Does Antarctic Oscillation have links and influence precipitation over the Uruguay River Drainage Basin in Southeastern South America?

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ABSTRACT

This article examines the links and the influence of Antarctic Oscillation (AAO) on precipitation over the Uruguay River Drainage Basin and adjacent regions, situated in Southeastern South America. In this article, we used monthly data of AAO Index obtained from the Climate Prediction Center/National Centers for Environmental Prediction (CPC/NCEP); monthly data of 500 hPa vertical motion through omega variable \(\omega = \frac{\partial p}{\partial t}\) and converted to vertical velocity (cm/s) from the NCEP/NCAR Reanalysis; monthly data of precipitation from the NCEP Reanalysis 2 and monthly data of precipitation rate from the CPC Merged Analysis of Precipitation (CMAP) with a latitude \(\times\) longitude spatial resolution of 2.5\(^\circ\) \(\times\) 2.5\(^\circ\). All data are monthly means and were obtained from January 1979 to December 2008. The methodological procedures used Grid Analysis and Display System (GrADS) software to generate composites of vertical motion and precipitation rates. In the case of CMAP precipitation data, the methodology consists of applying the Aspin Welch statistical test, which verifies the statistical significance of the difference between two means using a significance level of 5%. The study region indicates a tendency to present higher (lower) mean rates of precipitation during the AAO negative (positive) phase. The vertical motion analysis results corroborate with the precipitation rates since the higher vertical motions were found during the negative phase of AAO. The statistical test showed, to some areas of Uruguay River Drainage Basin and adjacent regions, statistically significant differences between mean rates of precipitation observed in both phases of AAO.

Key words | Antarctic Oscillation, precipitation, teleconnection, Uruguay River Drainage Basin

HIGHLIGHTS

- The study and the investigations of the Antarctic Oscillation – AAO (also called Southern Annular Mode – SAM) are relatively new in South America.
- The importance of climate change and climate variability in the environmental changes, such as water supply and global and local warming.
- We have few studies discussing the relations of AAO or SAM with precipitation over a drainage basin in South America.
- The impacts of extreme rainfall or severe droughts in water supply and agriculture over southeastern Brazil where population increases year after year.

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The importance of the study to hydroelectric power generation and to the agriculture sector, important economic activities in the study region.

INTRODUCTION

Climate connections between Antarctica and distinct regions of South America have been intensely studied in the last decades, mainly because of the relevance of the Antarctic continent in the global climate system’s balance and in controlling the southern hemisphere atmospheric system. Weather and climate in southern Brazil, where the Uruguay River Drainage Basin is located, are influenced by meteorological systems and large-scale patterns of climate variability that contribute to intense rainfall events or severe droughts. These extreme events can significantly affect the economic activities in southern Brazil, such as agriculture and hydroelectric power generation, and can cause floods and landslides. The Antarctic Oscillation (AAO), also called Southern Hemisphere Annular Mode (SAM), represents the main large-scale pattern of climate variability of extratropical latitudes and is characterized by anomalies in the pressure field between polar latitudes and midlatitudes indicating a north–south ‘seesaw’ pattern of atmospheric mass (Thompson et al. 2000).

In a context of environmental changes and climate variability, the Southern Hemisphere presents a vast control in the atmospheric circulation through the action of the Antarctic circumpolar vortex, which is associated with the significative volume of ice represented by the Antarctic continent. According to Bromwich & Parish (1998) and Thompson & Solomon (2002), the vortex leads to a western atmospheric mean circulation, extending from the surface to the stratosphere. Some research shows that the vortex behavior influences the surface atmospheric circulation up to high levels in the extra-tropics (Thompson & Solomon 2002). To these authors, the climate variability in high latitudes of Southern Hemisphere is dominated by AAO, a large-scale pattern of variability characterized by fluctuations in the strength of this vortex.

The climate of some regions of South America, including SESA, is influenced by atmospheric systems and teleconnection patterns that can contribute to anomalously rainy seasons, extended droughts and temperature variations (Silvestri & Vera 2003; Aquino et al. 2006; Reboita et al. 2010; Vasconcellos & Cavalcanti 2010; Grimm 2011; Aquino 2012). The extremes of weather and climate can significantly affect local and regional economic activities and generate problems related to water supply, floods and landslide events, mainly in urban areas.

