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Study of a Mesoscale Convective Complex associated with the coupling between jets in South America

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ABSTRACT

It is known as “coupling between jets” when the Upper-Level Jet (ULJ) overlaps the Low-Level Jet (LLJ). The literature shows that such couplings tend to generate or intensify surface instabilities. Thus, the objective of this study is to analyze the synoptic configuration of a Mesoscale Convective Complex (MCC) associated with the coupling between jets that occurred on November 18, 2009. The instabilities reached the south of Brazil, causing intense precipitation and several damages. The present study was carried out through the analysis of meteorological fields using ERA5 reanalysis data and images from the GOES-13 satellite. Upward vertical movements were observed at 500 hPa in the same area of occurrence of the upper-levels diffluent flow, as well as an intense northerly flow at 850 hPa, a large amount of moisture associated with the Northwestern Argentinean Low and the presence of a frontal system between Uruguay and southern Brazil. The coupling was observed on the LLJ exit and on the tropical sector of ULJ. Storm development was observed to the east (downstream) and under the area where the coupling occurred, which was observed before, during and after the meteorological system development. However, the peak of coupling did not occur at the same time of the most intense phase of the system, it occurred in its formation, where values close to orthogonality were observed. As indicated in the literature, there was low-levels warm advection and mid-levels cold advection according to the MCC life cycle.

Keywords: Severe Weather, Low Level Jet, Jet Stream, Diffluent Flow.

Estudo de Complexo Convectivo de Mesoescala associado a acoplamento entre jatos na América do Sul

RESUMO

Entende-se por acoplamento entre jatos quando o Jato de Altos Níveis (JAN) se sobrepõe ao Jato de Baixos Níveis (JBN). A literatura mostra que tais acoplamentos tendem a gerar ou intensificar instabilidades em superfície. Desta forma, o objetivo desse estudo é analisar a configuração sinótica de um caso de Complexo Convectivo de Mesoescala (CCM), associado a acoplamento entre os jatos, ocorrido no dia 18 de novembro de 2009. As instabilidades atingiram o sul do Brasil, causando precipitação intensa e diversos transtornos. O presente estudo realizou-se por meio da análise de campos meteorológicos usando dados de reanálise do modelo ERA5 e imagens do satélite GOES-13. Foram observados movimentos verticais ascendentes em 500 hPa na área de ocorrência do escoamento difluente em altos níveis, bem como um intenso escoamento de norte em 850 hPa, um grande aporte de umidade associado a Baixa do Noroeste Argentino, e a presença de um sistema frontal entre o Uruguai e o RS. O acoplamento foi verificado na saída do JBN e no setor tropical do JAN. Observou-se desenvolvimento de tempestades a leste (corrente abaixo) e sob a área onde ocorreu o acoplamento, que foi observado antes, durante e após o período de atuação do sistema meteorológico. Contudo, o pico de acoplamento não ocorreu junto a fase mais intensa do sistema, ocorreu na sua formação, onde valores próximos à ortogonalidade foram observados. Conforme indica a literatura, verificou-se advecção quente em baixos níveis e advecção fria em médios níveis de acordo com o ciclo de vida do CCM.

Palavras-chave: Tempo Severo; Jato de Baixos Níveis; Corrente de jato, Escoamento Difluente.

Introduction

South-central South America (SA) is located southern of the Tropic of Capricorn and mostly has a subtropical climate, with several forms of relief and surface coverage. The region is drastically influenced by the Andes. The conjunction of geographical factors with the intense meridional gradient of temperature, typical of this latitudinal zone, explains the development of different meteorological systems in this area (Reboita et al., 2012).

Little seasonal variability in precipitation is observed - the west of the southern region of Brazil stands out with approximately 2000 mm per year. Frontal systems, subtropical and extratropical cyclones, upper-tropospheric cyclonic vortices and different types of Mesoscale Convective Systems (MCS) are the main phenomena that influence the local rainfall regime (Grimm, 2009; Reboita et al., 2012).

