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GEOSCIENCES

Atmospheric circulation patterns associated with surface air temperature variability trends between the Antarctic Peninsula and South America

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Abstract: This study investigated the spatial patterns of atmospheric circulation associated with surface air temperature variability trends between the Antarctic Peninsula and South America, during the austral summer (1979-2020). The first mode shows a positive score trend, with warming in northern Antarctic Peninsula and southern South America. This mode is mainly associated with the positive/neutral Southern Annular Mode and La Niña phases. There is an anomalous low pressure in the Southeast Pacific, a strengthening (weakening) of the polar (subtropical) jet and a strengthening and/or south/southwest displacement of the South Atlantic Subtropical High, which can prevent the passage of transient systems over the continent. In addition, there is a negative phase pattern of the South Atlantic Dipole, which contributes to the strengthening of the South Atlantic Convergence Zone convective activity. The second mode shows a negative score trend, with cooling in the Antarctic Peninsula/southernmost South America and warming between 10-40°S over South America. This mode is mainly associated with the spatial pattern of Central Pacific El Niño. There is a strengthening of the low-level jet and a strengthening of the western branch of the South Atlantic Subtropical High, all of which contribute to the suppression of the South Atlantic Convergence Zone.

Key words: Climate, SAM, ENSO, SACZ.

INTRODUCTION

Since the Industrial Revolution, the increase in atmospheric concentrations of anthropogenic greenhouse gases has led to an increase in the global average temperature (Eyring et al. 2021). Among the associated consequences, there are increases in the intensity, frequency and duration of hot extremes, from daily to seasonal scales that are modulated by large-scale atmospheric circulation, feedbacks between snow/ice-albedo and soil moisture-evapotranspiration-temperature, among others (Seneviratne et al. 2021). The same pattern of increasing extremes is observed in South America, especially in recent years (Skansi et al. 2013, Ceccherini et al. 2016, Bitencourt et al. 2020, Regoto et al. 2021).

Extreme weather events significantly influence highly productive agricultural regions in South America. Polar air masses affect the continent´s weather and climate, through the abrupt drop in its air temperature (Ricarte et al. 2015, Lanfredi & Camargo 2018, Carpenedo et al. 2022), severe frost formations and occasional snow, which results in agricultural productivity losses (Marengo et al. 1997). These systems can trigger not only cold events, but also warm events (Rusticucci & Vargas 1995). Rusticucci & Vargas (1995) analyzed the synoptic conditions associated with air temperature extremes over Argentina. The authors observed that hot extreme periods, in summer and winter, occur due to the northerly flow associated with the passage of cold fronts, the high-low-high pressure pattern (with low pressure over South America and high pressure over Pacific and South Atlantic oceans), or the presence of warm fronts over northern Argentina.

The asymmetrical orography of the Antarctic continent in relation to the geographic South Pole favors Rossby wave formations. These modify the structure of the high-level flow and modulate the characteristics of transient systems, consequently affecting mid and low-latitude atmospheric circulation (Pezza et al. 2008, Carpenedo et al. 2022). Rossby waves originate at the contact zone, between cold polar air and relatively warm air at mid-latitudes, which is modulated by the polar jet stream. This undulation promotes exchanges between the subtropical and polar air masses through extratropical cyclones, migratory anticyclones and fronts that form around the Antarctic continent (Kidston et al. 2011). These systems directly influence the climate variability of South America, which, in turn, affect regional economies that are highly dependent on agricultural output.

The Southern Annular Mode (SAM) is the main mode of climate variability, between mid and high southern latitudes (Fogt & Marshall 2020). This mode is marked by zonally symmetric and out-of-phase geopotential height anomalies (Marshall 2003), presenting a significant non-annular component over the Amundsen Sea (Thompson & Wallace 2000). The positive phase of SAM is characterized by negative (positive) geopotential height anomalies in high (mid) southern latitudes, which strengthens the westerly winds, as well as increases the frequency of extratropical cyclones and cold fronts around the Antarctic continent. This contributes to cooling over Antarctica and warming over the Antarctic Peninsula and mid-latitudes (Rudeva & Simmonds 2015, Fogt & Marshall 2020). On the other hand, opposite conditions are observed during the negative phase of SAM, favoring the propagation of transient systems over southeastern South America, since the subtropical jet is strengthened and displaced towards the equator (Carvalho et al. 2005, Rudeva & Simmonds 2015).

There is evidence of climate teleconnections between Antarctica and South America (*e.g.*, Aquino 2012, Carpenedo et al. 2013, 2022, Parise et al. 2015, 2022, Queiroz et al. 2022), suggesting the need to better understand how climate variability, at high southern latitudes, is related to the lower latitude climate variability. This study investigates the spatial patterns of southern atmospheric circulation associated with surface air temperature variability trends, between the Antarctic Peninsula and South America, during the austral summer, between 1979 and 2020.

MATERIALS AND METHODS

Data

We use monthly atmospheric fields from the European Center for Medium-Range Weather Forecasts (ECMWF) v5 reanalysis (ERA5) from January 1979 to December 2020. ERA5 is the fifth generation ECMWF atmospheric reanalysis produced by the Copernicus Climate Change Service (C3S), in a global grid of 0.25° x 0.25° (Hersbach et al. 2019). In this study, we used the following variables: 2m air temperature, 850-hPa wind, 500-hPa geopotential height and 250-hPa zonal wind.

We also employed monthly global 1° x 1° sea surface temperature (SST) from the Met Office Hadley Centre's sea ice and sea surface temperature data set (HadISST1; Rayner et al. 2003), and the monthly global 2.5° x 2.5° outgoing longwave radiation (OLR) from the National Oceanic and Atmospheric Administration (NOAA) v2.2-1 Climate Data Record (Lee & NOAA CDR Program 2011).

We obtained the monthly precipitation time series from the Climate Prediction Center (CPC) Global Unified Gauge-Based Analysis of Daily Precipitation (NOAA/OAR/ESRL PSL), with a global grid of 0.5° x 0.5°. This dataset comprises data from more than 30,000 weather stations. Data quality control is done by comparing this dataset with historical records, satellite and radar observations, and numerical model predictions.

The SAM and the Oceanic Niño Index (ONI) indices came from the CPC/NOAA. The SAM index projects daily standardized anomalies by the standard deviation of the monthly 700-hPa geopotential height index, south of 20°S, over the main SAM mode. To determine the polarity of the SAM index, values below (above) a standard deviation were defined as the negative (positive) phase of SAM (Reboita et al. 2009), meaning indices ≤ -1.0 (≥ +1.0), and as neutral phase values between ±1.0. La Niña (El Niño) events are defined as the persistence of quarterly anomalies (three-month moving average) of SST, for at least five consecutive quarters, at the ≤ -0.5°C (≥ +0.5°C) threshold. Climate variability studies widely use CPC/NOAA climate indices to understand the relations between systems and phenomena with a same variability mode (*e.g.,* Oliveira et al. 2014, Rehbein et al. 2018, Reboita et al. 2021).

