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Atmospheric characteristics favorable for the development of mesoscale convective complexes in southern Brazil

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ABSTRACT: Mesoscale convective complexes (MCCs) are meteorological events that result in severe storms, hail, flood, and tornadoes, but they are difficult to forecast. In South America (SA), MCCs are usually larger and last longer than those in the USA. Southern Brazil (SB) is one of their preferred regions of occurrence. This study's objective was to contribute to the identification of the main physical characteristics and atmospheric environment that favors the occurrence of MCCs in SB and determine how these events are unique relative to other subtropical SA (OSSA) regions. Results indicate that SB MCCs last longer (+3 h) and their average maximum extent is at least 50 000 km^2 larger than OSSA MCCs. The atmospheric environment of SB MCCs meets the criteria already indicated in previous studies, with the northerly low-level jet (LLJ), which brings humidity from the Amazon Basin to the SB MCCs genesis area, coupling with the upper-level jet (ULJ). Moreover, SB MCCs have the South Atlantic as their second source of moisture, which is advected by anticyclonic circulation in the southwestern South Atlantic. This indicates that SB MCCs have unique characteristics compared to OSSA MCCs, including 2 main atmospheric circulation systems responsible for moisture advection to the SB genesis region. For comparison, OSSA MCCs are more dependent on the South Atlantic Convergence Zone (SACZ) and the advection of moisture by the LLJ from the Amazon Basin to north-central Argentina and west-central and southeast Brazil.

KEY WORDS: Mesoscale convective systems · Southern Brazil · Extreme climate events · Climate · South America

1. INTRODUCTION

Mesoscale convective complexes (MCCs) are large, quasi-circular structures of convective storms that are part of the mesoscale convective systems (MCSs) group. They occur around the world, often in South America (SA), including southern Brazil (SB). Based on MCC characteristics and common regions of occurrence, Velasco & Fritsch (1987) found that these phenomena are more frequent in the warmer months of the year in the Southern Hemisphere (October–May) and usually occur in SA, mainly in northern Argentina, Bolivia, Paraguay, and SB. Although MCSs are more frequent in southeastern SA during austral summer, they also occur over northern SA (Colombia and Venezuela) during austral winter (June–August) (Jaramillo et al. 2017).

MCC classification is based on a signature from infrared satellite imagery, which was first proposed by Maddox (1980). MCCs have a quasi-circular

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shape, with lifecycles of a minimum of 6 h and often with 6–12 h time frames. Much is still unknown about the environments responsible for MCCs outside of North America. In SA, the area of interest of this study, the Andes mountain range acts as an orographic barrier to the low-level jet (LLJ) near 850 hPa, by blocking the passage of the trade winds and humidity from the Amazon to the Equatorial Pacific, aiding in the displacement and formation of the northerly component of this low-level circulation. The northeast trade winds reach the Andes and are redirected from northeast to southeast, transporting warm, moist air from the tropical Atlantic Ocean and the Amazon Basin to the Paraná-Prata basin, intensifying convection and precipitation in this region (Gandu & Geisler 1991, Figueroa et al. 1995, Nascimento 2008, Marengo et al. 2009, Rasmussen & Houze 2016).

This air displacement at lower levels is strengthened by the presence of relatively low pressure formed in the region of Paraguay during the warm seasons, known as the Chaco Low (CHL). According to Nimer (1989), one of the mechanisms that allows the formation of this low-level pressure system is strong surface heating of the interior of the continent during the austral summer. In addition, Seluchi & Garreaud (2012) explained that the development of the CHL is linked, on average, to the occurrence of the LLJ immediately east of the CHL, which can result in the development of convective activity in much of southeastern SA. In 41% of the days when SA has registered a LLJ, at least one subtropical MCS developed, a larger category of mesoconvective systems that includes MCCs (Salio et al. 2007).

A new LLJ climatology developed by Montini et al. (2019) indicates that the LLJ is one of the main suppliers of the available water vapor for precipitation in southeastern SA, with the largest moisture flux occurring during austral spring (Sep–Nov) and summer (Dec–Feb). They also suggest that ENSO can influence the interannual variability of the LLJ's strength and frequency in SA. Enhanced moisture transport into SB was observed during spring and fall months of El Niño years from 1979–2016 (Montini et al. 2019).

