Conjecturas

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Relationship between air masses formed in the Antarctic Region and extreme minimum temperature events in Southern Brazil

Relação entre as massas de ar formadas na Região Antártica e eventos de temperaturas mínimas extremas no Sul do Brasil

Douglas da Silva Lindemann[1]*, Rose Ane Pereira de Freitas[1], Jackson Martins Rodrigues[2], Diulio Patrick Pereira Machado[1], e Elaine Alves dos Santos[3]

ABSTRACT

Antarctic is a region of origin of air masses that move and enter the Southern region of Brazil, driven by synoptic-scale atmospheric systems, which can have detrimental effects on the region. In this study, data from the weather station located in Pinheiro Machado-RS were used, where periods were analyzed during the southern winter of 2019, and 3 events with negative minimum temperature were identified. To identify the trajectory and surface characteristics of these masses, the HYSPLIT model was used, together with ERA5 reanalysis data. The results indicated that there are significant correlations with elements already known in the literature, starting with the presence of the anticyclone in the Southeast Pacific, followed by positive (negative) correlations of air and ocean temperatures in the Southwest Atlantic and central Argentina, associated with negative anomalies (positive) sea ice cover in the Bellingshausen Sea (west sector of the Weddell Sea). These conditions provide displacements totally different from the air masses in the South America, a displacement from the northeast in Case 1, by the east side of the continent in Case 2, while in Case 3 the air mass started to act on the continent in 50° S, on the west coast of the continent.

Keywords: sea ice; anticyclone; air masses; atmospheric circulation; synoptic meteorology.

RESUMO

A Antártica é uma região de origem das massas de ar que se movem e entram na região Sul do Brasil, impulsionadas por sistemas atmosféricos em escala sinótica, que podem ter efeitos danosos na região. Neste estudo, foram utilizados dados da estação meteorológica localizada em Pinheiro Machado-RS, onde foram analisados períodos durante o inverno austral de 2019, e foram identificados 3 eventos com temperatura mínima negativa. Para identificar a trajetória e as características da superfície dessas massas, foi utilizado o modelo HYSPLIT, juntamente com os dados de reanálise ERA5. Os resultados indicaram que existem correlações significativas com elementos já conhecidos na literatura, a começar pela presença do anticiclone no Sudeste do Pacífico, seguida por correlações positivas (negativas) das temperaturas do ar e do oceano no Atlântico Sudoeste e centro da Argentina, associadas a anomalias negativas (positivas) cobertura de gelo marinho no Mar de Bellingshausen (setor oeste do Mar de Weddell). Essas condições proporcionam deslocamentos totalmente diferentes das massas de ar na América do Sul, um deslocamento de nordeste no

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1 Faculdade de Meteorologia, Universidade Federal de Pelotas, Pelotas-RS, Brasil. *E-mail: douglas.lindemann@ufpel.edu.br
2 Departamento de Geografia e Políticas Públicas, Universidade do Estado do Rio de Janeiro, Angra dos Reis-RJ, Brasil.
3 Laboratório de Radioecologia e Mudanças Globais. Universidade do Estado do Rio de Janeiro, Rio de Janeiro-RJ, Brasil.

caso 1, a leste do continente no Caso 2, enquanto no Caso 3 a massa de ar passou a atuar no continente em 50° S, na costa oeste do continente.

Palavras-chave: gelo marinho; anticiclone; massas de ar; circulação atmosférica; meteorologia sinótica.

INTRODUÇÃO

The Antarctic continent, surrounded by the Southern Ocean, has an average altitude of 2500 meters above sea level (m.a.s.l.) and extending over $13.6x10^6$ km which 99.6% is covered by ice. Moreover, there is also the presence of sea ice surrounding the continent that has increased in the last decades up to 2016 (COMISO et al., 2017). Such of change in Antarctic sea ice driven by fluctuations in sea surface temperature (SST) and Southern Annular Mode (SAM) may contribute to the increase in the frequency of cold outbreaks to a large extent in the Southern Ocean (BRACEGIRDLE and KOLSTAD 2010; SMITH and SHERIDAN 2020).

Although the number of days of annual cold outbreaks has decreased for most regions since 1979, in the Southern Ocean west of the Antarctic Peninsula high latitudes it increased from 75% up to 100% (SMITH and SHERIDAN 2020). A general balance for the Southern Hemisphere (SH) of outbreaks, which is the sum of the spatial extension of each day of cold outbreaks each winter, it is noticed that it significantly for the SH. This rapid decrease in SH coincides with the large reduction in sea ice that has occurred in Antarctica since 2016 (MEEHL et al., 2019). This decrease in the annual average and in the total spatial extent suggests that not only has the duration of cold outbreaks decreased, but the spatial extent of each cold outbreak has also decreased (SMITH and SHERIDAN 2020).

The peculiar physical and geographical characteristics play an important role in cold outbreaks shift from Antarctica that, associated with the spatiotemporal variations of SST in the Pacific and South Atlantic oceans, result in a particular pattern of southern gradients, which aid in the transport of these cold anomalies towards South America. In addition, the geography of the South American continent contributes to recurrent atmospheric phenomena (anticyclones and extratropical cyclones) in periods of extreme minimum temperatures that occur over the continent (SELUCHI and NERI 1992; PEZZA and AMBRIZZI 2005; SPRENGER et al., 2013).

Previous studies (SELUCHI and NERI 2002; GONÇALVES et al., 2002; DRAGANI et al., 2013; RICARTE et al., 2015) have shown that the passage and intensification of cold air masses in southern Brazil are associated with frontal systems from the Antarctic region. Such displacement with transient anticyclones/cyclones, which can change pressure, temperature, wind and humidity along their trajectories, where the reduction in temperature is usually anticipated by an increase in surface pressure and a reduction in atmospheric humidity (METZ et al., 2013; DRAGANI et al., 2013). These phenomena, in turn, end up having a direct influence on the atmospheric and oceanographic circulation of SH, especially on the South and Southeast of Brazil (SELUCHI and NERI 2002; GONÇALVES et al., 2002; PEZZA and AMBRIZZI 2005; SPRENGER et al., 2013; DRAGANI et al., 2013; RICARTE et al., 2015).

Once these anomalous cold air masses detach from Antarctica and move to South America, they often provide frost days, minimum negative temperatures and even snowfall over a large extension of Argentina, Uruguay and southern Brazil. The persistence of these cold days is conditioned mainly by two large-scale dynamic factors; 1) the zonal propagation of the Rossby wave train through the Pacific Ocean, and 2) the location in relation to the continent and the magnitude of the confluence in the region where the jet enters at subtropical latitudes. The greater persistence of a cold day event combines the confluence/diffluence over regions of in/out jets, which depends on the disposition in relation to the continent of Rossby wave trains with zonal propagation (SELUCHI and MARENGO 2000; RUSTICUCCI, 2012; MÜLLER and BERRI 2012).

The brazilian state Rio Grande do Sul (RS) is located in the southern most of country and has approximately 90% year days controlled by extratropical atmospheric systems, such as air masses and polar and intertropical fronts, as well as tropical masses and disturbed currents (SARTORI, 2015). The State has four well-defined seasons marked by severe winters between May and August. During the winter, the southern region of Brazil is under influence of successive and intense passages of polar air masses, causing days of extreme cold, with the air temperature reaching 0ºC and and lower (KOUSKY, 1979; MARENGO et al., 1997; SPRENGER et al., 2013; MÜLLER and BERRI 2012; DRAGANI et al., 2013).

These events of extreme cold affect the most diverse areas in the State, being able to cause damages and losses to the economy, health, trade, tourism and others. Once RS economy is deeply dependent on agriculture, and its development is directly connected to weather and climate conditions, where extreme events can generate highly damaging effects (CARMONA et al., 2002; MÜLLER, 2006; KLERING, 2008; ALVES et al., 2017). Health is another important area strongly affected by cold conditions in RS, when periods of low temperatures can cause high rates of cardiovascular, rheumatic and respiratory diseases, which can overload the health system with maximum hospital admissions and increases in the number of hospital visits, worsening in periods of extreme cold (KASSOMENOS et al., 2007; NEDEL, 2009; HONDULA et al., 2013).