Previous studies over the last two decades have explored the role of AAO in modulating the climate of different regions in South America (Silvestri & Vera 2009; Oliva 2011; Pezza et al. 2012; Carpenedo 2017), principally related to atmospheric characteristic behavior, temperature variations and precipitation/discharge regimes. Nevertheless, the relationships between this teleconnection pattern and some regions of Brazil have not been investigated yet. Some research, such as Reboita et al. (2009), Raphael et al. (2011) and Aquino (2012), have discussed the relations between AAO and atmospheric systems in South America, with temperature in southern Brazil and with atmospheric characteristics in South America and Southern Hemisphere. The article of Pezza et al. (2012) related the AAO to Antarctic sea ice and El Niño–Southern Oscillation (ENSO) showing that in the AAO positive phase, stationary waves can be amplified by anomalous disturbances associated with high latitudes cyclones, resulting in larger sea ice. These authors discussed a similar association in years with ENSO (La Niña).

According to Tucci (2007), a drainage basin can be considered a physical system of precipitation water catchment. The system’s entrance is the volume of precipitation and the exit is the volume of flow through the estuary, considering as intermediate losses the evaporated and the transpired volumes of water. A drainage basin discharge depends on several factors, and the calculation to obtain the discharge rates correctly depends on the contribution of these factors. The article aims to investigate the precipitation regime over the study area considering precipitation, the main atmospheric variable that modulates the discharge.
of a river. Initially, the vertical motion was studied to understand the ascending motions that induce cloud formation and precipitation or subsiding motions that inhibit the precipitation formation.

The innovation of this article in the comparison of similar studies that are related to some aspects, such as (1) the investigation of AAO’s role in South America climate is relatively new, mainly in Brazil, (2) we have few studies discussing the links between AAO and rainfall focused in a drainage basin as the study area and (3) the relevance to better understand the causes of rainfall regime variations and their impact in water supply, economic activities and floods in the study area where population increases significantly. In this way, the article’s main purpose was to analyze the possible influences of AAO on precipitation regime over the Uruguay River Drainage Basin and adjacent regions in a 30-year period.

**MATERIALS AND METHODS**

**Study area**

The study area covers the Uruguay River Drainage Basin and adjacent regions. This basin includes a great deal of economic activity, such as agriculture and hydroelectric power generation, having great importance to the economy of Brazil. The Uruguay River is considered the second most important fluvial system of the Prata River Drainage Basin. It comprises 2,200 km and is formed by the confluence of Pelotas and Canoas rivers. In this section, the river flows to the west, forming the boundary of Rio Grande do Sul and Santa Catarina states. After the confluence with the Peperi-Guacu River, the Uruguay River turns southwest, forming the border between Argentina and Uruguay, up to the estuary of the Prata River (SRH/MMA 2006). The Uruguay River is divided into three sections: the upper river, characterized by a steep topographic gradient presenting rapids and a low time of concentration, allowing a high potential of hydroelectric power generation; the medium river, assuming the condition of borderline, with local economy stands for soy and corn agriculture; and the lower river which flows through the ‘Campanha Gaúcha’ region with the development of rice agriculture.

The total area drained by the Uruguay River Basin is 385,000 km², of which 174,412 km² is located in Brazil (27% in the State of Santa Catarina and 73% in the State of Rio Grande do Sul) representing 2% of all Brazilian territory (SRH/MMA 2006). Approximately 3.8 million people are living in the Brazilian sector of the Uruguay River Basin. The basin is limited by Geral Range (on the north and northeast), by the boundary between Uruguay and Brazil (on the south), by the Rio-Grandense Central Depression (on the east) and by Argentina (on the west).

One of the most important hydrological characteristics is the low capacity of storage due to the predominant geomorphology that presents steep relief in the upper Uruguay River, followed by a flat relief in ‘Campanha Gaúcha’, shallow soil that makes the Uruguay River flow on a rocky bed. Such characteristic implies a discharge regime that accompanies the precipitation regime: when intense rainfall occurs, floods occur, and when periods of drought occur, the discharges are suddenly reduced. As the precipitation regime in the basin is heterogeneous, the discharges follow this regime, making it harder to plan the use of water (SRH/MMA 2006). In the Uruguay River’s headwaters, some municipalities periodically present water rationing related to the lack of discharge regulation. The annual average discharge of the Uruguay River Basin is 4.117 m³/s, which corresponds to 2.6% of Brazil’s water availability (ANA 2019).