In order to have conditions favorable for the development of MCCs, it is also necessary to have a subtropical jet near 200 hPa. This upper-level jet (ULJ) difluence is a mechanism that enhances uplift and convection of humidity and winds acting at lower and medium altitudes (Satyamurty et al. 1998). Thus, when the ULJ and LLJ are coupled, conditional instability, sufficient wind shear, and forcing for lift result in upward air movement, enabling the formation of organized convection and subsequent precipitation (Guedes 1985, Vasquez 2011).

There is also a transequatorial circulation, known as the South Atlantic Convergence Zone (SACZ), which is often oriented northwest-to-southeast across the Amazon region and into the South Atlantic and is visible on satellite imagery as an elongated convective band of clouds and precipitation (Satyamurty et al. 1998, Liebmann et al. 1999, Carvalho et al. 2002). During SACZ events, part of the moisture flow coming from the northwest with the LLJ converges with the SACZ and part goes to SB, often determining which of these regions will receive greater precipitation (Grimm 2009). Recent studies have also suggested that Madden–Julian oscillation (MJO) convective activity in the western Pacific (phases 6 and 7) leads by 10 days almost 40% of the extreme rainfall events over the SACZ region, while the connection between MJO and SB extreme rainfall is not as clear (Hirata & Grimm 2016). Although the SACZ has only an indirect influence in SB, it can induce descending air movements in this region, which inhibits cloud formation and precipitation (Casarin & Kousky 1986).

A pseudo-climatological analysis for MCCs in southeastern SA was performed by Durkee & Mote (2010), who recorded more than 300 MCCs in the region between 1998 and 2007. Compared to convective storms that occur in the USA and other regions of the globe, the systems in SA are usually larger, more frequent, more extreme, and last longer (Durkee et al. 2009, Rasmussen & Houze 2016). Furthermore, Durkee et al. (2009) found that the area of MCCs producing precipitation in southeastern SA (381 000 km^2) is larger than that of events that occur in North America (320 000 km^2) and Africa (285 000 km^2).

Extreme convective storms are responsible for more than 40% of the summer rainfall in southeastern SA, showing the importance of MCSs in regional climatology (Rasmussen et al. 2016). Among the convective storms, MCCs specifically were responsible for up to 50% of the regional precipitation in the warm months of 1998–2007 (Durkee et al. 2009). Only in Rio Grande do Sul (RS), which is one of the 3 states in SB, have previous studies examined disasters associated with the occurrence of MCCs. There were 87 cases of disasters registered by the Civil Defense of RS between October and December 2003 (Viana et al. 2009), and 25 disasters related to a single event that occurred on 22–23 April 2011 (Moraes & Aquino 2018). MCSs are responsible for an average of 13 disasters yr^{-1} in RS (Abdoulaev et al. 1996).

The authors were unable to identify other research examining the synoptic-scale atmospheric environment favorable for the development of MCCs either in southeastern SA or specifically in SB. Previous studies, such as that by Maddox (1983), analyzed weather conditions associated with North American MCCs. Laing & Fritsch (2000) described the planetary atmospheric environment for the development of MCCs between 1981 and 1987, with a brief discussion of SA, but nothing specific to SB. Guedes (1985) included SB, but that study described the atmospheric environment for the development of all MCSs only for the month of September (1974–1978), and not specific to MCCs. Recently, Rehbein et al. (2018) developed a detailed climatology of MCSs, but they focused only on the Amazon Basin, which is part of northern SA.

