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SHORT-TERM CLIMATE PREDICTABILITY OF SUMMER RAINFALL ON THE PARANÁ BASIN BASED ON ATLANTIC AND PACIFIC SEA SURFACE TEMPERATURES

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1. INTRODUCTION

Climate prediction is necessary for many human activities. A better understanding of the variability and potential predictability of rainfall is vital for those regions where the hydroelectric power is essential to satisfy the energy demands. From this point of view, the Paraná River basin is important for Argentina, Brazil and Paraguay economies due to the large number of dams operating on this river and its tributaries that supply important amounts of the energy required in these countries. The annual rainfall cycle in the Paraná River basin shows abundant summer rainfall that leads to the management of water in the dams in a way that favours its accumulation during summertime and increases its release during winter, reducing the annual discharge amplitude of the river (Camilloni and Barros, 2000). Therefore, climate variations and particularly the interannual summer rainfall variability in this region carry important economic and social impacts.

The objectives of this study are (i) to analyze the extent to which the dominant patterns of interannual variability of the summer rainfall over the Paraná basin are linked to the Atlantic and Pacific sea surface temperatures (SSTs) and (ii) to address what features of the space-time evolution of these SSTs could lead to a successful forecast of the austral summer rainfall on the Paraná basin.

Most of tropical and subtropical South America receives more than 50% of the total annual precipitation in the austral summer season in the form of convective rain (Figueroa et al. 1995, Gandu and Silva Dias 1998). Nevertheless, the interannual variability of the summer precipitation is large, with interannual standard deviations of monthly means at individual stations often more than half the monthly average (Barros et al. 2000). The interannual rainfall variability in subtropical South America is related to the ENSO (El Niño/Southern Oscillation) phenomenon (e.g., Ropelewski and Halpert 1987, 1996; Grimm et al. 2000), with enhanced precipitation during the warm phase. Other authors related the interannual variability of precipitation in this region with the tropical convection in central Brazil (González and Barros 1998) and the SST variability of the south Atlantic and Pacific oceans (Diaz et al. 1998, Barros et al. 2000, Barros and Silvestri 2002). Zhou and Lau (2001) conducted a diagnostic study of the interannual and decadal variability of summer rainfall over South America and identified the El NIño/Southern Oscillation (ENSO) influence at the interannual time scale associated to an enhancement of the South American summer monsoon (Zhou and Lau, 1998) in response to an El Niño anomaly.

Many authors analyzed the relation between rainfall in subtropical South America and subtropical and tropical Pacific SST. Barros and Silvestri (2002) analyzed the influence of the subtropical south-central Pacific SST over the austral spring rainfall in subtropical South America and its role in modulating precipitation among El Niño events. Likewise, the Paraná River basin region has strong precipitation signal during ENSO events (Ropelewski and Halpert 1987; Aceituno 1988; Kiladis and Diaz 1989; Ropelewski and Halpert 1996; Camilloni and Barros 2000; Grimm et al. 2000). The El Niño phase is dominated by above-average rainfall with an enhancement of the river flow and flooding episodes (Berri et al. 2002; Camilloni and Barros 2003) and the La Niña phase shows almost the opposite situation. Grimm et al. (2000) found that the most significant impacts of El Niño events on rainfall over the Paraná basin start in November of the onset year of the event and end in July of the following year. Moreover, consistent evidences of the link between the Paraná River discharge and ENSO have been found. For example, Aceituno (1988) found a weak negative correlation between discharges at the gauging station Corrientes located immediately downstream the junction of the Paraná and Paraguay rivers and the southern oscillation index (SOI) during November-April. Amarasekera et al. (1997) reported a positive correlation between the annual discharge at Corrientes and the equatorial Pacific SST averaged on quarters lagging ahead of the discharge year. Robertson et al. (2001) analyzed the interannual to decadal predictability of the Paraná River extracting near-cycling components of the summer river streamflow. Their results show that the ENSO oscillatory

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component is associated to changes in the probability distribution of monthly flows and that the decadal modulation of ENSO may be important although the predictability due to ENSO at interannual lead times is small. Camilloni and Barros (2003) demonstrated that about two thirds of the major discharge anomalies in Corrientes occurred during El Niño events while none was registered during La Niña phases.