Methods

We calculated the Empirical Orthogonal Functions (EOF) based on 2m air temperature anomalies without detrend (ERA5), between January 1979 and December 2020. This study focuses on the spatial patterns of air temperature with linear trend, making it possible to examine changes over time in surface air temperature variability, between the Antarctic Peninsula and South America and the associated atmospheric circulation. To include both the South Pacific and South Atlantic sectors, our analysis is set within 10°S and 80°S latitudes and 130°W and 20°E longitudes.

Based on EOF score time series, we identified the months with negative (positive) scores ≤ -1 (≥ 1), with standard deviation scores of ≤ -0.3 (≥ +0.3), hereafter events with negative (positive) scores. These events were evaluated in the austral summer (December-February), which corresponds to the active phase of the South American Monsoon System, the continent´s rainy season (Rao et al. 1996, Carvalho & Cavalcanti 2016).

Atmospheric circulation anomalies and climate indices SAM and ONI were evaluated during events with negative (positive) scores in the austral summer. The statistical significance of the mean anomalies was obtained using the Student t-test, with a significance level of 5% (Wilks 2006).

RESULTS

The surface air temperature EOF

Figure 1a shows the energy spectrum of the sample covariance matrix expressed in percentages of explained variance of the surface air temperature EOF, between the Antarctic Peninsula and South America, along with the approximate 95% confidence. EOF1 explains 14.5% of the total variance observed (Figure 1a). In the South Pacific sector, EOF1 shows an alternated spatial pattern where two negative poles, in low- and high-latitudes, are separated by a positive pole over subtropical latitudes (~30°S). In the South Atlantic sector, EOF1 shows

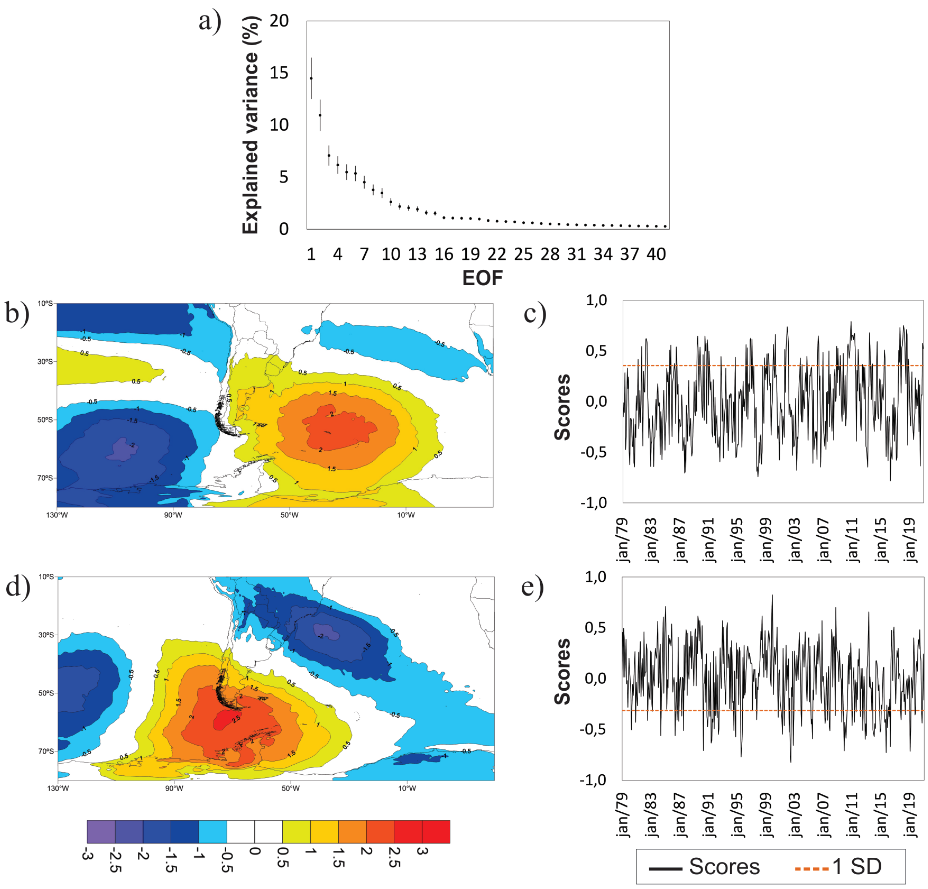

Figure 1. **Energy spectrum (in percentage) of the covariance matrix of explained variance of the EOF of the air temperature at 2 m, between the Antarctic Peninsula and South America (domain between 10°S-80°S and 130°W-20°E), from 1979 to 2020 (a); EOF1 spatial pattern and time series (b, c); and EOF2 scores (d, e). Vertical bars show approximate 95% confidence level, by rule of thumb (North et al. 1982). Dashed line indicates +1 (-1) standard deviation (SD) of the EOF1 (EOF2) scores. Continuous line indicates the linear trend of the EOF1 and EOF2 scores.**

an out-of-phase zonal pattern, between the low and mid-latitudes. This mode also characterizes a dipole pattern over the Antarctic Peninsula, with negative pole in the west and positive pole in the east (Figure 1b). This spatial pattern is similar to that observed in SST anomalies during the cold phase of ENSO (Cai et al. 2020). The EOF1 score time series (Figure 1c) shows interannual variability with minimums and maximums occurring every 2-4 years. The linear trend of the EOF1 scores is +0.202 (at the 1% significance level), between January 1979 and December 2020. Therefore, there is a trend towards positive EOF1 scores, meaning the spatial pattern of surface air temperature, as shown in Figure 1b.

The second mode of surface air temperature explains 10.9% of the observed variance (Figure 1a). The spatial pattern of surface air temperature shows negative anomalies from tropical South America to the extratropical South Atlantic and in the extratropical South Pacific, and positive anomalies from the Southeast Pacific to the Southwest Atlantic (Figure 1d). The time series of EOF2 scores (Figure 1e) shows interannual variability with minimums and maximums occurring every 1-4 years. The linear trend of the EOF2 score time series is -0.202 (at the 1% significance level), meaning a negative EOF2 score trend. This spatial pattern of surface air temperature presents the opposite signal to the results presented in Figure 1d.

Considering that the negative and positive score events presented spatial pattern of atmospheric field anomalies in opposite phases, hereafter, we chose to only present the positive EOF1 and negative EOF2 score events, according to the trends observed.