SB is an important agricultural region in Brazil and has a total population of about 27 million people (IBGE 2010). In 2017, total agricultural production of the 3 states in SB represented 30% of the total value of agricultural production in Brazil (IBGE 2018). The analysis of MCCs in SB is critical because the precipitation associated with these events is often related to hazards for both population and agriculture, including floods, landslides, hail, tornadoes, and windstorms (Viana et al. 2009, Moraes & Aquino 2018). Therefore, this work aims to contribute to the identification of the main physical characteristics and atmospheric environment that favors the occurrence of MCCs in SB. We were particularly interested in determining whether MCCs in SB are unique relative to other regions across subtropical SA. Specifically, we aimed to determine what the atmospheric environmental characteristics were prior to the development of MCCs in SB during the warm months (October–May) of 1998–2007, and what the differences are between the atmospheric characteristics that contribute to the development of MCCs in SB versus in other subtropical SA (OSSA) areas.

2. MATERIALS AND METHODS

2.1. MCC characteristics

MCCs are a sub-group of MCSs, which were defined by Houze (2004) as convective cloud agglomerates of varied forms presenting a continuous precipitation area that can be partially stratiform and partially convective. Among the MCSs there are squall lines, which have a linear format, and the quasi-circular shaped MCCs, whose physical characteristics were defined by Maddox (1980); these are summarized in Table 1. There are systems with linear characteristics that have the same dynamic characteristics of MCCs; these were defined by other studies as persistent elongated convective systems (PECSs; Anderson & Arritt 1998, Jirak et al. 2003, Mattingly & Mote 2017).

Given that the occurrence of MCCs in SB is commonly linked to disasters, it is important to understand the atmospheric environment in which these quasi-circular events develop. The MCCs analyzed here were from the data set assembled in the Durkee & Mote (2010) study, which contained 330 MCCs in subtropical SA during the warm season months (October–May) from 1998–2007. This data set was generated based on the GOES-8 and GOES-12 geostationary satellites, using a semi-automated approach to examine the sequence of images to determine the path and the individual characteristics of the systems (Durkee & Mote 2010, Mattingly & Mote 2017). The data set contains information such as duration, size, location, and eccentricity of each MCC.

Based on this data set, the current study examined 2 groups of MCCs: those that occurred in SB (96 events), and those that occurred in OSSA but did not reach SB during their life cycles (168 events). To be classified as an event that reached SB, a given MCC, during its life cycle of at least 6 h, must have devel-

Table 1. Classification and physical characteristics of mesoscale convective complexes (Maddox 1980)

	Physical characteristics
Size	A: Cloud shield with continuously low IR temperature ≤32°C must have an area ≥100000 km^2 B: Interior cold cloud region with temperature ≤52°C must have an area ≥50000 km^2
Initiate	Size definition A and B are first satisfied
Duration	Size definitions A and B must be met for a period ≥6 h
Maximum extent	Contiguous cold cloud shield (IR temperature ≤32°C) reaches maximum size
Shape	Eccentricity (minor axis/major axis) ≥0.7 at time of maximum extent
Terminate	Size definitions A and B no longer satisfied

oped and/or crossed the latitudes 22° and 33° S and the longitudes 48° and 57° W, which are the boundaries of SB for the purpose of this study (Fig. 1).

2.2. Climate Forecast System Reanalysis

National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) 6 hourly products (from January 1979 to December 2010) were used in this analysis, specifically in the region 14° N to 59° S and 90° to 31° W (corresponding to SA). CFSR was used in this work as the source of the atmospheric variables because it has higher spatial resolution (38 km) compared to the other NCEP reanalysis products.

Dates and times in which the MCCs occurred were selected, both in SB and in other parts of SA, and then the relevant meteorological fields were extracted from the CFSR beginning prior to the formation of each event (which ranged from 2.5–5.5 h before the development of the MCCs due to the 3 h CFSR data availability). Selected CFSR reanalysis fields were based on the works of Velasco & Fritsch (1987) and Laing & Fritsch (1997). The variables of interest included convective available potential energy (CAPE), zonal (u) and meridional (v) wind component (850 and 200 hPa), relative humidity (850 hPa), and geopotential height (850 and 200 hPa). Integrated vapor transport (IVT) was also included to show the total amount of water vapor transport in the low to mid levels of the atmospheric column (1000–700 hPa).