As the Antarctic continent is determinant for weather and climate regulation in the SH, especially over the southern region of Brazil, which stands out economically as the fourth economy in Brazil, it becomes extremely important to identify areas of origin, shifts and characteristics of air masses of cold formed in Antarctica that move into the territory of the state and exert a direct influence on the region. Such information can collaborate in actions to prevent and coordinate risks generated by extreme cold waves in the state of RS, assisting the most diverse sectors in the region. Thus, the objective of this work aims to identify extreme cases of minimum temperature, using as reference a automatic meteorological station (AWS) located in Pinheiro Machado-RS, which occurred during the southern winter of 2019, in addition to the identification of meteorological phenomena that could contribute to the occurrence of these minimum temperature events.

MATERIALS AND METHODS

Observed Data

The extreme negative temperature events were collected from the automatic weather station (AWS) located at coordinates 31.59° S and 53.51° W at 470 m.a.s.l in Pinheiro Machado municipality (PMM), Rio Grande do Sul state. The referred AWS is a private equipment supplied with weather sensors for temperature, pressure, wind and precipitation following traditional patterns (Figure 1).

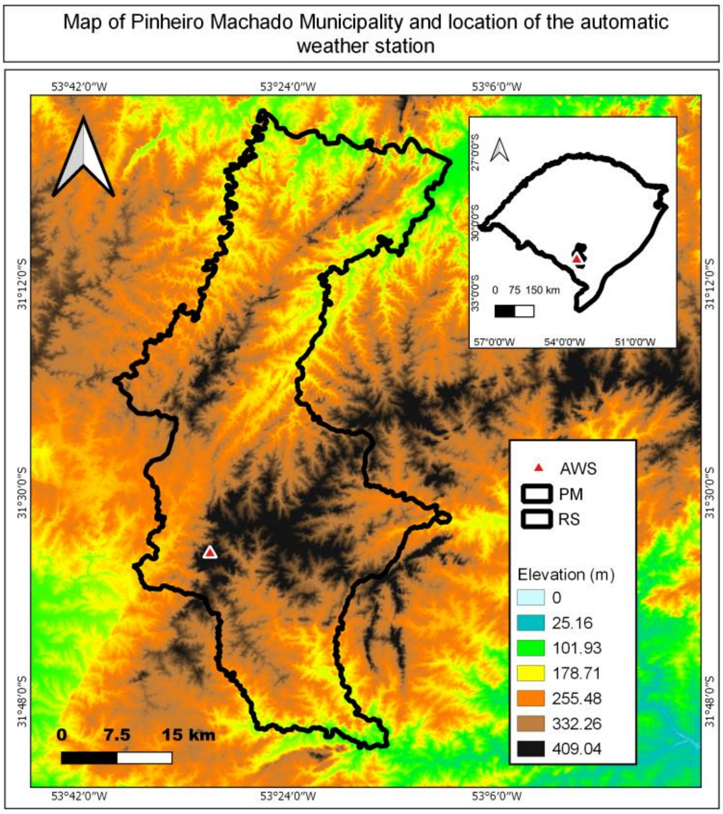
The study region is located in southernmost Brazil among the mountain chains named Serras das Asperezas, Serra do Passarinho and Serra do Velleda. The region is characterized by subtropical climate patterns with low temperatures during the winter (June, July and August) with frost events and high temperatures during the summer (December, January and February) (RIBEIRO JÚNIOR et al., 2019). Agricultural production that evolved its productive matrix for viticulture, floriculture, reforestation and wool (PINHEIRO MACHADO, 2021).

In this study at least 3 extreme negative temperature events from 2019 winter were analysed (Table I).

Hysplit

Airmass backward trajectory modeling was achieved using a HYSPLIT (Hybrid Single_Particle Lagrangian Integrated Trajectory) model provided by AIR resources Laboratory of National Oceanic and Atmospheric Administration, USA. The HYSPLIT is a useful air trajectory model, especially for long range transport air mass (STEIN et al., 2016; SANTOS et al., 2018).

Figure 1 - Location of the municipality of Pinheiro Machado and the meteorological station used to identify extreme temperature events



The climatology was made through compilation of climate data from NCEP/NCAR Reanalysis Project, a project of the Environmental Forecasting Centers (National Centers for Environmental Prediction NCEP) and the Atmospheric Research Center (National Center for Atmospheric Research - NCAR (https://www.ready.noaa.gov/archives.php) that were read by Hysplit 5.0. Directions of the selected trajectories was (backward trajectories) which is the reconstruction of trajectories to the reference point (Serra dos Veledas).

Table I - The three selected cases of extreme temperature.

Date	Extreme negative temperatures	Cases
2019/07/05	-2.2 °C	Case 1
2019/08/14	-2.0 °C	Case 2
2019/08/19	-1.3 °C	Case 3

Air Mass backward trajectory was performed for five days. The complete tutorial of the Hysplit program is available on the website https://www.ready.noaa.gov/HYSPLIT_Tutorials.php.

Reanalysis ERA5

For the spatial analysis of the variables, daily data the climatology of the ERA5 reanalysis were used. ERA5 is freely available data set from the European Center for Medium-Range Weather Forecast (ECMWF), with a spatial resolution of 0.25° which combines large amounts of historical observations in global estimates using advanced models and data assimilation systems (HERSBACH et al., 2020).

After the identification of the cases, it was rolled back up to 120h (lag -5) before the occurrence of the minimum temperature in PMM, in order to monitor the meteorological pattern on the surface. For each day prior to the event, the anomaly in relation to the climatology of the month was calculated.

Correlations

Correlation between minimum daily temperature of study regions from 07/01/2019 to 08/31/2019 and selected places from Antarctic ocean named: Bellingshausen Sea - Bel (67° S; 80° W), East Weddell Sea sector - EdW (65° S; 45° W), West Weddell Sea sector - WdW (65° S; 15° W) for calculation with sea ice cover. The points called Southeast Pacific Ocean - SEP (55° S; 80° W), Southwest Atlantic Ocean - SWA (45° S; 60° W) for the calculation with air temperature 2 meters from the surface (T2m), mean sea level pressure (MSLP) and SST. In addition to the Central Argentina - CAR - point (40° S; 68° W) for the calculation of T2m and MSLP. The significance of 95% was considered in the correlation.

RESULTS AND DISCUSSION

Synoptic description of cases

Case 1 - 2019/05/07

The winter is a season characterized by incursions of cold air masses over high and mid latitudes of South America. The most intense cold fronts events are registered during the period between June and July (LANFREDI and CAMARGO 2018). The climatological normals (1980 to 2010) from the National Institute of Meteorology (INMET) reports the monthly average values of the minimum temperature in the region of PMM vary from 8 to 10°C in July, and from 10 to 12°C in August.

The 1° case analysed began on 2019/06/30 (lag -5) which was characterized by a cyclogenesis with central pressure of 1008 hPa between the coastal regions of Uruguay and RS. The associated system with cold front shifts over RS is also coupled with the advance of another frontal system over the Atlantic Ocean. At the rear of the cold front there is an anticyclone of 1016 hPa around 43° S and 50° W (Figure 2a).

Such of atmospheric condition provides thermic contrast between the south-central regions of Argentina and Chile, with negative anomalies (-1 to -3 °C) of T2m, while south-central Brazil, Paraguay and Bolivia experience positive T2m anomalies (1 to 5 °C), as shown in Figure 2d.

Associated with T2m anomalies, there are also different MSLP anomalies, negative values (-10 to -15 hPa) of cyclones on the coast of RS and Uruguay and also on the Southwest Atlantic Ocean (55° S; 20° W) are associated with positive T2m anomalies. On the other hand, positive MSLP anomalies are coupled in regions with negative T2m anomalies over the southern tip of South America and in the Weddell Sea (Figure 2d). There is also the presence of a cyclone in the Southeast Pacific Ocean, between South America and Antarctica (60° S; 90° W).