The influence of SST anomalies in the Atlantic Ocean on precipitation in southeastern South America has been examined in recent years. For example, Díaz et al. (1998) investigated the annual cycle of precipitation in Uruguay and Southern Brazil and found links between its anomalies and those in SST in the southwestern Atlantic Ocean. Díaz et al. (1998) results support the existence of relationships between wet/dry rainfall anomalies in the northern sector of Uruguay and southern Brazil and warm/cold SST anomalies in the South Atlantic Convergence Zone (SACZ) region and the equatorial Atlantic in the November-February period. Barros et al. (2000) found that, during summer and principally in January, Southeastern South America rainfall is related to both the intensity and position of the SACZ as well as to the SST of the neighbouring Atlantic Ocean. Camilloni and Barros (2000) studied the simultaneous relationship between outgoing longwave radiation anomalies in the Paraná basin and South Atlantic Ocean SST anomalies comparing two periods of exceptional warm ENSO events: 1982/83 and 1997/98. In January, they found a pattern of SST anomalies in the South Atlantic Ocean with warm water to the north of the SACZ and cold water to the south, except near the American coast, which favours the convection over the upper Paraná basin probably because of the enhancement of the SACZ. Doyle and Barros (2002) analyzed the relation between the midsummer low-level circulation and precipitation in Southeastern South America and the SST anomalies in the South Atlantic. They found that the strongest relation between precipitation and SST is determined by the anomalies in the Atlantic region define by 20ºS-30ºS and 30ºW-50ºW. Paegle and Mo (2002) analyzed the linkages between summer rainfall variability over South America and global SST anomalies but in contrast to the studies mentioned previously the focus of their analysis are the links between SST and continental rainfall modes rather than regional patterns of precipitation.

More recently, Berri and Bertossa (2004) studied the spatial and temporal patterns of precipitation anomalies over north-central Argentina, Uruguay and Paraguay and their relationships with SST variability over the tropical and subtropical Atlantic and Pacific oceans. They identified the period November-December as one that mainly reflects the influence on precipitation of several oceanic regions particularly in the Pacific Ocean with a relationship of the type warm-wet and cold-dry. In contrast, the period January-February displays a weak relationship and represents a minimum of oceanic influence during the warm semester.

2. REGIONAL CLIMATE BACKGROUND

The South Atlantic Convergence Zone (SACZ) is a region of intense convection and represents an important feature of the summer circulation in South America. This band of minimum energy is oriented northwest to southeast from a region of intense convection over the Amazon Basin and is projected into the South Atlantic Ocean crossing the Brazilian coast at about 20ºS. The mechanism for the generation of the SACZ is the combined action of Amazonian latent heat source and the Andean topography (Figueroa et al. 1995).

The Paraná River is the most important tributary of the Río de la Plata with a drainage basin of 2.6 x 10^6 km^2. It begins at the confluence of the Grande and Paranaíba rivers and its main tributaries are the Paranapanema, Iguazú, and Paraguay rivers (Figure 1). The section of the river upstream from the confluence with the Paraguay is known as Upper Paraná, and from this point down to 32°S as Middle Paraná. Downstream this latitude, it is called Lower Paraná.

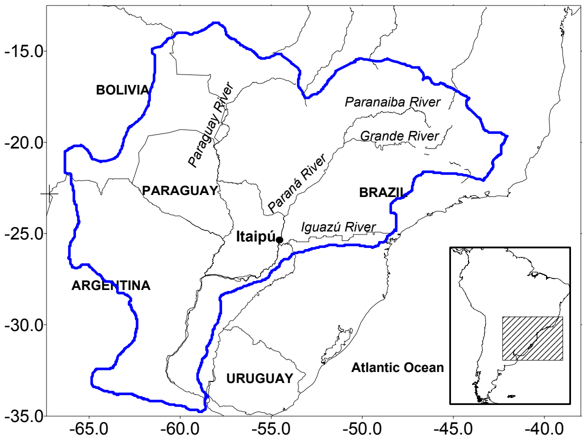


Figure 1. Paraná River basin.

