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INTERANNUAL VARIABILITY OF SUMMER RAINFALL IN SOUTH AMERICA: LARGE-SCALE INFLUENCES AND THE ROLE OF ANTECEDENT CONDITIONS IN SPRING.

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1. INTRODUCTION

The importance of the summer monsoon season to the annual total precipitation over most of South America (and Brazil) is well known. The variability of monsoon precipitation is of utmost importance for natural disaster preparedness, and activities with economic impact such as agriculture and reservoir management. Therefore, a detailed knowledge of interannual variability of the summer monsoon is an important element of water resources management. Most of Brazil hydroelectric power distribution networks are interconnected, allowing energy transfer from one region to another. Thus, a detailed knowledge of modes of variability in the different phases of the monsoon season and the relationships between them is useful in reservoir management and in validation or improvement of forecast models. Improving the ability to forecast the summer monsoon and its evolution is a worthwhile objective.

Two previous studies using reconstructed rainfall from satellite estimates and gauge-based monthly totals (Zhou and Lau 2001; Nogués-Paegle and Mo 2002), have stressed the influence of ENSO on summer precipitation. It is represented by the first mode of variability in these studies. The second mode represents the interannual and interdecadal variability in Northeast Brazil, whereas the third mode is completely different in both studies. The first two modes of summer precipitation in those studies do not have strongest components in the monsoon core region in South America. Are the regions with monsoon-like regime not prone to undergo strong interannual variations or, in other words, are the processes leading to monsoon rainfall in South America not prone to undergo interannual variations? If yes, would these processes be directly affected by remote or large-scale influences or indirectly, through regional interactions that are stronger in the summer season?

In this study we intend to cast some light on these questions. We pursue the following objectives: i) to determine the principal modes of interannual variability of summer monsoon rainfall on the basis of relatively long series of rain gauge data; ii) to establish connections between the conditions in the beginning of the monsoon season and its peak; iii) to verify connections with global SST.

2. DATA AND METHODS

Precipitation data from more than 9000 stations over most of South America (SA) are averaged in 2.5°×2.5° boxes (Figure 1). These data are mainly concentrated in the Southern Hemisphere (SH) part of South America, where austral summer rainfall mostly dominates the annual cycle. Mean precipitation series for spring (SON) and summer (DJF) are formed for each of those boxes in the period 1961-2000, and submitted to Empirical Orthogonal Function analysis (EOF). The same analysis was carried out for two isolated months (November and January), in order to stress their characteristic opposite relationship. Rotated and non-rotated modes of variability are determined. Their relationship with global sea surface temperature (SST) is assessed through correlation analysis of their principal component (PC) series with the data set HADSST1 (Rayner et. al. 2003). Furthermore, we analyze the relationship between spring and summer precipitation, in order to detect influence of antecedent soil moisture conditions in spring on the peak summer monsoon rainfall and, therefore, of regional land-atmosphere interaction processes on the summer precipitation variability. Linear correlations between PCs of the leading EOF modes in spring and summer are performed, as well as between those in November and January. This relationship is also tested by correlating spring (and November) precipitation in each box with summer (and January) precipitation in all the other boxes.

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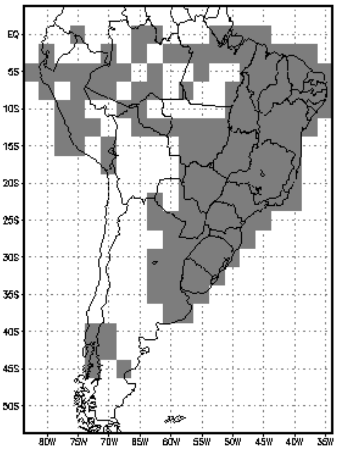


Figure 1: Spatial coverage of rainfall data.

From the EOF and correlation analysis emerges a region with significant inverse relationship between spring and summer precipitation. The tendency to opposite precipitation anomalies over this region at the beginning and the peak of the monsoon season is also verified by comparing its climatological 15-day sliding precipitation mean, between September 1st, and March 1st, with the corresponding means for years with opposite spring anomalies. These anomalous years are those in which the PCs of the first spring EOF (with strong components over this region) is above (below) 0.5 (-0.5) the standard deviation.

