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Month-to-Month Impacts of Southern Annular Mode Over South America Climate

Impacto Mês a Mês do Modo Anular Sul na América do Sul

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Resumo

Este artigo teve como objetivo analisar o impacto, mês a mês, das fases do Modo Anular Sul (Southern Hemisphere Annular Mode - SAM) na América do Sul (AS), visando fornecer melhores recursos para estudos e previsões climáticas. Para o cálculo do índice SAM (aqui chamado de NSAM), utilizou-se a Função Ortogonal Empírica nas anomalias de altura geopotencial em 700 hPA, na região ao sul de 30ºS. Análises de compostos foram realizadas excluindo os anos de El Niño-Oscilação Sul (ENOS). Os resultados indicam que o Sudeste da AS (SEAS) e parte das Regiões Sudeste e Centro-Oeste do Brasil são as regiões mais afetadas pelo SAM. Entretanto, seu impacto difere mês a mês e nem sempre há uma influência oposta entre as fases do SAM. Para a temperatura do ar, os meses de março, maio, julho, agosto, setembro e novembro mostram anomalias positivas (negativas) afetando as regiões citadas acima durante a fase negativa (positiva) do SAM. Entretanto, a abrangência dessas anomalias difere entre os meses. Fevereiro e dezembro apresentam um dipolo de anomalia de temperatura, com anomalias positivas (negativas) no SEAS e negativas (positivas) ao norte, na fase negativa (positiva) do SAM. Janeiro apresentou um comportamento diferente comparado aos outros meses, mas também mostra um sinal aproximadamente oposto entre as fases do SAM. As anomalias de precipitação indicam um enfraquecimento (intensificação) da Zona de Convergência do Atlântico Sul na fase negativa (positiva) do SAM (novembro-janeiro e março). A região do SEAS mostra anomalias positivas (negativas) de precipitação na fase negativa (positiva) do SAM, durante os meses de março a junho e dezembro. Contudo, em outubro, o SAM influencia essa região de forma oposta. Um estudo de caso (janeiro de 2017 – fase negativa do SAM – ENOS neutro) mostrou uma grande similaridade com o composto de precipitação de janeiro, ratificando os resultados. Porém, para a temperatura do ar, somente a região próxima à costa apresentou similaridade com o composto correspondente.
Palavras–chave: Modo Anular Sul; América do Sul; Variabilidade Climática

Abstract

The goal of this paper is to study month-to-month impacts of Southern Hemisphere Annular Mode (SAM) phases over South America (SA). Composite analyses were performed excluding ENSO years. Southeastern SA (SESA), part of Southeastern and Central-West of Brazil seem to be more affected by SAM. However, SAM influences are different for each month, and there are also differences of the influences between SAM phases (not always opposite). For air temperature, March, May, July, August, September, and November show positive (negative) anomalies affecting regions cited above during the negative (positive) SAM phase. Although, the coverage of these anomalies is different among these months. February and December present a temperature anomaly dipole, with positive (negative) anomaly at SESA and negative (positive) northward, in the negative (positive) SAM phase. January has a different behavior compared with other months but also presents a nearly opposite signal between SAM phases. Precipitation anomalies composites indicate a weakening (strengthening) of South Atlantic Convergence Zone configuration at negative (positive) SAM phase (November-January and March). SESA region shows positive (negative) precipitation anomalies at negative (positive) SAM phases, during March-June and December. Nevertheless, in October, SAM oppositely influences this region. A case study (January 2017 - negative SAM - neutral ENSO) shows great similarity with the precipitation composites, ratifying the results. However, for temperature, the coastal region is the only which presents similarity with the composites.
Keywords: Southern Annular Mode; South America; climate variability

1 Introduction

The leading modes of the extratropical circulation variability in both hemispheres are characterized by deep, zonally symmetric or annular structures, with geopotential height perturbations of opposing signs in the polar cap region and in surrounding the zonal ring, centered near 45° latitude. This mode is called Annular Mode. The positive (negative) phase for these oscillations indicates less (higher) than normal geopotential heights at high latitudes and an opposite signal at middle latitudes (Thompson & Wallace, 2000). An annular mode index is calculated by Empirical Orthogonal Function (EOF) from the geopotential height anomaly in 700 hPa, polewards of 20° (e.g. Thompson & Wallace, 2000). This index is available at: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml.

The impacts of Northern Hemisphere Annular Mode (NAM, also known as Arctic Oscillation) have been extensively documented, whereas for Southern Hemisphere (SH) the Annular Mode (SAM, also known as Antarctic Oscillation) has received less attention.