The distribution of precipitation over Southern Brazil throughout the year occurs homogeneously. The annual precipitation ranges from 1.200 to 2.200 mm, so there is no municipality where the cumulative precipitation is extreme, maximum or minimum. The circulation systems that cause precipitation act with a similar annual frequency throughout the region, and the relief does not interfere, creating significant differences in the total precipitation (NIMER 1979). Specifically, in the studied area, an annual average rainfall of around 1.750 mm is observed, considering the closer meteorological stations of the National Institute of Meteorology (INMET). The north sector of the Uruguay Basin presents the highest annual rainfall. We can highlight the municipality of Xanxerê, in Santa Catarina, with an average of 2.227 mm.

According to Cavalcanti et al. (2009), the climate of Southern Brazil has large spatial contrasts in precipitation and temperature regimes, due to its geographical location, between the tropics and midlatitudes. The precipitation...
regime has a well-defined transition. In the northern area of Southern Brazil, the typical monsoon regime with rainy season predominates. It starts in the spring and ends in early autumn, resulting in a large contrast between summer and winter. In the southern area, a homogeneous rainfall distribution occurs throughout the year with a regime similar to the midlatitudes. The South Atlantic Convergence Zone (SACZ) may also influence the rainfall regime in the northern area, depending on its latitudinal displacements. During the summer, the surface warming and the moisture flow into the continent tend to create instability, producing convection in association with the South
American monsoon. Warming and moisture convergence are higher in the northern sector, near the SACZ area. It is the reason why this is the area where summer rainfall is more intense (Grimm et al. 1998).

In transitional seasons, the high-level subtropical jet is centered over Southern Brazil/Northeastern Argentina, which influences the region’s maximum precipitation through the occurrence of Mesoscale Convective Complexes (MCC) (Cavalcanti et al. 2009). In the warmest period (October to April), MCC are responsible for much of the total precipitation, especially in spring and autumn. In the region, climate variability occurs in timescale in response to ENSO events representing the main source of interannual climate variability in Brazil. However, ENSO’s dominant influence does not disregard the possibility of influence by some other climate variability patterns.

**AAO index data**

This article used the AAO index monthly data obtained from Climate Prediction Center/National Centers for Environmental Prediction (CPC/NCEP) for the period between January 1979 and December 2008. The AAO index is computed daily by CPC/NCEP through the projection of 700 hPa geopotential height anomalies over the main mode of Empiric Orthogonal Function (EOF-1) obtained from monthly mean 700 hPa geopotential height anomalies from 20° to 90° (more information available in http://www.cpc.ncep.noaa.gov/products/). These data are based on Reanalysis of National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and were employed with a horizontal resolution of latitude \( \times \) longitude = (2.5° \( \times \) 2.5°). The seasonal cycle is removed from the geopotential monthly mean field, and the covariance matrix is used for the EOF analysis. The negative and the positive phases of AAO are considered significant to index values lower than −1 (negative phase) and index values higher than +1 (positive phase). The values between −1 and +1 would represent a neutral phase of AAO.

**500 hPa vertical motion data**

From NCEP/NCAR Reanalysis (Kanamitsu et al. 2002), this work also used monthly data of 500 hPa vertical motion through omega variable \( \omega = \frac{Dp}{Dt} \) available in Pa/s and converted to vertical velocity (cm/s) by the equation \( \omega = -\rho g \frac{Dp}{Dt} \) which is obtained by applying the hydrostatic approximation in the definition of the variable \( \omega \). The monthly data refer to the same 30-year period. To examine the relations between AAO and vertical velocity, we selected the months when AAO was in the negative phase and the vertical velocity monthly means associated with these months. The same method was applied to the positive phase. The software Grid Analysis and Display System (GrADS) was used to create composite maps showing mean fields of vertical motion when AAO < −1 and when AAO > +1, as well as the vertical motion difference fields when AAO is between +1 and −1 (neutral phase).

**Precipitation data**

**NCEP Reanalysis 2 precipitation data**

To investigate the influence of AAO on precipitation, we used precipitation monthly data from NCEP Reanalysis 2 in mm/day (Kanamitsu et al. 2002) employed with a horizontal resolution of latitude \( \times \) longitude = (2.5° \( \times \) 2.5°) and corresponding to the period between January 1979 and December 2008. The software GrADS was used to create composites showing mean fields of precipitation when AAO is positive (> +1) and when AAO is negative (< −1), as well as the precipitation difference fields when AAO is between +1 and −1 (neutral phase). These composites have the purpose of highlighting the possible differences in the precipitation mean fields observed in AAO opposite phases.