Figure 2 shows the annual cycle of the Paraná River at the gauging station Itaipú (Figure 1) for the 1961-80 period, when the Paraná was practically unregulated, and for 1984-92, after the Itaipú dam started to operate.

For the unregulated period, the Paraná regime shows a peak during February-March and a minimum during August-September. The maximum discharges during February and March are associated with copious austral summer rainfall over the Upper Paraná basin due to the intense convection in the SACZ. The impact of the water management on the annual cycle of the Paraná River can be also appreciated in Figure 2 and involves a significant reduction of the annual amplitude and a secondary maximum during autumn, both probably associated to the water release from the dams after the summer accumulation.

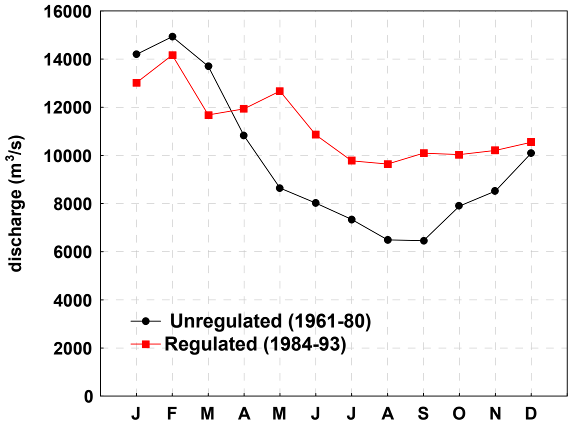


Figure 2. Annual cycle of the Paraná River at the gauging station Itaipú for unregulated (1961-80) and regulated (1984-93) periods.

The climatological austral summer (December, January and February) rainfall and over the Paraná basin is presented in Figure 3a. The largest seasonal amounts are found close to the SACZ region with a predominant northwest-southeast orientation and decreasing values to the south. The Upper Paraná basin exhibits summer precipitation amounts between 400 and 600 mm/season and the Middle and Lower Paraná values are between 300 and 400 mm/season. The standard deviations of summer means are presented in Figure 3b. Standard deviations are largest close to the SACZ mean position with small variations among the three Paraná subbasins.

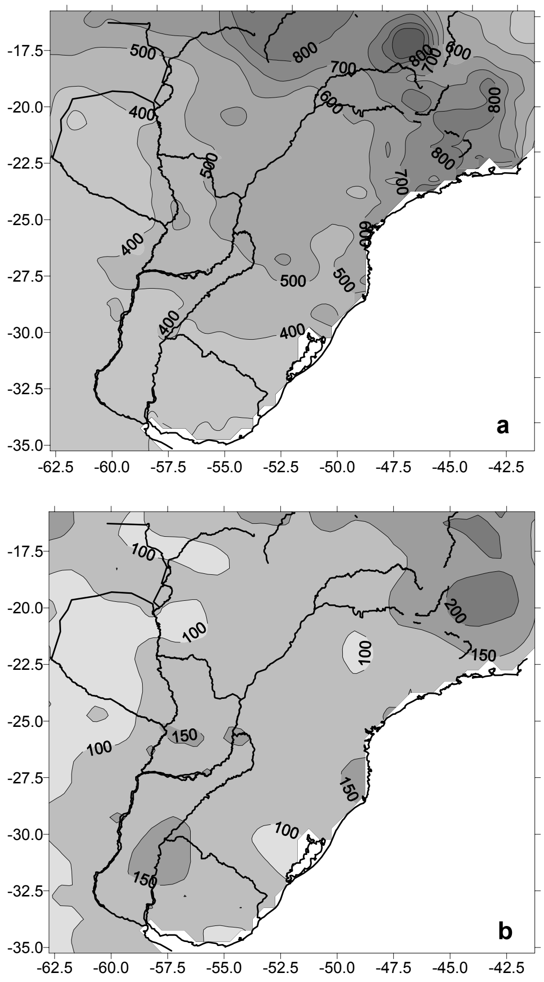


Figure 3. Mean climatological austral summer rainfall (a) and standard deviations from seasonal means (b) over the Paraná basin.