3. RESULTS AND DISCUSSION

3.1. EOF analysis and relationship between precipitation and SST variability

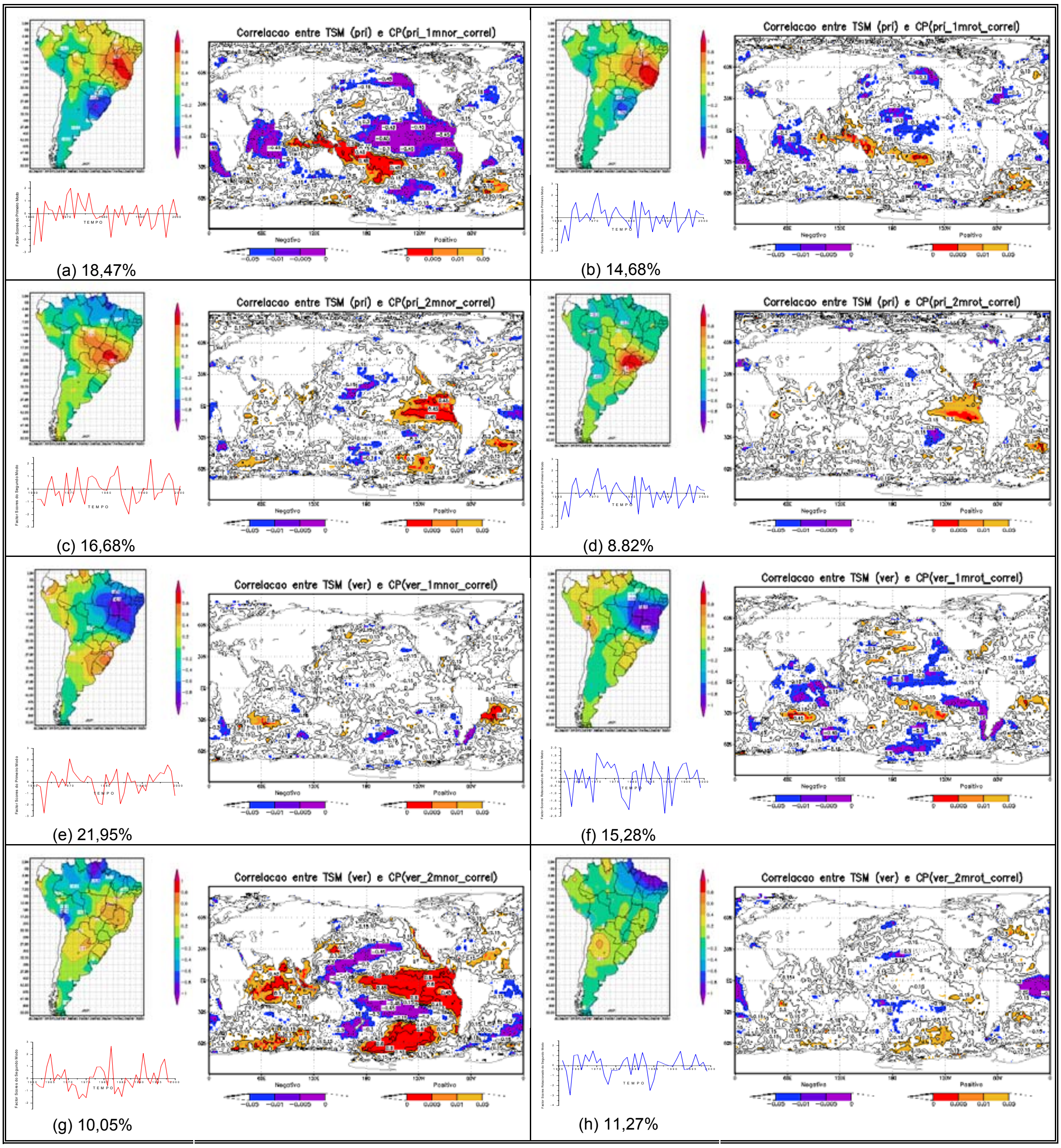
We will concentrate on the first two modes of spring and summer precipitation, which are the most important ones to our purpose of establishing a connection between spring and summer precipitation.

The first modes of precipitation variability, both in spring and winter, are dipole-like. This pattern is even maintained under rotation (Figures 2a, b for spring, and 2e, f for summer). It features opposite anomalies in Central-East Brazil and southeastern SA. Similar modes also represent the most important ones in November and January (Figures not shown).