The surface air temperature EOF and ENSO/ SAM phases during summer

During the positive EOF1 score events (Figure 1c) we observe a predominance of La Niña events (56% of events) during summer (Figure 2a). Particularly, 39% of events combine La Niña and positive SAM (Figure 2b); followed by the positive and neutral phases of the SAM (50% of events each; Figure 2a), with 28% of events combined (neutral ENSO and SAM; Figure 2b). There is no negative phase of the SAM during events with positive EOF1 scores in summer.

During the negative EOF2 score events (Figure 1e), we found a predominance of neutral SAM (75% of events) and neutral ENSO (50% of events; Figure 2a). Of these, 40% of events are combined (neutral ENSO and SAM; Figure 2b); followed by 35% El Niño events, in which 20% are combined El Niño and neutral SAM events.

The surface air temperature EOF and atmospheric circulation patterns during summer

Figure 3 shows the spatial pattern of summer atmospheric field anomalies during events with positive EOF1 scores of the surface air temperature between the Antarctic Peninsula and South America. We can observe an annular pattern of 500-hPa geopotential height anomalies, between subtropical/mid (positive anomalies) and high (negative anomalies) latitudes of the Southern Hemisphere (Figure 3a), similar to the spatial pattern of the positive SAM phase (Fogt & Marshall 2020).

At low levels, the western branch of the South Atlantic anticyclonic circulation (Figure 3b) transports warm air from subtropical latitudes towards the south of South America and the south of South Atlantic, contributing to the warming pattern observed in the surface air temperature EOF1 (Figure 1b). On the other hand, over the high latitudes, the western branch of a cyclonic circulation, located over the Bellingshausen and Amundsen Seas, transports cold air over the Antarctic continent towards the Southeast Pacific, contributing to the cooling pattern observed in the surface air temperature EOF1 (Figure 1b). At high levels, we can see a strengthening of the polar jet around 60°S and a weakening of the subtropical jet to the north

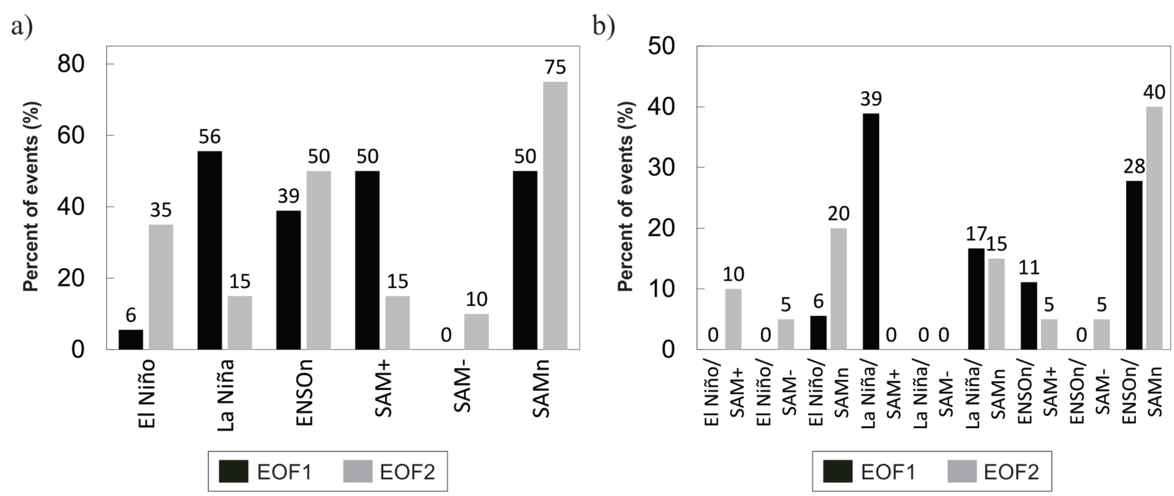

Figure 2. Number of events (in percentage) of El Niño, La Niña, ENOS neutral (ENSOn), positive (SAM+), negative (SAM-), and neutral (SAMn) SAM phases (a); and combined ENSO and SAM events (b), in events with scores equal to or greater than 1 EOF1 standard deviation (black bar) and in events with scores equal to or less than 1 EOF2 standard deviation (grey bar) of the air temperature at 2 m, between the Antarctic Peninsula and South America in the austral summer, from 1979 to 2020.

(Figure 3c). This is consistent with the pattern of 500-hPa geopotential height anomalies observed in the positive SAM phase (Figure 3a).

The same alternation pattern between negative and positive surface air temperature anomalies in EOF1 (Figure 1b) can be observed in SST (Figure 3d). There are negative SST anomalies in the east-central equatorial Pacific, with a pattern similar to cold ENSO events. In the South Atlantic, the SST anomaly dipole between the tropical and extratropical latitudes characterizes a negative phase of the South Atlantic Dipole (Nnamchi et al. 2011, Bombardi et al. 2014). There is anomalous suppressed convection (positive OLR anomalies) from the east-central equatorial Pacific to northeastern Argentina, Uruguay and southern Brazil, and anomalous convection (negative OLR anomalies) over northern South America towards southeastern Brazil, although not statistically significant (Figure 3e). The spatial pattern of OLR anomalies over South America, presenting negative OLR anomalies between the northwest and southeast Brazil and positive OLR anomalies over northeastern Argentina, Uruguay and southern Brazil, is similar to the seesaw pattern associated with the strengthening of convective activity in the South Atlantic Convergence Zone (SACZ; *e.g.*, Muza et al. 2009, Mattingly & Mote 2017). In the western South Pacific, between the equator and approximately 40°S-120°W, there is a negative anomalous convection, which may indicate a strengthening of the South Pacific Convergence Zone (Vincent 1994).

Figure 4 presents the spatial pattern of summer atmospheric field anomalies during events with negative EOF2 scores of the surface air temperature, between the Antarctic Peninsula and South America. We can observe a wave train pattern in the 500-hPa geopotential height anomalies (Figure 4a), between the tropical Pacific/Indonesia region and South America, similar to the Pacific-South America pattern (PSA; Mo & Higgins 1998, Mo & Paegle 2001).

Between the Amazon region and southern Brazil, there are northwesterly 850-hPa winds anomalies (Figure 4b), possibly indicating a strengthening of the South American low-level jet (SALLJ) and a warm air transport from tropical latitudes towards southern Brazil, contributing to the positive air temperature anomalies of the negative EOF2 scores (Figure 1d).