3. DATA

Monthly rainfall data for the austral summer months (December-January-February) were taken from a data set assembled by Willmott and Matsura (2001). Although these data are available in a 0.5° x 0.5° grid for the period 1950-99, only the 1970-99 period will be considered due to the sparse rainfall observations before 1970. To study the relationships between rainfall and SST anomalies, both in the Pacific and in the Atlantic oceans, SST monthly means were taken from the HadISST dataset t(Rayner et al. 2003) compiled and quality controlled by the Hadley Centre for Climate Prediction and Research available through the British Atmospheric Data Center. This dataset has a resolution of 1° latitude by 1° longitude and covers 1870 to present. In order to reduce the number of grid points SST monthly means were averaged into 5°x5 grids for the Pacific and Atlantic oceans covering the latitude band 10°N-40°S. Both for precipitation and SST data the seasonal cycle is defined as the monthly mean climatology at each grid point. Consequently, anomalies are defined as departures of monthly values from the seasonal cycle.

4. AUSTRAL SUMMER RAINFALL INTERANNUAL VARIABILITY

Principal component analysis was performed on seasonal rainfall anomalies for the austral summer for the 1970-99 period and the domain shown in Figure 1. Figure 4 shows the first (FL1) and second (FL2) spatial patterns that account for 22.8% and 19.4% of the total variance. The first mode has negative loadings over the SACZ region and positive ones over northern Argentina, Uruguay and southern Brazil. This pattern is associated to reduced/increased precipitation due to the northward/southward displacement of the SACZ (Nogués-Paegle and Mo 1997; Barros et al 2000). The second mode has positive loadings over the Upper Paraná basin and negative ones in the SACZ region and east-central Argentina and Uruguay.

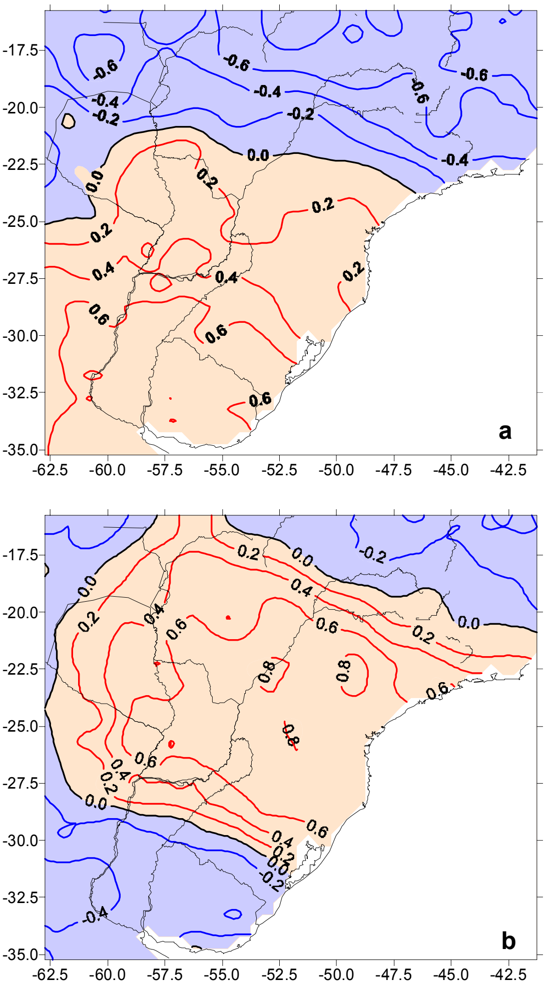


Figure 4. First (a) and second (b) eigenvectors of austral summer rainfall anomalies.