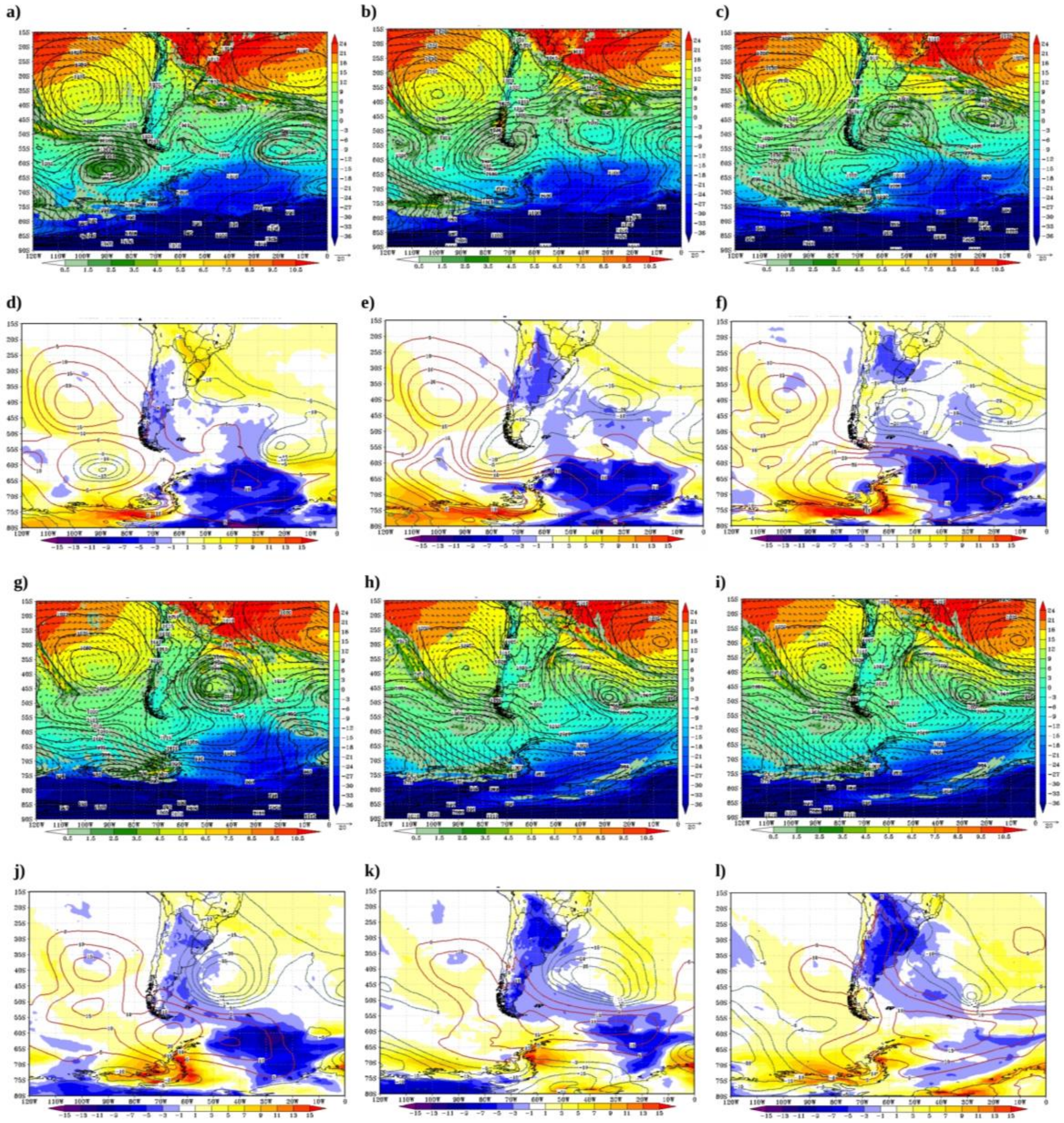
This cyclone mentioned over the Southeast Pacific Ocean moved over the southernmost South America at lag -4 (Figure 2b). This system is surrounded by anticyclones located over the Southeast Pacific Ocean (37° S; 100° W) with a central pressure of 1040 hPa, over the Bellingshausen Sea, west of the Antarctic Peninsula (1010 hPa), and the third one over the ocean Southwest Atlantic (50° S; 35° W) with 1005 hPa. The cyclone near the coast of RS and Uruguay shifted eastern and the associated cold front is already between the north of RS and Santa Catarina (Figure 2b).

The surface atmospheric conditions considered reports a temperature dipole surrounding Antarctica (Figure 2e) where negative (positive) anomalies of T2m over the Weddell Sea (Ross Sea), with values up to -9°C (7°C) below (above) the climatological average. The presence of negative MSLP anomalies over the southernmost South America (-10 hPa), associated with the low pressure center operating in the region, may provide a corridor of cold air from Antarctica.

During lag -3, the cyclone in the extreme south of South America shifted towards the Southwest Atlantic Ocean (Figure 2c), close to the coast of Argentina (45° S; 62° W), with a value of 990 hPa. At the rear of this system, a large anticyclone was formed over the Drake Strait (62° S; 72° W) with a value of 1020 hPa.

The presence of the cyclone on the Argentinian coast, associated with the anticyclone in the Drake Passage, contributed to an intense pressure gradient which intensified winds from the Southwest (Figure 2c), towards South America. The cold surface anticyclone that moved from the southeastern Pacific to the south of Argentina and the strengthened cyclone over the Southwest Atlantic are important elements for development of cold days over part of South America (GARREAUD, 2000; PEZZA and AMBRIZZI 2005).

Figure 2 – Synoptic patterns and anomalies for Case 1. Figures (a - c) and (g - i) the synoptic patterns from lag-5 to lag0, filled values are air temperature (°C) and precipitation (mm), the lines is the pressure at mean sea level (hPa). Figures (d – f) and (j – l) is the anomaly between each lag in relation to the climatology of the air temperature (filled values) and the pressure at mean sea level (lines).



Southern 30° S, both the continental anticyclone and the cyclone over the ocean strengthened mainly due to high level vorticity advection within the mid-latitude baroclinic wave. The existence of a top-level jet over subtropical South America (not shown here) is important for occurrence of strong and long-lasting cold waves, because it induces transverse and direct circulation that provides additional stress to the part center of the surface anticyclone and medium-level cooling at lower latitudes (GARREAUD, 1999; 2000).

This condition is observed in Figure 2f, with the presence of negative T2m anomalies over this region and negative (positive) anomalies of MSLP over the Southwest Atlantic Ocean (Drake Passage), with values of -25 hPa (25 hPa), providing a corridor connecting the Weddell Sea region with the Argentinian coast.

The northeast movement and an intensification (975 hPa) observed at lag -2, the cyclone is now acting close to the mouth of the Rio de la Plata (45° S; 50° W). As the anticyclone over the Drake Strait moves to the northeast (60° S; 70° W) and intensifies as well (1015 hPa), the cold air corridor from Antarctica still remains.

A serie of anticyclones are identified in Figure 2g, extending from the South Subtropical Pacific High, passing through another system south of the Southeast Pacific Ocean (52° S; 97° W), a third over the Drake Strait and finally, the fourth over the Weddell Sea. These systems have anomalies ranging from -20 to -15 hPa.

These anticyclones contribute to a warmer air supply of medium latitudes towards the Bellingshausen Sea and contribute to positive T2m anomalies (11°C), as shown in Figure 2j. Meanwhile, on the Atlantic side, negative T2m anomalies (-1 to -5°C) extend from the Weddell Sea to the southern regions of Brazil, northern Argentina and southern Paraguay, influenced by the presence of a cyclone in northern Argentina and the intensification of negative MSLP anomalies (-25 hPa) over the Southwest Atlantic Ocean.

