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Study of the life cycle of three extratropical cyclones in the South Atlantic Ocean

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ABSTRACT

Extratropical cyclones are meteorological systems with a center of low atmospheric pressure and hourly rotation in the Southern Hemisphere. As these systems significantly alter the weather of the regions where they act and since the east coast of South America is a cyclogenetic region all year long and with the densely populated coastal part, the study of these systems becomes of great importance. Therefore, the objective of the present study is the description of the synoptic characteristics of the life cycle of three cyclones that had genesis in the South Atlantic Ocean, near the east coast of South America. For this, the data of Reanalysis 1 of the National Centers for Environmental Prediction (NCEP /NCAR) were used. Initially, atmospheric fields were generated for each phase of the cyclone life cycle (pre-cyclogenesis, cyclogenesis, maturity, demise and dissipation). Among the results, the cyclone with the longest life was October 2016, which lasted for 10 days. The cyclone of 2011 was the one that reached lower atmospheric pressure (956 hPa) in its center. The formation of the three cyclones was associated with horizontal gradients of surface air temperature and current mass divergence below troughs at high levels of the atmosphere. The three cyclones moved toward the regions with positive air temperature advection and demised when the divergence at high levels of the atmosphere weakened.

Keywords: South Atlantic, atmospheric fields, extratropical cyclones.

Estudo do ciclo de vida de três ciclones extratropicais no Oceano Atlântico Sul

RESUMO

Os ciclones extratropicais são sistemas meteorológicos com centro de baixa pressão atmosférica e rotação horária no Hemisfério Sul. Como esses sistemas alteram significativamente o tempo das regiões onde atuam e uma vez que a costa leste da América do Sul é uma região ciclogênica o ano todo e com a parte litorânea densamente povoada, o estudo desses sistemas torna-se de grande importância. Portanto, o objetivo do presente estudo é a descrição das características sinóticas do ciclo de vida de três ciclones que tiveram gênese no oceano Atlântico Sul, próximo à costa leste da América do Sul. Para isso, foram utilizados os dados da Reanálise 1 do National Centers for Environmental Prediction (NCEP/NCAR). Inicialmente, foram gerados campos atmosféricos para cada fase do ciclo de vida dos ciclones (pré-ciclogênese, ciclogênese, fase de maturidade, decaimento e dissipação). Entre os resultados têm-se que o ciclone com maior tempo de vida foi o de outubro de 2016, que perdurou por 10 dias. Já o ciclone de 2011 foi o que atingiu menor pressão atmosférica (956 hPa) em seu centro. A formação dos três ciclones esteve associada a gradientes horizontais de temperatura do ar em superfície e divergência de massa corrente abaixo de cavados em altos níveis da atmosfera. Os três ciclones se deslocaram em direção às regiões com advecção de temperatura do ar positiva e decaíram quando a divergência em altos níveis da atmosfera enfraqueceu.

Palavras-chave: Atlântico Sul, campos atmosféricos, ciclones extratropicais.

Introduction

Extratropical cyclones are systems that have lower atmospheric pressure in their central region than in the periphery and, due to the Coriolis effect, present cyclonic movement clockwise in the Southern Hemisphere.

Bjerknes (1919) concluded that the formation of extratropical cyclones occurs by the interaction of a polar air mass with a tropical air mass. The colder air mass tends to force warmer air to rise resulting in cloud formation and also in the

low surface pressure system, since with the rise of air there is a decrease in the weight of the atmospheric column, propitiating low pressure at surface. Bjerknes and Solberg (1922) showed that extratropical cyclones have different stages during the lifecycle. Afterwards, it was observed that the formation of the extratropical cyclones occurs both by the presence of regions with intense horizontal gradient of surface air temperature (baroclinic zone) and by the influence of troughs in the medium and high levels of the atmosphere (Carlson, 1991; Reboita et al., 2017). In this second, the divergence downstream of the troughs at medium and high levels may lead to the removal of mass from the atmospheric column, which favors mass convergence at low levels.

According to Gan and Rao (1991) and Reboita et al. (2010, 2012, 2015), the South Atlantic Ocean (SAO) is a cyclogenetic region, mainly near the east coast of South America (SA). In this region, the southeastern coast of Argentina, Uruguay and the extreme south of Brazil and the coast of the southeast region of this country are the three regions most favorable to the cyclogenesis. These systems have a vertical scale of approximately 10 km (Hankin, 2005) that is much smaller than the horizontal scale, which can vary between 1000 and 5000 km in diameter.