**CPC Merged Analysis of Precipitation data**

Proceeding to investigate the influence of AAO on precipitation, we obtained precipitation rate monthly data from CPC Merged Analysis of Precipitation (CMAP) with a latitude \( \times \) longitude spatial resolution of 2.5° \( \times \) 2.5° to the same 30-year period previously mentioned. Precipitation rates are derived from five types of satellite estimates (GPI, OPI, SSM/I SCATTERING, SSM/I EMISSION and MSU). This data set consists of mean rates of precipitation in mm/day. The rates were obtained for a total of 36 gridded
points covering an area between the coordinates (20°–35° S; 45°–60° W), which includes the southern region of Brazil and adjacent continental and oceanic regions (Figure 2).

To associate the precipitation data in each gridded point with phases of AAO, we calculated the precipitation average during the negative and during the positive phases. Therefore, we obtained two precipitation means (negative and positive phases) to each of the 36 gridded points. In this case, the statistical test described in the next paragraph of the methodology was applied to verify if the differences between these two means are considered statistically significant. This analysis aims to verify the influence of AAO on precipitation using data with a different origin; in other words, not NCEP Reanalysis 2 data. In this way, to analyze the relations between AAO and CMAP precipitation data, we applied the Aspin Welch statistical test, whose statistic of tests is compared with the $t$-student distribution. The test significance level used was 5% ($\alpha = 0.05$). We calculated the precipitation average in both phases of AAO obtaining two different means of precipitation. Using the test is possible to know if the differences between these two means are just different or different and statistically significant. To reach this result, we must obtain the statistic of test $Z$. For the test to consider the differences significant, the value of $Z$ must be higher (lower) than $t\alpha/2$ (−$t\alpha/2$), which corresponds to the exclusion area of the null hypothesis ($H_0$) with a maximum probability error of 5%. The point $t\alpha/2$ represents the point of $t$-student distribution with $f$ degrees of liberty. To know the value of this point, we must consult Choi (1978, p. 244) using $f$ and the corresponding value of $\alpha/2$. The test considers the null hypothesis ($H_0$) when we do not have a significant difference between the means and considers the alternative hypothesis ($H_A$) in the cases in which we have a significant difference between the means.

Thus, the value of $Z$ can be determined by:

$$Z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}$$

where $\bar{X}_1$ is the average of temporal series in the negative phase, $\bar{X}_2$ is the average of temporal series in the positive phase, $S_1$ is the standard deviation of temporal series in the negative phase, $S_2$ is the standard deviation of temporal series in the positive phase, $n_1$ is the sample size in the negative phase and $n_2$ is the sample size in the positive phase. Formally, the test can be considered: null hypothesis ($H_0$: $\mu_1 = \mu_2$) and alternative hypothesis ($H_A$: $\mu_1 \neq \mu_2$). Being a bilateral test, $H_0$ must be excluded if:

$$Z = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}(−t\alpha/2 \text{ or } t\alpha/2)$$

where $\alpha = 0.05$ and $\alpha/2 = 0.025$.

Being $t\alpha/2$ the point of $t$-student distribution with $f$ degrees of liberty which is defined by: $f = \min (n_1, n_2) - 1$. If $H_0$ will be excluded, $H_A$ will be accepted where $\mu_1 \neq \mu_2$. If $\alpha = 0.05$ indicates that we will be making an error of no more than 5% exclusion of the null hypothesis ($H_0$) (Figure 3).
RESULTS AND DISCUSSION

Relationships between AAO and 500 hPa vertical motion

Figure 4 shows the composite maps of mean fields of vertical motion in 500 hPa during the negative (right) and the positive (left) phases of AAO. In the composites, during the negative phase, it is possible to verify values between 0.3 and 0.8 cm/s in the Uruguay River Drainage Basin and adjacent regions, suggesting ascending vertical motion that would contribute to cloud formation and precipitation. In the positive phase, the mean fields recorded values between 0 and 0.3 cm/s in the study area and adjacent regions. These values are lower than the values observed during the negative phase. The values observed during the positive phase also suggest ascending vertical motion that contributes to cloud formation and precipitation. However, the values...
are considerably lower and show ascending vertical motion with lower intensity when compared with the ascending motion observed during the negative phase.