According to Carvalho *et al.* (2005), the tropical convection and tropics-extratropics interactions play an important role in the SAM variability. Following this line, some papers, such as L'Heureux & Thompson (2006), point to a relationship between El Niño-Southern Oscillation (ENSO) and SAM. However, some studies suggest that these patterns have different mechanisms and scales, even if they are related (Cai & Watterson, 2002; Pezza *et al.*, 2012). Han *et al.* (2017) studied the relationship between SAM and ENSO during austral spring, using the Niño 3.4 index and the SAM index. According to the authors, during 1979–93, the ENSO (SAM) spatial signatures were restricted to the tropics–midlatitudes (midlatitudes-Antarctic) of SH, with a weak connection between the two patterns. However, after the mid-1990s, they identified atmospheric signals related to El Niño, during the negative phase of SAM at middle and high latitudes of SH.

Impacts of SAM pattern over South America (SA) climate have been discussed by some authors. Silvestri & Vera (2003) showed negative correlations of SAM phase with precipitation over Southern Brazil, part of Paraguay and extreme northeast of Argentina in November/December. Besides, there were positive correlations in July/August, in the same region. However, typical hemispheric circulation patterns, associated with SAM, change in decades, particularly over SA and Australia, as shown by Silvestri & Vera (2009). These authors found that during the 1960–70s decades, springs with SAM positive phase were associated with anomalous anticyclonic circulation developed in the southwestern subtropical Atlantic that enhanced moisture advection and promoted precipitation increase over southeastern SA (SESA). On the other hand, during 1980–90s springs, the anticyclonic anomaly, induced by the SAM's positive phase, covered most of southern SA and the adjacent Atlantic, producing a weakened moisture convergence and a decrease of precipitation over SESA as well as positive temperature anomaly advection over southern SA.

Reboita *et al.* (2009) evaluated seasonal precipitation anomalies over SA for different SAM phases during the 1980-1999 period. In the negative SAM phase, positive precipitation anomalies were observed over Southern Brazil, Uruguay, and central-north Argentina, mainly in the summer and autumn. The maximum rainfall occurred during autumn extending to all over the southern part of SA. In the summer, it was observed a large positive precipitation anomaly over Southern Brazil. On the other hand, negative precipitation anomalies were observed over the climatological position of the South Atlantic Convergence Zone (SACZ). This region with negative precipitation anomalies usually has maximum rainfall activity during SA monsoon period (Carvalho *et al.*, 2004; Vera *et al.*, 2006), mainly because of SACZ occurrences. Vasconcellos & Cavalcanti (2010) analyzed summers that were extremely dry and wet, over Southeastern Brazil during summer (DJF mean) in the 1980-2006 period. They found that excessive precipitation over this region occurs in the positive SAM phase whereas extremely dry conditions over Southeastern Brazil display a negative SAM phase.

As represented above, various studies presented SAM impacts over SA climate. However, these impacts are analyzed in a limited way. These analyses have been restricted to some seasons or specific months, evaluating only positive SAM phase or using techniques such as correlation (which do not allow to see differences between SAM phases). It is essential for the climate prediction centers a complete and updated study of SAM impacts on SA climate. As others teleconnections patterns, opposite SAM phases could not have a reverse impact over climate or with the same magnitude. SAM effects also could be different, depending on the month. Besides, it is important to know SAM impacts without ENSO influence. The goal of this paper is to show month-to-month effects of both SAM phases, excluding ENSO influence on SA climate, especially on the air temperature and precipitation. We expect that the results presented in this paper could be applied to climate studies and help to improve climate predictions.

2 Data and Methodology

The precipitation data used in this study is the monthly mean rainfall from the global precipitation climatology project (GPCP). The GPCP is based on station gauges and satellite estimates with spatial resolution 2.5º x 2.5º latitude/longitude (Adler *et al.*, 2003). The advantage of using GPCP is its global coverage, including oceanic areas. In addition, Muza & Carvalho (2006) have shown that GPCP has a good correspondence with a gridded precipitation from stations (described in Liebmann & Allured, 2005) in areas over tropical and subtropical Brazil.

Monthly datasets of Era-Interim reanalysis from European Centre for Medium Range Weather Forecasts (ECMWF) were used for the following variables: 2 m air temperature and geopotential height at 700 hPa. ERA-Interim features a global spatial coverage, with a horizontal resolution of 0.5º x 0.5º latitude/longitude and 60 vertical levels from the surface to 0.1 hPa. Details on the data assimilation system of ERA-Interim can be found in Dee *et al.* (2011). The datasets are used for the 1981-2010 period and for a case study of January 2017. Monthly anomalies were constructed subtracting, for each month, 1981-2010 mean (climatological mean) of the respective month.