Some studies such as Mikiy Funatsu et al. (2004), Piva et al. (2001), Dias Pinto and da Rocha (2006), Reboita et al. (2009), Gan and Reboita (2016) and Reboita et al. (2017) performed the synoptic analysis of some cases of extratropical cyclones over the SAO. Dias Pinto and da Rocha (2006), for example, have shown that intense horizontal gradients of sea surface temperature (SST) can influence the atmosphere, making possible the cyclogenesis. Mikiy Funatsu et al. (2004) and Gan and Reboita (2016) describe the processes associated with the cyclogenesis near Uruguay and highlight the impact of the Andes topography. Although this mountain chain is distant at about 1000 km from the Uruguay coast and southern Brazil, it can favor cyclogenesis due to the establishment of a semi-stationary trough at medium levels (Reboita et al., 2012) and also favor warm advection at low levels on its leeward side (Mikiy Funatsu et al., 2004). The effect of topography is also important for systems that are formed in southeastern Argentina, but differently than in Uruguay. According to Reboita et al. (2012), disturbances moving from the Pacific Ocean toward the Atlantic Ocean, crossing southern South America, weaken upon encountering the Andes, but reestablish to leeward,

in the SAO, by intensifying the vorticity associated with the effect of stretching.

Since extratropical cyclones greatly affect the time of the regions where they act (changes in air temperature, strong winds, rainfall etc.), the physical knowledge of these systems becomes necessary. Thus, the main objective of this work is to describe the synoptic characteristics during the lifecycle of three extratropical cyclones over the SAO, near the east coast of South America. The present study can serve as a guide for students of different areas of knowledge that want to understand the physical structure of the cyclones.

Material and methods

Data

We used data from three periods: from August 16 to 22, 2011, from September 23 to October 1, 2016 and from October 26 to November 4, 2016. Data were obtained from Reanalysis 1 of the National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP / NCAR; Kalnay et al., 1996). These data have horizontal resolution of $2.5^\circ \times 2.5^\circ$ of latitude by longitude and frequency of 6 hours. The variables obtained were: sea level pressure, air temperature, zonal and meridional wind component, vertical velocity, relative humidity and geopotential height. In addition to these data, the cloud top temperature was obtained in the infrared channel from the National Climatic Data Center (NCDC) - Gridded Satellite Data with horizontal resolution of $0.07^\circ \times 0.07^\circ$ latitude by longitude. With the Grid Analysis and Display System (GrADS) software, it was possible to determine some secondary variables: horizontal advection of air temperature, layer thickness 500-1000 hPa, zonal deviations of temperature and geopotential height, relative vorticity and mass divergence.

For each cyclone studied, lifetime, distance traveled and average speed were determined. According to the equation adopted by Van Brummelen (2012), the distance traveled by the cyclone (D) can be obtained through equation 1, given by:

$$D = \text{acos}[\text{sen}(\phi_1)\text{sen}(\phi_2) + \cos(\phi_1) \cos(\phi_2) \cos(\Delta\lambda)]R \quad (1)$$

being: ϕ_1 is the latitude (radians) from where the cyclone forms; ϕ_2 is the latitude (radians) where the cyclone dissipates; $\Delta\lambda$ is the difference between the lengths (radians) at the cyclogenesis and dissipation points of the cyclone and R is the radius

of the Earth. The mean velocity of the system is simply the ratio of the distance traveled (km) to the duration of the system (hours).

Synoptic Analysis

The study of the evolution of the extratropical cyclones was carried out through the analysis of five stages of the lifecycle of each cyclone, in order to document the main characteristics of these systems. The selected phases were called: (i) pre-cyclogenesis, (ii) cyclogenesis, (iii) maturity, (iv) demise and (v) dissipation.

The pre-cyclogenesis phase corresponds to 06 hours before the occurrence of the first closed isobar in the field the mean sea level pressure, which marks the formation of the system (cyclogenesis). This follows the methodology of Gan and Rao (1991). The maturity stage describes the stage at that the system reaches the lowest surface pressure, ie when it is more intense (also known as occlusion). The demise phase is when the pressure rises again on the surface and the cold air tends to take over the center of the system. Finally, the dissipation phase is the phase in which no closed surface isobars are observed, according to Dutra et al. (2012).

