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Tropical–Antarctic connections of an explosive cyclone in southern Brazil: rainfall stable isotope ratios and atmospheric analysis

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Abstract This study analyzes the stable isotopic ratio ($\delta^{18}O$) and the synoptic characteristics of a precipitation event that occurred in the southernmost state of Brazil, Rio Grande do Sul, a region sensitive to explosive cyclogenesis in years with enhanced tropic-pole interactions. The main objective was to evaluate the influence of tropical and Antarctic climate systems on the event. Cavity ring-down spectroscopy was used for the water isotopic analysis, and NCEP CFSv2 data were employed for the synoptic analysis of rainfall over a 48-h period. An Amazonian isotopic signature on precipitated water was identified. A strong, low-level meridional flow from the Amazon Basin, combined with the development of a frontal system, resulted in intense cyclogenesis that generated an explosive cyclone.

Keywords **Antarctica, Amazon, South American low-level jet (SALLJ), cyclogenesis**

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1 Introduction

This study analyzes a severe precipitation event that occurred in southern Brazil. On September 13, 2016, an explosive extratropical cyclone hit the coast of the southernmost state of Brazil, Rio Grande do Sul, causing gale-force winds, floods, and hail. An anomalous cyclogenesis was observed in the austral mid-latitudes during the winter and spring of 2016. Investigations revealed that this anomaly was related to the fast and early Antarctic sea ice extent (SIE) retreat during the austral spring of 2016 (Turner et al., 2017). The intensification of the north meridional flux significantly contributed to the decrease in Antarctic sea ice cover between 2014 and 2016 (Wang et al., 2019). The year 2016, and the month of September in particular, were worldwide the hottest on modern record (from 1880 to present day; NOAA, 2017). However, South America registered multiple negative temperature anomalies during September, influenced by a positive Southern Annular Mode (SAM) and a positive zone wave 3 (ZW3), carrying polar masses to the region (Schossler et al., 2019). Moreover, when anomalous low frequency anticyclones (cyclones) are present over the southeast of South America with a +SAM (−SAM), the cyclonic activity reduces (increases) and the precipitation over the region also reduces (increases) (Silvestri and Vera, 2003).

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The La Plata Basin (LPB), a region with a population of 136 million people (41% of the population of South America) has its climate regulated by polar and tropical air masses. This region periodically undergoes precipitation extremes, often modulated by the El Niño–Southern Oscillation (ENSO) phenomenon and its variants. In abnormal events, as in 2015/2016, the frequency of these extremes increases (Cavalcanti et al., 2015). Several studies that have attempted to describe where cyclones happen in the South America point to the LPB region (Gan and Rao, 1991, 1994; Vera et al., 2002; Mendes et al., 2007; Reboita et al., 2010, 2018; Gramcianinov et al., 2019). By the end of the 21st century, the incidence of such systems is predicted to decrease north of the Southern Ocean (Fyfe, 2003; Reboita et al., 2018). On the other hand, according to Gramcianinov (2019), cyclogenesis over the LPB should increase up to 6.1%, responding to an increase in meridional moisture transport. Moreover, extratropical cyclones with rapid intensification (with a deepening rate of 1 $mb \cdot h^{-1}$ within 24 h), classified as explosive, have a 2.4% to 4.1% frequency rate in the LPB region (Bitencourt et al., 2013).

The low-level circulation in South America is influenced by the moisture transport from equatorial regions to the southeast of the continent by the South American low-level jet (SALLJ) (Marengo, 2002; Vera et al., 2006; Guedes do Nascimento et al., 2016; Oliveira et al., 2018). The intensity of this transport is predicted to increase during the 21st century, due to a warmer atmosphere (Soares and Marengo, 2009; Seth et al., 2010). The South Brazilian region is currently experiencing a 10% increase in precipitation compared to the 1941–1970 climatology (Viana et al., 2006), and the presence of the SALLJ increases the amount of rainfall during each event by 32% (Guedes do Nascimento et al., 2016).

In the 1950s, the first studies on stable isotopes contributed to the understanding of the natural abundance of oxygen-18 and deuterium on Earth (Dansgaard, 1953; Epstein and Mayeda, 1953). In 1961, the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) began a global study on the stable isotopic composition of monthly precipitation. This data would later be useful to describe the temporal and spatial variations in the isotopic compositions of precipitation in different parts of the planet, and used in different studies such as climatology, oceanography, and hydrometeorology (Rozanski et al., 1993). These analyses have demonstrated that latitude, altitude, distance from the coast, precipitation amount, and air surface temperature all influence the geographic distribution of the stable isotopic content (Rozanski et al., 1993; Jouzel, 2003).

In this study, we combine the measurements of stable isotopes in the water collected during the extreme meteorological event on September 13, 2016, with the interpretation of atmospheric fields from climate reanalysis, in an attempt to understand the physical processes regulating the hydrological cycle in the southern part of South America. This article is divided into three parts: data and methods, a description of the prevailing atmospheric environment and the origin of water precipitated during the event, and a summary of the results.

2 Data and methods

A description of the atmospheric environment was built using the daily data (updated once every six hours) from National Centers for Environmental Protection (NCEP) Reanalysis Climate Forecast System version 2 (CFSv2) (NCEP, 2020). The variables taken into account were: temperature (℃, at 925 hPa), meridional and zonal winds ($m \cdot s^{-1}$, at 850, 700, and 250 hPa), geopotential height (gpm, at 500 hPa), specific humidity ($g \cdot kg^{-1}$, at 850 hPa), and sea level pressure (hPa) between September 11 and 13, 2016. Temperature and wind anomalies during September 2016 were calculated with respect to the September climatology in 1979–2018. Then, the event daily anomalies were compared to those in September 2016.