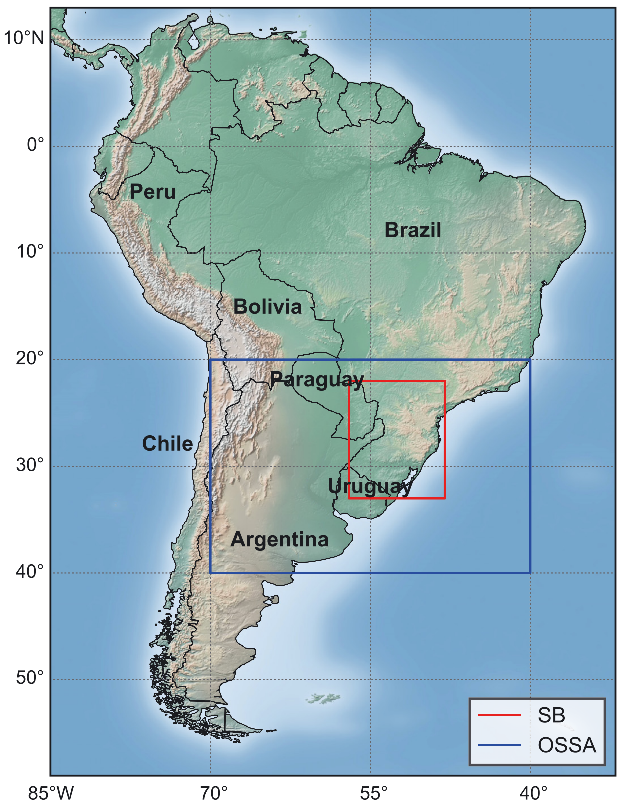

Fig. 1. Area of study. Red box: southern Brazil (SB) region (22°–33° S, 48°–57° W), the area where mesoscale convective complexes (MCCs) should cross to be considered a SB MCC. Blue box: other subtropical South America (OSSA) region (20°–40°S, 70°–40°W), the area where MCCs should cross to be considered OSSA MCC (excluding SB)

2.3. Principal component analysis

Principal component analysis (PCA) is a method that analyzes a single field variable in order to find spatial patterns of variability through time. PCA also provides a measurement of the explained variance of each pattern identified (Bjornsson & Venegas 1997). Therefore, PCA was utilized to identify patterns of atmospheric variability over the period of 1998–2007. This analysis was performed separately for each of the 2 different MCC groups (i.e. SB versus OSSA) to identify similarities and differences in their atmospheric environment prior to initiation. The OSSA group excluded all SB events.

The geopotential heights at 850 hPa were used as input data to run the PCA, since winds at this pressure level characterize well the conditions associated with the LLJ, which is essential for MCC development. We then used the method proposed by Bjornsson & Venegas (1997), transposing the data into a matrix $p \times t$, where each line is a point of latitude and longitude (p) and each column represents time (t). As suggested by Compagnucci & Richman (2008), T-mode is recommended if the purpose is to locate spatial synoptic or flow patterns, while S-mode is used to find spatial clusters or teleconnections. Because this research sought to identify atmospheric pressure patterns that indicate meteorological characteristics prior to the development of MCCs, we used the T-mode. The varimax orthogonal rotational method was applied which, according to Compagnucci & Richman (2008), is the criterion of maximization most commonly used in atmospheric research. The purpose of this and other methods of rotation is to simplify the rows and columns of the factorial matrix to facilitate interpretation (Hair et al. 2009).

After analyzing the principal components correlated with the 96 MCCs that occurred in SB and the 168 MCCs that occurred in OSSA sites, we selected the first 2 components of each group based on the their explained variance. The first 2 components of the SB and OSSA groups explained more than 50 and 70% of the variance, respectively. That is, both SB and OSSA groups had 2 principal components of geopotential height at 850 hPa representing more than half of their spatial variability. The T-mode component scores for covariance-based data must be interpreted as anomalous spatial patterns (Compagnucci & Richman 2008), and the principal component loadings are represented in maps as numerical values corresponding to each grid point (Jolliffe 1990, Jolliffe & Cadima 2016).