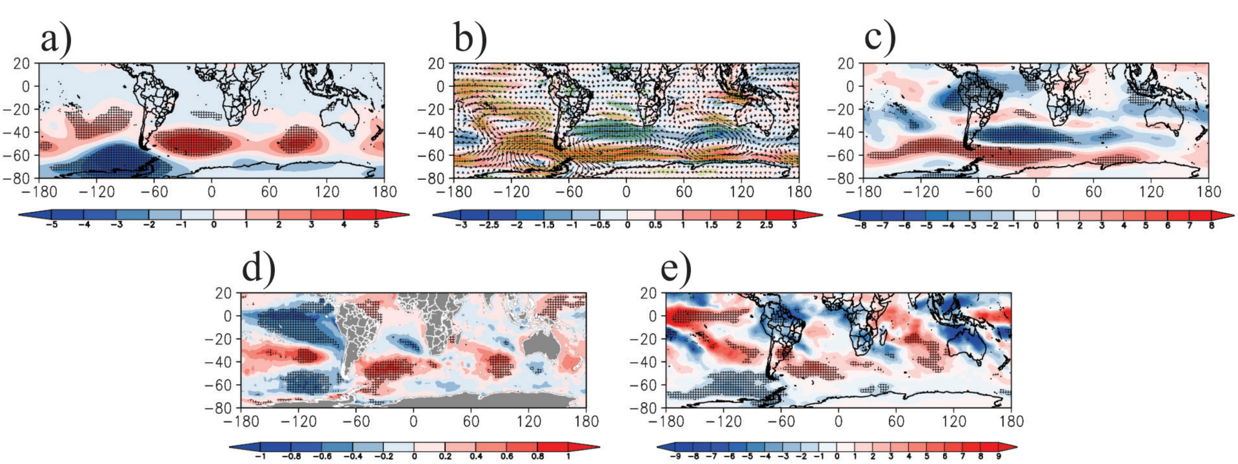

Figure 3. Anomalies composites of the 500-hPa geopotential height (m) (a); 850-hPa wind (m/s) (b); 250-hPa zonal wind (m/s) (c); sea surface temperature (°C) (d); and outgoing longwave radiation (W/m²) (e), in the austral summer, during the positive scores (equal to or greater than 1 standard deviation) of the EOF1 2m air temperature, between the Antarctic Peninsula and South America. Gridded areas are significant at the 5% level.

At high levels, there is a weakening of the polar jet around 60°S, between the South Pacific and South Atlantic, and a strengthening of the subtropical jet in southern South America (Figure 4c). Between the west of the Antarctic Peninsula and northern South America, a pole-equator teleconnection pattern is evident through 250-hPa zonal wind anomalies, which can act as Rossby waveguides (Hoskins & Ambrizzi 1993).

In the ocean there is a similar spatial pattern (Figure 4d) of surface air temperature of the negative EOF2 scores (Figure 1d), with SST positive anomalies in the central equatorial Pacific and negative anomalies between the southernmost South America and Antarctic Peninsula. Anomalous convection occurs in the central-west equatorial Pacific and between southern Brazil, Uruguay and northeastern Argentina (Figure 4e). On the other hand, there is an anomalous suppressed convection between northern and southeastern Brazil, with northwest-southeast orientation. This is similar to the seesaw pattern associated with the weakening of the SACZ (*e.g.*, Muza et al. 2009, Mattingly & Mote 2017).

DISCUSSION AND CONCLUSIONS

This study analyzed the spatial patterns of atmospheric circulation associated with trends in surface air temperature variability between the Antarctic Peninsula and South America (domain between 10°S-80°S and 130°W-20°E), during the austral summer, from 1979 to 2020.

The main variability mode of surface air temperature shows a warming in northern Antarctic Peninsula and southern South America, with a linear trend of positive EOF1 scores. The second mode shows a dipole pattern between the Antarctic Peninsula and South America, with a linear trend of negative EOF2 scores (cooling in the Antarctic Peninsula and southernmost South America and warming between 10-40°S over South America).

The spatial patterns of surface air temperature of both positive EOF1 and negative EOF2 scores are directly related to the SST anomalies. The likely causes of low frequency atmospheric patterns are attributed to the energetic and high thermal inertia roles of the ocean surface mixed-layer, which couples directly with the atmosphere (Holton 2004). Therefore,

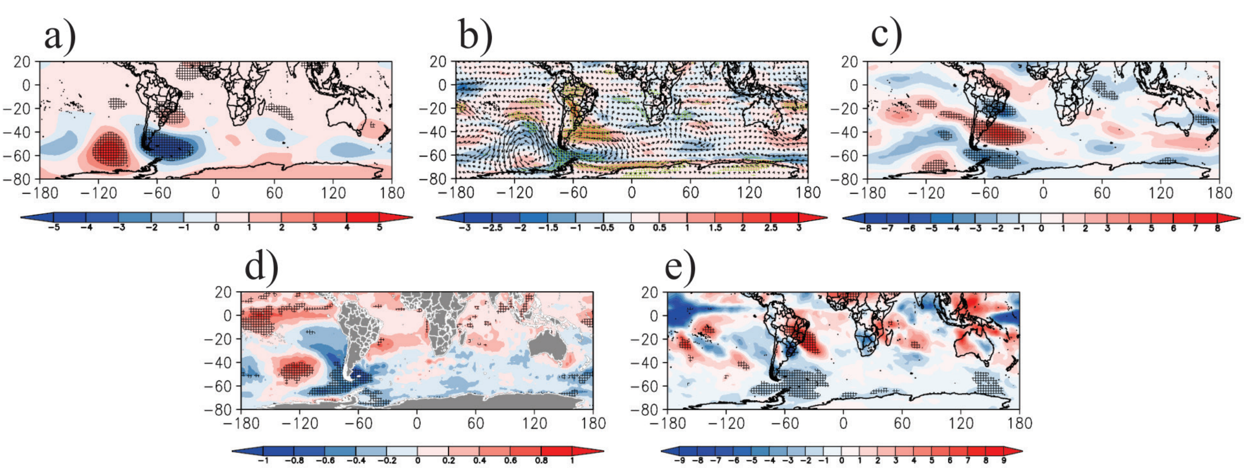

Figure 4. Anomalies composites of the 500-hPa geopotential height (m) (a); 850-hPa wind (m/s) (b); 250-hPa zonal wind (m/s) (c); sea surface temperature (°C) (d); and outgoing longwave radiation (W/m²) (e) in the austral summer, during the negative scores (equal to or less than 1 standard deviation) of the EOF2 2m air temperature, between the Antarctic Peninsula and South America. Gridded areas are significant at the 5% level.

spatial patterns of SST anomalies, on seasonal and interannual timescales, act as a thermal forcing to the atmosphere (Hoskins & Karoly 1981). Anomalous troughs (ridges) at middle levels contribute to SST patterns and surface air temperature by: (1) weakening (strengthening) of downward movements or strengthening (weakening) of upward movements, which may contribute to cooling (warming) by adiabatic expansion (compression); (2) increase (decrease) of cloud cover, observed through negative (positive) OLR anomalies, allows less (more) solar radiation to reach the surface, which may contribute to surface cooling (warming); and (3) cold (warm) advection by anomalous southerly (northerly) winds on the west (east) branch of the trough and east (west) of the ridge.