Results and discussion

Figure 1 shows the trajectory of each studied cyclone. This was obtained by registering the position (latitude and longitude) of the cyclone

center. Such cyclones had different lifetime. The cyclone occurred in 2011 lasted approximately 6 days (12Z on August 16, 2011 at 06Z on August 22, 2011); the cyclone occurred in September 2016 lasted 8 days (06Z from September 23, 2016 to 18Z on October 1, 2016), while the cyclone in October lasted for almost 10 days (12Z on the 26th of October 2016 to 06Z on November 4, 2016).

Figure 1 also shows that the systems of August 2011 (red color) and October 2016 (green color) were formed on the northeast of Argentina and Uruguay, respectively, which corresponds to the RG2 cyclogenetic region in Reboita (2008). The cyclones in this region act in a way to intensify the southeast winds on the surface which generates a local phenomenon called "*sudestada*" (Seluchi, 1995). In addition, cyclones are responsible for intensification of sea waves in much of the eastern coast of South America (da Rocha et al., 2004). The September 2016 cyclone formed further away from the coast (Figure 1).

The main characteristics (lifetime, distance traveled and average speed) associated to the three cyclones are summarized in table 1. It is observed that there is a great difference in the average velocities of the cyclones studied here, being that of August 2011 about four times faster than the slower cyclone (September 2016). Although the distance traveled and average speed are variable, climatological studies such as that of Reboita (2008) indicate an average velocity of 10.5 ms^{-1} over the SAO.

Figure 1. Trajectory of the three extratropical cyclones under study. The colors red, blue and green refer to cyclones from August 2011, September 2016 and October 2016, respectively. Each point denotes the time interval every 6 hours.

Table 1. Characteristics of extratropical cyclones in the South Atlantic.

Extratropical Cyclone	Lifetime	Travelled distance	Average speed
August 2011	5.7 days	7596 km	15.3 ms ⁻¹
September 2016	8.4 days	2786 km	3.8 ms ⁻¹
October 2016	9.7 days	6719 km	8.9 ms ⁻¹

Pre-cyclogenesis

The pre-cyclogenesis phase of the cyclones from August 2011 and October 2016 is quite similar. There is the presence of a trough acting at high levels between the Pacific Ocean and South America (SA) about 30 ° S (Figs 2c and 4c). At the same time, an elongated low pressure area is observed over Argentina, southern Brazil and Uruguay (Figs. 2a and 4a). The case of the cyclone of September 2016 has also the presence of a trough at high levels in the region where the surface cyclone will form (Fig. 3c), but over the ocean.

In the case of 2011 (Fig. 2a), a closed isobar is observed between northern Argentina and Paraguay, but this is not the precursor of the cyclone. As shown by Necco (1982a, b), Miky Funatsu et al. (2004) and Vera et al. (2002), cyclones influenced by troughs that move from the

Pacific to the Atlantic form only about 1000 km from the topographic barrier near the Uruguay border. The isobar mentioned is related to thermo-orographic effects.

The formation of the three cases analyzed have as dynamic support a trough at high levels. This configuration makes the vertical profile of the geopotential height zonal deviation to slope westward with the height increase (Figs. 2e, 3e and 4e). Another evidence supporting the baroclinic condition of the systems is the presence of horizontal gradients of surface air temperature, which in Figures 2b, 3b and 4b are represented by the proximity of the thickness lines of the layer 500/1000 hPa.

In the satellite images, in the pre-cyclogenesis phase, it is already possible to observe some cloudiness in the regions where the cyclones will form (Figs. 2d, 3d and 4d).

Figure 2. Pre-ciclogenesis phase of the extratropical cyclone of August 2011 (06Z of August 16, 2011): a) atmospheric pressure at mean sea level (hPa, black lines) and advection of surface air temperature ($^{\circ}\text{C}/06$ hours in color); b) layer thickness at 500-1000 hPa (mgp / 10, black lines) and wind speed at 300 hPa (m/s, colors); c) geopotential height at 300 hPa (mgp/10, black lines) and divergence ($\times 10^{-5} \text{ s}^{-1}$, colors); d) brightness temperature ($^{\circ}\text{C}$, grayscale); e) zonal deviation of temperature ($^{\circ}\text{C}$, black lines) and zonal deviation of geopotential height (meters, colors); f) vertical profile of relative vorticity ($\times 10^{-5} \text{ s}^{-1}$, black lines) and relative humidity (% , colors); g) divergence ($\times 10^{-5} \text{ s}^{-1}$, blue lines indicate convergence and red divergence) and omega (Pa/s, colors). The "X" markings in the figures

indicate the location of interest according to the analysis phase.