In spring, the northern anomalies extend from Central-East Brazil to northern SA, while in southeastern SA the opposite anomalies are stronger over southern Brazil, northern Argentina and Uruguay (Fig. 2a). This pattern of anomalies is characteristic of the ENSO impact on precipitation during spring (Grimm et al. 2000; Grimm 2003, 2004). The connection of this mode with ENSO is confirmed by the correlation patterns with SST, which reproduce the main aspects of the ENSO signature in the Pacific Ocean. The first rotated mode reproduces the dipole pattern, but is now much more concentrated on its northern center (Fig. 2b). Some characteristic components of the ENSO impact are weaker in the rotated mode, such as the anomalies in southeastern SA and in northern SA. Accordingly, the correlation coefficients are weaker in eastern Pacific, although still strong in central and western Pacific. In the Atlantic Ocean, the associated anomalies do not change. Near the southeast coast of Brazil, where the precipitation anomalies are positive (negative), SST is colder (warmer) than normal, indicating influence of cloud coverage on the SST via radiation flux. For both rotated and non-rotated mode the forcing associated with tropical and subtropical SST anomalies in the Pacific seem to be important, as circulation anomaly leading to the precipitation anomaly in central-east Brazil seems to be associated with a wave train from this region.

The second spring mode features a dipole shifted to the north with respect to the first mode (Fig. 2c). The southern center is over southeastern Brazil (south of the climatological SACZ) and the northern center is over northern Brazil. This mode is connected with SST anomalies in the eastern Pacific, off the equator. The SST anomalies in southwestern Atlantic do not seem to keep with precipitation in this area the same kind of relationship as in the first mode, for there are no cold SST anomalies off the southeast coast of Brazil corresponding to enhanced precipitation in this region. The corresponding rotated mode features anomalies concentrated on a narrower region and lacks the character of a dipole (Fig. 2d).

The first summer mode is also dipole-like (Fig. 2e), as is the first spring mode. However, there is an important difference: the anomalies in the northern center do not extend to northwestern SA, as in spring. While spring precipitation anomalies in southern and northern halves of SA are essentially opposite in the first spring mode, the summer first mode anomalies in northwestern and southeastern SA are of the same sign and opposite to those in central-east SA. Therefore, the relationships observed in spring do not hold in summer. The correlation analysis of PC and SST indicates no important SST anomalies forcing this variability. On the contrary, the correlation patterns indicate that the atmospheric anomalies are probably triggering the SST anomalies. The most outstanding example is in southwestern Atlantic, which, as in the first spring mode, responds to less cloudiness with warm SST anomalies. The corresponding rotated mode is similar but more concentrated on the Central-East Brazil anomalies. The associated SST anomalies have similarities with those associated with the first spring mode (except in the Atlantic), but the phase of the precipitation mode is opposite. This indicates clearly that either the relationship between SST and the circulation anomalies is completely different or the reversal of phase is due to regional processes. In the southwestern Atlantic, off the southeast coast of Brazil, the SST anomalies are opposite in spring and summer, according to the precipitation anomalies in Central-East Brazil.



(a) 18,47%

(b) 14,68%

(c) 16,68%

(d) 8.82%

(e) 21,95%

(f) 15,28%

(g) 10,05%

(h) 11,27%

Figure 2: Modes of interannual variability of spring and summer precipitation in South América: factor loadings, principal components, explained variance, and correlation patterns with SST for the period 1961-2000. In the correlation maps, the colors represent levels of statistical significance. (a) Spring EOF1, (b) spring rotated EOF1 (c) spring EOF2, (d) spring rotated EOF2, (e)) summer EOF1, (f) summer rotated EOF1, (g) summer EOF2, (h) summer rotated EOF2.

The second summer mode features strong anomalies in northern SA and opposite anomalies in Central-East Brazil (Fig. 2g). It differs from the first summer mode in that it does not have opposite anomalies in southeastern SA. This mode is associated with ENSO, for the correlation patterns in the Pacific Ocean reproduce ENSO-like SST anomalies. Under rotation, the main features of this mode are distributed in the three first rotated modes. The variations in Northeast Brazil are isolated in the second rotated mode (Fig. 2h), which is very significantly associated with SST anomalies in tropical South Atlantic. The connection with tropical North Atlantic is much weaker. The third summer rotated mode (not shown) has maximum factor loadings in southeastern SA (and weaker ones of opposite sign in northern SA), and close relationship with ENSO.