The positive EOF1 scores of surface air temperature are mainly associated with the cold phase of ENSO and the positive/ neutral phase of SAM. Studies show that the relationship between ENSO and SAM tends to favor the positive phase of SAM during La Niña events (Gong et al. 2010, Fogt et al. 2011, Wilson et al. 2016). Atmospheric circulation during the cold phase of ENSO and the positive phase of SAM is related to an anomalous low pressure in the Southeast Pacific, a strengthening of the polar jet and a weakening of the subtropical jet (Carvalho et al. 2005, Oliveira et al. 2014), as observed in this study. The intense polar jet disfavors the occurrence of atmospheric blockings in the South Pacific (Oliveira et al. 2014, Oliveira & Ambrizzi 2017), by making it difficult to bifurcate the zonal flow at high levels for blocking formations (Rex 1950, Dole 1986). Atmospheric blockings are systems that are associated with extreme weather events in South America (Rodrigues & Woollings 2017, Rodrigues et al. 2019).

In the South Atlantic, the high-pressure anomaly observed through the positive anomalies 500-hPa height and the 850-hPa anticyclonic circulation, suggest a strengthening of the south/southwest branch and/or a south/ southwest displacement of the South Atlantic Subtropical High (SASH). This anomalous configuration can prevent the normal passage of extratropical cyclones and frontal systems over the east coast of South America (Seth et al. 2015, Coelho et al. 2016, Gozzo et al. 2022). This results in the suppression of convection in southern Brazil, Uruguay and northeastern Argentina. As the SASH corresponds to the descending branch of the Hadley cell, we suggest that the Intertropical Convergence Zone (which is associated with the ascending branch of this cell) also shows a southward displacement, as observed through anomalous convection in northern South America. These results are in agreement with those observed by Carpenedo & Ambrizzi (2020), who analyzed the position of the SASH in both phases of the SAM.

In addition to the strengthening and/or poleward displacement of the SASH, there is a dipole of SST anomalies in the South Atlantic (negative in the tropics and positive in the extratropics), similar to the negative phase of the South Atlantic Dipole (Bombardi et al. 2014). Bombardi et al. (2014) show that in the negative phase of the South Atlantic Dipole, there is an increase in cyclogenesis and low track density of the cyclones on the southeast coast of Brazil, resulting in more precipitation over the eastern South America. This is likely associated with the strengthening of SACZ.

In the South Pacific, the high-pressure anomaly indicates a strengthening of the South Pacific Subtropical Anticyclone, which contributes to the strengthened South Pacific Convergence Zone pattern (OLR negative anomalies), commonly observed in the cold phase of ENSO (Vincent 1994).

The negative EOF2 scores of surface air temperature are mainly related to the neutral

ENSO and SAM, and secondly to the warm ENSO phase. The SST spatial pattern is similar to the Central Pacific El Niño (Capotondi et al. 2015), with SST anomalies warmer in the Niño 3.4 and Niño 4 regions. Central Pacific El Niño events are associated with a frequency increase of extreme rainfall in southern Brazil and a frequency decrease between north/northeast and southeastern Brazil (Tedeschi et al. 2014), which corroborates the results observed in this study of increased convection in the south and suppression of convection between the north and southeast of Brazil. A spatial pattern similar to the PSA pattern is observed through 500-hPa height anomalies, which is the dominant mode of low-frequency climate variability between the tropical Pacific/Indonesia region and South America continent (Mo & Higgins 1998, Mo & Paegle 2001). This is a pattern more directly related to the variability of the ENSO phenomenon, generating persistent anomalous high (low) pressure centers in the Southeast Pacific during El Niño (La Niña) events, respectively (Yuan 2004).

The anomalous high pressure in the Southeast Pacific contributes to the bifurcation of the polar jet, observed through the weakening of the 250-hPa zonal wind in this region and strengthening to the south. This configuration is favorable for the formation of atmospheric blockings in the Southeast Pacific (Rex 1950, Dole 1986), thus being more frequent in warm phase of ENSO (Oliveira et al. 2014). On the other hand, the strengthening of the jet between southern South America and the Southwest Atlantic disfavors the formation of atmospheric blockings.

The anomalous high pressure in the tropical South Atlantic, more intense along east coast of southern and southeastern Brazil, may indicate a strengthening of the SASH, especially in its western branch. Variations in the position of the SASH can contribute to precipitation anomalies and even hydrological extremes over Brazil. For example, the severe droughts of 2013-2014 and 2014-2015 in southeastern Brazil and of 2018 in the state of São Paulo were associated with the westward shift of SASH, preventing the normal passage of transient systems and, thus, contributing to a weakening of SACZ events (Seth et al. 2015, Coelho et al. 2016, Gozzo et al. 2022).

The strengthening of the 850-hPa winds between the Amazon region and southern Brazil indicates a strengthening of SALLJ, favored by the warm phase of ENSO (Silva & Ambrizzi 2006). The SALLJ is responsible for the transport of moisture from the Amazon and tropical Atlantic towards southern Brazil, favoring the development of mesoscale convective systems and high precipitation (Marengo et al. 2004, Moraes et al. 2020). When SALLJ is strengthened, SACZ events are weakened (Marengo et al. 2004).

Therefore, both the strengthening of the western branch of SASH and the strengthening of SALLJ, in the negative EOF2 scores of surface air temperature, result in a suppression spatial pattern of SACZ and tropical convective activity (Marengo et al. 2004, Muza et al. 2009). This presents anomalous suppressed convection between the northern and southeastern Brazil, and anomalous convection in southern Brazil, Uruguay and northeastern Argentina.

South America warmed significantly in recent decades, especially in the tropical region and adjacent oceans (Carvalho & Jones 2013, Barros Soares et al. 2017), accompanied by an increase in the frequency and intensity of heat waves (Bitencourt et al. 2020, Feron et al. 2019). These changes can alter the temperature gradients between the ocean and the continent, affecting regional atmospheric circulation patterns and moisture transport. Studies show an increasing trend in precipitation and heavy precipitation in southeastern South America

(Gonzalez et al. 2013, Cerón et al. 2021, Regoto et al. 2021), which is associated with an increase in moisture transport from the Amazon towards the subtropics, via SALLJ (Montini et al. 2019). Moisture transport by SALLJ creates the necessary conditions for the formation and maintenance of persistent mesoscale convective systems with a large spatial scale (Salio et al. 2007, Moraes et al. 2020). Generally, mesoscale convective systems are associated with intense precipitation and severe meteorological phenomena, such as wind gusts, electrical storms, hail, tornadoes, among others (Maddox 1983, Viana et al. 2009).