Figure 3. Similar to Figure 2, but for the September 2016 cyclone (00Z of September 23, 2016).

Figure 4. Similar to Figure 2, but for the October 2016 cyclone (06Z of October 26, 2016).

Cyclogenesis

The cyclogenesis is marked by the appearance of a first closed isobar in the field of mean sea level pressure according to Gan and Rao (1991). In the system of August 2011, the isobar appears closed at 12 Z with central pressure of 1004 hPa between Argentina and Uruguay (Fig. 5a). The first closed isobar for the case of the September 2016 has a value of 1000 hPa and it is positioned on the SAO near the east coast of Argentina (Fig. 6a). Finally, in the case of October 26, 2016, the closed isobar is identified at 12 Z with a value of 1008 hPa also between Argentina and Uruguay (Fig. 7a). In the figures, the region of cyclone formation is indicated with the letter B; in some cases this mark masks the value of the mentioned isobar.

The genesis of the three systems has similar characteristics: there is mass divergence at high levels, over the closed isobar region, and convergence at low levels, as well as the presence of upward movements in the atmosphere (Figs. 5c, 5g, 6c, 6g, 7c and 7g). The magnitude of the divergence in high levels is greater than that of the convergence in surface.

In this phase of the cyclone lifecycle, the relative vorticity tube begins to appear inclined to

the west with the height increase (Figs. 5f, 6f and 7f), as occurs in the zonal deviation of the geopotential height (Figs. 5e, 6e and 7e), which characterizes the baroclinic environment. This occurs because the center of the mid/high trough is west of the surface low.

On the surface, the lines of thickness cross the center of the cyclones (indicating the position of the fronts on the surface). In addition to these horizontal temperature gradients, the high-level jets begin to form slightly to the west in relation to surface cyclones (Figs. 5b, 6b and 7b), but with less intensity in the September 2016 cyclone (Fig. 6b).

These surface systems provide vertical movements in the atmosphere, which favors the development of cloudiness around the center of the cyclones. From the satellite images, it is possible to observe the presence of large areas with cloudiness near these regions of cyclogenesis (Figs. 5d, 6d and 7d).

A distinction in the cyclogenesis phase of the three events studied is that the October 2016 cyclone forms associated with a cyclonic vortex embedded in the trough at high levels, as well as the case studied by Miky Funatsu et al. (2004).

Figure 5. Cyclogenesis phase of the extratropical cyclone of August 2011 (12Z of August 16, 2011): a) atmospheric pressure at mean sea level (hPa, black lines) and advection of surface air temperature ($^{\circ}\text{C}/06$ hours in color); b) layer thickness at 500-1000 hPa (mgp / 10, black lines) and wind speed at 300 hPa (m/s, colors); c) geopotential height at 300 hPa (mgp/10, black lines) and divergence ($\times 10^{-5} \text{ s}^{-1}$, colors); d) brightness temperature ($^{\circ}\text{C}$, grayscale); e) zonal deviation of temperature ($^{\circ}\text{C}$, black lines) and zonal deviation of geopotential height (meters, colors); f) vertical profile of relative vorticity ($\times 10^{-5} \text{ s}^{-1}$, black lines) and relative humidity (%), colors); g) divergence ($\times 10^{-5} \text{ s}^{-1}$, blue lines indicate convergence and red divergence) and omega (Pa/s, colors). The "X" markings in the figures indicate the

location of interest according to the analysis phase.

Figure 6. Similar to Figure 5, but for the September 2016 cyclone (06Z of September 23, 2016).

Figure 7. Similar to Figure 5, but for the October 2016 cyclone (12Z of October 26, 2016).

Maturity

The stage of maturity of the extratropical cyclones can be defined when the central pressure reaches the lowest values, that is, the phase in which the cyclones present the highest intensity, also known as the occlusion phase.