The SAM index was calculated from the principal component time series of geopotential height monthly anomaly at 700 hPa polewards of 30°S, using EOF analysis and hereafter called NSAM index, to differentiate from the common SAM index. The area used to calculate EOF differs from Climate Prediction Center (CPC)/ National Centers for Environmental Prediction (NCEP) (available online at http://www.cpc.noaa.gov) and other papers (20º-90ºS). The choice of 30°-90°S latitude range had the purpose of minimizing tropical influences. Positive (negative) values of NSAM index are associated with negative (positive) geopotential height anomalies over Antarctica and positive (negative) geopotential height anomalies at middle latitudes.

Composite analyses are made in order to assess the month-to-month influence of extreme SAM phases on climate over SA (air temperature and precipitation). From the NSAM index series, years of ENSO occurrences (Niño 3.4 region) were withdrawn (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/). The purpose of this procedure was to observe only SAM influence, filtering a possible ENSO influence on the results. Then, composite analyses were constructed selecting four highest (extreme positive phase) and four lowest (extreme negative phase) NSAM index for each month. The exception occurred in December, when, after the withdrawal of ENSO years, only 3 (5) years remained for negative (positive) SAM phase. So, the composite for this month was made with three years, with a positive NSAM index, and three years with the lowest negative values of NSAM index. Table 1 shows the years used in the composites. In order to build anomaly composites (air temperature and precipitation), means of anomaly fields for the years described in Table 1 were calculated for each month. The Student's t-test (Wilks, 2006) was applied to the composites to determine regions in which the composite variables have a confidence level of 90%.

A case study outside the 1981-2010 period was analyzed to corroborate composites results. We choose January 2017 because it was a recent negative SAM month, without ENSO (neutral Niño 3.4). Precipitation and air temperature anomalies maps were created using climatological values described above. The results were compared with January composites for an extreme negative SAM.

Month	Positive				Negative			
January	1991	1994	2002	2004	1982	1986	1990	1993
February	1990	1994	2002	2005	1986	1991	2001	2004
March	1982	1994	1997	2004	1981	1986	2002	2007
April	1982	2003	2005	2010	1981	1990	1991	2007
May	1995	1996	2006	2010	1984	1986	1990	2002
June	1989	2004	2008	2010	1991	1994	2005	2007
July	1983	1985	1993	2006	1995	1990	2007	2009
August	1993	1994	2001	2003	1981	1996	2006	2009
September	1985	1990	1992	1993	1981	1991	1996	2000
October	1993	1996	2001	2008	1981	1990	1992	2003
November	1981	1985	1992	2008	1990	1996	2003	2005
December	1985	1981	2001	****	1989	1990	2003	****

Table 1 Classification of extreme positive and extreme negative SAM years for each month, using NSAM index and extracting ENSO (Niño 3.4) years. These years were used in composite analysis.

3 Results

In this section, a comparison between NSAM index and CPC SAM index is shown to validate our index. Then, the month-to-month influence of SAM phases over SA climate is presented and described. After this, a case study is analyzed and compared to composites results.

3.1 Comparison Between NSAM Index and Traditional SAM Index

SAM pattern is shown in the first EOF pattern for anomaly geopotential height of 30º-90ºS (Figure 1A). Figure 1B shows monthly time series (1981-2010) from NSAM (blue line – principal component time series of first EOF presented in Figure 1A) and SAM index calculated by CPC (red line – this index uses 20º-90ºS area, as explained in Section 2). The two series have a very similar behavior (temporal correlation of 95%). Differences are found mainly in the extremes (Figure 1B), where NSAM index usually presents more intense values in these cases. The tropical influences on the circulation pattern may be acting on CPC SAM index, dumping extreme values. Since we restrict EOF calculation to the extratropical region (30º-90ºS), this amortization should not occur.

3.2 Month-to-month SAM impacts

3.2.1 Air temperature at 2m

Composites for air temperature (Figure 2) show significant anomalies for almost all months, but varying month-to-month. Despite variations among these months, SESA, part of Southeastern and Central-West of Brazil are the most affected area. In general, the months present nearly opposite configurations between SAM phases. March, May, July, August, September, and November show similar behaviors, with positive (negative) temperature anomalies over regions cited above in the negative (positive) SAM phase. However, the coverage of these anomalies is different among these months. It is important to highlight that, for air temperature, November has the largest area affected by SAM, comparing with other months. This month is considered to be in the "active phase" of SAM (Thompson & Wallace, 2000).