Precipitation data of the event were obtained from the Brazilian National Institute of Meteorology (Instituto Nacional de Meteorologia, INMET, 2020) automatic meteorological station A801, located at Porto Alegre (30°55'60"S, 51°07'29"W, altitude of 41 m). The precipitated water was collected using a Palmex Rain Sampler RS1 pluviometer located at the Federal University of Rio Grande do Sul (30°04'26.8"S; 51°07'13.9"W). Cavity ring-down spectroscopy (with a CRDS Picarro LD 2130i) was used to determine the stable isotopic ratios of each sample. Isotope data are reported as $\delta^{18}O$ values (in ‰) relative to the VSMOW/SLAP scale with δ_{VSMOW} defined as the zero point: $\delta_{VSMOW} = ((R_{sample} - R_{VSMOW}) - 1) \times 1000$ (‰), where R corresponds to the absolute isotope abundance ratios of $^{18}O/^{16}O$.

The tropical influence on the development of cyclogenesis was assessed by the SALLJ intensity and position 48 h prior to the event. For the intensity, the Bonner (1968) and Whitemann et al. (1997) criteria were used, while the exit jet position was determined following Nicolini et al. (2004).

A cyclone is considered explosive when it has a deepening rate of 1 Bergeron unit (B), equivalent to a drop of 1 $mb \cdot h^{-1}$ within 24 h at 60°S. The normalized deepening pressure rate in the center (NDR_c, equation 1) was used to identify the cyclone intensity at the event's latitudinal domain (Sanders and Gyakum, 1980):

$$NDR_c = \left(\frac{\sin 60°}{\sin \phi} \right) \cdot \left(\frac{\Delta p_c}{24} \right), \quad (1)$$

where Δp_c is the system pressure variation within 24 h, and ϕ is the median latitude in the center of the cyclone at its maximum depth.

3 Results and discussions

3.1 Description of the synoptic environment

In September 2016, we observed an anomalous south airflow at the 925 hPa and 850 hPa levels over South America. This feature is associated with a ZW3, as it directly interferes with the meridional component of the large-scale atmospheric circulation, driving cold air towards the equator and hot air towards the South Pole (Raphael, 2004). Anomalous conditions in the Tropical Indian Ocean and Western Pacific, associated with a record-breaking Indian Ocean Dipole negative event, conditioned the intense ZW3 in the spring of 2016. These intense sea level atmospheric anomalies in the Southern Hemisphere were responsible for remarkable storms over the Southern Ocean and the rapid decline of SIE from September to October 2016 (Turner et al., 2017; Wang et al., 2019). The intense meridional flow enhanced the cold and warm air advection and, consequently, the strong winds associated with intense cyclogenesis, providing conditions for sea surface warming at high latitudes in the Southern Hemisphere (Wang et al., 2019). A ZW3 index of +1.67 in September 2016 propelled southern heat exchanges, as identified by the Southern Hemisphere temperature anomalies.

The warm air flow driven towards the Antarctic had its consequences (fast sea ice retreat and high temperatures on the surface of the Southern Ocean), while the cold air in the middle latitudes caused temperature anomalies in South America. The positive and negative extremes of the monthly and seasonal mean temperature in southern Brazil resulted partly from variations in the Antarctic Peninsula atmospheric circulation (Aquino, 2012). A contrasting ocean-continent temperature of over 10 ℃ was identified at the 925 hPa level on September 12 at 30°S (at 12:00 and 18:00 UTC). At the time, the Chaco Region had air temperatures above 40 ℃, while, simultaneously, the advance of a cold front caused an air temperature drop from 20 ℃ to 10 ℃ within 24 h in southwest Rio Grande do Sul. The 2015/2016 El Niño stationary effects followed by a weak La Niña and the fast transport of equatorial air by the SALLJ (Stuecker et al., 2017; Montini et al., 2019) may have been the decisive cause behind the anomalous cyclonic circulation pattern observed during the studied event (Figure 1).