The lowest atmospheric pressure observed among the cases studied occurred in the 2011 cyclone, where the central pressure reached 956 hPa (Fig. 8a). In the cyclones of September and October 2016 the central pressure was 992 hPa and 980 hPa, respectively (Figs 9a and 10a).

One of the characteristics of the maturity is that the vertical profile of relative vorticity does not have inclination with the increase of the height. This occurs because the center of the middle/high trough is practically in phase with the surface system (Figures 8c, 9c and 10c). Thus, the tubes of vorticity and negative deviation of

geopotential height are also practically without slope with height (Figs. 8e, 8f, 9e, 9f, 10e and 10f). When the patterns in low and medium/high levels of the atmosphere are aligned, this confers the atmosphere to a barotropic state.

In the maturity phase, the maxima values of vertical movement are around the low surface pressure centers (Figs. 8g, 9g and 10g). This fact reinforces the occurrence of cloudiness with an inverted comma appearance in the cyclone region (Figs. 8d, 9d and 10d). Another feature of the occlusion phase is the presence of the polar and/or subtropical jet on the equatorial side of the surface low (Figs 8b, 9b and 10b). The occurrence of the cold air advection in the sector west of the center of the cyclones and of warm air to the east (Figures 8a, 9a and 10a) is still visible on the surface.

Figure 8. Maternity phase of the extratropical cyclone of August 2011 (12Z of August 19, 2011): a) atmospheric pressure at mean sea level (hPa, black lines) and advection of surface air temperature (°C/06 hours in color); b) layer thickness at 500-1000 hPa (m/gp / 10, black lines) and wind speed at 300 hPa (m/s, colors); c) geopotential height at 300 hPa (m/gp/10, black lines) and divergence ($\times 10^{-5} \text{ s}^{-1}$, colors); d) brightness temperature (°C, grayscale); e) zonal deviation of temperature (°C, black lines) and zonal deviation of geopotential height (meters, colors); f) vertical profile of relative vorticity ($\times 10^{-5} \text{ s}^{-1}$, black lines) and relative humidity (% , colors); g) divergence ($\times 10^{-5} \text{ s}^{-1}$, blue lines indicate convergence and red divergence) and omega (Pa/s, colors). The "X" markings

in the figures indicate the location of interest according to the analysis phase.

Figure 9. Similar to Figure 8, but for the September 2016 cyclone (18Z of September 23, 2016).

Demise

In this phase, the cold air advection continues to predominate in the systems taking the place of the warmer air (Figs. 11a, 12a and 13a), with this, the energy of the cyclone begins to decrease and then the dissipation phase occurs. The pressure gradient in the cyclones became less intense (greater spacing between the isobars) when compared to the phase of maximum intensity, reinforcing the fact that the systems are now in phase of energy loss.

In September 2016 the South Atlantic Subtropical High (SASH) centered at 1°E and 30°S acts together with another high pressure center positioned at 11°E and 52°S (Fig. 12a). This configuration contributes to the delay of the displacement of the cyclones eastward. The study by Reboita et al. (2009) also concluded that this

pattern of anticyclones may aid in the limited zonal propagation of extratropical cyclones.

The high-level jet no longer provides the dynamic support necessary for the development of the cyclone as in the other phases. This can be observed with respect to the position of the surface system: at this stage the jet is located north of the surface cyclones (Figs. 11b, 12b and 13b).

The divergence is practically absent at high levels in the cyclone region (Figs. 11c, 12c, 13c), which is favorable to the demise of the system. In addition, the cloudiness begins to disorganize when compared to the previous stages (Figs. 11d, 12d and 13d).

The zonal deviation of geopotential height is similar in the three cases studied. In these, negative deviations practically aligned vertically on the surface system. At this stage, there is predominance of cold air in the vertical profile of the systems (Figs. 11e, 12e and 13e).