The two first principal components (PCs) are shown in Figure 5. PC1 and PC2 have respectively positive statistically significant linear trends at the 1% and 5% confidence level according to a two-tailed t-Student test since 1979. These linear trends are associated to enhance austral summer rainfall over most of Southeastern South America. These results coincide with other studies on regional rainfall trends. Barros et al. (2000) found positive annual precipitation trends in Northeastern Argentina for 1916-91 that were larger when considering the shorter period 1956-91. Likewise, Giorgi (2002) identified also secular positive rainfall trends in Southern South America for both the austral summer season and yearly values. Recently, Liebmann et al. (2004) identified in the period 1976–99, the largest positive trend in Central-South America precipitation south of 20ºS and centered over southern Brazil during the January–March season.

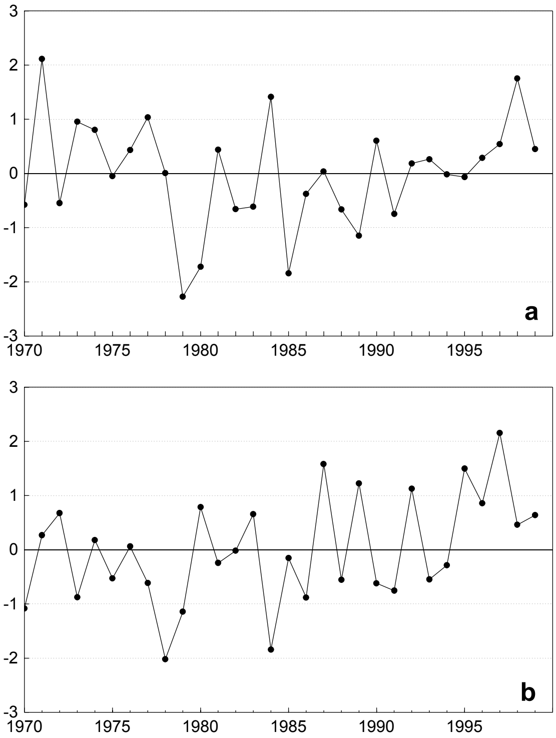


Figure 5. Principal components corresponding to the first (a) and (b) second loadings of austral summer rainfall anomalies.

FL1 shows two regions with opposite behavior: one comprising approximately the band 16ºS-20ºS from now identified as region 1-north (R1N) that includes the beginning of the Paraná River and the other one in the band 27ºS-35ºS denominated region 1-south (R1S) that comprises the Middle and Lower Paraná basins

(Fig. 4a). FL2 shows only one large region with significant values with a northwest-southeast orientation identified as region 2 (R2) that includes the Upper Paraná (Fig. 4b). Linear correlation coefficients between mean summer rainfall anomalies of each of these regions and Altantic+Pacific SST anomalies are presented in Figure 6.

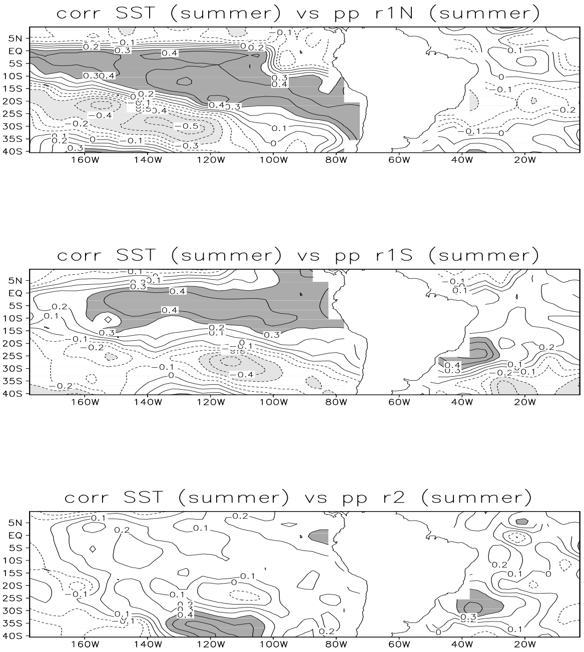


Figure 6. Linear correlations between summer rainfall anomalies in region R1N (upper panel), R1S (middle panel) and R2 (lower panel) and summer SST anomalies.