The intensification of South Atlantic Subtropical High (SASH) during lag -1, the old frontal system remains positioned over the north of RS and Santa Catarina (Figure 2h), which extends over the Atlantic Ocean. This system prevents the advance of the cyclone that was close to the outfall of the Rio de la Plata, providing an eastward displacement, and according to Pezza and Ambrizzi (2005) this cyclone close to the coast plays an important role as a dynamic mechanism. Associated with this condition, anticyclones operating in the mid and high latitudes, advanced towards the northeast, contributing to an amplification of negative T2m anomalies over the South American continent (Figure 2k), with negative anomalies ranging from -1 to -5°C in relation to the climatological average, from the extreme south of the continent to the southeast of Bolivia, also influencing the Midwest and South regions of Brazil, Paraguay and Argentina.

The positioning of the cyclone in the Southwest Atlantic Ocean and the anticyclone on the continent are important factors for the occurrence of widespread frosts over the region known as Pampa Úmido (Wet Pampa) in northeastern Argentina, as well as in Uruguay and RS. When analyzing the occurrence of generalized frosts on the Wet

Pampa during the winters from 1961 to 1990 with data from the NCEP-NCAR, Müller and Berri (2007; 2012) identified that frosts are caused because this anticyclonic anomaly that enters South America and it causes wind anomalies in the south quadrant and advection of cold air, which are reinforced by the cyclonic anomaly over the Southwest Atlantic Ocean. In the case of more persistent events, the wind anomaly increases during the previous days and becomes almost stationary.

During lag 0, the cyclone over the South Atlantic Ocean loses intensity (990 hPa) and moves to the Southeast (50° S; 28° W), but it still contributes to the occurrence of precipitation on the coast of RS and Uruguay (Figure 2i). Simultaneously, the presence of cold air mass that moves to the rear of this system becomes more intense on the continent, specifically on the south of Brazil. Escobar et al., (2004) used rotated principal component analyzes to obtain, among other results, the basic patterns of 1000 hPa geopotential heights. The authors analyzed the cold waves during the southern winter for the period 1979-1993, and found that seven patterns occurred at 1000 hPa. The most classic pattern shows a post-frontal anticyclone at its lower level, producing advection of cold air over Central Argentina, that is, a condition similar to lag 0 in the present study.

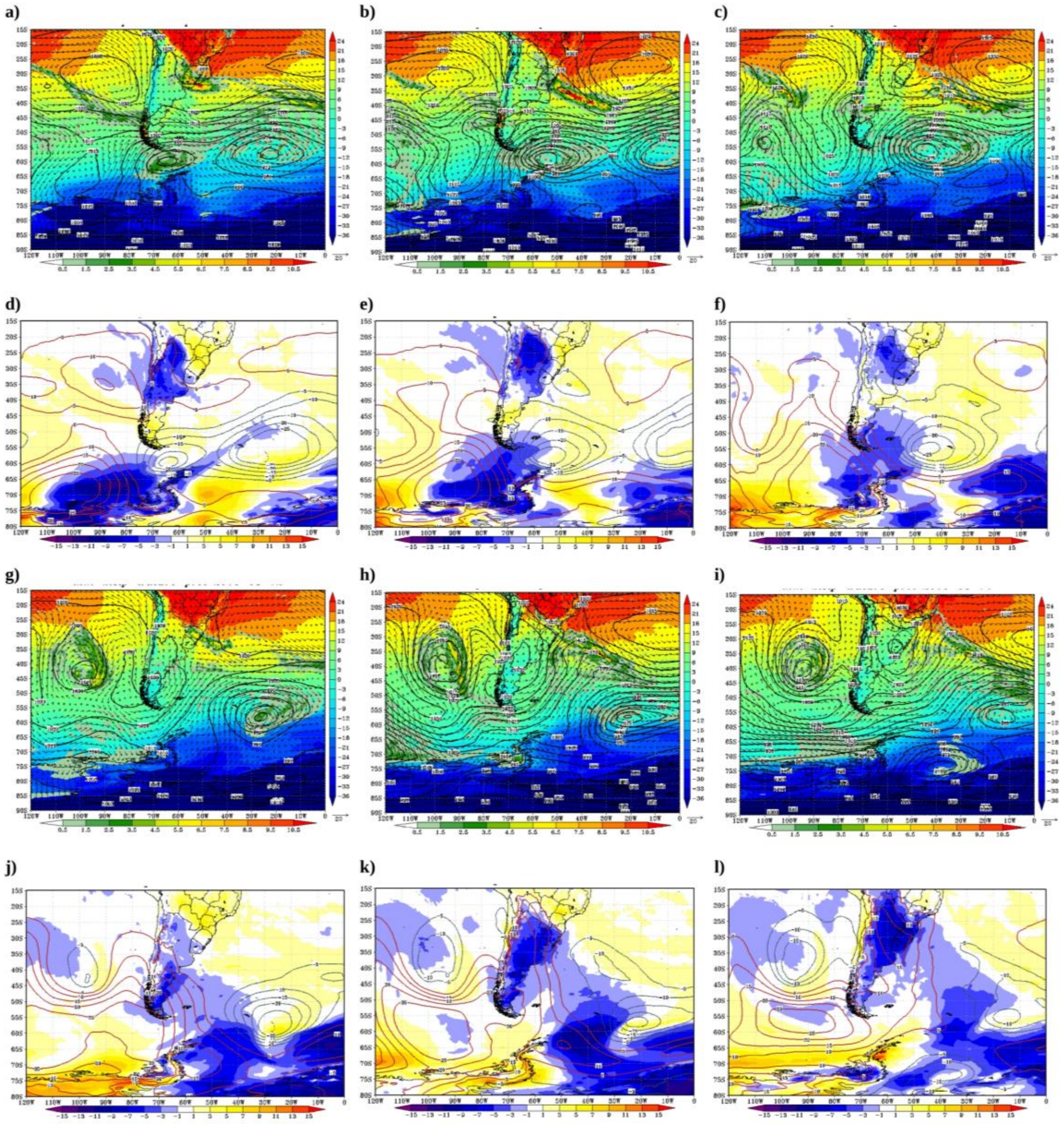
This configuration contributes to the weakening of the T2m negative anomaly corridor previously observed between the high latitudes of SH and South America (Figure 2l), however, on the continent negative T2m anomalies predominate, with values of up to -5°C over the north of RS and midwest of Santa Catarina. While the southern region of RS (where AWS is located) has anomalies of up to -3°C in relation to climatology.

Case 2 – 2019/08/14

Case 2 presents different meteorological conditions in comparison to Case 1 (Figure 2a) during lag -5. In Figure 3a it is observed a cyclone over the Drake Strait with a value of 970 hPa (60° S; 65° W). This cyclone associated with the presence of an anticyclone (1010 hPa) over the Southeast Pacific Ocean (65° S; 100° W), contributes to a cold air mass incoming from the western region of the Antarctic Peninsula driving it towards the southern tip of South America.

In the South Atlantic Ocean it was also noticed the presence of an intense cyclone (55° S; 22° W), with a value of 960 hPa. It is also possible to verify the presence of a frontal system between Uruguay, southern Brazil, Argentina and southern Paraguay. In addition to the identification of the two semi-permanent anticyclones over the Atlantic and South Pacific oceans.

Figure 3 – Same configuration as Case 1, but for Case 2.



The strong positive anomaly of MSLP (25 hPa) over the Southeast Pacific Ocean (Figure 3d) trapped negative anomalies of T2m (up to -11°C) in western portion of the Antarctic Peninsula. These T2m anomalies are also captured due to presence of the negative MSLP anomaly (-20 hPa) in the Drake Passage, associated with the cyclone. Meanwhile, the intense negative anomaly of MSLP (-25 hPa) over the South Atlantic Ocean provides the direction of positive anomalies of T2m (up to 7°C) of medium latitudes towards the Weddell Sea.

Over South America, the presence of the frontal system mentioned above creates a condition of post-frontal anomalies and the region experiences conditions of negative (positive) anomalies of T2m (MSLP) with values of -3°C (5 hPa).