In different parts of the globe, mainly in the lee of mountain ranges, intense meridional flows are observed in the lower troposphere (about 1 to 2 km high) (Gimeno et al., 2016), with horizontal extensions around 500 km. Bonner (1968) suggested criteria to characterize these winds as Low Level Jet (LLJ). There are similarities between the mechanisms for generating LLJ cases of the Rocky Mountains in the United States and those of the Andes in SA, since both mountain ranges extend meridionally for thousands of kilometers and thus prevent zonal flow in the lower troposphere of the continent. This contributes to channeling the flow poleward (Marengo and Soares, 2002; Marengo et al., 2004).

LLJ is a component of the SA monsoon system, transporting heat and humidity from the Amazon basin to the Paraná-Prata basin and therefore corroborates to the development of convective activities at the jet exit, where moisture often condenses due to convergence at low levels (Nascimento et al., 2016). Field experiments show the relationship between the LLJ and the formation of MCS (Vera et al., 2006). Analyzing the warm period, Salio et al. (2007) related the presence of LLJ to the development and duration of MCSs specifically in northern Argentina, western of south Brazil and Paraguay. When there was no LLJ the duration of the instabilities decreased due to the lack of thermodynamic support.

Rasmussen and Houze (2016) performed numerical simulations of MCS for SA reducing the role of the Andes by 50% and observed that the beginning of convections would be more spaced if mountain range were not as high or extensive.

These changes resulted in a decrease in the frequency of MCSs and an increase in propagation eastward in the subtropics.

MCSs are atmospheric systems made up of a fusion of vertically developed clouds (Wallace and Hobbs, 2006). These systems are easily identified in satellite images due to their intense cloudiness of non-symmetrical shape. Such systems influence the distribution of precipitation in both the tropics and mid-latitudes and are capable of negatively impacting society due to the intensity of storms (Haberlie and Ashley, 2019; Li et al., 2019; Schumacher and Rasmussen, 2020). Mesoscale Convective Complexes (MCCs) are a type of MCS whose features were identified by Maddox (1980) to define criteria for classifying these systems according to shape, size and life span. MCCs are characterized as a cluster of clouds with very cold tops and have an approximately circular shape, with explosive vertical growth and duration of more than 6 hours. These systems are susceptible to causing high rates of precipitation and storms that may be accompanied by gusts of wind, hail and even tornadoes (Velasco and Fritsch, 1987; Moraes and Aquino, 2018; Lima et al., 2018). This complex of convective clouds develops in an environment with strong advection of warm and humid air at low levels, usually from the Amazon region (Laing and Fritsch, 2000).

Associated with these meteorological phenomena acting in SA, there are two continental low-pressure systems, Chaco Low (CL) and Northwestern Argentinean Low (NAL), which are often confused or even treated as a single system (Seluchi and Saulo, 2012). The region eastern of Andes, where such low-pressure systems are formed, is constantly influenced by the LLJ (Satyamurty et al., 1998). Several works, such as Teixeira and Satyamurty (2007), Riquetti et al. (2018), Caballero et al. (2018) and Dorneles et al. (2020), indicate the association between the conjunctions LLJ-CL or LLJ-NAL with events of intense precipitation in southern Brazil.

CL is a typical summer system, since it develops in a more unstable atmosphere. Its thermal origin is related to the release of latent heat caused by the convection that occurs in the Chaco Plain (Seluchi and Saulo, 2012). Unlike CL, NAL is also observed in cold seasons and is usually located closer to the Andes. Its origin is related to orographic forcing and transient activities, such as that of the Subtropical Jet (Escobar and Seluchi, 2012). Rasera et al. (2018) associates the formation of MCS with NAL.

The Subtropical Jet is the most tropical branch of the jet stream. Close to the tropopause over the mid latitudes, a very narrow and approximately horizontal wind channel is observed in the basic zonal flow, with speeds of at least 30 m s^{-1} , called Upper Level Jet (ULJ) or simply jet stream (Reiter and Bierly, 2005; Escobar, 2009). This synoptic system plays an important role in most events of intense convection, since it is directly associated with baroclinic instabilities such as extratropical cyclones and frontal systems (Fedorova and Lyra, 2017). The position and intensity of the ULJ varies according to the El Niño phase (Lima and Nunes, 2018) and seasonally. In winter, the ULJ can be divided into two branches and the subtropical can reach up to 30° latitude (Satyamurty et al., 1998).