Regions R1N and R1S show positive correlations over the eastern and central Pacific and negative ones in the subtropical Pacific indicating the ENSO influence over these areas of Southeastern South America. The correlation between austral summer rainfall in regions R1N and R1S and the Niño 3.4 index for the same season is 0.39 in both cases confirming the well-known warm-wet and cold-dry pattern between the equatorial SST and rainfall over these regions. Barros and Silvestri (2000) show that during the austral spring the subtropical south-central Pacific (SSCP) modulates the rainfall variability over Southeastern South America among El Niño events. Additional they show that the circulation field has enhanced cyclonic (anticyclonic) advection over subtropical SSA when SST in the SSCP is cold (warm). It seems that this same pattern extends to the austral summer. The correlation with Atlantic SSTs is significant for region R1S showing enhanced precipitation in this region with a pattern of SST anomalies with warm water to the north of the SACZ, especially west of 20°W, and cold water to the south. Camilloni and Barros (2000) showed that this pattern is correlated with convection over the Upper and Middle Paraná basins, as occurred during summer 1983.

Region R2 is not correlated with the equatorial Pacific and only shows positive correlations with the Pacific centered in 40°S, 120°W and the Atlantic sector of the SACZ. This region includes a vast extension of the basin that does not show an ENSO relationship during the season suggesting a probable limit for seasonal climate predictions.

5. LAGGED CORRELATIONS BETWEEN AUSTRAL SUMMER RAINFALL AND SST

Canonical correlation analysis (CCA) is a linear multivariate technique that finds the optimum linear combination between two sets of data. The strength of this methodology is its ability to operate with fields and define the most highly related patterns between them. By including time lag data in one of the fields it is possible to obtain the best space-time evolution of it that is best associated to a pattern of the other field. In recent years, this method has been used both in diagnostics and predictability studies (i.e.Barnett and Preisendorfer 1987; Barnston and Ropelewski 1992; Chu and He 1994; Díaz *et al.* 1998; Chu 1998; Montecinos *et al.* 2000, Barros and Silvestri 2002). A detailed mathematical description can be found in Barnett and Preisendorfer (1987) and Wilks (1995).

In order to reduce spatially redundant information and to eliminate noise, principal component analysis was used. The number of components retained for the rainfall and SST anomalies (*p* and *q*, respectively) was selected according to the total variance explained criterion. In this case, we retained as many components as they explained at least 80% of the total variance of the corresponding field. For rainfall anomalies *p* is equal to 8, and for the bimonthly SST anomalies *q* equals 11. The CCA method produces *r* linear combinations [r=min(p,q)] of the time series of the principal components for the rainfall and SST anomalies. These linear time-dependent combinations, $u_i(t)$ and $v_i(t)$, are the canonical component vectors and their correlation μ_i are the canonical correlation coefficients. When the CCA is applied to fields, as in this study, it is possible to plot maps of the canonical vectors by associating their magnitude and geographic location. In this context, the canonical vectors are called canonical patterns that show the spatial patterns in which the original variables contribute to the canonical variables.

Figure 7 presents the first canonical patterns for the austral summer rainfall anomalies and the preceding Jun-Jul, Ago-Sep and Oct-Nov Atlantic+Pacific SST anomalies. Correlation significances were calculated with the Student's t-test and correlation coefficients significant at the 95% level (larger than 0.30) are shaded. The correlation between the canonical vectors (not shown) is +0.97. The SST patterns in the Pacific are typical of El Niño indicating that during Jun-Nov positive/negative rainfall anomalies over the Middle and Lower Paraná basins and the SACZ region are associated to a pattern of warm/cold SST anomalies over the tropical Pacific in the EN 1+2, EN 3 and EN 4 regions and cold/warm SST anomalies to the south with the coldest anomalies centred in 30ºS-160ºW. The Atlantic Ocean shows only one region with statistically significant correlations located in the tropics between 5ºN and 20ºS indicating that cold/warm SST anomalies during Jun-Sep are associated to positive/negative rainfall anomalies in the continental SACZ region and in the Middle and Lower Paraná. During Oct-Nov the signal is weaker in the tropical Atlantic.