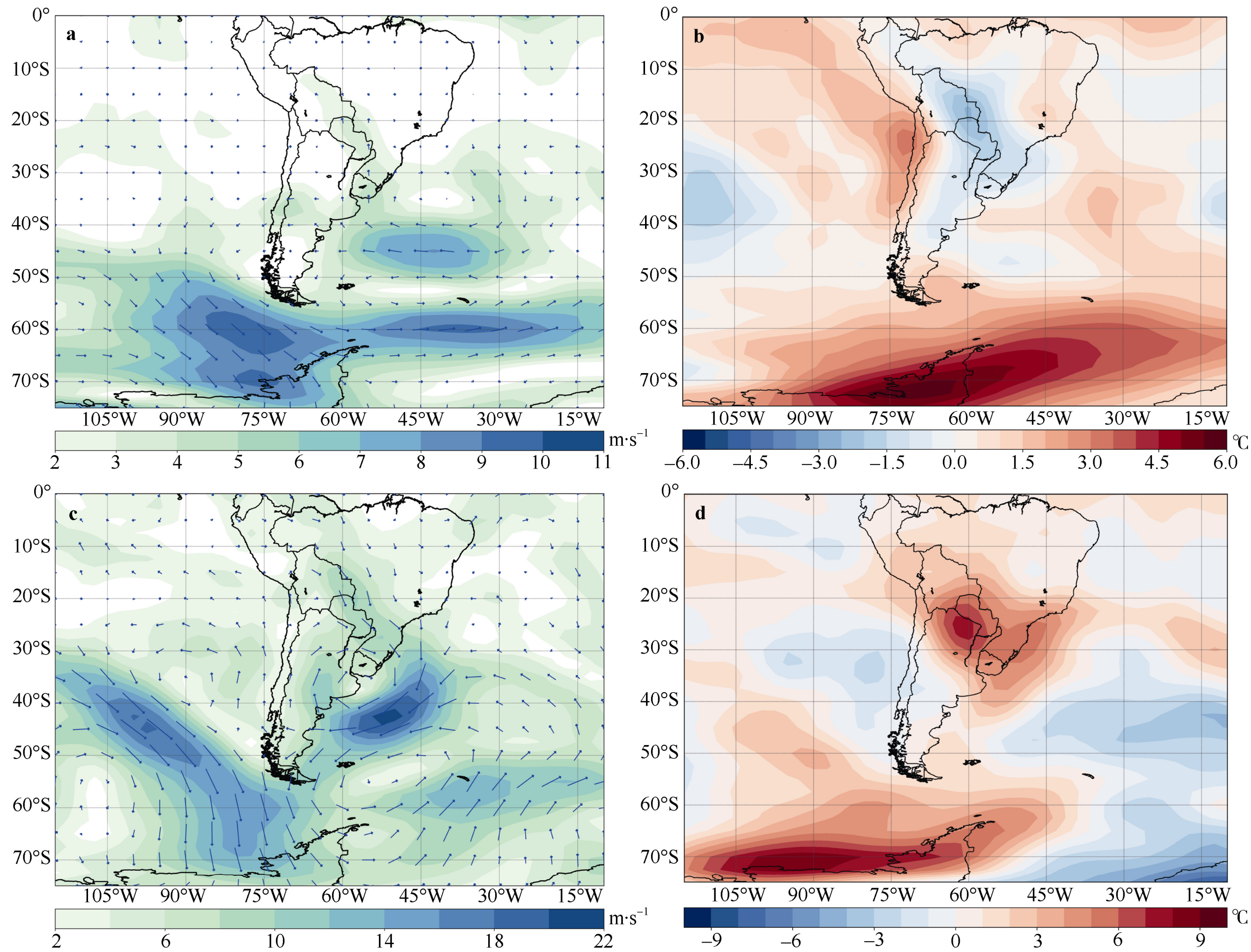

Figure 1 Vector wind at 850 hPa and temperature anomaly at 925 hPa for September 2016 (**a**, **b**), and for the studied event anomaly (**c**, **d**).

The SALLJ is one of the major mechanisms at low levels in South America, where its intensity is higher during the warm months (Marengo et al., 2009), and trade winds deviate to the southeast by the Andes, supplying moisture to the middle latitudes. During the 48-h period prior to the event, this meridional flow met the criteria for a low-level jet category, with a minimum intensity of 12 $m \cdot s^{-1}$ at 00:00 UTC on September 11, reaching a peak of 30 $m \cdot s^{-1}$ at 18:00 UTC on September 12, 50% above the LLJ-3 category threshold (Figure 2). From Nicolini et al. (2004), this SALLJ is classified as the Chaco Jet Event, sustaining an exit between 25°S and 32°S during the preceding 48 h, which favors convective development over the LPB (Nascimento, 2008). The 850 hPa specific humidity fields indicate the moisture flux coming primarily from the Amazonian region (Figure 3).

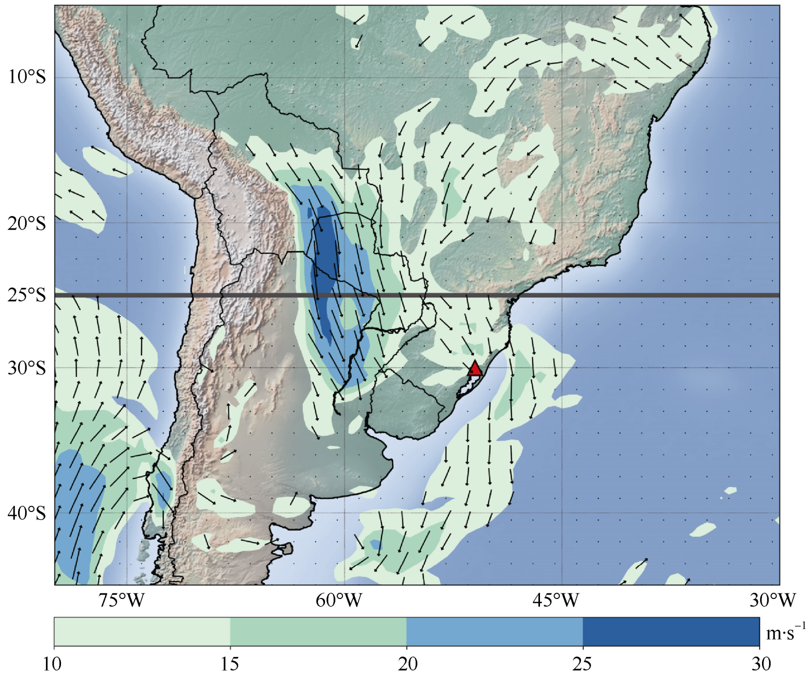

Figure 2 SALLJ wind speed at 850 hPa on September 12, 2016, 18:00 UTC. Red triangle locates Porto Alegre.