Considering the differences of ascending vertical motion showed in both composite maps to the different phases of AAO, we generated a third map to present the differences of vertical motion between the positive and the negative phases. The results show values between $-0.2$ and $-0.3$ cm/s in the study area and adjacent regions (purple and dark blue areas) confirming an ascending vertical motion with higher intensity in the negative phase of AAO. The largest differences occur in the western area of Rio Grande do Sul and Santa Catarina and a part of northeastern Argentina (purple area) where almost the total area of Uruguay River Drainage Basin is located, besides adjacent regions (purple and dark blue areas) such as part of the State of Paraná, northeastern Argentina, southern Paraguay and almost the totality of Uruguay (Figure 5). The negative value of $-0.1$ cm/s (light blue area) also shows ascending vertical motion with higher intensity during the negative phase.

### Relationships between AAO and precipitation (mean fields)

Related to the influence of AAO on precipitation, Figure 6 reproduces composites that show mean fields of precipitation to both phases of AAO. In the negative phase (right), we observed precipitation rates between 4 and 6 mm/day in almost the total of study area and adjacent regions, except for the northwestern Rio Grande do Sul that presented higher rates (between 6 and 8 mm/day).
During the positive phase (left), the precipitation rates observed were lower. During this phase, although the rates varied between 4 and 6 mm/day in the study area, these rates presented reduced values (between 2 and 4 mm/day) in the south sector of Rio Grande do Sul where a large portion of the Uruguay River Drainage Basin is located. In this context, the mean rates of precipitation verified during the negative phase were higher. These values corroborate the values showed in the analysis of the relations between AAO and vertical motion, once the negative (positive) phase presented higher (lower) ascending vertical motion and higher (lower) mean rates of precipitation. Further details related to precipitation rates can be observed in Figure 7, which presents a highlight of the study area and adjacent regions. In the composite of the negative phase, we can observe higher rates of precipitation between 4.5 and 6 mm/day and lower rates between 3.5 and 5 mm/day in the positive phase.

The results related to the mean rates of precipitation registered during the opposite phases of AAO, where we can note higher means of precipitation in the negative phase, motivated the elaboration of a third composite map that shows the differences between the mean fields of precipitation observed during the positive and negative phases of AAO. The results show values between −0.5 and −1.0 mm/day in the central portion of Rio Grande do Sul and the west portion of Santa Catarina (darker blue area) and values varying between −1.0 and −1.5 mm/day in the southwest portion of Rio Grande do Sul (purple area) (Figures 8 and 9). The light blue area also presents negative values and includes adjacent regions of Uruguay River Drainage Basin. These negative values, mainly the values corresponding the southwest of Rio Grande do Sul, confirm higher means of precipitation during the negative phase, corroborating with the results previously presented in the composite maps AAO × Vertical Motion which suggested ascending vertical motion more intense during the negative phase that would induce an increase of precipitation in the region. These maps highlight the differences between the previous mean fields and the distinct behavior of precipitation between both phases of AAO with opposite signals.

**Relationships between AAO and precipitation (gridded points)**

In the analysis of relations between the phases of AAO and the precipitation means verified through gridded points, the results indicate that almost all gridded points presented higher mean rates of precipitation during the negative phase of AAO except for points 23, 35 and 36. These points showed higher precipitation rates during the positive phase. These three points include all the coastal area of the
The other 33 points presented higher mean rates of precipitation during the negative phase, which corroborates with the previously described results. The statistical test considered in 8 of all 36 gridded points the observed differences statistically significant between the mean rates of precipitation observed during both phases of AAO (Figure 10), such as south-center of Uruguay (point 2), South Atlantic Ocean adjacent to the coast of Uruguay (points 4 and 5), west, north-center and northeast of Rio Grande do Sul (points 14, 15 and 16), southern Paraguay (point 20) and east of Santa Catarina, southwest of Paraná and part of northeast of Argentina (point 21).

The information presented in Figure 11 shows, in each point that revealed statistically significant differences, the comparison between the precipitation means observed during the opposite phases of AAO. In this figure, it is evident that precipitation is always higher during the negative phase. The higher mean rates of precipitation were observed in the gridded points 15, 16 and 21, which including a sizeable territorial area of the Uruguay River Drainage Basin. It is important to highlight that this figure shows only the eight gridded points that indicate statistically significant differences between the precipitation rates in the opposite phases of AAO. In relation to the other 28 gridded points, we observed a total of 25 points that showed higher precipitation rates during the negative phase, but not statistically significant. Thus, approximately 92% of the gridded points showed higher precipitation in the negative phase.