Because of the different number of MCCs most correlated with each principal component, we selected the 10 MCCs most highly correlated with their respective components for further analysis. This created more uniform groups representing each principal component, and more interpretable composite maps. The composites created included winds at 850 and 200 hPa (*u* and *v* components), CAPE, relative humidity at 850 hPa, IVT between 1000 and 700 hPa, and vertical wind shear between 700 and 850 hPa, for the LLJ analysis (Saulo et al. 2000, Marengo et al. 2004), and between 700 and 1000 hPa, as one of the indicators of atmospheric instability needed for MCC development (Laing & Fritsch 2000, Markowski & Richardson 2011).

Synoptic charts via the Direction of Hydrography and Navigation of the Brazilian Navy were also used for qualitative analysis to investigate the atmospheric environment of each of the principal components. Based on the dates of occurrence of the 10 MCCs most correlated with each principal component, synoptic characteristics of the groups of events that occurred in SB versus in OSSA were analyzed.

2.4. LLJ, ULJ, and vertical wind shear

In order to define the LLJ (850 hPa), we used both criteria 0 and 1 from Bonner (1968), which states that if the wind meets one of those 2 criteria, a LLJ is identified. Saulo et al. (2000) and Marengo et al. (2004) applied criterion 1 of Bonner (1968) to identify LLJs in SA. These authors, however, adapted criterion 1 by establishing that a LLJ should have the following characteristics: magnitude of the wind ≥12 m s^{-1} at 850 hPa; vertical wind shear of at least 6 m s^{-1} between 850 and 700 hPa (here calculated as the difference in wind speed between the 850 and 700 hPa levels); and the *v* component of the wind must have a southward direction and must be greater in magnitude than the *u* component in the region of higher wind speed (Saulo et al. 2000, Marengo et al. 2004). Criteria 0 was applied considering these same levels in the troposphere, but considering LLJ events with wind magnitude ≥10 m s^{-1} and with vertical wind shear of at least 5 m s^{-1}.

Chaco Jet Event (CJE) criteria were also applied. Nicolini et al. (2002) used the same criteria described above to identify a LLJ but further stipulated that the jet should originate in tropical latitudes and extend to at least 25° S in the presence of the CHL to be classified as a CJE. The value of the vertical wind shear in the first 3 km of the troposphere (between 1000 and 700 hPa) was also considered, because other studies indicated its intensity in this atmospheric layer (≥6–8 m s^{-1}) as important when studying MCCs in SA (Laing & Fritsch 1997, Markowski & Richardson 2011). The ULJ was identified when the center of maximum wind speed (the jet streak) was at least 32 m s^{-1} and the vertical shear was 5–11 m s^{-1} (Maddox 1983, Guedes 1985).

3. RESULTS

3.1. Morphologic characteristics of MCCs in SB and SA versus in the USA

The similarities between the developmental mechanisms of MCCs that occur in SA and in the USA, compared to the global population of MCCs, have already been highlighted by Laing & Fritsch (1997). However, there are some differences in frequency of occurrence, duration (hours) and size (area) (Durkee & Mote 2010). In this study, we extend the Durkee & Mote (2010) comparison by examining the characteristics of the USA and subtropical SA events versus SB events. Based on published data from the USA, a comparative table was drawn for the USA, SA (total events), and SB MCCs (Table 2). Note that there are lifecycle differences between SA and USA MCCs data sets. The SA group of events has a data set from 1998–2007. The USA period of record is from 1978–1987 and from 1992–1999 (i.e. 15 yr in total).

The comparison between subtropical SA and the USA MCCs indicates that in SA these events typically last longer (an average of +4 h) and are nearly 100 000 km^2 larger in maximum extent compared to the those in the USA. One-third of the MCCs that occurred in subtropical SA between 1998 and 2007 were active over SB. MCCs from SB last longer than over the USA (+5 h) and over OSSA (+3 h). Moreover, SB has the largest continental convective system, at least 50 000 km^2 larger on average than the maximum extent of those in the other regions. December had the greatest number of MCCs, with 22 of the 96 events (Fig. 2). Aside from the physical characteristics, we also analyzed and compared the characteristic atmospheric environments between OSSA and SB MCCs groups.