In February, there is a temperature anomaly dipole, with positive anomaly at SESA and negative northward, in the negative SAM phase. The dipole signal reverses itself during positive SAM phase. In December, this dipole is also present but is not well characterized as February, mainly in negative SAM phase. January has a different behavior compared with other months cited above. During this month, a significant negative temperature anomaly is observed for approximately all tropical SA in the negative SAM phase. Exceptions (positive anomalies) occur near eastern coast southward 15°S and over Southern Region of Brazil. Positive anomalies occur in the positive SAM phase over central SA and southern part of Northeast Brazil, including parts of Southeast Brazil, northern Argentina, and Paraguay,

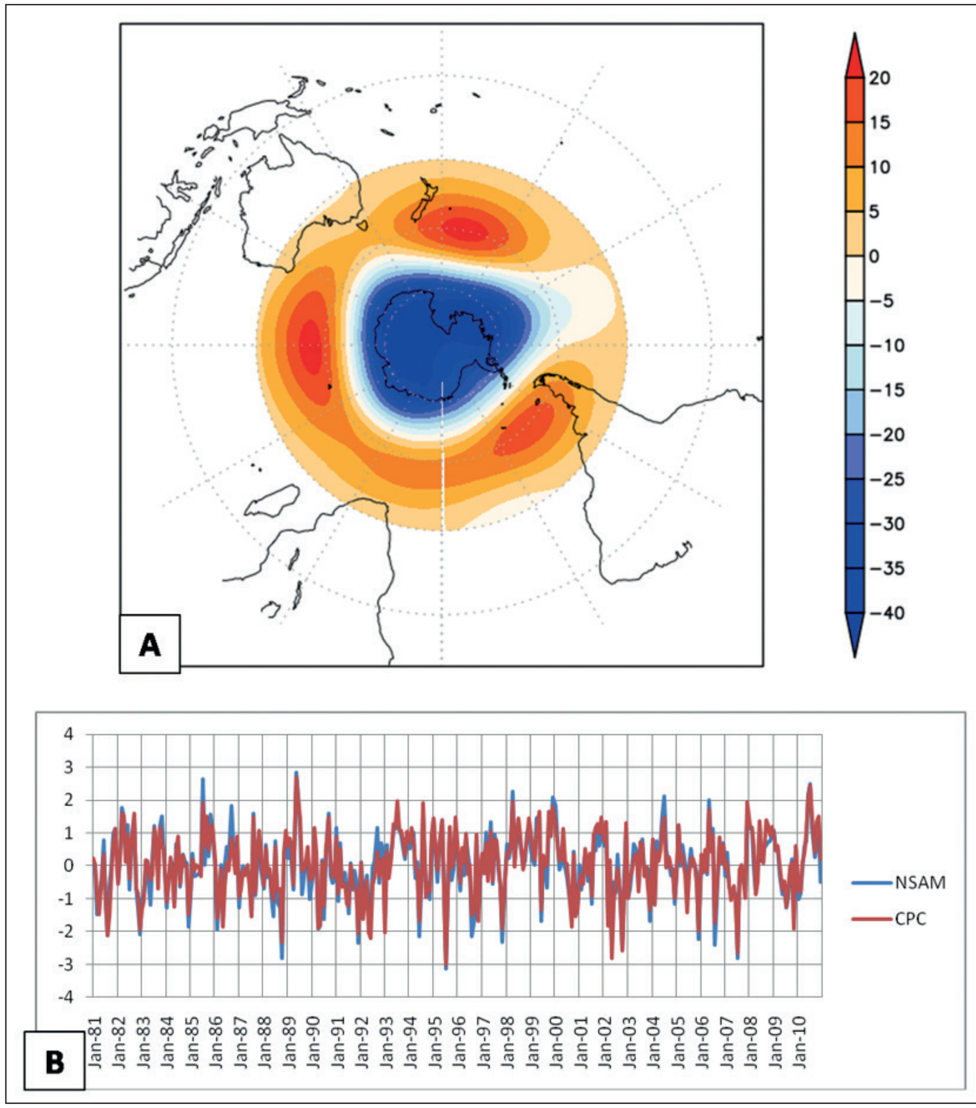

Figura 1 A. First EOF pattern for anomaly geopotential height (m) 30º-90ºS and B. SAM index for January 1981-December 2010 period. Blue line is NSAM index. Red line is SAM index from CPC/NOAA (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml).

thus presenting an opposite configuration to the negative SAM phase.

Only April, June, and October seem to have little influence of SAM over temperature since there are not large differences in the temperature anomalies between SAM phases. Besides, in June, most of the areas are without significant temperature anomalies.

