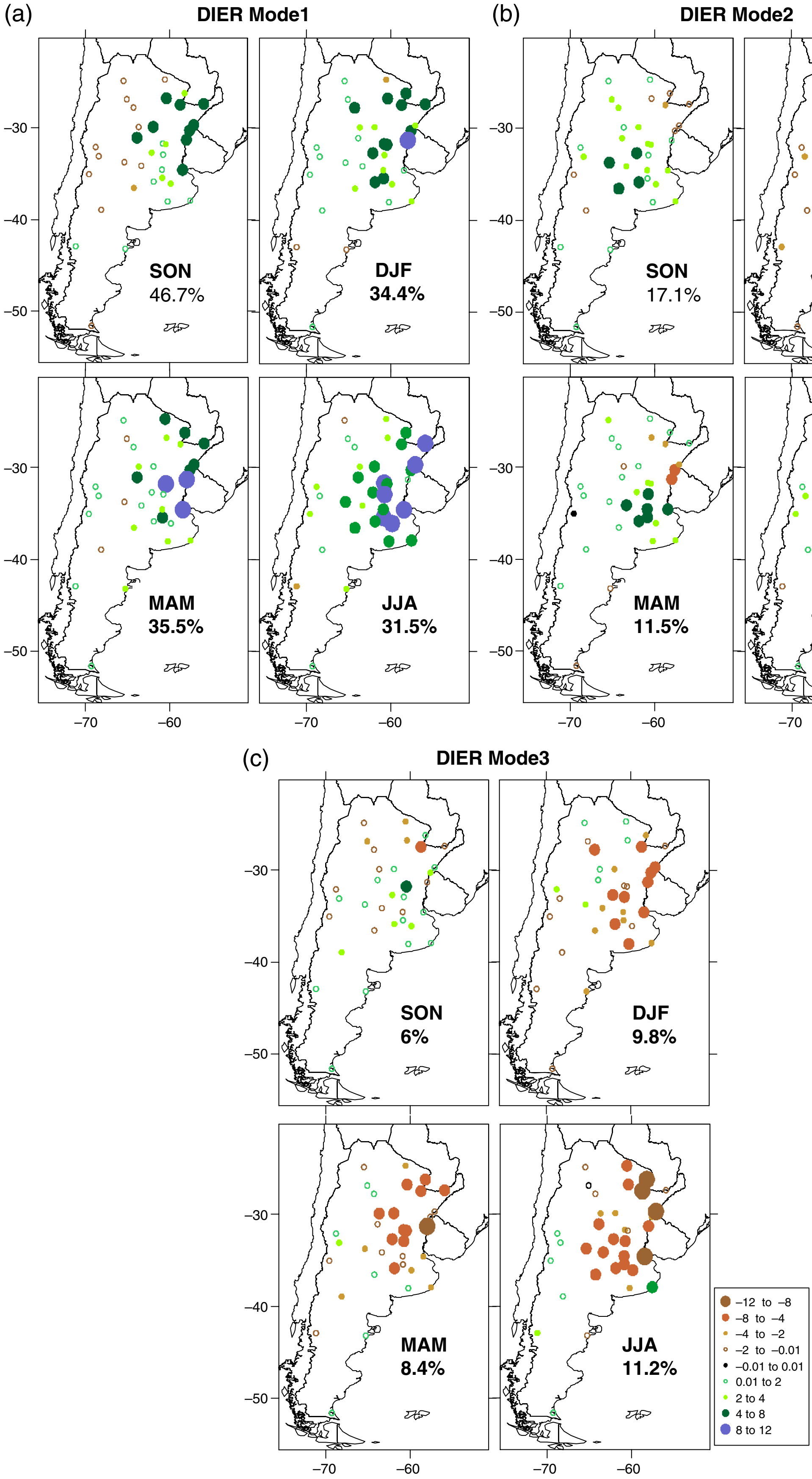

Figure 2. Linear regression maps of DIER75 against DIER75 SVD times series for all seasons and for (a) Mode 1, (b) Mode 2 and (c) Mode 3. Values larger in magnitude than |4| are significant at 10% significant level (according to Student's *t*-test). Units in mm day^{-1}. Below the season are presented the percentage of the variance explained for each mode.