Table 2. Comparison between the morphologic characteristics of South America (SA), United States (USA) and southern Brasil (SB) Mesoscale Convective Complexes (MCCs). Sources: Durkee & Mote (2010) for SA; Ashley et al. (2003) for USA

Physical characteristics of MCCs	Area of MCCs occurrence SA (total)	USA	SB
Average MCCs in each warm season (Oct–May)	33.7	35	10.7
Duration (h)	14	10	15.78
Average maximum extent (km^2)	256500	164600	276070

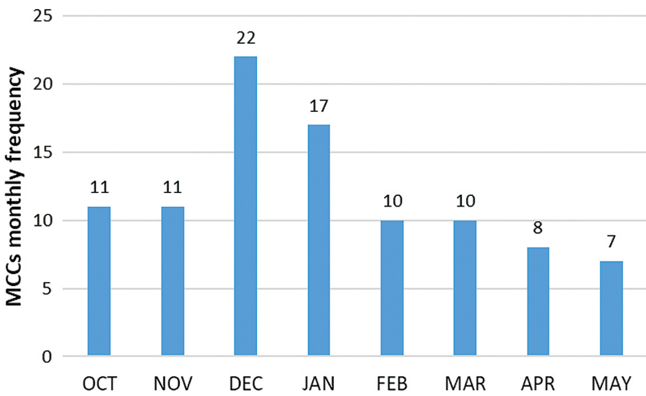

Fig. 2. Monthly frequency of mesoscale convective complexes in southern Brazil (1998–2007)

3.2. Primary modes of variability and their associated atmospheric characteristics

3.2.1. MCCs over SB

The first principal component of 850 hPa geopotential height for the subset of MCC that occurred in SB represents 30.9% of the variance (Fig. 3a), with the correlation values of the 10 most highly correlated MCCs ranging from 0.76–0.89.

The positive loading patterns of the first principal component shown in Fig. 3a are mirrored in the synoptic charts of the 10 MCCs most highly associated with this component, showing the presence of a well-