Figure 11. Demise phase of extratropical cyclone of August 2011 (12Z of August 21, 2011): a) atmospheric pressure at mean sea level (hPa, black lines) and advection of surface air temperature (°C/06 hours in color); b) layer thickness at 500-1000 hPa (mgp / 10, black lines) and wind speed at 300 hPa (m/s, colors); c) geopotential height at 300 hPa (mgp/10, black lines) and divergence ($\times 10^{-5} \text{ s}^{-1}$, colors); d) brightness temperature (°C, grayscale); e) zonal deviation of temperature (°C, black lines) and zonal deviation of geopotential

height (meters, colors); f) vertical profile of relative vorticity ($\times 10^{-5} \text{ s}^{-1}$, black lines) and relative humidity (% , colors); g) divergence ($\times 10^{-5} \text{ s}^{-1}$, blue lines indicate convergence and red divergence) and omega (Pa/s, colors). The "X" markings in the figures indicate the location of interest according to the analysis phase.

Figure 12. Similar to Figure 11, but for the September 2016 cyclone (06Z of September 30, 2016).

Figure 13. Similar to Figure 11, but for the October 2016 cyclone (06Z of November 03, 2016).

Dissipation

In the dissipation phase, surface isobars are no longer closed and there is predominance of cold air advection (Figs. 14a, 15a and 16a).

In this phase, the jet at high levels remains positioned to the north of the troughs (Figs. 14b, 14c, 15b, 15c, 16b and 16c). It should be noted here the weakening of the vertical profile of the zonal deviations of geopotential height and temperature (Figs. 14e, 15e and 16e).

The relative humidity profiles presented similar characteristics between the cyclones of August 2011 and the one of October of 2016. In these cases, it is observed an increase of the

humidity between the phases of pre-ciclogeneses until the phase of dissipation. On the other hand, in the case of September 2011, the relative humidity had opposite behavior between these phases (Figs. 14f, 15f and 16f). These results are satisfactory taking into account the formation areas of these cyclones.

With respect to the vorticity tube, in August 2011 and October 2016 cases a slope to the east at this stage. In the case of September 2016, the tube is not well configured, but the highest values are also to the east of the position where the cyclone dissipated (Figs. 14f, 15f and 16f).

Figure 14. Dissipation phase of extratropical cyclone of August 2011 (06Z of August 22, 2011): a) atmospheric pressure at mean sea level (hPa, black lines) and advection of surface air temperature (°C/06 hours in color); b) layer thickness at 500-1000 hPa (mgp / 10, black lines) and wind speed at 300 hPa (m/s, colors); c) geopotential height at 300 hPa (mgp/10, black lines) and divergence ($\times 10^{-5} \text{s}^{-1}$, colors); d) brightness temperature (°C, grayscale); e) zonal deviation of temperature (°C, black lines) and zonal deviation of geopotential height (meters, colors); f) vertical profile of relative vorticity ($\times 10^{-5} \text{s}^{-1}$, black lines) and relative humidity (% , colors); g)

divergence ($\times 10^{-5} \text{ s}^{-1}$, blue lines indicate convergence and red divergence) and omega (Pa/s, colors). The "X" markings in the figures indicate the location of interest according to the analysis phase.

Figure 15. Similar to Figure 14, but for the September 2016 cyclone (October 18, 2016).

Conclusions

This work aimed to describe the synoptic characteristics during the lifecycle of three extratropical cyclones that formed over the SAO. The first cyclone studied occurred in August 2011 and lasted 6 days. The second cyclone had a lifetime of 8 days and occurred in September 2016. The third cyclone occurred in October 2016, and had a lifetime of 10 days. These three cyclones had a longer life span than the Reboita (2008) climatology.

The formation of the three cyclones was associated with the downstream mass divergence of the troughs at high levels of the atmosphere and horizontal gradients of surface air temperature. In the genesis phase, the thickness lines cross the center of the cyclone which characterizes the system as baroclinic. This feature disappears at the maturity stage, and in addition, at this stage the jet at high levels is located on the equatorial side of the surface system. As the trough in medium/high levels is coupled with the surface system, this confers a barotropic atmosphere pattern. Throughout the lifecycle, the three cyclones moved towards the region with warm air advection and demise when the divergence in high levels of the atmosphere weakened.

The cyclone of October 2016 had a dynamic precursor similar to that of Mikiy Funatsu et al. (2004) and Reboita et al. (2009), where a cyclonic vortex in medium/high levels moved from the Pacific Ocean towards the Atlantic Ocean and contributes to the formation of the cyclone to the leeward of the Andes. Finally, it is mentioned that the studied cyclones reveal the basic characteristics of these systems in SAO, being this study a reference for those interested in the subject.

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