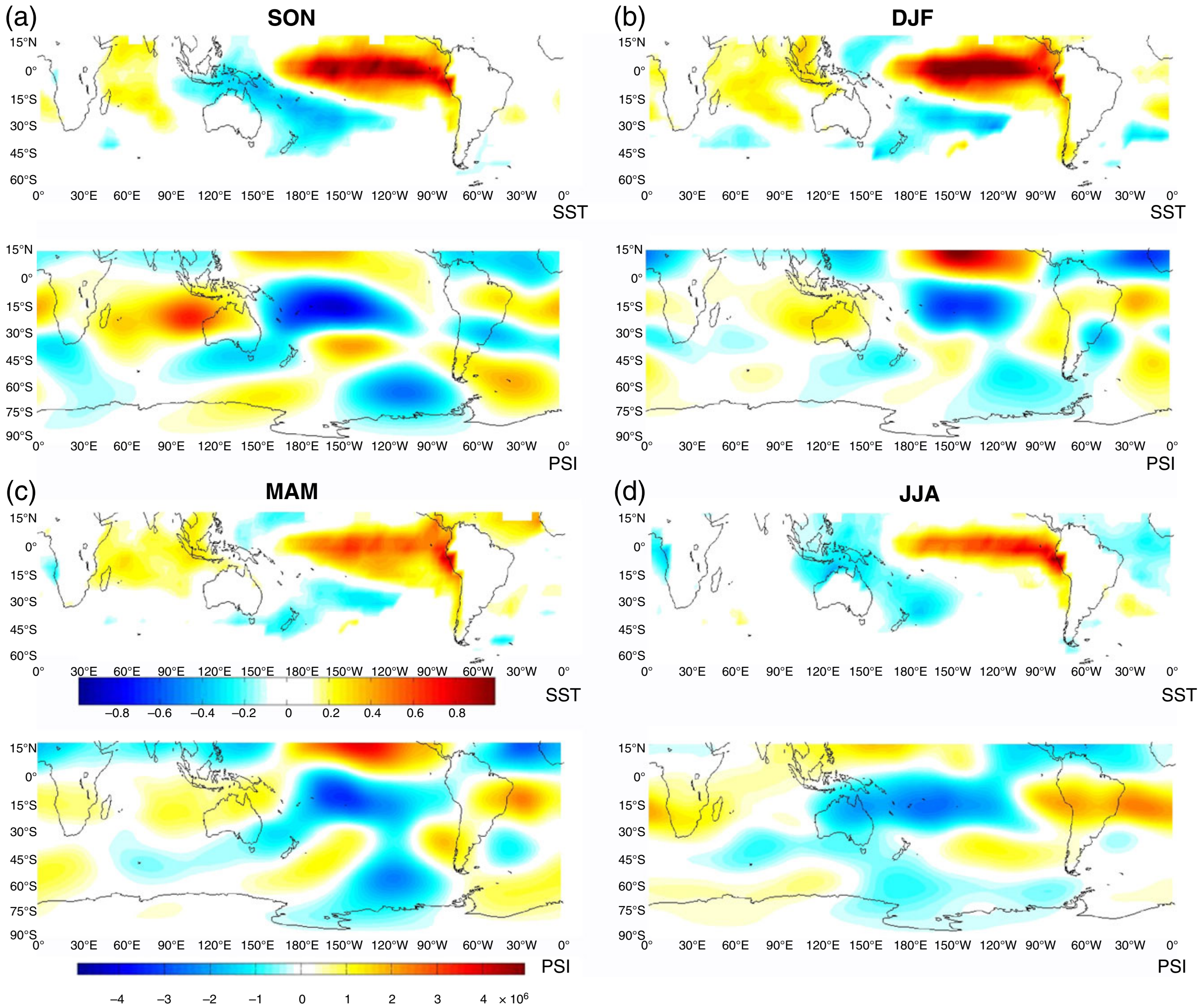

Figure 3. Linear regression maps of (top) SST anomalies (degrees) and (bottom) 200-hPa streamfunction anomalies ($m^2 s^{-2}$) against DIER75 SVD time series of Mode 1, for (a) SON, (b) DJF, (c) MAM and (d) JJA.

the largest anomalies in the tropical Pacific with a pattern resembling that associated with ENSO warm events (e.g. Ropelewski and Halpert, 1987). Also Grimm and Tedeschi (2009) found that the most consistent relationship between ENSO and heavy rainfall occurrence is found over SESA. On the other hand, in spring, summer and autumn, positive SST anomalies are found over central and western tropical Indian Ocean in relationship with Mode 1. Positive (negative) SST anomalies are observed over northern tropical Atlantic during autumn (winter). In agreement, Mo and Berbery (2011) showed that in MAM, opposite phases of SST anomalies in the North Atlantic and equatorial Pacific may intensify extreme precipitation anomalies in SESA.

A comparison between regression maps for SST anomalies and those for streamfunction anomalies shows clear links between the sources of the wavetrains and the regions with large tropical SST anomalies. Some seasonal variations are evident though. In spring and autumn, PSA-like patterns are strongest at both subtropical and high latitudes, while in summer and winter, extratropical circulation anomalies are much weaker. Large-scale circulation anomalies associated with Mode 1 show for all seasons, evidence of two wave trains emanating from tropical Indian and central Pacific Oceans, respectively (Figure 3). The trajectories of these wave trains are bow shaped, and they reflect west of the Antarctic Peninsula towards lower latitudes. The circulation pattern seems a combination of those associated with PSA1 and PSA2 (Mo, 2000).

In the vicinity of South America, the two large-scale wave trains merge into one determining a cyclonic anomaly located at around the southern tip of SSA, and an anticyclonic anomaly extended further to the equator (Figure 3). They exhibit an equivalent barotropic vertical structure (not shown), and thus the region located between the downstream portion of the upper-level cyclonic anomaly is associated with low-level moisture convergence in SESA region (Figure 4). This mechanism explains the positive DIER anomalies associated with Mode 1 identified over eastern Argentina (Figure 1(a)).