During lag -4 (Figure 3b), the atmospheric systems present at around 60° S show zonal shift and intensification, with the anticyclone over the Southeast Pacific Ocean increasing to 1015 hPa. Such anticyclone strengthening in the Pacific may revealed the occurrence of future extreme events of minimum temperature and the occurrence of frosts in northeastern Argentina, Uruguay and RS (MÜLLER and BERRI 2007). However, the most persistent events of extreme minimum temperatures and frosts are directly related to the almost stationary character of the anticyclonic anomaly that will move inland, as well as to its intensity (MÜLLER et al., 2005; MÜLLER and BERRI 2007; 2012). The cyclone that was in the Drake Strait moved to the southern Atlantic Ocean (57° S; 55° W), it did not deepen (maintaining 970 hPa), however, it increased in area.

The semipermanent anticyclones also became larger, maintaining the value of 1030 hPa while the anticyclone over northern Argentina intensified, contributing to the frontal system being directed towards the South Atlantic Ocean.

In Figure 3e it is observed that cold air mass, which will provide the T2m drop on the RS in the future, is still occupying the western sector of the Antarctic Peninsula and the Drake Strait, with values of up to -9°C. This air mass is trapped by the negative and positive anomalies of MSLP that are at the front and rear of the air mass, respectively.

The spatial increase in anticyclones at 60° S is maintained during lags -3 and -2 (Figure 3c and 3g), the anticyclone in the Southeast Pacific Ocean connects with the semi-permanent anticyclone, creating a large anticyclone. With the pressure gradient created between the two atmospheric systems at 60° S, there is an intensification of the winds from the Southwest quadrant.

According to Müller and Ambrizzi (2007), generalized frost events in central South America may be related to the hypothesis that large-scale specific patterns are associated with the frequency of occurrence of these frost events through the propagation of Rossby waves that are remotely triggered. According to the authors, the results are validated by means of a baroclinic model, which simulates the Rossby wave patterns responsible for teleconnection. Numerical experiments confirm that the main activity of the waves occurs within the subtropical and polar jets. In particular, for the basic state with the maximum frequency of generalized frosts occurring, the wave trains that propagate within the subtropical and polar jets merge shortly before entering the continent. This configuration contributes to the development of an intense wind anomaly in the southern quadrant, with a large southern extension, which results in the intensification of anticyclonic circulation in southern South America (MÜLLER and BERRI 2007; 2012), as seen in Figure 3c.

The southwest wind will contribute to the negative T2m anomaly moving towards the south end of South America and the Southwest Atlantic Ocean (Figure 3f). Several positive MSLP anomalies are observed over the high latitudes, with values ranging from 10 to 25 hPa. Negative anomalies are already observed over RS in lag -3, influenced by the displacement to the ocean of the frontal system, providing that the anticyclone that was previously over northern Argentina, starts to act in the region. However, T2m anomalies are not very intense.

During lag -2, a large area with a positive MSLP anomaly (25 hPa) is noticed over the South Pacific Ocean (Figure 3j). This system contributes to the negative anomalies of T2m being displaced over the southern region of South America, while directing warmer air from medium latitudes towards the western region of the Antarctic Peninsula, providing strong positive anomalies of T2m (11°C). In addition, another anticyclone over the Weddell Sea contributes to more cold air being propelled towards the South American continent.

The negative T2m anomaly, which is directed towards South America, is also supported by the presence of negative MSLP anomalies (-25 hPa) over the South Atlantic Ocean (57° S; 27° W). Such conditions presented in Case 2 are similar to those found by Garreaud (2000), where the author indicates that the cold waves along the eastern side of the Andes are the main mode of variability in the synoptic scale of the circulation at low levels of the atmosphere in the largest part of subtropical South America. Also according to Garreaud (2000), the episodes that occur in winter have a pronounced impact on the air temperature close to the surface, occasionally causing freezing conditions in the subtropical regions.

The anticyclone that positioned over the southern tip of South America at lag -2 is now over central Argentina during lag -1 (Figure 3h), with a value of 1035 hPa. There are records of rain on the northern coast of RS and along the ocean. This frontal branch, in turn, is associated with the cyclone over the ocean (57° S; 21° W). This condition described on the anticyclone is similar to the case analyzed by Lanfredi and Camargo (2018) about intense cold air incursions in South America for the period from 1979 to 2016, with the July 17, 2010 case being one of the most intense, when the extratropical anticyclone over Argentina reached 1044 hPa.

The anticyclone over Argentina, described above, contributes to the negative T2m anomalies starting to act on RS (Figure 3k). These negative anomalies that also act on Argentina, Chile and southern Paraguay are influenced by intense and wide positive anomalies of MSLP, which extend from the Southeast Pacific Ocean to the Weddell Sea, providing a great support of cold air, and that it becomes dry when entering the continent, towards RS.

During lag 0, the anticyclone is over Uruguay (1035 hPa), while the frontal system is totally over the South Atlantic Ocean (Figure 3i). The presence of this anticyclone provides positive MSLP anomalies over the region and further amplifies the negative

T2m anomalies (Figure 3l), with values of -5°C over the south of RS. It is also noteworthy that this positive MSLP anomaly covers the entire south-central region of South America, passing through the Southeast Pacific Ocean and going to the Ross Sea region in Antarctica.

The advance of the cold air incursion along the Andes is configured by the topographic blocking of the flow on a synoptic scale. The subsequent propagation in low latitudes, however, arises from a bidirectional interaction between the fields of mass and wind: the strong pressure gradient (temperature) produces the acceleration of low level winds parallel to the Andes Mountains (balance of ageostrophic forces along from the mountain), while the horizontal advection of cold air by the ageostrophic flow to the south maintains the strong temperature gradient against dissipation by surface heat flows (GARREAUD, 1999; 2000).