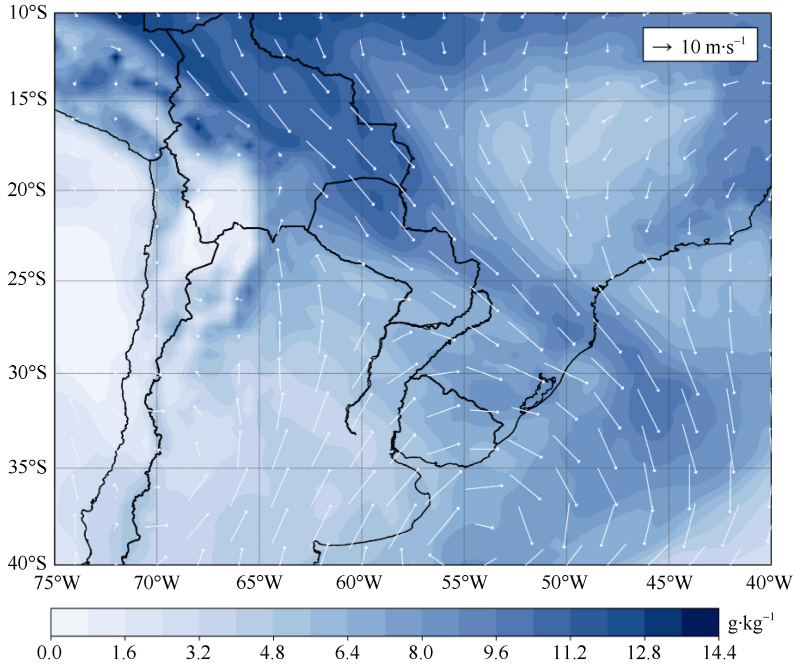

Figure 3 Mean vector wind and specific humidity at 850 hPa on September 13, 2016.

Extreme precipitation events in the LPB usually begin with a low-pressure area, positioned longitudinally to the east of the Andes at approximately 30°S, generated by a horizontal air flow and frontal systems approach called the Northwestern Argentinean Low (Seluchi et al., 2003). A forced downstream subsidence in the Andes favors its formation, and it has been correlated with precipitation and transportation of moisture to northeastern Argentina, southern Brazil, and Uruguay (Lichtenstein, 1980).

In the high troposphere, the presence of jet streams also intensifies convective systems. In South America, the preferred paths of the propagation waves at the synoptic scale are on subtropical jets at 30°S and on subpolar jets at 60°S, as they speed up and bend when crossing the narrow channel between the Andes and the top of the troposphere (Vera et al., 2002). In cold and transition seasons, the coupling frequency between the subtropical and subpolar sections are high, as the polar jet section displacement is associated with cold fronts at lower levels. During the entirety of the studied event, the SALLJ was associated with the subtropical jet and the northern section of the subpolar jet over Rio Grande do Sul (Figure 4). Thus, the divergence of air at high levels favored its convergence at lower levels, where warm and humid air next to surface rises, fueling the formation of convective clouds in the region.

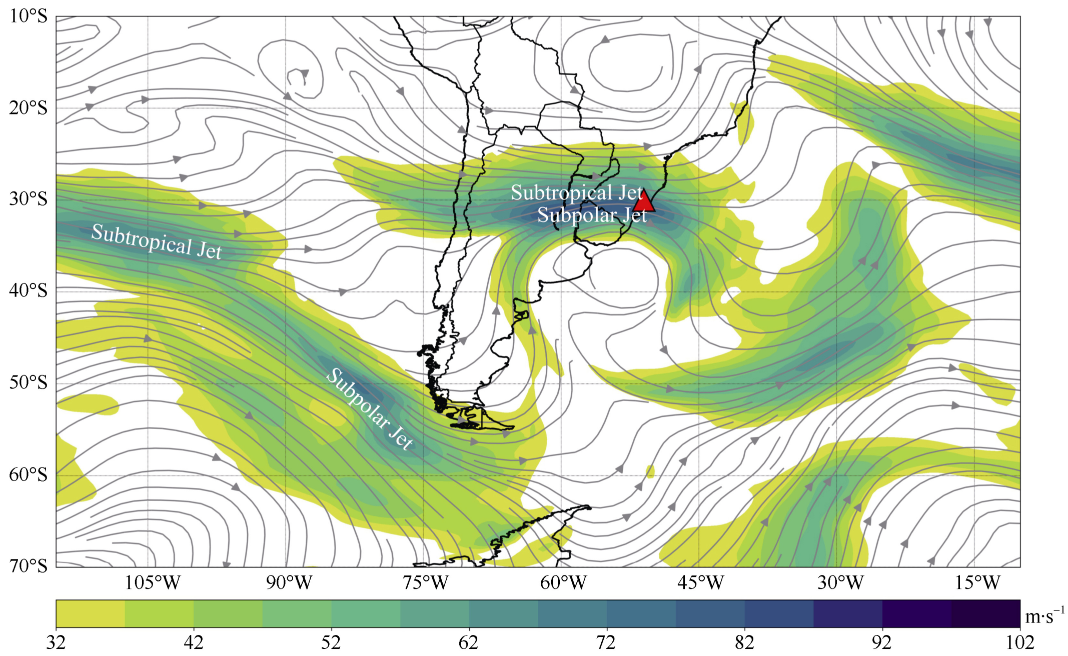

Figure 4 Vector wind at 250 hPa at 18:00 UTC on September 13, 2016.