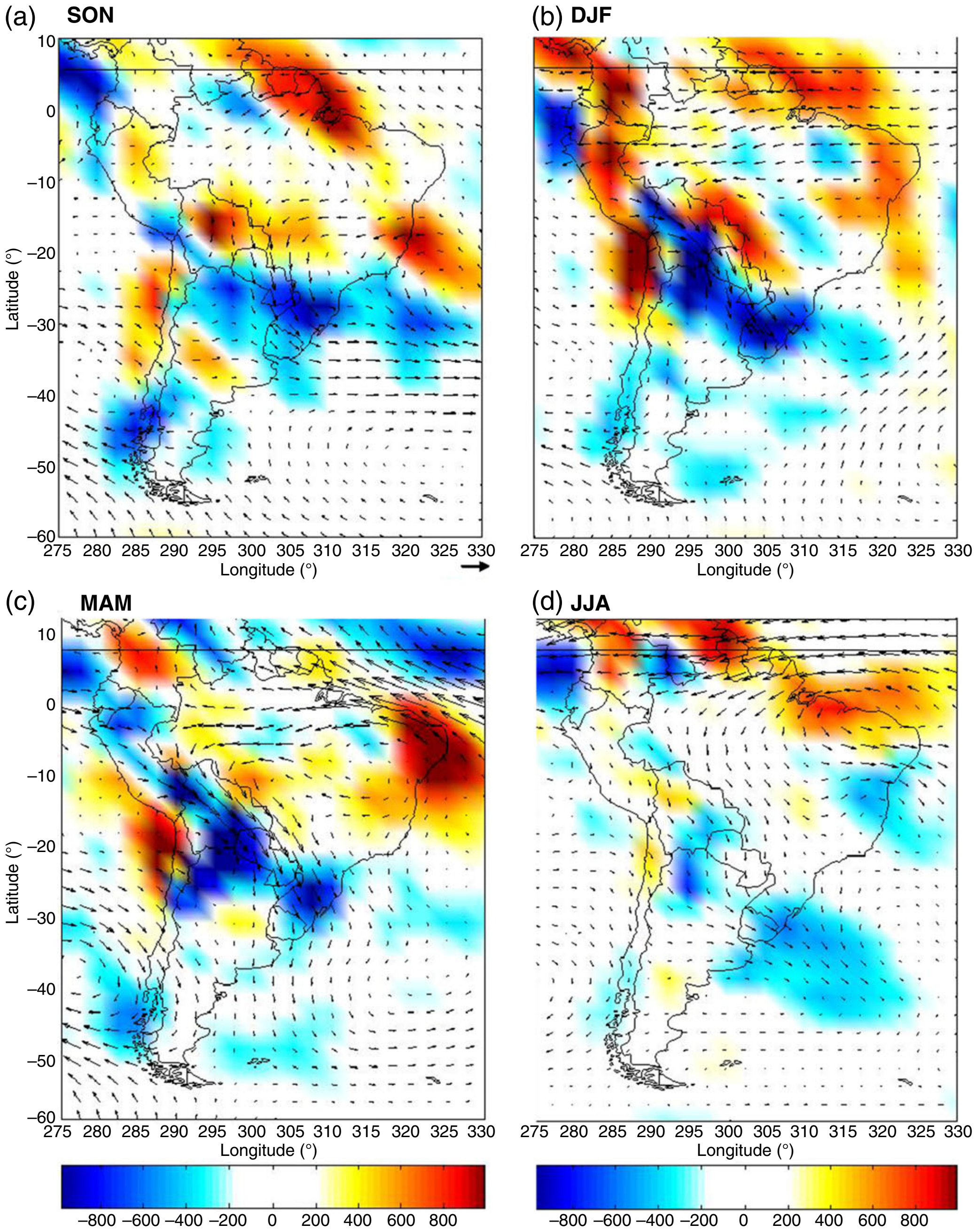

Figure 4. Linear regression maps of moisture fluxes (vectors, 10^3 g kg^{-1} m s^{-1}) vertically integrated in the 1000/500 hPa thickness against DIER75 SVD time series of Mode 1, and its corresponding divergence (shaded 10^3 g kg^{-1} s^{-1}). Reference vector is 20×10^3 g kg^{-1} m s^{-1}.

In fact, moisture flux anomalies exhibit all year around a continental-scale anticyclonic gyre, but with seasonal variations. In spring, the moisture is transported from southwestern tropical Atlantic to the subtropics, favouring moisture convergence (divergence) in SESA (southeastern Brazil). On the other hand, in summer, autumn and winter (with much less intensity), largest moisture flux anomalies penetrate into the continent through South America northeastern coast, deflect southeastward right along the eastern slope of the Andes and converge in SESA. In agreement, Mo and Berbery (2011) show that South America circulation response to ENSO affects the tropical-subtropical moisture transport, through modulations of the low-level jet maximum located in Bolivia east of the Andes, which in turn favours or suppresses the occurrence of extreme events in SESA. In addition, an Indian Ocean basin-wide warming (considered as a response to ENSO) seems to reinforce from March to May the anomalous circulation in SSA favourable to increased rainfall in SESA and decreased rainfall further north (e.g. Taschetto and Ambrizzi, 2012).