The climate variability of surface air temperature, between the Antarctic Peninsula and South America, seems to be associated with changes in the intensity and/or frequency of atmospheric systems operating in South America, such as SALLJ, mesoscale convective systems, atmospheric blockings, SACZ, SASH, and others. In the present study, we evaluated air temperature variability related to low frequency variability, considering only ENSO and SAM. However, other climate variability modes act to contribute to these variations, such as Madden-Julian Oscillation, Indian Ocean Dipole, Pacific Decadal Oscillation, Atlantic Multi-decadal Oscillation, and others (Chylek et al. 2010, Yoo et al. 2012, Nuncio & Yuan 2015, Turner et al. 2020). The influence of these atmospheric systems (and the related climate variability modes) on surface temperature variability are beyond the focus of this work and will be addressed in a future study.

The previous study by Aquino (2012) evaluates the rotated EOF of surface air temperature, without detrend, between the Antarctic Peninsula and South America (domain 130.5°W-21°E and 9°S-81°S), from 1979 to 2010. The author shows a spatial pattern, with EOF1 (EOF2) explaining 10.9% (7.5%) of the total observed variance, similar to our results in the present study in which EOF1 (EOF2) explains 14.5% (10.9%) of the variance. However, the EOF1 (EOF2) found by Aquino (2012) is similar to the EOF2 (EOF1) in this study, which suggests a change in the dominant spatial pattern, determined for recent years (2011-2020). The EOF1 in the present study is related to the spatial pattern, especially in relation to 500-hPa height and 250-hPa zonal wind anomalies, of the positive phase of SAM. These observations are consistent with the highest positive indices during the 21st century, since the last millennium, and with the positive polarity trend of the SAM (*e.g.,* Abram et al. 2014, Fogt & Marshall 2020). This SAM trend is associated with the hole in the ozone layer and increased concentrations of greenhouse gases (Thompson & Solomon 2002, Marshall et al. 2004, Gillett et al. 2013). With these SAM trends, it is possible that the EOF1 air temperature spatial pattern (warming in northern Antarctic Peninsula, southern South America and the Southwest Atlantic) will persist in the coming years. Historical air temperature records on the Antarctic Peninsula show a warming trend over the last 40 years (Meredith et al. 2019, Turner et al. 2020, Arias et al. 2021, Carrasco et al. 2021, Fox-Kemper et al. 2021, and references therein). Although there was a cooling trend in the beginning of the 21st century until mid-2010 - some studies point to it as part of the “global warming hiatus” (Turner et al. 2016, Carrasco et al. 2021) - the same was not enough to reverse the warming trends observed in the Antarctic Peninsula (Carrasco et al. 2021). Understanding oceanic and atmospheric processes, associated with possible changes in the air temperature spatial pattern between the Antarctic Peninsula and South America in recent years, is crucial to identify the likely drivers of such changes. Future studies will answer such questions.

These results add to understanding of how climate variability in high southern latitudes are related with tropical and subtropical latitudes in the South America, offering a more adequate representation for large-scale atmospheric general circulation models, thus increasing the forecasting abilities for South America.

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REFERENCES

ABRAM N, MULVANEY R, VIMEUX F, PHIPPS SJ, TURNER J & ENGLAND MH. 2014. Evolution of the Southern Annular Mode during the past millennium. Nature Clim Change 4: 564-569.

AQUINO FE. 2012. Climate connection between the Southern Hemisphere Annular Mode with the Antarctic Peninsula and southern Brazil. Thesis/doctoral thesis. Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

ARIAS PA ET AL. 2021. Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, In: Masson-Delmotte V et al. (Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 33-144.

BARROS SOARES D, LEE H, LOIKITH PC, BARKHORDARIAN A & MECHOSO CR. 2017. Can significant trends be detected in surface air temperature and precipitation over South America in recent decades? Int J Climatol 37(3): 1483-1493.

BITENCOURT DP, FUENTES MV, FRANKE AE, SILVEIRA RB & ALVES MPA. 2020. The climatology of cold and heat waves in Brazil from 1961 to 2016. Int J Climatol 40: 2464-2478.

BOMBARDI RJ, CARVALHO LMV, JONES C & REBOITA MS. 2014. Precipitation over eastern South America and the South Atlantic Sea surface temperature during neutral ENSO periods. Clim Dynam 42: 1553-1568.

CAI W ET AL. 2020. Climate impacts of the El Niño - Southern Oscillation on South America. Nature Reviews Earth Environ 1: 215-231.

CAPOTONDI A ET AL. 2015. Understanding ENSO diversity. B Am Meteorol Soc 96(6): 921-938.

CARPENEDO CB & AMBRIZZI T. 2020. South Atlantic Subtropical Anticyclone Associated with the Southern Annular Mode and Climate Impacts in Brazil. Braz J Meteorol 35: 1-9.

CARPENEDO CB, AMBRIZZI T & AIMOLA LAL. 2013. Possible relationships between the interannual variability of Antarctic sea ice and precipitation in South America. Ciência e Natura, p. 87-89.

CARPENEDO CB, CAMPOS JLPS, AMBRIZZI T & BRAGA RB. 2022. The High-Frequency Variability of Antarctic Sea Ice and Polar Cold Air Incursions over Amazonia. Int J Climatol 42(6): 3397-3407.

CARRASCO JF, BOZKURT D & CORDERO RR. 2021. A review of the observed air temperature in the Antarctic Peninsula. Did the warming trend come back after the early 21st hiatus? Polar Sci 28: 100653.

CARVALHO LM & JONES C. 2013. CMIP5 simulations of low=level tropospheric temperature and moisture over the tropical Americas. J Climate 26(17): 6257-6286.

CARVALHO LM, JONES C & AMBRIZZI T. 2005. Opposite phases of the Antarctic Oscillation and relationships with intraseasonal to interannual activity in the tropics during the austral summer. J Climate 18(5): 702-718.

CARVALHO LMV & CAVALCANTI IFA. 2016. The South American Monsoon System (SAMS). In: Carvalho L & Jones C (Eds), The monsoons and climate change. Springer.