3.2.2 Precipitation

Composites analyses for precipitation (Figure 3) also show differences month-to-month, and there are more differences between SAM phases comparing with air temperature composites (Figure 2). For March, November, and December, in the negative SAM phase, there is a band of negative precipitation anomalies with NW-SE orientation. This configuration has a similarity with the weakness of the SACZ pattern. Precipitation anomalies are approximately opposite in the positive phase, suggesting a strengthening of SACZ configuration. We can notice that, for November, this pattern is not well characterized for negative SAM phase as in the positive SAM phase. In some of these months, there is an opposite signal northward of this NW-SE band, which is a typical compensation of SACZ. January also has negative (positive) precipitation anomalies at SACZ region in negative (positive) SAM phase, but different of other months cited above, these anomalies

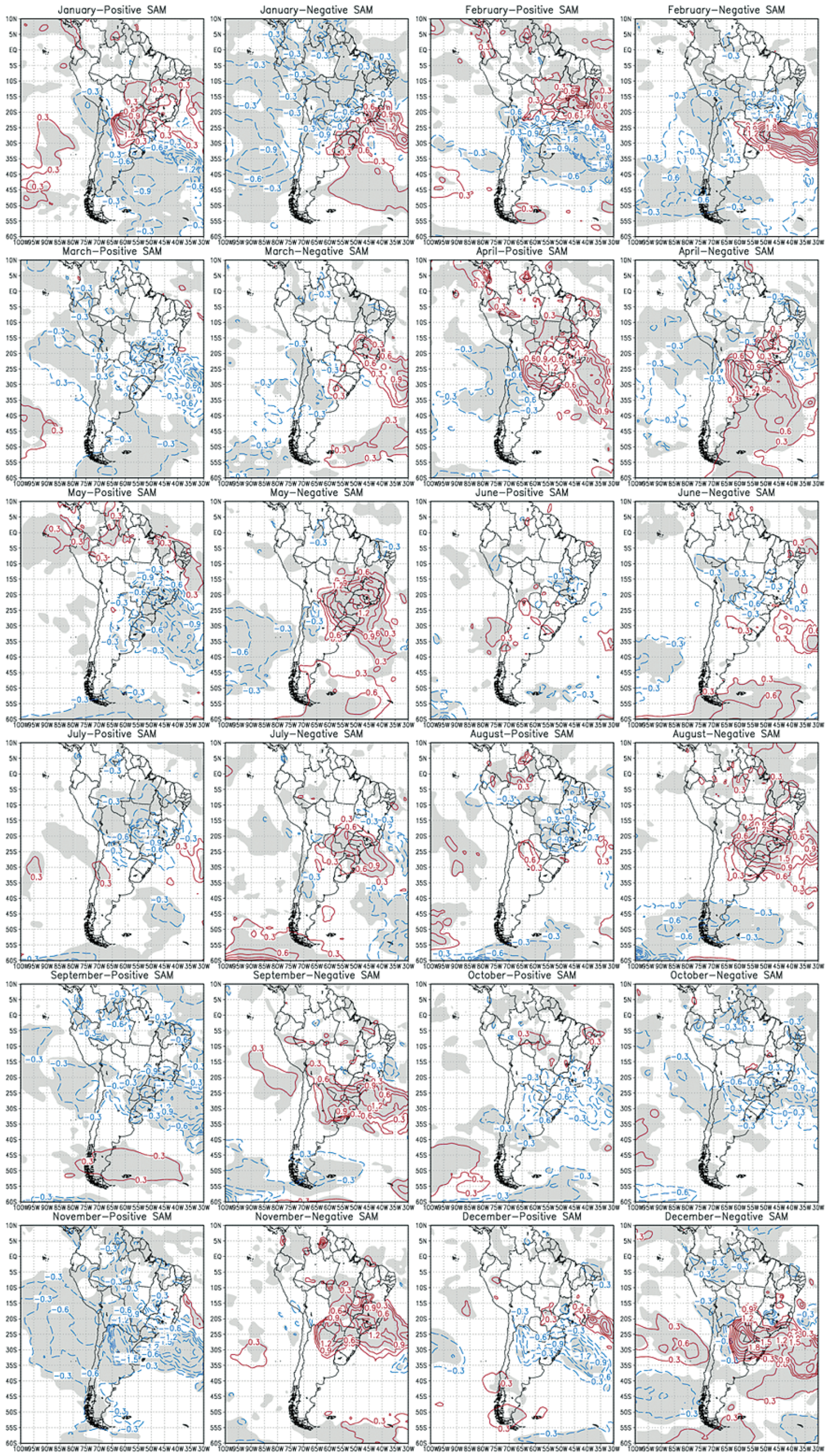

Figure 2 Composites of 2 m air temperature anomaly (ºC) for both SAM phase (January to December). Contour are 0.3ºC (red: positive; blue: negative). Areas with 90% significance are shown in shaded (t-student test).