3.2. Mode 2

Regressed DIER anomalies over SSA related to Mode 2 activity are presented in Figure 2(b). In spring and autumn, large positive DIER anomalies are found in

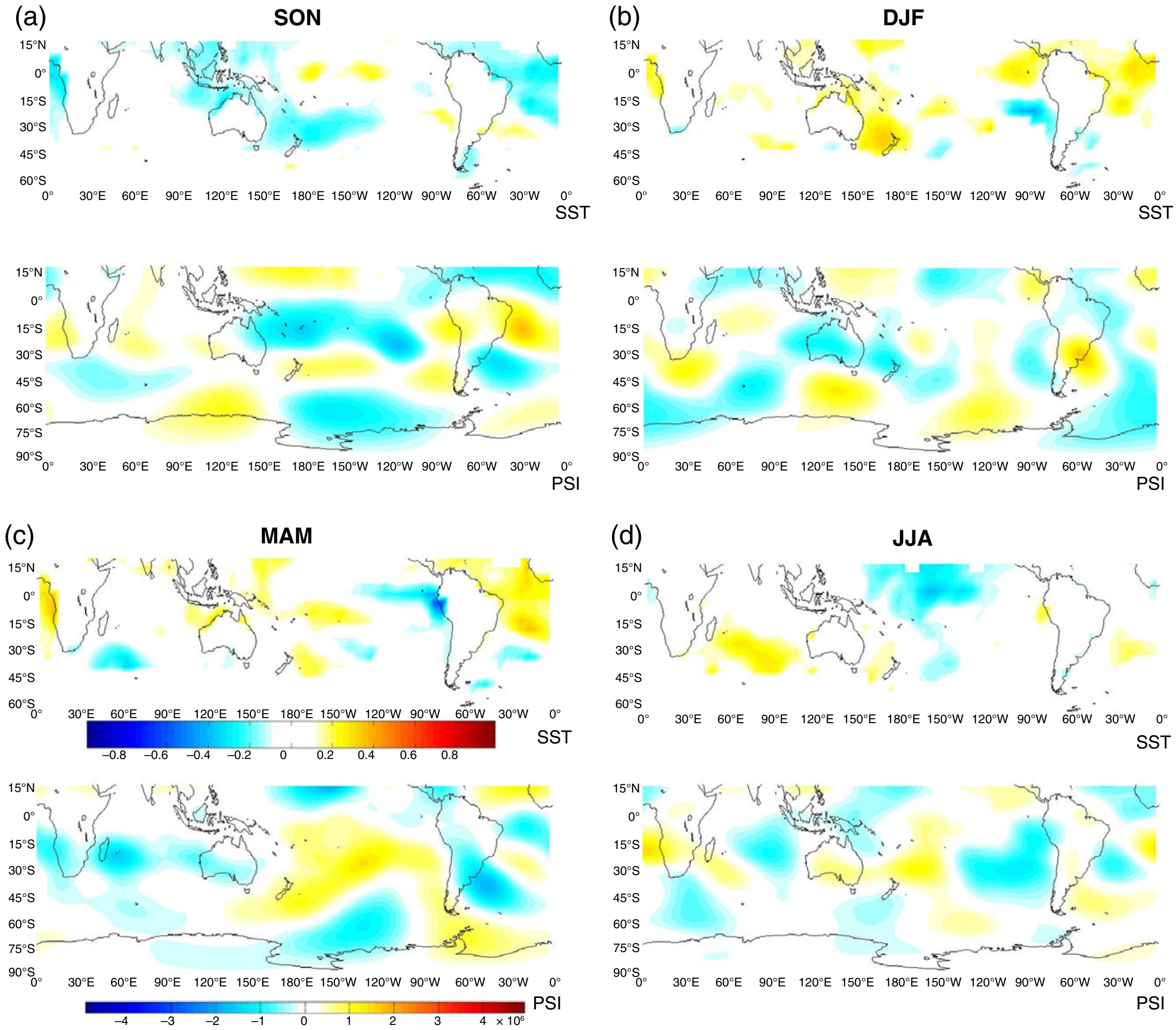

Figure 5. Linear regression maps of (top) SST anomalies (degrees) and (bottom) 200-hPa streamfunction anomalies ($m^2 s^{-2}$) against DIER75 SVD time series of Mode 2, for (a) SON, (b) DJF, (c) MAM and (d) JJA.

central Argentina while weaker anomalies of opposite sign locate further northeast. A comparison with Figure 1 shows that in central Argentina DIER is increased by 15% from the mean value in both spring and autumn, and even exceeding 40 mm day^{-1} in autumn. On the other hand, the pattern reverses in winter, with DIER anomalies over central Argentina that are more than 30% smaller than the mean ones. In summer, negative DIER regressed values essentially prevail over eastern Argentina.