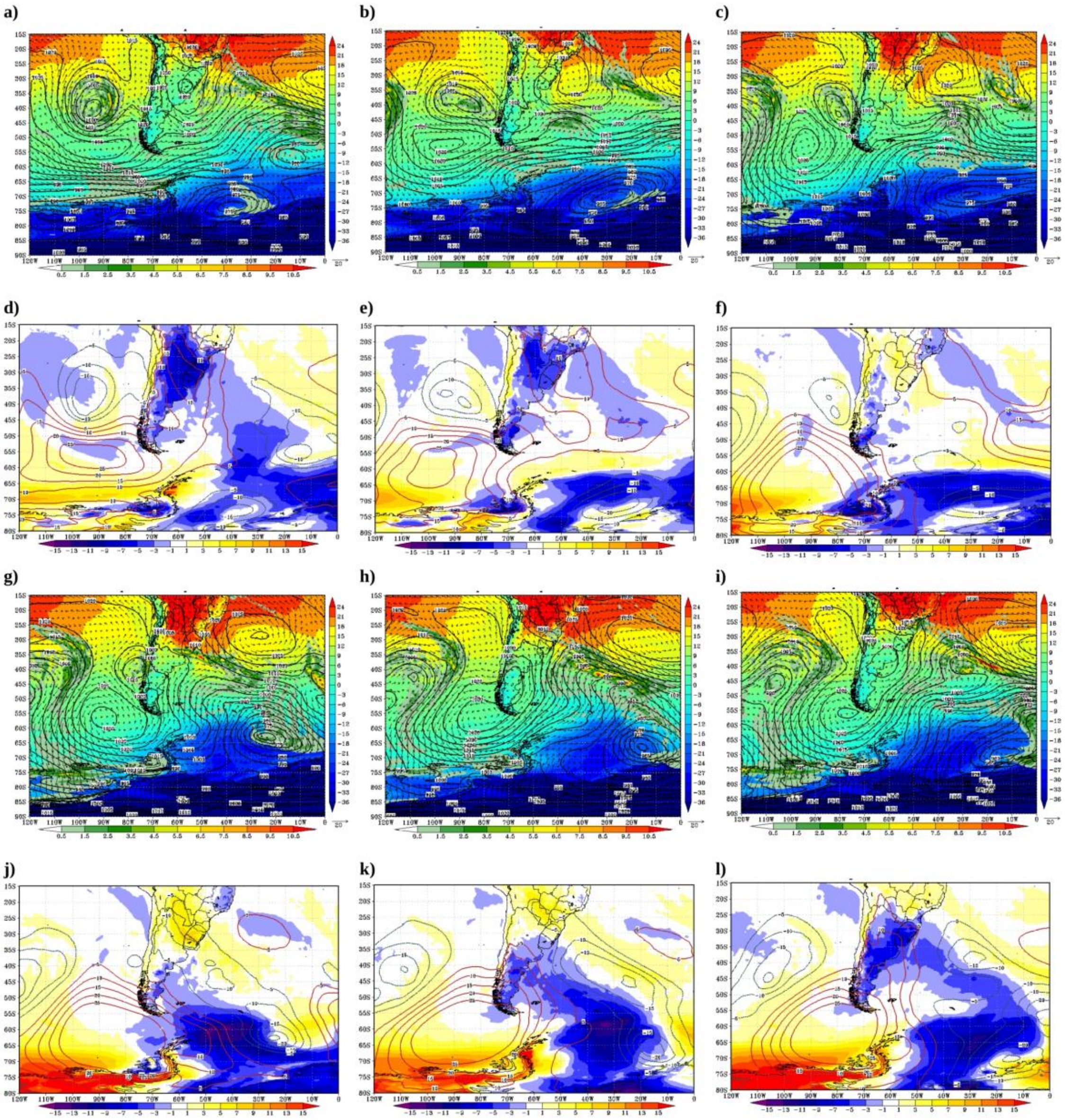
Case 3 – 2019/08/19

Case 3 is a sequence of Case 2, where lag-5 coincides with lag 0 in the previous case (Figures 4a = 3i and 4d = 3l). Thus, the analyzes start with lag -4, on 2019/08/15 it is possible to observe the anticyclone (1030 hPa) acting in the coastal region of southern Brazil (Figure 4b). In the mid and high latitudes it is observed an intense cyclone (965 hPa) over the Weddell Sea, as well as the presence of an anticyclone over the Southeast Pacific Ocean (55° S; 95° W), with a value of 1025 hPa. To the north of this system is a cyclone (40° S; 90° W), displacing the semi-permanent anticyclone from the South Pacific to the Northwest.

When analyzing the anomalies of lag -4, it can be seen in Figure 4e that an intense gradient of MSLP occurs at high latitudes, with negative (positive) anomalies over the Weddell Sea (South Pacific Ocean) with values of up to -20 hPa (25 hPa). This condition favors the transport of cold air from Antarctica inland over the Weddell Sea, while the anticyclone in the Southeast Pacific Ocean contributes to warmer air being transported from mid-latitudes towards the western region of the Antarctic Peninsula. Also according to Figure 4e, a large portion of South America is under the influence of the anticyclone, providing positive anomalies (5 to 10 hPa) of MSLP.

During lag -3 there is a spatial increase in atmospheric systems at high latitudes (Figure 4c), this conditions a more zonal circulation close to the surface at high and medium latitudes. As the anticyclone starts to move away from the coast of southern Brazil.

Figure 4 – Same configuration as Case 1, but for Case 3.



The condition described above contributes to the appearance of a large area with negative T2m anomaly over the Weddell Sea and in the South Atlantic Ocean (Figure 4f), with values reaching up to -7°C. On the other hand, the positive MSLP anomaly in the Southeast Pacific Ocean increases in area, contributing to the entry of warmer air into the Ross Sea region.

The cyclone moves to the northeast over the South Atlantic Ocean (62° S; 25° W), with values of 965 hPa in the central region during lag -2 (Figure 4g). Associated with this system, there is a frontal branch that extends to the region of Buenos Aires, Uruguay and the extreme south of RS. The anticyclone over the Southeast Pacific Ocean continues to amplify (reaching 1030 hPa) and to increase spatially, interfering even more in the zonal wave flow around 60° S.

The amplification of atmospheric systems in the 60° S range is even clearer on the anomaly map (Figure 4j), with values of -25 hPa over the Weddell Sea and 25 hPa over the Southeast Pacific Ocean. These anomalies of MSLP, in addition to providing a more undulating zonal movement, contribute to the occurrence of significant T2m anomalies around Antarctica, such as an anomaly of 15 °C over the Ross Sea and the western sector of the Antarctic Peninsula, while the Weddell Sea and the eastern sector of the Peninsula experience temperatures as low as -15 °C below average.

The strong anomalies observed at high latitudes in lag -3 (Figures 4f and 4j) are conditions already identified by Pezza et al., (2010) for an anomalous blizzard event in Buenos Aires in 2007. According to the authors, the fundamental driver is a dipole around the Antarctic Peninsula (stronger anticyclones to the west and stronger cyclones to the east, as shown in Figure 4j of the present study), and this condition is closely related to the inequalities in the mass adjustment between the subtropical and polar latitudes, for which the SAM is one of the indicators. Still according to Pezza et al., (2010), this dipole configuration reflects the out-of-phase relationship between the polar regions of the Pacific and the Atlantic and the variability in the extent of sea ice. This winter 2007 case had the second smallest SAM ever recorded in the era of satellites, contributing to the intensification of polar anticyclones.

As occurred in lag -1 in Case 2, the anticyclone that was over the Southeast Pacific Ocean began to act on the southern region of South America during lag -1 (Figure 4h), with a value of 1030 hPa in the region and contributing to the cooler air from the Weddell Sea being propelled towards the South American continent. Over the Southwest Atlantic Ocean, the high pressure system, which was previously on the coast of RS, loses intensity and increases its area of operation (30° S; 15° W). But it contributes to the frontal system associated with the cyclone that is close to Antarctica, to act with light rain over the north of RS and the central-east of Santa Catarina.

At the beginning of the incursion of this cold air, the geostrophic wind from the south (between the high and low pressure cells) produces cooling near surface along the east coast of South America and further inland to 30° S. Outbreak studies of cold that have a great impact on the eastern side of the continent emphasized the rapid development of the surface cyclone over the Southwest Atlantic. In these cases, the flow from the south along the western flank of the downtown produces strong cold advection over central Argentina and southern Brazil (MARENGO et al., 1997; GARREAUD, 2000).

During lag -1, the first negative T2m anomalies begin to occur over Argentina, Uruguay and the extreme south of RS (Figure 4k), with values from -1 to -3°C below the climatological average. As there are the presence of two very intense MSLP anomalies, the positive one covering a wide area involving the south of South America, the Southeast Pacific Ocean and the western sector of the Antarctic Peninsula, while the negative MSLP anomaly is found from the ocean Austral, passing through the Southwest Atlantic Ocean and southern Brazil. This condition provides an intense pressure gradient, and consequently, more intense winds from the south, contributing for the polar air to be directed to the south of Brazil.

In lag 0, there is a wide domain of the anticyclone over Argentina, Chile, Uruguay and RS, with a value of 1030 hPa in the central region of the system (Figure 4i). When compared to the previous cases, this anticyclone is less intense, and according to Müller and Berri (2007) the permanence and intensity of this system that will determine the intensity of the extreme events of minimum temperature on the region of the Argentine Pampa Wet, as well as in RS.

The synoptic characteristics described in lags -1 and 0, configure the conditions established by Pezza and Ambrizzi (2005). According to the authors, the wind anomalies of the southern quadrant that appear in previous lags in the extreme south of South America occur as a result of the geostrophic balance between the migrating anticyclone under development near the southern coast of Chile and the extratropical cyclone over the Atlantic South-west. These anomalies of wind are accompanied by advection of cold air and, therefore, the pressure begins to increase rapidly on the continent. When the pressure becomes very high in the south of the continent, a strong meridional pressure gradient is established and, as a consequence, the blocking effect of the Andes produces mass accumulation northwest of the high pressure cell. As a result, wind speed is slowed, reducing the Coriolis effect and generating an ageostrophic component from the south (driven by the pressure gradient), directing cold air to lower latitudes on the eastern side of the Andes. The center of the anticyclone tends to move north towards the region of maximum advection of cold air, with subsidence and advection of anticyclonic vorticity increasing in the heights.