An important aspect of the ULJ is the confluent or diffluent flow. Krishnamurti et al. (2018) states that the diffluence is a kinematic aspect of the horizontal wind field and at upper-levels causes an increase in the evacuation of air, resulting in the divergence of mass at higher levels and the convergence at lower levels, which may increase the severity of an instability that is already established at low levels (Bluestein, 1993; Sanders, 1993). Lara et al. (2019) verified the occurrence of an upper-level diffluent flow during a tornado case in Tapejara, and the existence of coupling between jets (when ULJ overlaps LLJ) in a tornadic event in Canela, both cities of Rio Grande do Sul State (RS), the southernmost State of Brazil. Coelho and Nunes (2020) observed the diffluence in a case of heavy rain on Rio de Janeiro City.

Few studies in the literature address the relationship between MCC events and the coupling between jets. The understanding of this coupling is important to know the profile of the storms observed in the south-central of SA, as well as if such coupling is associated with these storms and in which phase of life it appears. The overlapping of the jets indicates strong vertical wind shear, implying intense convective instability, which is fundamental for the formation of storms. In this way, the understanding of the coupling becomes an important factor for the improvement of weather forecasts.

Uccellini and Johnson (1979) investigated the role of the coupling between jets in the formation of storms and observed that when there is an orthogonality between the axes of the jets, conditions are created for the occurrence of convective instabilities due to the advection of the cold and dry air of the ULJ at mid-levels, coupled with the transport of moisture and sensitive heat by LLJ at low levels, favoring the advection of temperature and cloud formation (Nascimento,

2005). Brill et al. (1985) performed numerical simulations on the case studied by Uccellini and Johnson (1979) and observed an indirect transversal circulation associated with LLJ at the exit of jet stream. Similar behavior was found by Sortais et al. (1993). According to Bruick et al. (2019), in El Niño years there is a more intense LLJ and ULJ, generating deeper storms at the tropical inlet of the jet stream.

The purpose of this paper is to analyze the synoptic configuration and the coupling between jets associated with an MCC that caused several damages on November 18, 2009 in southern Brazil.

Data and Methodology

The event was analyzed by means of meteorological fields using reanalysis data from ERA5 model, the fifth generation of European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (Hersbach et al., 2020). ECMWF reanalysis is widely used in synoptic scale analysis. For example, Montini et al. (2019) compared different types of reanalysis in the detection of SA LLJ and that of ERA-Interim, a version prior to ERA5, presented a better performance. Dos Santos and Reboita (2018), compared two reanalyses and found that the higher resolution reanalysis more accurately detected the LLJ, same result found by Montini et al. (2019). The ERA5 data have 0.25° horizontal resolution, 1h time interval and 137 vertical levels. The spatial domain used in this study comprises the area of south-central South America.

The following ERA5 variables were obtained: mean sea level pressure (mslp), direction and magnitude of the zonal (u) and meridional (v) components of the wind, geopotential height, omega vertical velocity, relative humidity and air temperature. Temperature advection (field and mean over a selected area) was calculated. The cloudiness of the phenomenon was observed through images of the GOES-13 (Geostationary Operational Environmental Satellite 13) thermal infrared channel, available on the Division of Satellites and Environmental Systems of the National Institute for Space Research (DSA/INPE) website.

The ULJ was detected whenever the 250 hPa westerlies strength was greater than or equal to 30 m s^{-1} , as indicated by the World Meteorological Organization (Reiter and Bierly, 2005). The LLJ was identified according to the criteria established by Bonner (1968), where it is described that the wind magnitude at 850 hPa must be greater than or equal to 12 m s^{-1} and the southern component of the

wind must be negative and with absolute value greater than the zonal component. However, the 6 m s^{-1} vertical wind shear between 850 and 700 hPa criterion was not considered, as it can rule out significant cases of LLJ (Oliveira et al., 2018).