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beginning in Central-West region of Brazil, not reaching western Amazon (which presents opposite anomalies).

It is also important to highlight that SESA is similarly affected by SAM during March-June and December, with positive (negative) precipitation anomalies at negative (positive) SAM phases. Nevertheless, not all the anomalies are statistically significant. In May, this behavior also affects parts of Central-West and Southeastern Region of Brazil.

October has a different behavior for SESA, comparing with other months cited above. In the negative SAM phase, there are negative anomalies over SESA. Positive anomalies are found over Central-West and Southeastern Region of Brazil. At the positive SAM phase, there is an opposite signal but with less significant areas.

In February, July, August, and September, SAM phases seem to have little influence over precipitation, presenting no opposition between SAM phases. However, there are occurrences of precipitation anomalies in some areas of the continent during each phase.

3.3 Case Study

To corroborate composites results presented above (Section 3.2), precipitation and temperature anomalies patterns were analyzed by January 2017, as a case study (Figure 4). Notice that this month is outside of the period used in composites analyses. January 2017 presented negative SAM phase (-0.98) with neutral ENSO (Niño 3.4 region, see Section 2). The results show more similarity with composites analysis for precipitation than the temperature.

As in the precipitation anomaly composite (Figure 3), January 2017 shows positive anomalies over northwestern SA and negative anomalies over central-eastern SA, northern Argentina, Paraguay and Bolivia (Figure 4A). Like the composite, these results indicate a weakness of SACZ pattern. According to the climate bulletin of Center for Weather Forecasts and Climate Studies (CPTEC) (Infoclima - http://infoclima1.cptec.inpe.br/ - in Portuguese), during this month there was a formation of only two weak SACZ episodes, contributing to above historical mean precipitation only over São Paulo and part of Mato Grosso do Sul states (Brazil). Notice that these positive anomalies also are seen in the composite analyses. The differences between the composite and January 2017 anomaly precipitation results are: positive anomalies at the northern part of continent extend eastward more than in the composite; the negative anomalies over SACZ region extend more westward than the composite. However, these small differences are expected because a composite analysis indicates only what is common in all cases.

In relation to the temperature anomaly for January 2017 (Figure 4B), there are positive temperature anomalies over almost the whole continent, contrasting with composite analysis (negative temperature anomalies – Figure 2). However, the composite shows positive anomalies near coast southward 15°S until southern Brazil, which is also present in this case study.

4 Summary and Conclusions

This paper aimed to study month-to-month impacts of SAM phases over SA. For excluding the tropical region, composite analyses were performed excluding ENSO (region Niño 3.4) years, and SAM index was calculated using EOF for the 30º-90ºS region. SESA and parts of Southeastern and Central-West Regions of Brazil seem to be more affected by SAM pattern. However, regions influenced by SAM are different in each month, and there are differences between SAM phases (not exactly opposite in some months).

February and December show an anomaly temperature dipole, with negative anomaly over SESA and positive anomalies northward, at the positive SAM phase. The dipole signal reverses at negative SAM phase. However, the dipole in December is not as well configured as February, mainly in negative SAM phase. On March, May, July to September and November, negative (positive) temperature anomalies are presented at positive (negative) SAM phase over tropical and subtropical SA. Nonetheless, these regions affected vary for each month. November (active period of SAM – Thompson & Wallace,