On September 11 at 00:00 UTC, the Northwestern Argentinean Low was found at approximately 30°S. On the following day, a low-pressure system located to the west of South America at 40°S began moving towards the northeast. On September 13 at 00:00 UTC, this low met the Northwestern Argentinean Low over the LPB, forming a center of 998 hPa (Figure 5a). While constantly intensifying until 18:00 UTC on September 13, the cyclone migrated to the southeast—the preferred direction of displacement in this area—positioning itself over the Atlantic Ocean and reaching its maximum deepening of 973 hPa (Figure 5b). Once a cyclone is displaced to the east of the Andes and settles over the Atlantic Ocean, it is boosted by the heat flow from the Brazilian Stream (Gan and Rao, 1991; Vera et al., 2002). In this case, the mountain range played a key role in establishing instability, by favoring the arrival of cold Antarctic air and driving it to the east, towards the tropics, allowing the jet to approach and the advance of the cold front over warm air. Thus, the meridional flow coming from the Amazon and the Antarctic regions were the thermal sources of the traditional instability over the Northwestern Argentinean Low.

Cyclone development at subtropical latitudes is generally characterized by a higher baroclinicity and a lower influence of low-level moisture transport (Gramcianinov et al., 2019). Consequently, the unusual activity of the SALLJ in September contributed to the exceptional intensity of the cyclone. It caused intense precipitation on September 13 and was classified as an explosive cyclone of intermediate intensity. At its mid-latitudinal point (38°30'S), a 25 hPa fall occurred in 24 h, resulting in an NDR_c of 1.45 B. Explosive cyclones are predominantly oceanic and cold season phenomena, and their occurrence over the ocean indicates a remarkable exchange of energy between the surface and low atmosphere (Kuo et al., 1991).

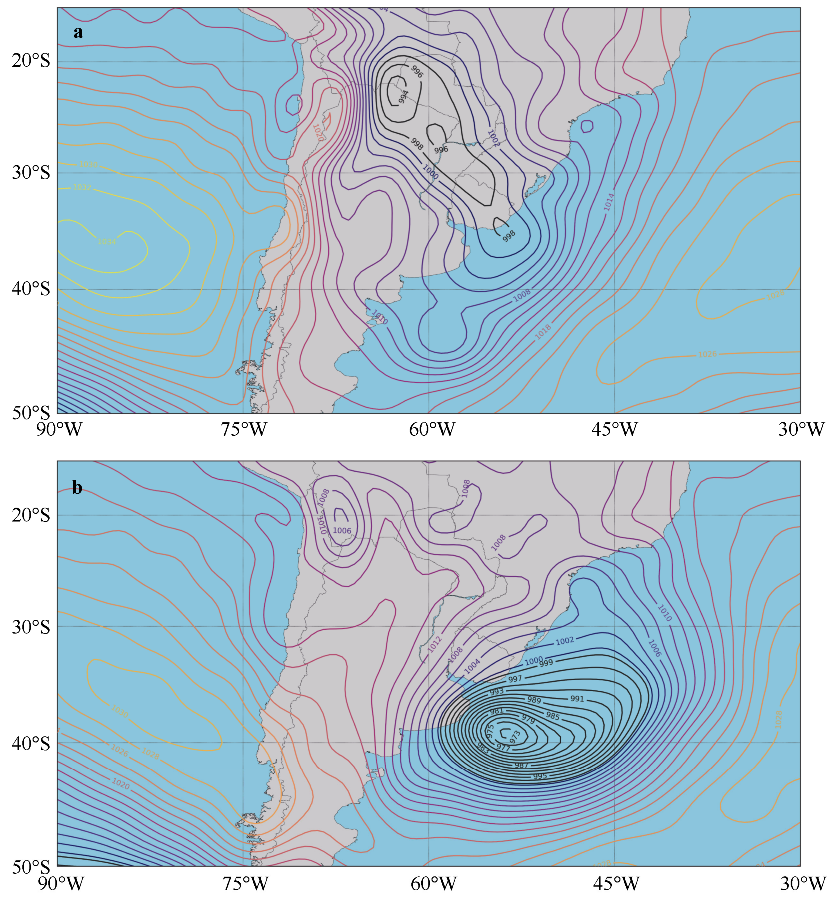

Figure 5 Mean sea level pressure (hPa) showing the cyclogenesis evolution between 00:00 UTC(**a**) and 18:00 UTC (**b**) on September 12, 2016.

3.2 Precipitation and isotopic composition

To analyze the precipitation, it is necessary to consider the crucial role that the SALLJ plays on the hydrological cycle of the LPB. At lower latitudes, the SALLJ is more intense in summer, but there is a phase change south of 15°S, and the strongest moisture flux can be found in winter and spring. This is an uncommon feature not detected in other regions such as the Great Plains of the USA, where the LLJ develops during the hot season (Berbery and Barros, 2002).

Table 1 compares the precipitation contribution of the September 2016 event to the total accumulation during September 2016 and the 1990–2018 historical record. The Porto Alegre automatic meteorological station recorded on September 13, 2016 a total precipitation of 32.3 mm. This figure is 35.6% of the month accumulation and 23% of the historical September mean (1990–2018). The amount and number of days of precipitation in September 2016 were lower than the long-term mean for September and may be further explained by +SAM, which is known to curb cyclogenesis in the study area (Schossler et al., 2018).