The second canonical patterns are presented in Figure 8. The correlation between the canonical vectors (not shown) is +0.91. These patterns show that summer rainfall over the Upper Paraná basin seems not to be related to SSTs as only weak correlations are obtained mainly in the Pacific Ocean during the six previous months. The Atlantic Ocean shows positive and significant correlations only during Aug-Sep in a subtropical region far away from the South American continent. Consequently other mechanisms not related to SSTs could be responsible for the austral summer rainfall over the Upper Paraná basin.

The relative predictive importance (RPI) of each bimonthly SST anomaly field can be evaluated according to the equations proposed by Barnett and Preisendorfer (1987). The RPI index can be thought as a percent of the predictability due to a predictor data in a specific period. The corresponding RPIs for the first and second canonical component (CC1 and CC2 respectively) are presented in Table 1. They show that the skill in the summer rainfall forecasts would come similarly from SST variations in the Jun-Jul and Aug-Sep bimonthly periods but mainly from the last period (Oct-Nov) for CC1 and principally from Aug-Sept for CC2.

	CC1	**CC2**
June - July	29.9	26.5
August - September	28.0	43.8
October - November	42.1	29.7

Table 1. Relative predictive importance (RPI) for each bimonthly SST period of the first (CC1) and second (CC2) canonical patterns.

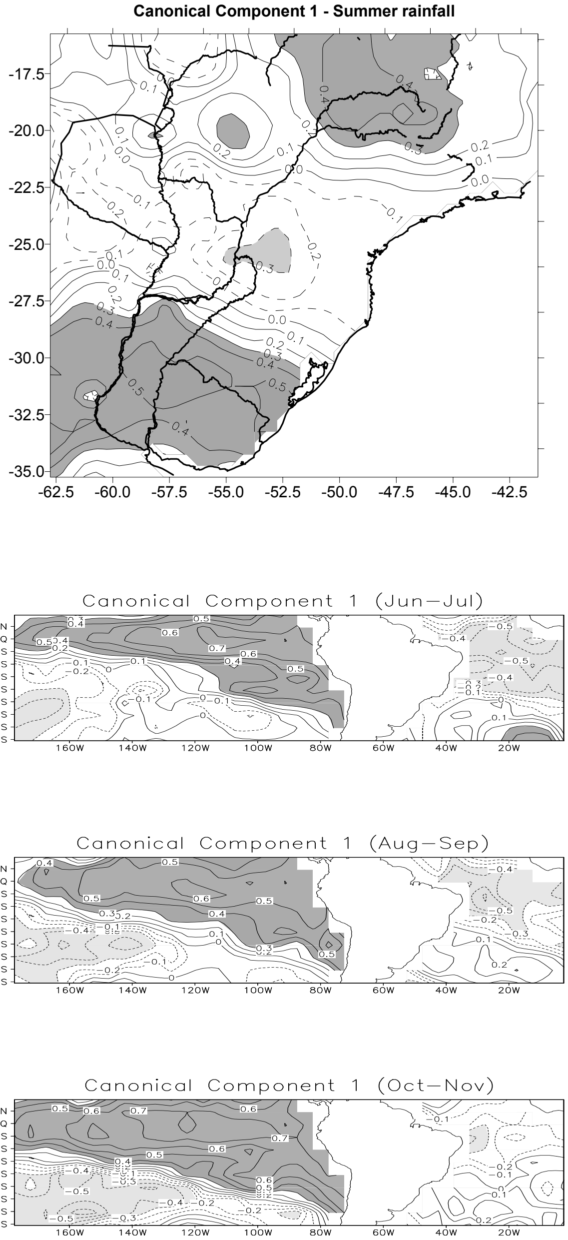
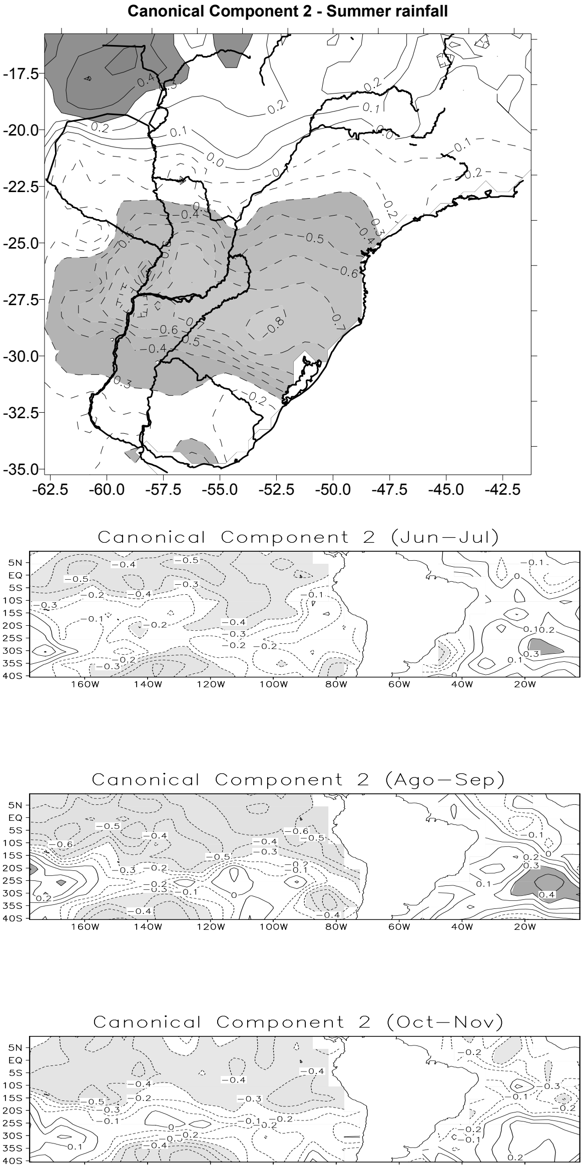