The modes determined in our analysis show similarities with the modes calculated by Zhou and Lau (2001) and Nogués-Paegle and Mo (2002). The first summer mode in these studies is connected with ENSO, similar to our second mode. Their second mode describes the interannual variability of the Northeast Brazil precipitation. This appears in our analysis as the second rotated mode. The third mode in Paegle and Mo analysis is similar to our first mode, while the third mode in Zhou and Lau is similar to our third non-rotated mode (not shown). There are some differences in the patterns between the three studies, due to different origins of the data sets and different periods of analysis. However, the main characteristics are similar. The main difference in our analysis is that the dipole-like mode describing oscillations between South and Central-East Brazil precipitation is the first mode, whereas either not present or present as a higher order mode in previous studies.

3.2. Relationship between spring and summer modes of variability

Precipitation anomalies during spring in Central-East Brazil produce soil moisture anomalies and, therefore, near surface temperature anomalies. These anomalies could influence circulation and precipitation anomalies in summer. Grimm (2003) disclosed an inverse relationship between spring and summer precipitation anomalies in Central-East during ENSO events, and proposed a surface-atmosphere feedback hypothesis to explain it. Here, we test whether this inverse relationship also holds between the spring and summer principal modes of variability.

The first two PCs of spring variability are correlated with the first two PCs of summer variability to reveal whether the inverse relationship in Central-East Brazil holds for all years in the analyzed period, or is a peculiar feature of ENSO events (Table 1).

Table 1. Correlation coefficients between PC1 and PC2 of spring and summer . Cells in yellow (pink) indicate significant correlation to a level better than 0.10 (0.05).

		SPRING	
		PC1	PC2
SUMMER	PC1	0,24	0,29
	PC2	-0,31	0,30

The first PCs in spring and summer are positively correlated, as are also the first rotated PCs. From Figs. 2a and 2e (or 2b and 2f) it is clear that this positive correlation indicates that when rainfall is above normal in Central-East Brazil during spring, it tends to be below normal in the same region in summer. During ENSO events this inverse relationship is even stronger as shown by the significant negative correlation between PC1 in spring with PC2 in summer (Figs. 2a and 2g). The positive correlation between PC2 in spring with PC1 in summer confirms this same inverse relationship, although in this case the anomalies in spring are more concentrated in the southern part of Central-East Brazil. This part (near the SACZ) probably plays a more important role in setting up antecedent conditions. The PC series mentioned above are displayed in Fig. 3. It shows clearly, for instance, the strong inverse relationship between PC1 in spring and PC2 in summer (Fig. 3c). The correlation between the second PCs in spring and summer (Figs. 2c and 2g) is not related with the inverse relationship under focus, but with the fact that the strongest components in northern SA have the same sign in spring and summer for the SST conditions associated with these modes.

The corresponding PCs for November and January precipitation show an even stronger relationship (not shown).

3.3. Relationship between spring and summer precipitation

As another way of disclosing the inverse relationship between spring and summer precipitation, we performed the correlation between spring (and November) precipitation in each box of Fig. 1 with summer (and January) precipitation in all the other boxes. From this analysis, it is clear that there is an area in Central-East Brazil in which spring and summer precipitation are negatively correlated (Fig. 4).