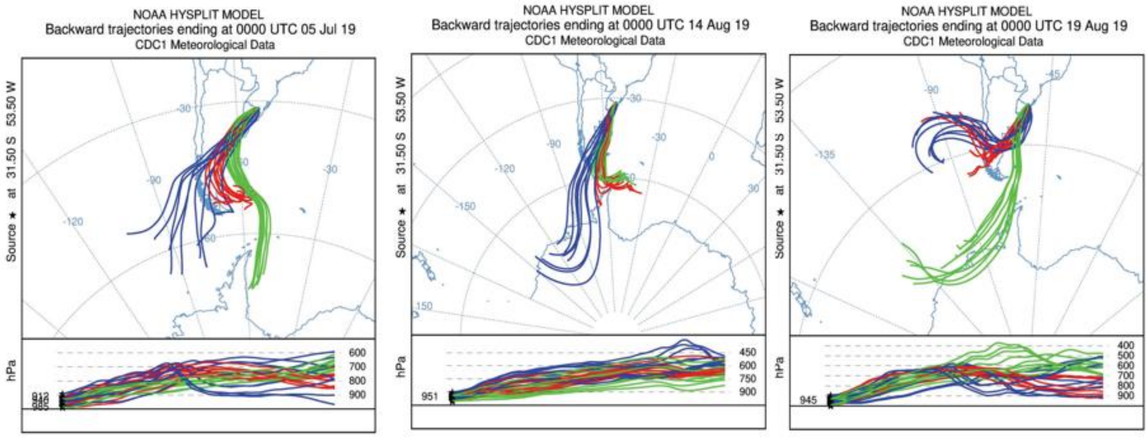
Still during lag 0, negative T2m anomalies (Figure 4l) are present mainly in a large part of Argentina, Uruguay and RS, with anomalies between -1 to -5°C. These T2m anomalies are mainly influenced by the positive MSLP anomalies that extend from the western sector of the Antarctic Peninsula and extend to RS and northern Argentina. While the negative MSLP anomalies begin to shift to the east, according to the zonal flow.

The relationship of the trajectory of the air masses with SST and the sea ice cover

After the synoptic description of the three cases that caused the extreme minimum temperature events in PMM, discussing their similarities and peculiarities with the literature, in this topic the trajectories that these masses described during the five days prior to the extreme minimum temperature event will be presented, as well as the behavior of SST and sea ice cover around Antarctica during those days.

To follow the trajectories of the air masses, HYSPLIT simulations were used, as shown in Figure 5. 120h were considered before the records of negative minimum temperature in PMM, despite the indication of the different levels of the atmosphere, the discussion in the present study will be restricted to atmospheric behaviors close to the surface.

Figure 5 – Trajectory of air masses (120 h) for the three cases analyzed.



For Case 1 (2019/07/05) it is observed that the surface air mass surface (blue line) originated over the boundary between the Southeast Pacific Ocean and the Bellingshausen Sea, subsequently moving over the region coast of Chile and crossing in the northeast direction over Argentina, passing through Uruguay, until arriving at RS. The presence of the semi-permanent anticyclone in the Southeast Pacific Ocean further south of its climatological position and of an intense cyclone in the Subtropical Atlantic Ocean (Figures 2g and 2j) contribute to the formation of a blockade over the oceans and thus contributing to the mass of air travel in a northeasterly direction over Chile and Argentina, until reaching Uruguay and RS.

The trajectory for Case 2 (2019/08/14) was different from Case 1, with the air mass originating over the tip of the Antarctic Peninsula and the Weddell Sea (green line) and displacing meridionally over the coast of Argentina and the Atlantic Ocean Southwest. It is important to mention that in addition to a different positioning on the surface in relation to Case 1, the displacements at higher levels of the atmosphere also occurred in an inverse way between the two cases. The cyclone that in Case 1 was further north of the Southwest Atlantic Ocean, in Case 2 is closer to the Drake Passage (Figures

3c and 3f), forming a dipole in the southern tip of South America, due to the presence of an anticyclone in the Southwest Pacific Ocean.

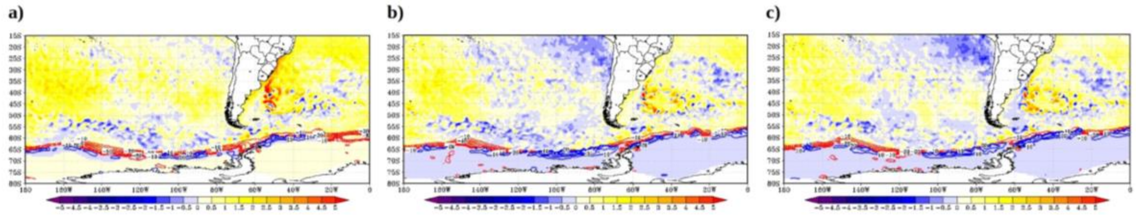
A more zonal behavior was observed in Case 3 (2019/08/19), with the air mass originating close to 45° S in the Southeast Pacific Ocean (blue and red lines), crossing Chile and Argentina, until reaching the Southwest Atlantic Ocean and from this moment, move south over the ocean until reaching the RS. The presence of the anticyclone over the Southeast Pacific Ocean (Figures 4c and 4f) helped the air mass to form in a region far from Antarctica, however, when crossing the South American continent, this mass suffered a loss of heat and acquiring drier characteristics.

Anomalies in SST and sea ice cover during these events can influence the formation, behavior and trajectory of these air masses that originates in medium and high latitudes, in addition to impacting the trajectory of extratropical cyclones in high latitudes of SH (CARPENEDO and AMBRIZZI 2016; FREITAS et al., 2018; 2019). In Case 1 (Figure 6a), there are positive SST anomalies, mainly over the Southwest Atlantic Ocean, with values exceeding 3°C, mainly in the Brazil-Malvinas Confluence region. In the South Pacific Ocean, anomalies are minor, and there is a predominance of negative SST anomalies south of 50° S.

As for the sea ice cover, there is a predominance of negative anomalies over the Ross and Bellingshausen seas, with values of up to -60% in relation to the average in the Ross Sea, mainly influenced by the presence of the anticyclone in the Southeast Pacific Ocean (Figure 2), which favored the advection of medium-latitude hot air towards the western sector of the Antarctic Peninsula. Blank et al., (2011) correlated the Antarctic sea ice cover with the number of cold days in RS, and found negative correlations during the month of July between the Bellingshausen Sea region and the AWS located in the city of Bagé (located less than 100 km of PMM AWS), indicating that periods of sea ice retraction in the Bellingshausen Sea coincide with extreme minimum temperature events in RS, as in Case 1 (Figure 2). On the other hand, in the Weddell Sea there is a predominance of positive anomalies over the Antarctic Peninsula (20%), while in the western sector of the Weddell Sea, negative anomalies prevail, with values of up to -60%.

For Cases 2 (Figure 6b) and 3 (Figure 6c), there is a predominance of negative SST anomalies over the South Pacific Ocean, mainly in the region close to the South American continent. Positive anomalies are concentrated mainly west of 140° W. In the sector of the Southwest Atlantic Ocean there is also a spatial reduction of positive SST anomalies, when compared to Case 1 (Figure 6a), with negative anomalies close to 20° W.

Figure 6 – Sea surface temperature and sea ice cover anomalies, for Case 1 (a), Case 2, (b) and Case 3 (c).



According to Carpenedo and Ambrizzi (2016) during extreme sea ice retraction events in the Ross Sea sector (west of 120° W) and expansion in the Weddell Sea during the southern winter, there is a warming of SST in the Pacific South, which results in warming of the adjacent atmosphere. Therefore, there is a reduction in the southern gradients of temperature and pressure between the edge of the sea ice and the open sea region, which results in relaxation of the low pressure circumpolar belt and the polar jet. As a consequence, there is a weakening of the ascending branch of the Ferrel cell by 60° S in the Southeast Pacific Ocean. Due to mass conservation, in the mid-latitudes the upward movement is strengthened. Thus, with the Ferrel cell weakened further south when there are extremes of sea ice reduction, the advection of air masses to the north is encouraged (LIU et al., 2002; RAPHAEL et al., 2010; CARPENEDO and AMBRIZZI 2016).