Table 1 Precipitation on September 13, 2016 compared to September 2016 and to the climatology in September 1990–2018 at Porto Alegre, Brazil (INMET, 2020)

September 13, 2016	September 2016	September climatology (1990–2018)	Rainy days in September 2016	Average rainy days in September 1960–2018
32.3 mm	90.6 mm	147 mm	9 d	12 d

The water precipitated at Porto Alegre on September 13 had a $\delta^{18}O$ = 1.05‰, which is highly positive anomalous when compared to the historical monthly mean for this city (Figure 6) and to the September 2016 mean ($\delta^{18}O$= −3.85‰; Griebler Júnior, 2018). The isotopic composition of precipitation events is dominated by large-scale synoptic systems—specifically, by the history/source of the air masses involved—while it is independent of local factors like the precipitation intensity (Rindsberger et al., 1990). One of the controls of the $\delta^{18}O$ ratio is the latitude, with a higher ratio in the tropics and a lower ratio towards the polar regions, mainly due to the difference in air temperature.

Porto Alegre registered three precipitation events during September 2016 (Figure 7), all related to the

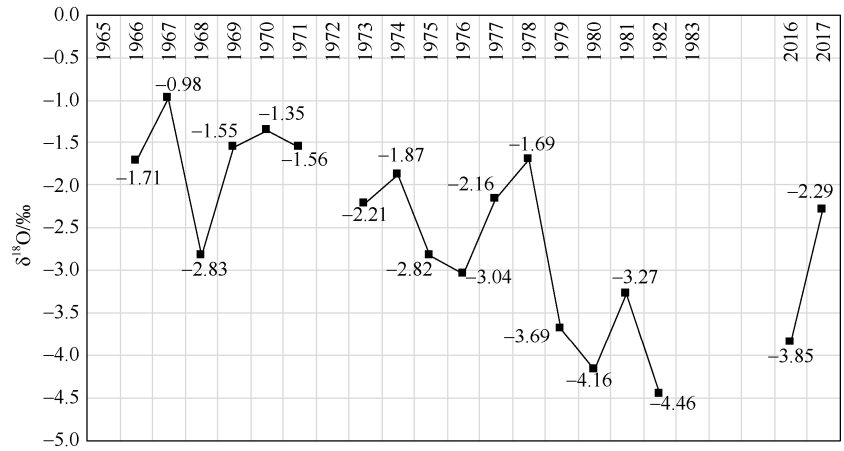

Figure 6 September $\delta^{18}O$ ratio from Porto Alegre, Brazil. Sources: IAEA, 2018 (1965–1983) and Griebler Júnior, 2018 (2016–2017).

passage of frontal systems. The isotopic ratio of the precipitation during the first week, when two of these events occurred, was anomalously low ($\delta^{18}O = -6.30‰$). The synoptic context of the studied event affirms that the anomalously high $\delta^{18}O$ ratio at Porto Alegre was due to the presence of the high-intensity SALLJ. Although the SALLJ speed is irrelevant to the quantity of moisture transported in South America (Montini et al., 2019), it played a crucial role in preventing the depletion of the hot air mass during this event, ensuring an Amazonian isotopic signature. In addition, this positive delta value presents an isotopically heavy rain, which characterizes moisture sources resulting from recycling processes that occur in the Amazon Basin.

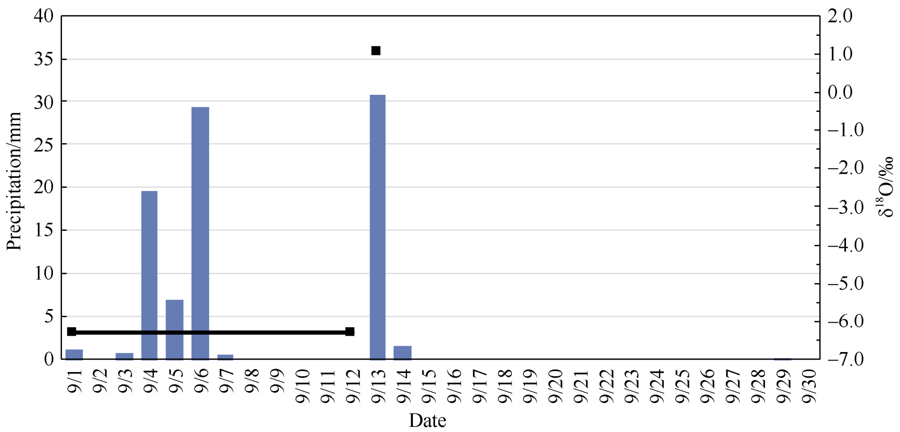

Figure 7 September 2016 precipitation (blue columns, INMET, 2020) and $\delta^{18}O$ ratio (the black line represents one sample, the black dot on top represents the event analyzed in this article) from Porto Alegre, Brazil.

The southern Brazilian region lacks studies on the isotopic composition of individual precipitation events. Therefore, it is difficult to classify the event's unique nature. However, the synoptic and isotopic analyses contribute to the understanding of the dynamics of air masses and hydrological behavior on a warming planet. Future scenarios suggest an increased frequency of such extreme precipitation events in the LPB (Liebmann et al., 2004; Cavalcanti et al., 2015).

4 Conclusions

The synoptic and isotopic analysis of an extreme precipitation event in southern Brazil indicated that the transport of Amazonian moisture by the SALLJ can interact with cold front passages and enhance the cyclogenesis process. This event analysis is significant in the context of the persistent contrast in tropic-pole interactions during the austral spring of 2016, which were under the influence of El Niño 2015/2016 and a positive SAM, causing a record SIE retreat and higher cyclonic activity in the middle latitudes. The synoptic pattern found in September 2016 corresponds to the anomalous temperature dipole between southern Brazil and the Antarctic Peninsula, which intensified the extreme temperature and precipitation events in the LPB and South Brazil.