Observing Table 1, we can note that points 15 and 21 are, among all points, the gridded points that presented the higher means in the negative phase (with 5.82 and 5.55 mm/day, respectively). In the positive phase, precipitation is higher in point 21 (4.46 mm/day), followed by point 15 and point 5 (4.37 mm/day). This fact can indicate that the regions related to these points are rainy, once they revealed higher rates of precipitation in both phases. We also observed that the Z value of point 15 is the higher (3.207) followed by point 20 (2.591). These results demonstrate the significative difference between the opposite phases of AAO; once higher will be the value of Z, more
statistically significant will be the difference between the precipitation means.

In this case, the thresholds to determine the statistical significance are \( -t \alpha/2 = -2.009 \) e \( t \alpha/2 = +2.009 \). We note that all eight gridded points showed values above 2.009. The statistical test did not reject the null hypothesis \((H_0)\) to the other 28 gridded points because the values of statistics of test Z related to these points were located between \(-2.009\) and \(+2.009\). We can conclude that the points 15 and 21 recorded the highest precipitation means during both phases of AAO, and they revealed high Z values.

To configure a situation where the differences would be statistically significant, considering \(H_A\) as true, Z's values must be lower than \(-2.009\) or higher than \(+2.009\). The value of Z does not depend only on precipitation means (as shown by the equation in the methodology) but also is conditioned to standard deviation observed in the time series. A high standard deviation indicates a large variability between the series' values and strongly influences the value of Z. We noted that point 2 presents a standard deviation in the positive phase closer to the average precipitation in this phase. This fact revealed lower values of Z. Because of that the gridded point 2 presents the lowest value of Z comparing with all other points indicated in Table 1. Although the statistical test did not consider the differences statistically significant to the other 28 gridded points, we should highlight that 25 points showed higher precipitation during the negative phase.

The practical aspects of this research refer to applying the results in climatic prediction to support the planning of water use, electric sector and agriculture activities due to an increase or reduction of rainfall in the study area. As discussed in scientific literature, the variations of precipitation volume in the region are related to many factors. One of them seems to be the variability of teleconnection patterns which have intensively been studied by the academic community in the last two decades, such as the AAO or SAM.

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**Figure 8** Differences between the mean fields of precipitation observed in the positive and negative phases of AAO. Unit: mm/day. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2020.001.
CONCLUSIONS

Analyzing the links between AAO and precipitation, the statistical test considered the significant differences between precipitation means during each phase of AAO. The significant differences were considered in 8 out of a total of 36 gridded points including the study area and adjacent regions. Although the differences were statistically significant for only 8 points (approximately 22% of the total), we verified higher mean rates of precipitation during the negative phase in 33 points, out of a total of 36 gridded points. This amount reaches approximately 92% of the total.

In the analysis of relations between AAO and precipitation using composite maps, the mean fields showed higher (lower) precipitation volume during the negative (positive) phase in the study area and adjacent regions (south region of Brazil, areas of São Paulo, northeastern Argentina, Uruguay and other sectors of SESA). These results agree with Vasconcellos & Cavalcanti (2010).
These authors observed, over Uruguay and northeastern Argentina, positive anomalous precipitation in the negative phase of AAO.

The results agree with Reboita et al. (2019) once these authors showed that cyclone trajectories are influenced by AAO, and this fact can also modify the precipitation regime over South America. These authors detected more (less) intense frontogenesis and positive (negative) anomalous precipitation over Uruguay and southern Brazil during the negative (positive) phase. A tendency of higher rates of precipitation during the negative phase seems quite visible in contrast with reduced rates in the positive phase.

The results observed in the composites associated with the relations between AAO and vertical motion have shown ascending vertical motion in both phases of AAO, however more intense during the negative phase in the studied area. Vertical motion with more intensity contributes to convection and cloud formation, allowing higher volumes of precipitation. Once this situation is more active during the negative phase of AAO with higher intensity of vertical motion, we can say these results corroborated with the results presented related to precipitation because the negative phase showed the higher volumes of this variable.

Therefore, it is possible that AAO considerably influences the precipitation over the Uruguay River Drainage Basin and adjacent regions. The information and the results presented here can be useful to climatic prediction as well as environmental and economic planning, once variations in precipitation volumes and oscillations of climatic patterns in different time scales can affect important economic activities in the region, such as agriculture and the electric sector.

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**Table 1**  
Precipitation means, standard deviations (SD) and statistic of test ($Z$) of the gridded points that presented statistically significant differences between opposite phases of AAO

<table>
<thead>
<tr>
<th>Gridded point</th>
<th>AAO negative phase</th>
<th>AAO positive phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Precipitation mean</td>
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</table>

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**Figure 11**  
Precipitation means observed during both phases of AAO in the gridded points that presented statistically significant differences.
DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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