According to Robledo *et al.* (2013), Mode 2 exhibits dominant variability at around 8 and 12 years for summer and spring. From spring to autumn, the Mode displays the largest relationship with SST anomalies in the tropical Atlantic (Figure 5) but with seasonal variations. During autumn (spring), Mode 2 positive phase is related to positive (negative) tropical Atlantic SST anomalies and negative (positive) tropical eastern (central) Pacific SST anomalies. On the other hand, summer SST anomalies are positive at both tropical Pacific and Atlantic oceans while winter SST anomalies associated with Mode 2 are only discernible over the central equatorial-north Pacific and subtropical south Indian Ocean.

Spring atmospheric circulation anomalies associated with Mode 2 show a wave train extended from southern Africa towards high latitudes and reflecting equatorwards in the southeastern Pacific Ocean, and a second wavetrain emanating from tropical central Pacific, which resembles the PSA1 pattern (e.g. Mo, 2000), merging with the first one in the vicinity of South America (Figure 5). In summer while the former wavetrain identified in spring is evident, the second wavetrain is not discernible. Moreover, in autumn, the PSA1-like wavetrain emanating from tropical central Pacific to extratropical regions becomes more coherent. For the three seasons considered, large agreement is found between the regions of large SST anomalies at the tropics and the wavetrain sources. On the other hand, winter circulation anomalies are very weak at high latitudes, while at subtropical latitudes, large anomalies of

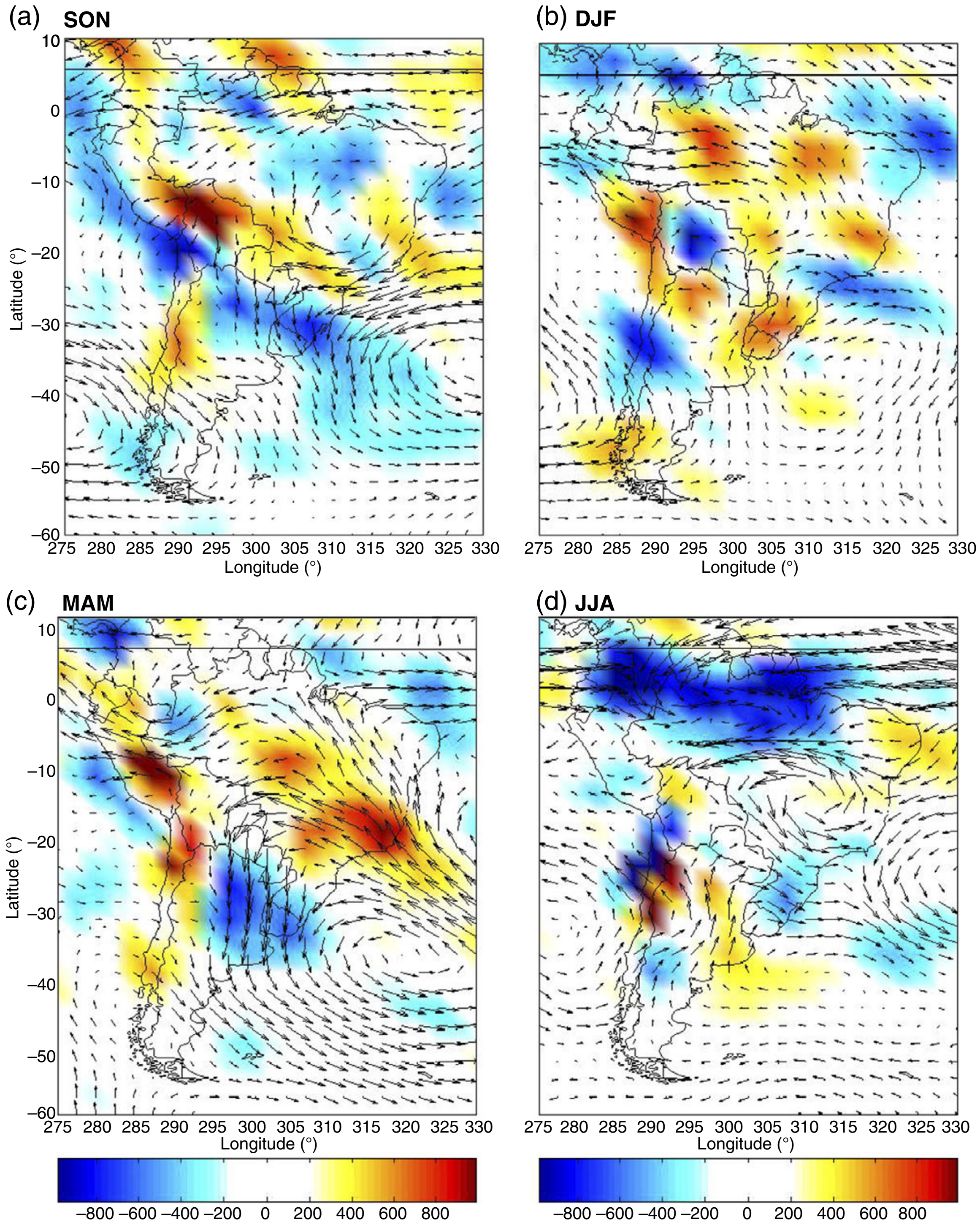

Figure 6. Linear regression maps of moisture fluxes (vectors, 10^3 g kg^{-1} m s^{-1}) vertically integrated in the 1000/500 hPa thickness against DIER75 SVD time series of Mode 2, and its corresponding divergence (shaded 10^3 g kg^{-1} s^{-1}). Reference vector is 20×10^3 g kg^{-1} m s^{-1}.

opposite sign are zonally extended, without a clear relationship to SST anomalies.