The condition of sea ice cover anomalies indicates positive (negative) values in the west (east) of 120° W in the South Pacific Ocean. While in the Antarctic Peninsula there is a predominance of negative anomalies at the end of the sea ice cover, while in the subsequent layers, towards Antarctica, the prevalence of positive anomalies occurs. This condition is similar to the case analyzed by Carpenedo and Gandu (2011), who identified the relationship between atmospheric circulation on the surface and sea ice in the period from 04 to 28/08/2006. The authors proposed that during a further expansion of sea ice in the Weddell Sea sector, the authors also found a relationship between the position of cyclonic centers and the areas of greatest expansion of sea ice west of low pressures, which possibly results from advection cold air from the greater latitudes. Blank et al., (2011) also found positive correlations between the expansion of sea ice cover in the Weddell Sea and the number of cold days in RS during the month of August, according to Cases 2 and 3 of the present study.

Another way of indicating the influences of regions previously considered important in the minimum temperature of PMM, is by calculating the correlation between the time series with daily data from 2019/07/01 to 2019/08/31, and applying daily lags, as they may occur a lag between the passage of phenomena in different regions. According to Table 2, there are significant negative correlations with a 5-day lag (lag -5) between the minimum temperature of PMM and the sea ice cover at the Bellingshausen sea points - BEL - (-0.29) and the western sector of Weddell - WdW - (-0.37), while in the eastern sector of Weddell (EdW) the correlation was positive (0.23), indicating that in periods of minimum temperature reduction in PMM they coincide with the increase (reduction) of sea ice in BEL and WdW (EdW). The results found here are in agreement with those obtained by Blank et al., (2011) and Carpenedo and Ambrizzi (2016).

Also during lag -5, there was also a significant negative correlation (-0.37) with MSLP in the Southeast Pacific Ocean (SEP), indicating that the intensification of the anticyclone in this region of the ocean is characteristic of the formation of a blocking system. This significant negative correlation remains in the next lags, obtaining the highest value during lag -3 (-0.54) and remaining until lag 0 (-0.25).

During lag -4, in addition to the significant negative correlation with BEL (-0.21), other regions and variables begin to have a relationship with the minimum temperature of PMM. For example, the significant negative correlation with MSLP in the SEP (-0.47) and positive in the Southwest Atlantic Ocean - SWA - (0.20). In addition to the positive correlations in SWA and Central Argentina (CAR) with values of 0.38 and 0.24, respectively. Indicating that the temperature drops in PMM are in accordance with the reduction of T2m over the central region of Argentina and the Southwest Atlantic Ocean. As observed in Cases 1 (Figure 2) and 3 (Figure 4), in addition to other cases recorded in the literature (GARREAUD, 2000; PEZZA and AMBRIZZI 2005).

From lag -3, some variables maintain positive correlations up to lag 0 with the minimum temperature in PMM, such as T2m over SWA and CAR, where the highest correlation values are obtained during lag -2 (0.66) in SWA and lag -1 in the CAR (0.46). Also on SWA, positive correlations with SST occur up to lag 0, with the highest correlation value obtained at lag -1 (0.50), as well as at T2m, indicating a perfect coupling between the ocean-atmosphere interface.

Still during lag -2, significant positive correlations with sea ice cover begin to appear in WdW and remain until lag 0, with the highest correlation value obtained in lag -1 (0.42). Associated with the negative correlation found for the MSLP on the CAR, with the highest values also found in lag -1 (-0.54). And finally, the significant negative correlations on the SWA (-0.41), that is, the increase in the MSLP over the central regions of Argentina and over the Southwest Atlantic Ocean may be supported by the reduction of sea ice cover in the western sector Weddell Sea, increasing the southern gradient, and consequently the winds, in the high latitudes of SH.

Table 2 - Correlations between the minimum daily temperature of PMM, with the variables sea ice cover, MSLP, T2m and SST, for the period from 2019/07/01 to 2019/08/31. Considering different regions: Bellingshausen Sea (BEL), East Weddell Sea sector (EdW), West Weddell Sea sector (WdW), Southeast Pacific Ocean (SEP), Southwest Atlantic Ocean (SWA) and Central Argentina (CAR).

	lag 0	**lag -1**	**lag -2**	**lag -3**	**lag -4**	**lag -5**
sea ice cover						
BEL	0.09	0.09	0.01	-0.09	**-0.21***	**-0.29***
EdW	0.07	0.09	0.11	0.12	0.19	**0.23***
WdW	**0.32***	**0.42***	**0.37***	0.11	-0.18	**-0.37***
MSLP						
SEP	**-0.25***	**-0.44***	**-0.53***	**-0.54***	**-0.47***	**-0.37***
SWA	**-0.42***	**-0.41***	-0.19	0.04	**0.20***	0.18
CAR	**-0.41***	**-0.53***	**-0.34***	-0.07	0.08	0.09
T2m						
SEP	-0.08	-0.13	-0.16	-0.11	0.06	0.16
SWA	**0.33***	**0.56***	**0.66***	**0.60***	**0.38***	0.13
CAR	**0.33***	**0.46***	**0.39***	**0.30***	**0.24***	0.16
SST						
SEP	-0.06	0.03	0.13	0.15	0.18	0.09
SWA	**0.39***	**0.50***	**0.45***	**0.32***	0.14	0.01

Values in bold and with (*) are 95% significant.

CONCLUSIONS

The present study showed the atmospheric conditions on the surface on three occasions that resulted in extreme minimum temperature events in Pinheiro Machado, RS. The synoptic evolutions of the five days prior to the events, the trajectory of these air masses, as well as the behavior of SST in the Atlantic and South Pacific oceans and the sea ice cover around Antarctica were described. The events that took place in the months of July and August 2019 demonstrate particularities, confirming the intense dynamics of the atmosphere in regions of medium and high latitudes in the Southern Hemisphere.

Case 1 (2019/07/05), which presented the most extreme minimum temperature, portrayed characteristics similar to the literature, with elements considered key in action, such as the cold surface anticyclone that moves in the Southeast Pacific Ocean, as well as the cyclone deepening over the Southwest Atlantic Ocean. Associated with negative anomalies of sea ice cover in the Bellingshausen Sea, which has already been observed in the literature in cold events in RS.

Cases 2 (2019/08/14) and 3 (2019/08/19) indicated particularities in relation to the literature, with the cyclone located closest to Antarctica over the Southwest Atlantic Ocean and with a wide anticyclone located between the Southeast Pacific Ocean and the southernmost tip of South America. This synoptic pattern, associated with a predominance of positive anomalies in sea ice cover over the Bellingshausen Sea, helped lower air masses to travel through different regions of South America.

While Case 2 the air mass moved mainly over the Southwest Atlantic Ocean, acquiring maritime conditions, in Case 3 the air mass entered South America at 50° S, acquiring a completely zonal displacement, until it found the Southwest Atlantic Ocean, and then migrate towards RS.

Future works involving the atmospheric characteristics of higher levels are necessary to obtain a better understanding of the vertical behavior of the atmosphere, as well as the analysis of the influence of the climatic variability modes and teleconnections in these extreme events of minimum temperature in RS.

The correlations found in Table 2 are mostly in agreement with the existing literature on cases of cold events in South America that occurred in previous years. It is possible to verify that a sequence of events occurs, starting with the retraction (expansion) of the sea ice cover in the Bellingshausen Sea and the west (east) sector of the Weddell Sea, associated with the increase of MSLP in the Southeast Pacific Ocean. This initial condition is decisive for a subsequent fall of T2m (positive correlations) over the Southwest Atlantic Ocean (associated with the fall in SST) and central Argentina. And finally, implying an increase in MSLP over the central region of Argentina and the southwest Atlantic Ocean, supported by the increase in the southern gradient caused by the retraction of sea ice over the western sector of the Weddell Sea.

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