CECCHERINI G, RUSSO S, AMEZTOY I, ROMERO CP & CARMONA-MORENO C. 2016. Magnitude and frequency of Heat and Cold Waves in recent decades: the case of South America. Nat Hazard Earth Sys 16(3): 821-831.

CERÓN WL, KAYANO MT, ANDREOLI RV, AVILA-DIAZ A, RIVERA IA, FREITAS ED, MARTINS JA & SOUZA RAF. 2021. Recent intensification of extreme precipitation events in the La Plata Basin in Southern South America (1981-2018). Atmos Res 249: 105299.

CHYLEK P, FOLLAND CK, LESINS G & DUBEY MK. 2010. Twentieth century bipolar seesaw of the Arctic and Antarctic surface air temperatures. Geophys Res Lett 37: L08703.

COELHO CAS ET AL. 2016. The 2014 southeast Brazil austral summer drought: regional scale mechanisms and teleconnections. Clim Dynam 46: 3737-3752.

DOLE RM. 1986. The life cycles of persistent anomalies and blocking over the North Pacific. Adv Geophys 29: 31-69.

EYRING V ET AL. 2021. Human Influence on the Climate System. In: Masson-Delmotte V et al. (Eds), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

FERON S ET AL. 2019. Observations and Projections of Heat Waves in South America. Sci Rep 9: 8173.

FOGT RL, BROMWICH DH & HINES KM. 2011. Understanding the SAM influence on the South Pacific ENSO teleconnection. Clim Dynam 36(7-8): 1555-1576.

FOGT RL & MARSHALL GJ. 2020. The Southern Annular Mode: Variability, trends, and climate impacts across the Southern Hemisphere. WIREs Clim Change 11(4): e652.

FOX-KEMPER B ET AL. 2021. Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, In: Masson-Delmotte V et al. (Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1211-1362.

GILLETT NP, FYFE JC & PARKER DE. 2013. Attribution of observed sea level pressure trends to greenhouse gas, aerosol, and ozone changes. Geophys Res Lett 40: 2302-2306.

GONG T, FELDSTEIN SB & LUO D. 2010. The impact of ENSO on wave breaking and Southern Annular Mode events. J Atmos Sci 67(9): 2854-2870.

GONZALEZ PLM, GODDARD L & GREENE AM. 2013. Twentieth-Century summer precipitation in South Eastern South America: Comparison of gridded and station data. Int J Climatol 33(13): 2923-2928.

GOZZO LF ET AL. 2022. Intraseasonal Drivers of the 2018 Drought Over São Paulo, Brazil. Front Clim 4:852824.

HERSBACH H ET AL. 2019. ERA5 monthly averaged data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 05-08-2021).

HOLTON JR. 2004. Introduction to Dynamic Meteorology. 4th Edition, Elsevier, Amsterdam, 535 p.

HOSKINS BJ & AMBRIZZI T. 1993. Rossby Wave Propagation on a Realistic Longitudinally Varying Flow. J Atmospher Sci 50(12): 1661-1671.

HOSKINS BJ & KAROLY DJ. 1981. The steady linear response of a spherical atmosphere to thermal and orographic forcing. J Atmospher Sci 38(6): 1179-1196.

KIDSTON J, TASCHETTO AS, THOMPSON DWJ & ENGLAND MH. 2011. The influence of Southern Hemisphere Sea-ice extent on the latitude of the mid-latitude jet stream. Geophys Res Lett 38(15): L15804.

LANFREDI IS & CAMARGO R. 2018. Classification of Extreme Cold Incursions over South America. Weather Forecast 33: 1183-1203.

LEE H-T & NOAA CDR PROGRAM. 2011. NOAA Climate Data Record (CDR) of Monthly Outgoing Longwave Radiation (OLR), Version 2.2-1. [indicate subset used]. NOAA National Climatic Data Center. doi:10.7289/V5222RQP [Accessed on 07-12-2021].

MADDOX RA. 1983. Large-Scale Meteorological Conditions Associated with Midlatitude, Mesoscale Convective Complexes. Mon Weather Rev 111: 1475-1493.

MARENGO JA, NOBRE CA & CULF AD. 1997. Climatic impacts of "friagens" in forested and deforested regions in Amazon Basin. J Appl Meteorol Clim 36(11): 1553-1566.

MARENGO JA, SOARES WR, SAULO C & NICOLINI M. 2004. Climatology of the Low-Level Jet East of the Andes as Derived from NCEP-NCAR Reanalyses: Characteristics and Temporal Variability. J Climate 17(12): 2261-2280.

MARSHALL GJ. 2003. Trends in the Southern Annular Mode from observations and reanalyses. J Climate 16: 4134-4143.

MARSHALL GJ, STOTT PA, TURNER J, CONNOLLEY WM, KING JC & LACHLAN-COPE TA. 2004. Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. Geophys Res Lett 31(14): L14205.

MATTINGLY KS & MOTE TL. 2017. Variability in warm-season atmospheric circulation and precipitation patterns over subtropical South America: relationships between the South Atlantic convergence zone and large-scale organized convection over the La Plata basin. Clim Dynam 48: 241-263.

MEREDITH M ET AL. 2019. Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, In: Pörtner H-O et al. (Eds), Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 203-320.

MO KC & HIGGINS RW. 1998. The Pacific-South American modes and tropical convection during the Southern Hemisphere Winter. Mon Wea Rev 126: 1581-1596.

MO KC & PAEGLE JN. 2001. The Pacific-South American modes and their downstream effects. Int J Climatol 21: 1211-1229.

MONTINI TL, JONES C & CARVALHO LMV. 2019. The South American low-level jet: A new climatology, variability, and changes. J Geophys Res-Atmos 124: 1200-1218.

MORAES FDS, AQUINO FE, MOTE TL, DURKEE JD & MATTINGLY KS. 2020. Atmospheric characteristics favorable for the development of mesoscale convective complexes in southern Brazil. Clim Res 80: 43-58.

MUZA MN, CARVALHO LMV, JONES C & LIEBMANN B. 2009. Intraseasonal and Interannual Variability of Extreme Dry and Wet Events over Southeastern South America and the Subtropical Atlantic during Austral Summer. J Climate 22: 1682-1699.

NNAMCHI HC, LI J & ANYADIKE RN. 2011. Does a dipole mode really exist in the South Atlantic Ocean? J Geophys Res-Atmos 116(D15).

NORTH GR, BELL TL, CAHALAN RF & MOENG FJ. 1982. Sampling errors in the estimation of empirical orthogonal functions. Mon Wea Rev 110: 699-706.

NUNCIO M & YUAN X. 2015. The Influence of the Indian Ocean Dipole on Antarctic Sea Ice. J Climate 28(7): 2682-2690.