Events like this may become more common on a warmer planet, particularly with a greater Amazon-Antarctic thermal contrast. Thus, we must understand how teleconnections between the tropics and poles contribute to extreme precipitation events in southeast South America.

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References

Aquino E F. 2012. Conexão climática entre o Modo Anular do Hemisfério Sul com a Península Antártica e o Sul do Brasil. PhD thesis, Porto Alegre, Rio Grande do Sul, Universidade Federal do Rio Grande do Sul.

Berbery E H, Barros V R. 2002. The hydrological cycle of the La Plata Basin in South America. J Hydrometeor, 3(6): 630-645, doi: 10.1175/15257541(2002)003%3C0630:THCOTL%3E2.0.CO;2.

Bitencourt D P, Fuentes M V, de Souza Cardoso C. 2013. Climatologia de ciclones explosivos Para a área ciclogenética Da América do Sul. Rev Bras Meteorol, 28(1): 43-56, doi: 10.1590/s0102-778620130001 00005.

Bonner W D. 1968. Climatology of the low level jet. Mon Weather Rev, 96(12): 833-850, doi: 10.1175/15200493(1968)096<0833:COTLLJ> 2.0CO;2.

Cavalcanti I F A, Carril A F, Penalba O C, et al. 2015. Precipitation extremes over La Plata Basin – Review and new results from observations and climate simulations. J Hydrol, 523: 211-230, doi: 10.1016/j.jhydrol.2015.01.028.

Dansgaard W. 1953. The abundance of ^{18}O in atmospheric water and water vapour. Tellus, 5(4): 461-469, doi: 10.3402/tellusa.v5i4.8697.

Gan M A, Rao V B. 1991. Surface cyclogenesis over South America. Mon Weather Rev, 119(5): 1293-1302, doi: 10.1175/1520-0493 (1991)119<1293:scosa>2.0.co;2.

Gan M A, Rao V B. 1994. The influence of the Andes Cordillera on transient disturbances. Mon Weather Rev, 122(6): 1141-1157, doi: 10.1175/1520-0493(1994)122<1141:tiotac>2.0.co;2.

Gramcianinov C B. 2019. Changes in South Atlantic cyclones due climate change (Mudanças nos Ciclones do Atlântico Sul devido às Mudanças Climáticas). PhD thesis, São Paulo, São Paulo, Universidade de São Paulo.

Gramcianinov C B, Hodges K I, Camargo R. 2019. The properties and genesis environments of South Atlantic cyclones. Clim Dyn, 53(7-8): 4115-4140, doi: 10.1007/s00382-019-04778-1.

Griebler Júnior J C. 2018. Origem da precipitação do Rio Grande do Sul a partir da composição isotópica. M S thesis, Porto Alegre, Rio Grande do Sul, Universidade Federal do Rio Grande do Sul.

Guedes do Nascimento M, Herdies D L, Oliveira de Souza D. 2016. The South American water balance: the influence of low-level jets. J Clim, 29(4): 1429-1449, doi: 10.1175/jcli-d-15-0065.1.

International Atomic Energy Agency (IAEA). 2018. Global Network of Isotopes in Precipitation (GNIP). https://www.iaea.org/services/networks/gnip.

Instituto Nacional de Meteorologia (INMET). 2020. Banco de Dados Meteorológicos para Ensino e Pesquisa (BDMEP). http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep.

Jouzel J. 2003. Water stable isotopes: atmospheric composition and applications in polar ice core studies. Treatise Geochem, 4: 213-243, doi:10.1016/B0-08-043751-6/04040-8.

Kuo Y-H, Reed R J, Low-Nam S. 1991. Effects of surface energy fluxes during the early development and rapid intensification stages of seven explosive cyclones in the western Atlantic. Mon Weather Rev, 119(2):457-476, doi:10.1175/1520-0493(1991)119<0457:eosefd> 2.0.co;2.

Lichtenstein E R. 1980. La depressión del noroeste argentino. PhD thesis, Buenos Aires: Universidad de Buenos Aires.

Liebmann B, Vera C S, Carvalho L M V, et al. 2004. An observed trend in Central South American precipitation. J Climate, 17(22): 4357-4367, doi: 10.1175/3205.1.

Marengo J A. 2002. The South American low-level jet east of the Andes during the 1999 LBA-TRMM and LBA-WET AMC campaign. J Geophys Res, 107(D20): 8079, doi:10.1029/2001jd001188.

Marengo J A, Ambrizzi T, Soares W R. 2009. Jato de Baixos Níveis ao longo dos Andes //Cavalcanti I F A et al. in Tempo e Clima no Brasil, São Paulo, Oficina de Textos, 185-196.

Mendes D, Souza E P, Trigo I F, et al. 2007. On precursors of South American cyclogenesis. Tellus A: Dyn Meteorol Oceanogr, 59(1): 114-121, doi:10.1111/j.1600-0870.2006.00215.x.

Montini T L, Jones C, Carvalho L M V. 2019. The South American low-level jet: a new climatology, variability, and changes. J Geophys Res: Atmos, 124(3): 1200-1218, doi: 10.1029/2018JD029634.

Nascimento M G. 2008. Análise dos impactos dos jatos de baixos níveis sobre a Bacia do Prata. M S thesis, São José dos Campos, São Paulo, Instituto Nacional de Pesquisas Espaciais.