The coupling field was obtained by the difference in degrees of the directions of the jets at each grid point that ULJ overlaps LLJ. This difference is subtracted from 90° , so that the smallest value in the field indicates the most intense (most orthogonal) coupling. Among the regions where coupling between jets occurred, an area with more orthogonal coupling was selected, where the spatial average was made in order to make an Eulerian analysis of temperature advection during the system's life cycle. Accumulated precipitation data from conventional stations of the National Institute of Meteorology (INMET) were used to identify the rainfall rates caused by the MCC.

Results and discussion

The system caused several damages in RS, according to reports by Climatempo (2009). In Mostardas, in the coastal region of RS, the gusts reached 126 km h^{-1} and in Porto Alegre there was rain accompanied by thunderstorms and gusts records of 65 km h^{-1} . At the INMET meteorological stations, 81 mm were recorded in Pelotas and 114 mm in Bagé, south and center-south of RS, respectively.

The satellite images (Figure 1) show that around 00 UTC on November 18th, 2009 the first clouds appeared in northern Argentina (Figure 1a). At 06 UTC the convective clouds that were over Argentina gathered and originated an MCS, reaching RS and Uruguay (Figure 1b). The clouds that were in the interior of RS (Figure 1a) are now more concentrated on the RS and Santa Catarina State (SC) coastal regions (Figure 1b). The intensification of instabilities that now also affect SC, with clouds of great vertical development (cumulonimbus with temperature of the tops reaching -80°C), it is noted. At this time, the MCC reaches its maturation stage, obtaining its most symmetrical shape (Figure 1c). At 18 UTC (Figure 1d) the system moved to the northeast and reached its dissipation stage and is no longer characterized as MCC. It is observed the region of the west of RS without the presence of cumulonimbus, these clouds were then found over the north of RS and SC (Figure 1d). At 00 UTC on the November 19 (Figure 1e) the system has already completely dissipated, being possible to observe new instabilities only in the south of Argentina.

A low-pressure system with 998 hPa core was observed in northern Argentina (Figure 2a), configuring the NAL, according to Seluchi and Saulo (2012). The system persists throughout November 18, extending the inverted trough axis over RS and Uruguay (Figure 2). This trough is connected to a frontal system located in the south of Uruguay, where negative temperature advection is observed, which indicates transport of colder air (Figure 2a). There is a high-pressure center at the rear of the frontal system, moving away from the continent in the following hours. NAL intensified and spread towards RS, together with high positive temperature advection values (Figure 2a, b), characterizing the warmer air transport (which may indicate the presence of LLJ) and contributing to the intensification of the low pressure system itself.

The 850 hPa northerly flow throughout the day (Figure 3) indicates the transport of warm air from low to mid latitudes, providing support for development of storms. With part of this northerly flow converging over southern Uruguay, a contrast between two air masses with different humidity characteristics is noted, highlighting the frontal system.

An above 12 m s^{-1} speed core over the north of Paraguay (Figure 4) is observed, extending less sharply to the west and north of RS, indicating the presence of the LLJ. It intensifies throughout the night and weakens during the day. The LLJ enhancement at night is well reported in the literature (for example, Rife et al., 2010), characterizing the so-called Nocturnal Jet. The LLJ contributes to the destabilization of the synoptic environment, providing the origin of storms, as it is an element that brings a supply of humidity to the southern center of the continent (Nascimento et al., 2016).

High values of geopotential height (Figure 5), around 5750 m, mean a more unstable atmospheric layer due to the presence of warm and moist air. At this same time, there were intense locations of vertical upward movements in RS, Uruguay and northern Argentina (Figure 5a, b and c), enabling the development of the diffluence already established at 250 hPa. As from 12 UTC, these vertical movements have been weakened.

Figure 6a shows the ULJ and diffluent flow over RS and Uruguay. At 06 UTC this diffluence is located over Argentina, but at 12 and 18 UTC it returns to the system's area of acting. Diffluence had a constant behavior throughout the entire event, except 00 UTC on November 19th (Figure 6e). This dispersion of the flow at 250 hPa indicates the convergence of mass at low levels, favoring the growth of instabilities.