OLIVEIRA FNM & AMBRIZZI T. 2017. The effects of ENSO-types and SAM on the large-scale southern blockings. Int J Climatol 35(7): 3067-3081.

OLIVEIRA FNM, CARVALHO LMV & AMBRIZZI T. 2014. A new climatology for Southern Hemisphere blockings in the winter and the combined effect of ENSO and SAM phases. Int J Climatol 34(5): 1676-1692.

PARISE CK, PEZZI LP, CARPENEDO CB, VASCONCELLOS FC, BARBOSA WL & LIMA LG. 2022. Sensitivity of South America climate to positive extremes of Antarctic sea ice. An Acad Bras Cienc [online] 94(suppl 1): e20210706.

PARISE CK, PEZZI LP, HODGES KI & JUSTINO F. 2015. The Influence of Sea Ice Dynamics on the Climate Sensitivity and Memory to Increased Antarctic Sea Ice. J Climate 28: 9642-9668.

PEZZA AB, DURRANT T, SIMMONDS I & SMITH I. 2008. Southern Hemisphere synoptic behavior in extreme phases of SAM, ENSO, sea ice extent, and southern Australia rainfall. J Climate 21(21): 5566-5584.

QUEIROZ MGS, PARISE CK, PEZZI LP, CARPENEDO CB, VASCONCELLOS FC, TORRES ALR, BARBOSA WL & LIMA LG. 2022. Response of southern tropospheric meridional circulation to historical maxima of Antarctic sea ice. An Acad Bras Cienc 94: e20210795. https://doi.org/10.1590/0001-3765202220210795.

RAO VB, CAVALCANTI IFA & HADA K. 1996. Annual variation of rainfall over Brazil and water vapor characteristics over South America. J Geophys Res 101: 539-551.

RAYNER NA, PARKER DE, HORTON EB, FOLLAND CK, ALEXANDER LV, ROWELL DP, KENT EC & KAPLAN A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J Geophys Res 108(D14): 4407.

REBOITA MS, AMBRIZZI T, CRESPO NM, DUTRA LMM, FERREIRA GWDS, REHBEIN A, DRUMOND A, DA ROCHA RP & SOUZA CAD. 2021. Impacts of teleconnection patterns on South America climate. Ann NY Acad Sci 1504: 116-153.

REBOITA MS, AMBRIZZI T & ROCHA RP. 2009. Relationship between the Southern annular mode and Southern hemi-sphere atmospheric systems. Brazilian Journal of Meteorology 24(1): 48-55.

REGOTO P, DERECZYNSKI CP, CHOU SC & BAZZANELA ACF. 2021. Observed Changes in Air Temperature and Precipitation Extremes over Brazil. Int J Climatol 41: 5125-5142.

REHBEIN A ET AL. 2018. Severe Weather Events over Southeastern Brazil during the 2016 Dry Season. Adv Meteorol 2018: 1-15.

REX DF. 1950. Blocking action in the middle troposphere and its effect upon regional climate, Part II: The climatology of blocking action. Tellus 2: 275-301.

RICARTE RMD, HERDIES DL & BARBOSA TF. 2015. Patterns of atmospheric circulation associated with cold outbreaks in southern Amazonia. Meteorol Appl 22(2): 129-140.

RODRIGUES RR, TASCHETTO AS, SEN GUPTA A & FOLTZ GR. 2019. Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. Nat Geosci 12: 620-626.

RODRIGUES RR & WOOLLINGS T. 2017. Impact of Atmospheric Blocking on South America in Austral Summer. J Climate 30(5): 1821-1837.

RUDEVA I & SIMMONDS I. 2015. Variability and Trends of Global Atmospheric Frontal Activity and Links with Large-Scale Modes of Variability. J Climate 28(8): 3311-3330.

RUSTICUCCI M & VARGAS W. 1995. Synoptic situations related to spells of extreme temperatures over Argentina. Meteorol Appl 2: 291-300.

SALIO P, NICOLINI M & ZIPSER EJ. 2007. Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. Mon Weather Rev 135(4): 1290-1309.

SENEVIRATNE SI ET AL. 2021. Weather and Climate Extreme Events in a Changing Climate. In: Masson-Delmotte V et al. (Eds), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In: Masson-Delmotte V et al. (Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1513-1766.

SETH A, FERNANDES K & CAMARGO SJ. 2015. Two summers of São Paulo drought: Origins in the western tropical Pacific. Geophys Res Lett 42: 10816-10823.

SILVA GAM & AMBRIZZI T. 2006. Inter- El Niño variability and its impact on the South American low- level jet east of the Andes during austral summer–two case studies. Adv Geosci 6: 283-287.

SKANSI MM ET AL. 2013. Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. Global Planet Change 100: 295-307.

TEDESCHI RG, GRIMM AM & CAVALCANTI IFA. 2014. Influence of Central and East ENSO on extreme events of precipitation in South America during austral spring and summer. Int J Climatol 35(8): 2045-2064.

THOMPSON DWJ & SOLOMON S. 2002. Interpretation of recent southern hemisphere climate change. Science 296(5569): 895-899.

THOMPSON DWJ & WALLACE JM. 2000. Annular modes in the extratropical circulation. Part I: Month-to-month variability. J Climate 13(5): 1000-1016.

TURNER J, MARSHALL GJ, CLEM K, COLWELL S, PHILLIPS T & LU H. 2020. Antarctic temperature variability and change from station data. Int J Climatol 40: 2986-3007.

TURNER J, LU H, WHITE I, KING JC, PHILLIPS T, HOSKING JS, BRACEGIRDLE TJ, MARSHALL GJ, MULVANEY R & DEB P. 2016. Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. Nature 535: 411-415.

VIANA DR, AQUINO FE, BRAGA RB & FERREIRA NJ. 2009. Mesoscale convective complexes in Rio Grande do Sul between October and December of 2003 and associated precipitation. Braz J Meteorol 24: 276-291.

VINCENT DG. 1994. The South Pacific Convergence Zone (SPCZ): A review. Mon Wea Rev 122: 1949-1970.

WILKS DS. 2006. Statistical Methods in the Atmospheric Sciences: An Introduction. 2nd ed.,New York: Academic Press.

WILSON AB, BROMWICH DH & HINES KM. 2016. Simulating the mutual forcing of anomalous high southern latitude atmospheric circulation by El Niño flavors and the Southern Annular Mode. J Climate 29(6): 2291-2309.

YOO C, LEE S & FELDSTEIN S. 2012. The impact of the Madden-Julian oscillation trend on the Antarctic warming during the 1979-2008 austral winter. Atmosph Sci Lett 13: 194-199.

YUAN XJ. 2004. ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. Antarct Sci 16(4): 415-425.

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