A cyclonic anomaly centre located at the southern tip of South America and an anticyclonic anomaly centre located further northeast, offshore in the southwestern Atlantic, are the most distinctive features of the regional circulation in both spring and autumn in association with Mode 2 (Figure 6). That circulation configuration promotes poleward moisture flux intensification into central and eastern Argentina favouring moisture convergence, and positive DIER anomalies (Figure 2(b)). On the other hand, in summer and winter, a sign reversal of the regional circulation anomalies is evident, which influences the regional moisture transport anomalies associated with Mode 2. Summer moisture flux anomalies display an anomalous cyclonic circulation centred in the southwestern Atlantic, contributing to an anomalous moisture flux divergence and negative DIER anomalies at central-eastern Argentina. In winter,

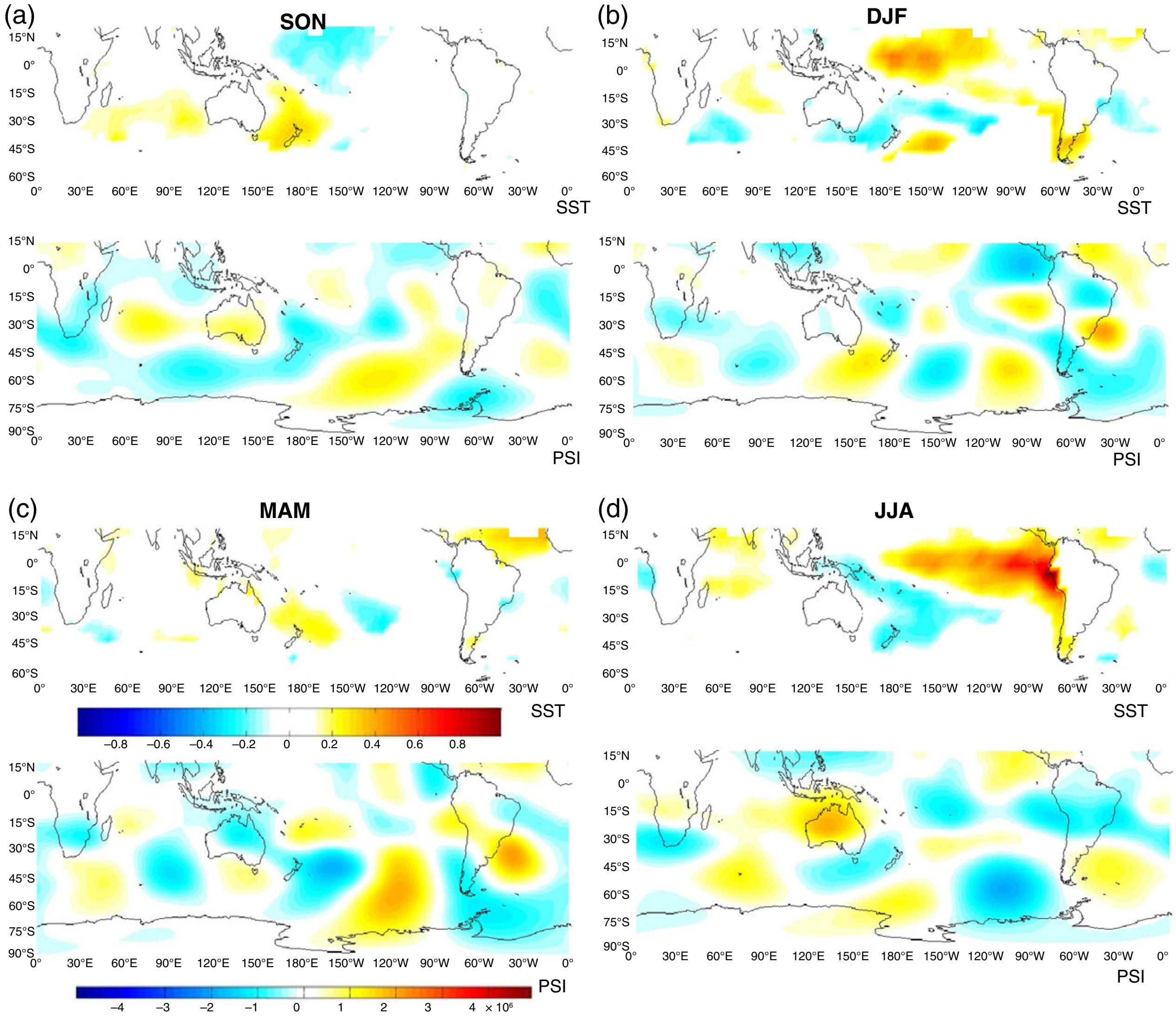

Figure 7. Linear regression maps of (top) SST anomalies (degrees) and (bottom) 200-hPa streamfunction anomalies ($m^2 s^{-2}$) against DIER75 SVD time series of Mode 3, for (a) SON, (b) DJF, (c) MAM and (d) JJA.

moisture flux anomalies exhibit a similar cyclonic gyre influencing moisture transport and DIER anomalies in the region, although the pattern is weaker.