Figure 7. First spatial canonical components of summer rainfall anomalies and previous bimonthly SSTs anomalies. Significant correlation coefficients at the 95% level are shaded.



Canonical Component 2 - Summer rainfall

Canonical Component 2 (Jun−Jul)

Canonical Component 2 (Ago−Sep)

Canonical Component 2 (Oct−Nov)

Figure 8. Second spatial canonical components of summer rainfall anomalies and previous bimonthly SSTs anomalies. Significant correlation coefficients at the 95% level are shaded.

6. CONCLUSIONS

A principal component analysis was performed on summer rainfall anomalies of the austral summer for the period 1970-99. The first and second leading modes account for the 22.8% and 19.4% of the total variance respectively. The first mode has negative loadings over the SACZ region and positive ones over northern Argentina, Uruguay and southern Brazil. This pattern is associated to reduced/increased precipitation due to the northward/southward displacement of the SACZ. The second leading mode has positive loadings over the Upper Paraná basin and negative ones in the SACZ region and east-central Argentina and Uruguay. Time series of these two principal components show positive trends associated to enhanced summer rainfall over most of Southeastern South America. Three key regions were identified from this analysis: the beginning of the Paraná region (SACZ region) and the Upper Paraná and Middle-Lower Paraná basins.

Linear correlation coefficients were calculated between summer rainfall anomalies over these regions and simultaneous SST anomalies in the Atlantic and Pacific oceans. The SACZ region and Middle-Lower Paraná basin rainfall anomalies are highly correlated with SSTs anomalies in the Pacific Ocean that reflect the ENSO pattern. The Upper Paraná basin summer rainfall anomalies are positively correlated with SST anomalies in the South Pacific. Results derived from a canonical correlation analysis indicate that only during ENSO events there is some predictability of summer rainfall in the Middle-Lower Paraná basins based on Atlantic and Pacific SSTs up to six months before summer. Likewise, the Upper Paraná basin is weakly correlated with the Pacific Ocean and rainfall over this basin is probably a consequence of other mechanisms rather than Atlantic and Pacific SSTs.

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