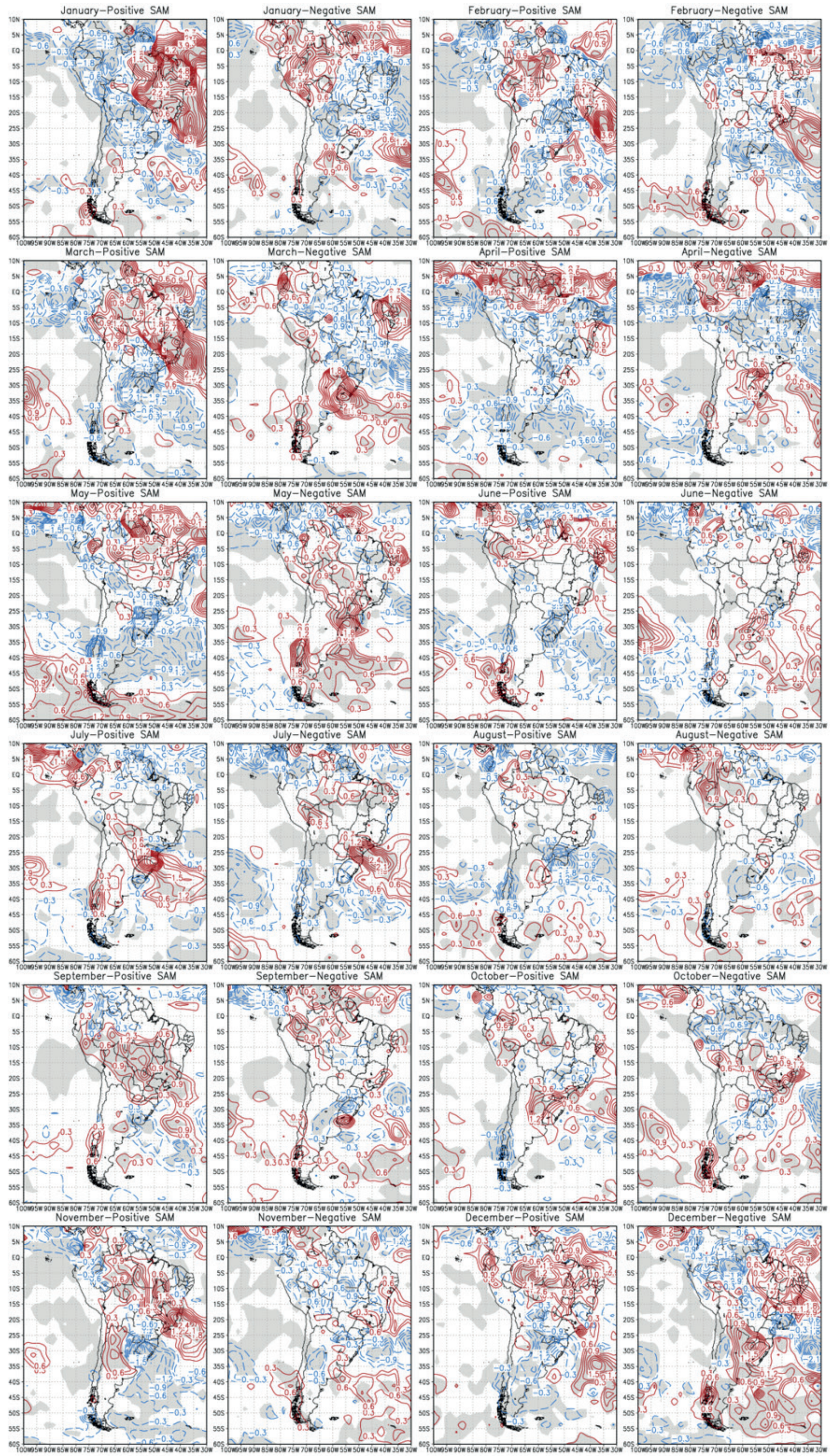

Figure 3 Composites of precipitation anomaly (mm.dia^{-1}) both SAM phase (January to December). Contour are 0.5 mm.dia^{-1} (red: positive; blue: negative). Areas with 90% significance are shown in shaded (t-student test).