3.3. Mode 3

Regressed DIER anomalies over SSA related to Mode 3 activity are presented in Figure 2(c). From summer to winter, negative DIER anomalies dominate in central and northeastern Argentina with a decrease of around 40% in DJF and MAM and of around 30% in JJA, as compared to the mean values. On the other hand, positive although weak DIER anomalies prevail over the region in spring.

Large positive (negative) SST anomalies in the equatorial central Pacific (southwestern subtropical Pacific) are associated with Mode 3 in both summer and winter (Figure 7). In agreement, positive and significant correlation values between Mode 3 time series and ENSO indexes like Nino3.4 have been found in those two seasons (not shown). On the other hand, in spring, negative (positive) SST anomalies in the equatorial central Pacific (southwestern subtropical Pacific) are associated with Mode 3, while in autumn the relationship with SST anomalies is almost negligible.

The analysis of the circulation anomalies related to Mode 3 activity shows for all seasons evidence of a wave train extended along an arch from Australia-western tropical Pacific Ocean southeastwards (Figure 7). In addition, anomalies of alternating sign extended zonally along the subtropical south Pacific are observed, likely associated with extratropical sources of circulation variability. At high latitudes, circulation anomalies depict for all seasons a wave-3 pattern, particularly clear in summer and autumn. Such pattern is linked during those two seasons to an anticyclonic anomaly centred over SSA and a cyclonic anomaly located further northeast. In winter, circulation anomalies over SSA are weaker, while in spring the most conspicuous circulation feature in the vicinity of the continent is a cyclonic anomaly centred off the coast of central Chile.