National Centers for Environmental Prediction (NCEP). 2020. NCEP climate forecast system version 2 (CFSv2) 6-hourly products. https://rda.ucar.edu/datasets/ds094.0/.

Nicolini M, Salio P, Ulke G, et al. 2004. South American low level jet diurnal cycle and three dimensional structure. http://www.clivar.org/publications/exchanges/ex29/pdf/s29_nicolini.pdf.

NOAA. 2017. Data show 2016 warmest year on record. https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally.

Oliveira M I, Nascimento E L, Kannenberg C. 2018. A new look at the identification of low-level jets in South America. Mon Weather Rev, 146(7): 2315-2334, doi:10.1175/mwr-d-17-0237.1.

Raphael M N. 2004. A zonal wave 3 index for the Southern Hemisphere. Geophys Res Lett, 31(23): 4, doi:10.1029/2004gl020365.

Reboita M S, da Rocha R P, Ambrizzi T, et al. 2010. South Atlantic Ocean cyclogenesis climatology simulated by regional climate model (RegCM3). Clim Dyn, 35(7-8): 1331-1347, doi:10.1007/s00382-009-0668-7.

Reboita M S, da Rocha R P, de Souza M R, et al. 2018. Extratropical cyclones over the southwestern south Atlantic ocean: HadGEM2-ES and RegCM4 projections. Int J Climatol, 38(6): 2866-2879, doi:10.1002/joc.5468.

Rindsberger M, Jaffe S, Rahamim S, et al. 1990. Patterns of the isotopic composition of precipitation in time and space: data from the Israeli storm water collection program. Tellus B: Chem Phys Meteorol, 42(3): 263-271, doi: 10.3402/tellusb.v42i3.15218.

Rozanski K, Araguás-Araguás L, Gonfiantini R. 1993. Isotopic patterns in modern global precipitation//Swart P K, Lohmann K C, MacKenzie J, et al. Climate change in continental isotopic records. AGU, Washington, D. C.: American Geophysical Union, 1993: 1-36, doi:10.1029/gm078p0001.

Sanders F, Gyakum J R. 1980. Synoptic-dynamic climatology of the "Bomb". Mon Weather Rev, 108(10): 1589-1606, doi: 10.1175/1520-0493(1980)108%3C1589:SDCOT%3E2.0.CO;2.

Schossler V, Aquino F E, Reis P A, et al. 2019. Antartic circulation anomalies on the spring of 2016 as a inductor of a explosive cyclogenesis in the Rio Grande do Sul. Revista de Geografia da UFJ, 8(2): 54-64, doi: 10.34019/2236-837X.2018.v8.25992.

Schossler V, Simões J C, Aquino F E, et al. 2018. Precipitation anomalies in the Brazilian southern coast related to the SAM and ENSO climate variability modes. Revista Brasielira de Recursos Hídricos, 23(14): 1-10, doi: 10.1590/2318-0331.231820170081.

Seluchi M E, Saulo A C, Nicolini M, et al. 2003. The northwestern Argentinean low: a study of two typical events. Mon Weather Rev, 131(10): 2361-2378, doi: 10.1175/1520-0493(2003)131<2361:tnalas>2.0.co;2.

Seth A, Rojas M, Rauscher S A. 2010. CMIP3 projected changes in the annual cycle of the South American Monsoon. Clim Chang, 98(3-4): 331-357, doi: 10.1007/s10584-009-9736-6.

Silvestri G E, Vera C S. 2003. Antarctic Oscillation signal on precipitation anomalies over southeastern South America. Geophys Res Lett, 30(21): L2115, doi: 10.1029/2003GL018277.

Soares W R, Marengo J A. 2009. Assessments of moisture fluxes east of the Andes in South America in a global warming scenario. Int J Climatol, 29(10): 1395-1414, doi: 10.1002/joc.1800.

Stuecker M F, Bitz C M, Armour K C. 2017. Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. Geophys Res Lett, 44: 9008-9019, doi: 10.1002/2017GL07469110.1002/2017GL074691.

Turner J, Phillips T, Marshall G J, et al. 2017. Unprecedented springtime retreat of Antarctic sea ice in 2016. Geophys Res Lett, 44(13): 6868-6875, doi: 10.1002/2017GL073656.

Vera C, Baez J, Douglas M, et al. 2006. The South American low-level jet experiment. Bull Am Meteorol Soc, 87(1): 63-78, doi:10.1175/BAMS-87-1-63.

Vera C S, Vigliarolo P K, Berbery E H. 2002. Cold season synoptic-scale waves over subtropical South America. Mon Weather Rev, 130(3): 684-699, doi: 10.1175/1520-0493(2002)130%3C0684:CSSSWO%3E2.0.CO;2.

Viana D R, Aquino F E, Matzenauer R. 2006. Comportamento espaço-temporal da precipitação no Rio Grande do Sul entre 1945-1974 e 1975-2004. Florianópolis, Brasil: XIV Congresso Brasileiro de Meteorologia 14, Florianópolis: SBMET, 2006. Anais, CD-ROM.

Wang G M, Hendon H H, Arblaster J M, et al. 2019. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. Nat Commun, 10(13): 9, doi: 10.1038/s41467-018-07689-7.

Whiteman C D, Bian X, Zhong S. 1997. Low-level jet climatology from enhanced rawinsonde observations at a site in the Southern Great Plains. J Appl Meteorol, 36(10): 1363-1376, doi:10.1175/1520-0450(1997)036<1363:lljcfe>2.0.co;2.