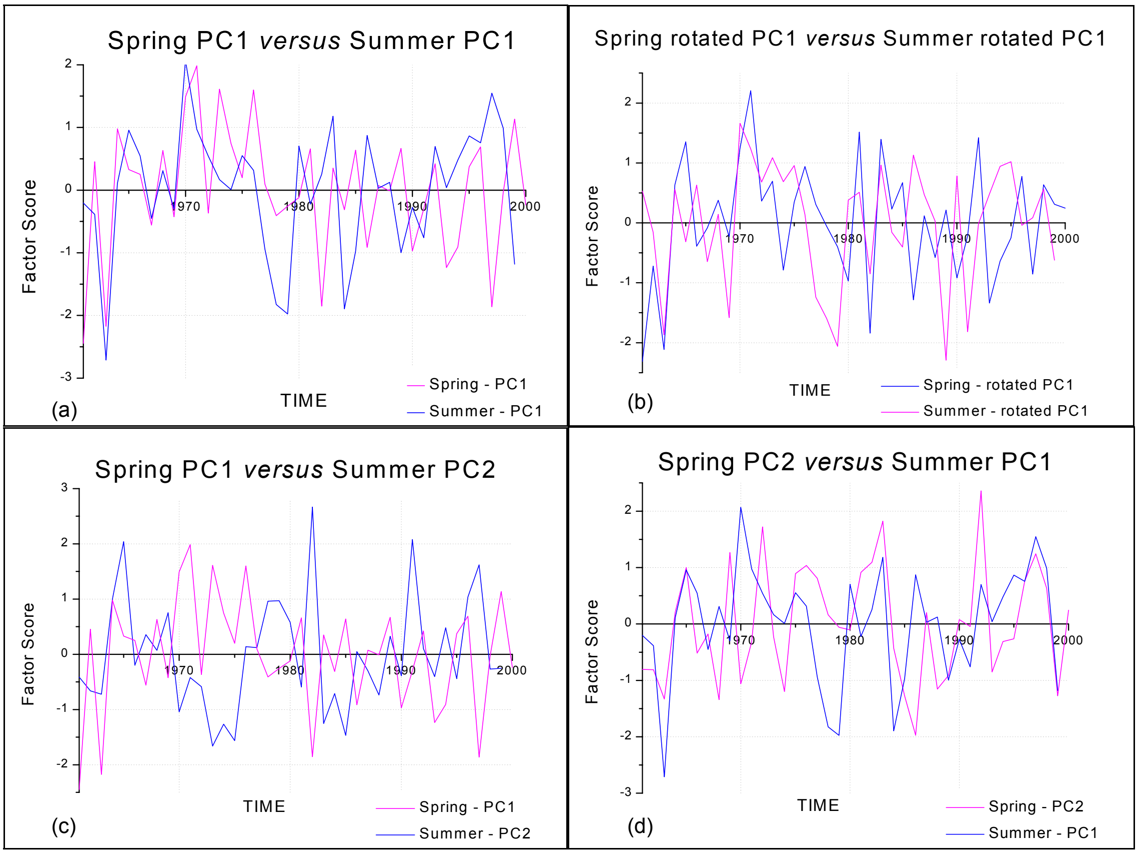


Figure 3. PCs of spring (blue) and summer (pink) modes of precipitation variability: (a) spring and summer PC1; (b) spring and summer rotated PC1; (c) spring PC1 and summer PC2; (d) spring PC2 and summer PC1.

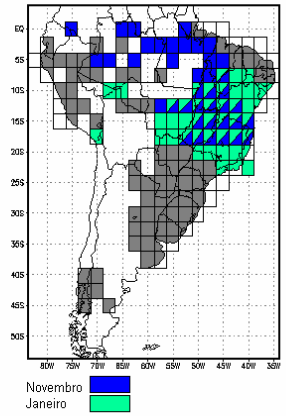


Figure 4. Blue regions have November precipitation negatively correlated with January precipitation in the green regions, with level of significance better that 0.10.

An additional view of the reverse precipitation anomalies in spring and peak summer is offered by the composite evolution of the precipitation over the region in which these anomalies tend to be reversed (Fig. 5). The composite evolution of the 15-day running mean precipitation averaged over this area was computed for all years and for those years in which the spring PC1 is above (below) 0.5 (-0.5) standard deviation. The region chosen for this analysis is within latitude range 6.25º S - 23.75º S and longitudes 41.25º W - 51.25º W (Fig. 5).

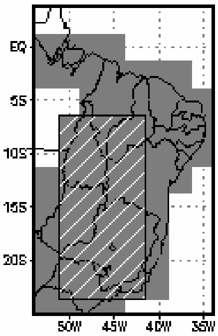


Figure 5. Area (hatched rectangle) in which the average precipitation was calculated for the analysis in Fig. 6.

The composite evolution in Fig. 6a shows that wet springs in Central-East Brazil are followed by dry peak monsoon season, while dry springs lead to a precipitation peak in January. This peak lasts for a shorter period than the dry anomalies after a wet spring.