In figure 7 intense jets (both ULJ and LLJ) are observed, being superimposed over the south center of the AS, reaching the maximum speed at the most intense MCC phase. This is confirmed in the coupling field (Figure 8). At 00 and 06 UTC the coupling occurred between the exit of LLJ and the tropical sector of ULJ, as found in Brill et al. (1985).

The intensities of the two jets indicate a strong vertical wind shear, which implies intense convective activity, an important factor for the

formation of storms. The interaction between the jets was observed since the formation of instability (Figure 1a), during the mature phase of MCC (Figure 1c) and even after the dissipation of the system (Figure 1d, e). The occurrence of coupling was identified over the same area where the instability was observed (Figures 8b, c) and the values closest to the perfect orthogonality occurred before the moment of greatest intensity of MCC (Figure 8a, b).

Figure 1. GOES 13 thermal infrared images. (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 1130 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 2. Mean sea level pressure (mslp) in hPa (contour) and 850 hPa temperature advection (shaded) in $K s^{-1}$. (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 3. 850 hPa streamlines and relative humidity in % (shaded). (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 4. 850 hPa wind strength (shaded) in m s^{-1} and streamlines. (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 5. 500 hPa omega (shaded) in Pa s^{-1} and geopotential height (contour) in mgs. (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 6. 250 hPa streamlines and wind strength (shaded) in m s^{-1} . (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 7. Strength of LLJ (shaded) and ULJ (contour) in m s^{-1} . (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 8. Coupling between jets in degrees. (A) 18/11 00 UTC, (B) 18/11 06 UTC, (C) 18/11 12 UTC, (D) 18/11 18 UTC e (E) 19/11 00 UTC. The red polygon in (A) represents the area used for Eulerian analysis. RS is Rio Grande do Sul and SC is Santa Catarina States.

Figure 9. Spatial average over the polygon in Figure 7a of temperature advection in K s^{-1} (absolute values), from 18 UTC on 17 November until 00 UTC on 19 November 2009. Full line is 850 hPa warm advection and dotted line is the 500 hPa cold advection. The intense coupling started at 00 UTC on the 18th.

Eulerian analysis of the region of intense coupling (time variation of spatial average of temperature advection over the polygon of Figure 8a) showed the growth of warm (at low levels) and cold (at mid-levels) advections from 3 hours before coupling and 6 hours before the first clouds outbreak (Figure 9). The 500 hPa cold advection indicates the role of ULJ while the 850 hPa warm advection means the role of LLJ as baroclinic forcing. Cold advection showed less intense behavior than warm because, as expected, thermal advections have greater magnitude at low levels. The peak of warm advection occurred 3 hours before the MCC mature stage, decaying as the system dissipated. It appears, therefore, that the MCC developed in a baroclinic environment.

Conclusions

A coupling between low-level jet and jet stream on November 18, 2009 was observed and instabilities, that later gave rise to an MCC causing intense precipitation and several damage in southern Brazil, has developed downstream. Coupling has been observed throughout the life cycle of MCC. During the period of intensification and maturation, the coupling occurred in the same area of action of the storm. It should be noted that the most orthogonal coupling did not occur simultaneously with the most intense phase of the system, it occurred before. As the literature indicates, the coupling is associated with strong vertical wind shear, which must have contributed to the development of the instability shown here.

During the day, there were intense upward movements at 500 hPa together with the occurrence of diffluent flow in the jet stream. An

intense northerly transport driven by LLJ and a large amount of moisture associated with the NAL trough were also noted. The presence of a frontal system was observed between Uruguay and RS. The time variation of the spatial average of the temperature advection in the area where the coupling occurred behaved as expected for a baroclinic instability: the warm advection grows simultaneously with the increase in cloudiness and decreases with its dissipation. Cold advection at mid-levels - associated with ULJ according to Uccellini and Johnson (1969) - showed a similar behavior.

Future studies will be carried out, in order to verify if in other cases of MCC the coupling between jets occurs and in which phase of storms life it appears.

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