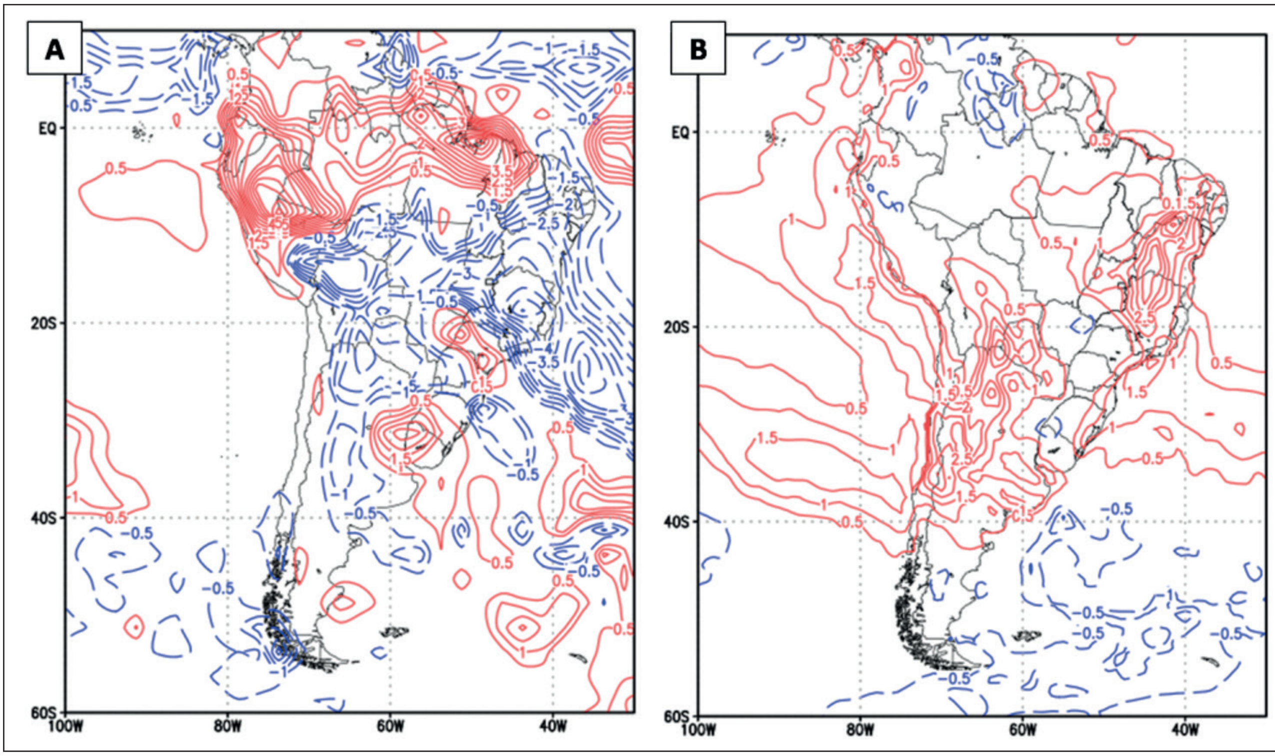

Figure 4 A. Anomaly precipitation (contour of 0.5 mm.dia-[1]) and B. 2 m air temperature anomaly (contour of 0.3ºC) on January 2017. Red contour: positive values; blue contour: negative values.

2000) has a larger area with opposite anomaly signal between SAM phases. These results differ from Silvestri & Vera (2009). They found a positive correlation between SAM phase and temperature over SESA, during 1980–90s springs. In this paper, composites for September and November present opposition between SAM phases but with configuration similar to a negative correlation. In October, both SAM phases present negative temperature anomalies over SESA (significant only in negative phase).

January has a different behavior compared with other months cited above. It shows that significant negative temperature anomalies occur in approximately all tropical SA in the negative SAM phase, with an opposite signal in the positive SAM phase over central and northeast SA, including part of Brazil, northern Argentina, and Paraguay. SAM pattern also influences precipitation over SA, but there are more differences between SAM phases comparing with air temperature composites.

In January, March, and December, precipitation anomalies indicate a weakening (strengthening) of SACZ configuration at negative (positive) SAM phase. November also presents the influence of SAM at SACZ characteristics, but with a better configuration at positive SAM phase. Reboita *et al.* (2009) and Vasconcellos & Cavalcanti (2010) also found an influence of SAM phase over SACZ configuration (DJF mean), with strengths (weakness) at positive (negative) SAM phase. However, in Reboita *et al.* (2009) the anomalies in ZCAS region are better configurated in negative SAM phase.

SESA region is affected by SAM similarly during March-June and December, with positive (negative) precipitation anomalies at negative (positive) SAM phases. Nevertheless, not all months present significance. It is noteworthy that, in October, SAM influence over SESA region is opposite to March-June and December, with negative (positive) precipitation anomalies at negative (positive) SAM phase. These results complement those presented by Silvestri & Vera (2003, 2009), using correlation techniques. Silvestri & Vera (2009) found, during 1980–90s springs, negative correlation between SAM and precipitation over SESA. Silvestri & Vera

(2003) found significant (not significant) negative (positive) correlations of SAM phase with precipitation over SESA in November/December (September/October). We found similar results in October and December (both significant). For November, positive SAM phase presents significant negative precipitation anomalies, however, negative SAM phase also present negative precipitation anomalies at SESA region (not significant). These authors also show significant positive correlations between SAM and precipitation in July/August, in the same region. But, when we analyzed both SAM phase separated, this opposition between phases is not configurated for both months. It shows the importance of analyzing both phases separated. Different SAM phases do not have necessarily opposite results (which is admitted when using the correlation between two variables). Reboita *et al.* (2009) analyzed both SAM phases separated (for each season). They also found positive (negative) precipitation anomalies at negative (positive) SAM phases in SEAS, but only for summer and autumn.

A case study for January 2017 (negative SAM, without ENSO) shows great similarity with precipitation composites, ratifying results. However, for temperature, only coastal region presents similarity with the composites.

As a final conclusion, the detailed documentation of SAM impacts over SA climate, analyzing each month and both phases, proved to be essential for a better understanding of climate variability at this continent. Future works will be important to discuss the physical mechanisms of these influences in different parts of South America.

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