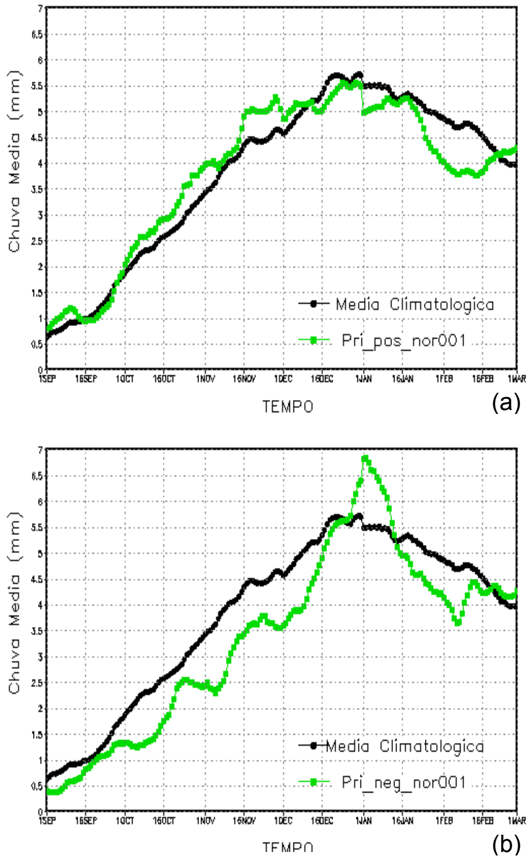


Figura 2: Composite evolution of the 15-day running mean precipitation (mm day^{-1}), averaged over Central-East Brazil (region in Fig. 5) for all years (black line) and (a) for years in which spring PC1 is above 0.5 standard deviation (green line) or (b) for years in which spring PC1 is below -0.5 standard deviation (green line).

4. CONCLUSIONS

Grimm (2003) reported that during spring of El Niño events, remotely produced anticyclonic low-level anomalies prevail over northern and central Brazil. Easterly moisture inflow from the Atlantic is directed toward south Brazil. There are negative precipitation anomalies in north and central-east Brazil and positive ones in south Brazil. During spring, positive surface temperature anomalies prevail over southeast Brazil. In January, a well established anomalous low-level convergence and cyclonic anomaly appears over southeast Brazil. This anomalous circulation directs moisture flux from northern Brazil toward central-east Brazil, causing moisture convergence in this region, with enhanced precipitation, while in southern Brazil the precipitation is reduced. This causes the precipitation dipole between Central-East and South Brazil. In February, after the above-normal precipitation of January, the surface temperature anomalies in the southeast turn negative, the low-level cyclonic anomalies disappear and the precipitation anomalies diminish and reverse their sign. During La Niña events, opposite anomalies are observed (Grimm 2004). A surface-atmosphere feedback hypothesis was proposed to explain the inverse relationship between spring and peak summer precipitation anomalies in Central-East Brazil during El Niño years.

The present study shows that this inverse relationship does also hold during other years, provided that the precipitation anomalies during spring are strong enough in Central-East Brazil. This relationship manifests itself in the connection between the first modes of precipitation variability in spring and summer, as well as in the correlation analysis of precipitation in the two seasons.

Dry (wet) conditions in central-east Brazil (including SACZ) during November are associated with less (more) soil moisture and higher surface temperature in late spring. Besides, less cloudiness produces more net surface solar radiation and higher SST off the southeast Brazil coast. A surface thermal low sets up and, associated with the topographic effect in southeast Brazil, produces convergence and cyclonic circulation that directs moisture flux into central-east Brazil, where it converges, enhancing precipitation in this region in January.

The inverse relationship in Central-East Brazil is stronger in ENSO years because the precipitation anomalies in spring, which are supposed to set up the anomalies in summer, are stronger during these events. Yet during ENSO the anomalies in southeastern SA are generally not opposite (except for the northern part of southern Brazil), because remote forcing associated with ENSO still influences precipitation in this region in summer, especially in the southernmost part of southern Brazil and northeastern Argentina (Fig. 2g). However, during non-ENSO years the regional circulation anomaly set up from November to January that produces precipitation anomalies in Central-East Brazil tends to produce opposite anomalies in southern Brazil (Fig. 2e).

The present analysis indicates that possible remote influences from SST anomalies on the dipole mode are stronger in spring than in summer (see correlation patterns between PC1 and SST in Fig. 2). This lends support to the hypothesis that the reversal of anomalies in summer might be associated with regional processes of surface-atmosphere interaction that are important during the monsoon season. Therefore, processes leading to monsoon rainfall in South America are prone to undergo interannual variations and regional interactions that are stronger in the summer season may be important in shaping this variability.

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