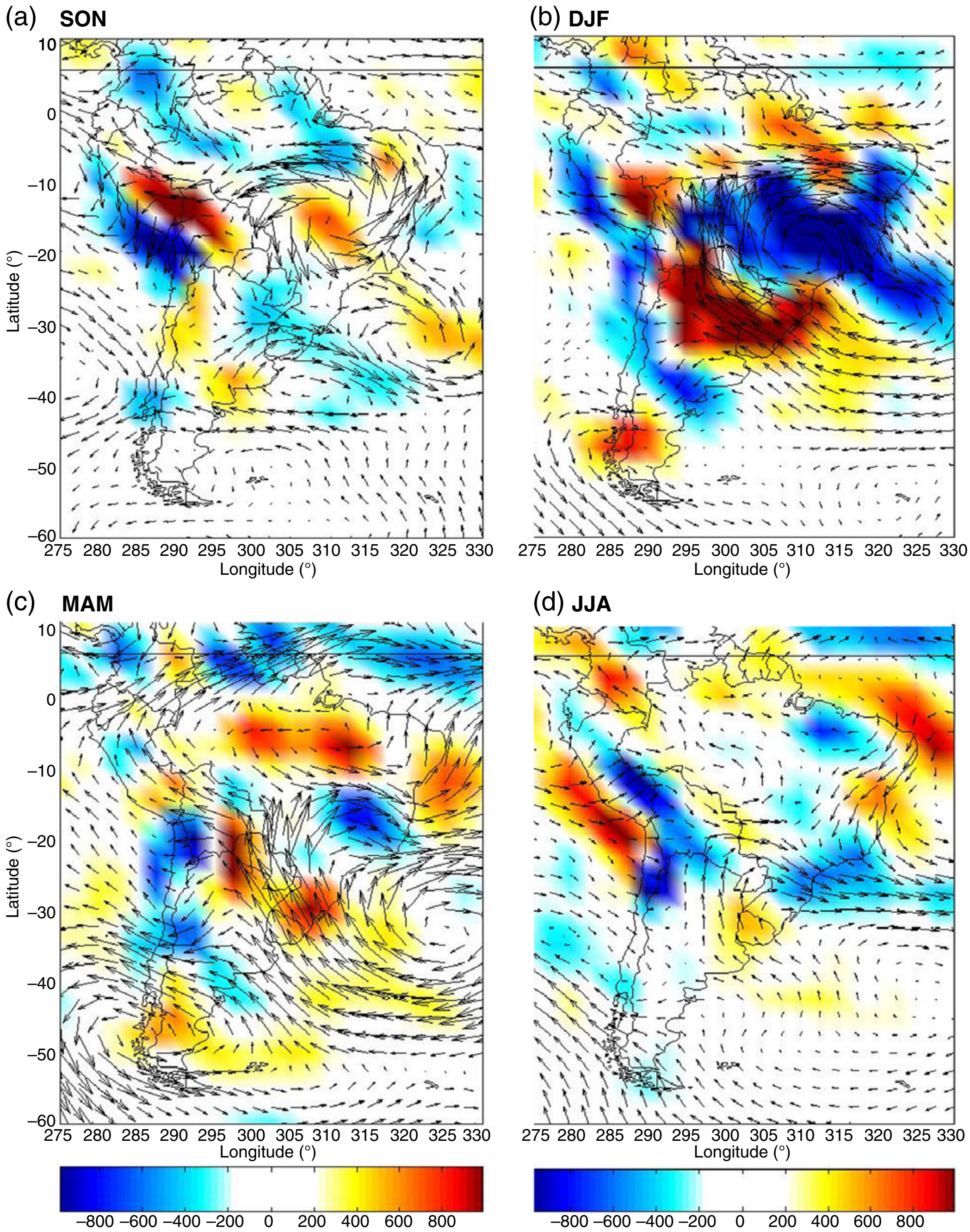

Figure 8. Linear regression maps of moisture fluxes (vectors, 10^3 g kg^{-1} m s^{-1}) vertically integrated in the 1000/500 hPa thickness against DIER75 SVD time series of Mode 3, and its corresponding divergence (shaded 10^3 g kg^{-1} s^{-1}). Reference vector is 20×10^3 g kg^{-1} m s^{-1}.

The changes in the regional circulation in association with Mode 3 affect the moisture transport as displayed in Figure 8. From summer to autumn, a large anticyclonic gyre extended between tropical and subtropical eastern South America characterizes the moisture flux anomalies. As a consequence, large anomalous moisture divergence (convergence) is found in SESA (southeastern Brazil), which largely explains the negative DIER anomalies detected in eastern Argentina in association with Mode 3 activity (Figure 2(c)). In winter, such moisture flux anomaly pattern, although weaker, persists (Figure 8). On the other hand, in spring, moisture flux anomalies induce weak anomalous divergence (convergence) in western (eastern Argentina), at least partially explaining the small positive (negative) DIER anomalies observed there.

4. Conclusions

In this paper, we studied the dynamical processes associated with the influence of the SST variability on extremes of daily rainfall in Argentina. The study is based on the analysis of the three leading modes of co-variability between anomalies of DIER index (described in Section 2) in Argentina and SST anomalies between 17.5°N and

90°S. Mode 1 variability is mainly related with ENSO. SST anomalies in the central-eastern tropical Pacific and western Indian Oceans excite wave trains extended along the South Pacific towards South America. SST anomalies in the tropical Atlantic also influence the large-scale circulation anomalies associated with Mode 1 particularly in autumn and winter. The large-scale teleconnections favour the development of an anomalous continental-scale circulation gyre that modulates moisture flux anomalies promoting moisture convergence in SESA, and in turn favouring positive DIER anomalies in eastern Argentina. These dynamical processes associated with Mode 1 activity are evident in all seasons, although in winter are somewhat weaker.

The activity of Mode 2 is mainly related with SST anomalies in the tropical Atlantic, particularly in spring and autumn, which are of opposite (same) sign than those observed at eastern-central (western) tropical Pacific. In agreement, large-scale circulation anomalies develop from western-central tropical Pacific towards the Antarctica coast and then deflect equatorward along South America-southwestern Atlantic Ocean sector. Accordingly, a circulation gyre extended between eastern Argentina and southeastern Brazil strongly modulates moisture flux anomalies, which in turn influences DIER anomalies in eastern Argentina. On the other hand in summer and winter, SST influence on DIER anomalies in Argentina associated with Mode 2 activity is not that clear and regional circulation anomalies are weaker and of opposite sign than those in the other two seasons.

The activity of Mode 3 is also modulated by SST anomalies in central tropical Pacific in summer, winter and spring, while in autumn that modulation seems negligible. As for the previous modes, large-scale teleconnections characterize the circulation anomalies in the South Pacific, extended from Australia to South America. Such teleconnections alter the regional circulation promoting the development of a cyclonic circulation gyre between SESA and southeastern Brazil that favours anomalous moisture divergence in SESA and negative DIER anomalies in eastern Argentina, in summer, winter and autumn. On the other hand, in spring, the cyclonic circulation develops further south over southeastern Argentina, promoting moisture convergence in SESA and positive DIER anomalies in eastern Argentina.

In summary, the study confirms the important role of the remote influence of the tropical ocean variability on the year-to-year variability of daily precipitation extremes in Argentina. Such influence provides a fundamental contribution to future development of climate prediction tools of DIER variability. Besides the dominant role of ENSO influence, SST anomalies in the tropical Atlantic Ocean and the Indian Ocean could influence and even modulate the ENSO effects on extremes daily precipitation in Argentina. However, predictability studies and sensitivity experiments using global numerical models are needed to make progress in predicting DIER variability with seasons in advance. Also, future studies should be conducted to describe and determine the influence of other sources of climate variability on DIER, such as changes in the land surface conditions, the position and strength of the tropical convergence zones, water vapour transport and large-scale anomaly patterns (Vera *et al.*, 2006). In particular, changes in the low-level jet can influence the development of the mesoscale convective system in SESA that might induce heavy rainfall events (Salio *et al.*, 2007). Also, the activity of the SAM, associated with the intensification and weakening of the SH westerlies, could be related with extreme rainfall variability in Argentina. Previous studies have shown the relation between the activity of that mode with the precipitation interannual variability of seasonal precipitation in SESA (Silvestri and Vera, 2003).

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