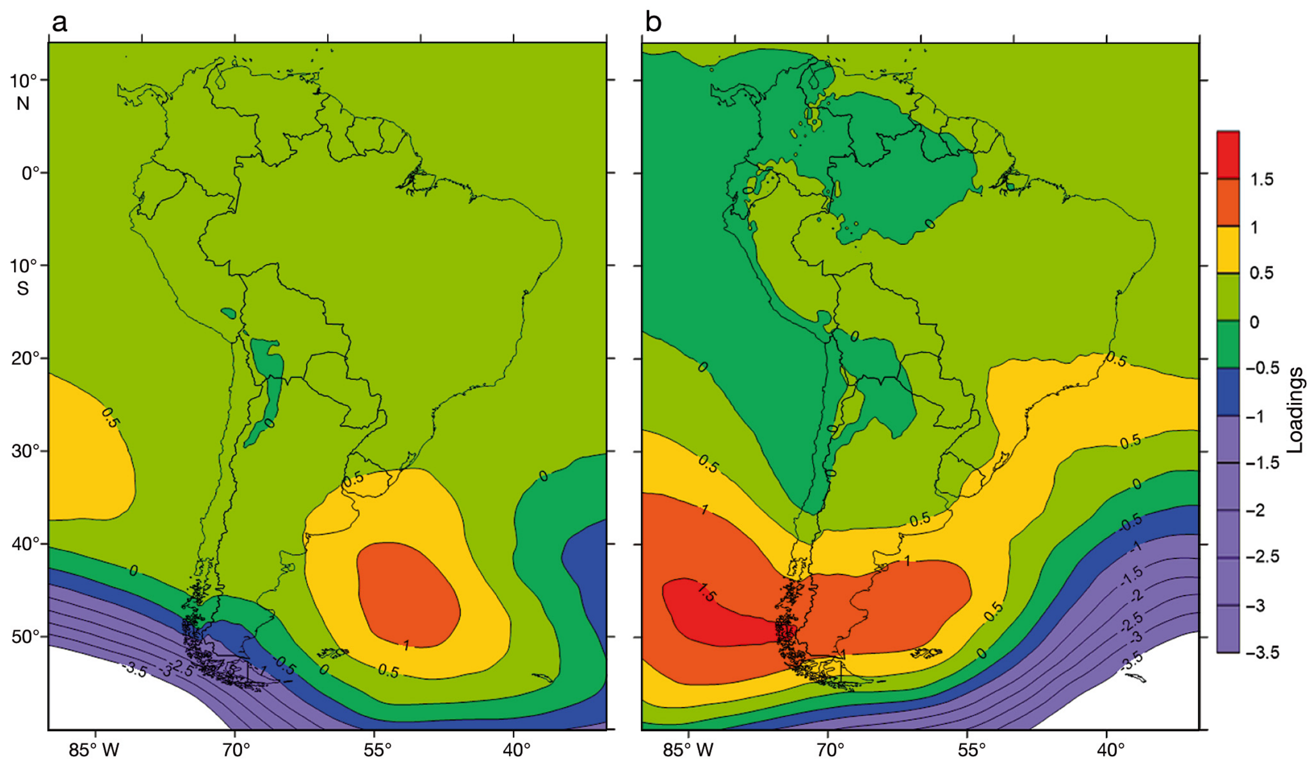

Fig. 3. Loading patterns of the (a) first and (b) second principal components of geopotential height (850 hPa) for southern Brazil mesoscale convective complexes

defined high-pressure system in the southwestern South Atlantic. As observed in the 850 hPa wind field (Fig. 4a), this high-pressure is tied to the anticyclonic circulation in the region, which adds to the northerly flow at low levels and contributes to the moisture concentration in SB (nearly 80% of relative humidity). Fig. 4a also shows strong IVT patterns >250 kg m^{-1} s^{-1} along the LLJ and the anticyclonic circulation partly over the southwestern Atlantic Ocean and partly over the SA continent, which indicates moisture advection in the genesis area of MCCs.

The *v* flow shown in Fig. 4a was classified as a LLJ because it meets criterion 0 of Bonner (1968). The mean magnitude of the LLJ jet streak for the 10 MCCs was 10 m s^{-1} (white vectors in Fig. 4a), with mean vertical shear (between 850 and 700 hPa) around 5.5 m s^{-1}. These values were also found by Maddox (1983) in large-scale MCC training environments in the USA. In addition, these LLJs had an exit-region position south of 25° S, which classify them as CJEs (Nicolini et al. 2002). With regards to the probability of convection, the mean CAPE reached 1000 J kg^{-1} in the MCC development area (Fig. 5a), and the vertical shear in the first 3 km of the atmosphere (between 8 and 10 m s^{-1}) was above the average found in other convective-system development areas in SA (Laing & Fritsch 1997, Markowski & Richardson 2011, Tavares & da Mota 2012).

The second principal component of 850 hPa geopotential height represents 20.2% of the variance of the MCCs that occurred in SB (Fig. 3b), with correlation values of the 10 most highly correlated MCCs ranging from 0.63–0.86.

In the second principal component group, 80% of events had a high-pressure system located in southern SA and the eastern Pacific. Nevertheless, the CHL was well marked in 90% of the events. This high-pressure does not inhibit the northerly low-level flow, as shown by the 850 hPa wind field (Fig. 4b) which is responsible for moisture advection from the Amazon as shown by the strong IVT patterns >300 kg m^{-1} s^{-1}. There is also a high concentration of moisture in northern Argentina and SB, represented by relative humidity between 70–90% (Fig. 4b). In this event, the LLJ met criterion 1 of Bonner (1968), with the mean magnitude of the LLJ jet streak ≥12 m s^{-1} (white vectors in Fig. 4b) and the vertical shear between 6 and 8.7 m s^{-1}. The CHL and the latitude of the LLJ exit region also allowed us to classify it as a CJE (Nicolini et al. 2002).

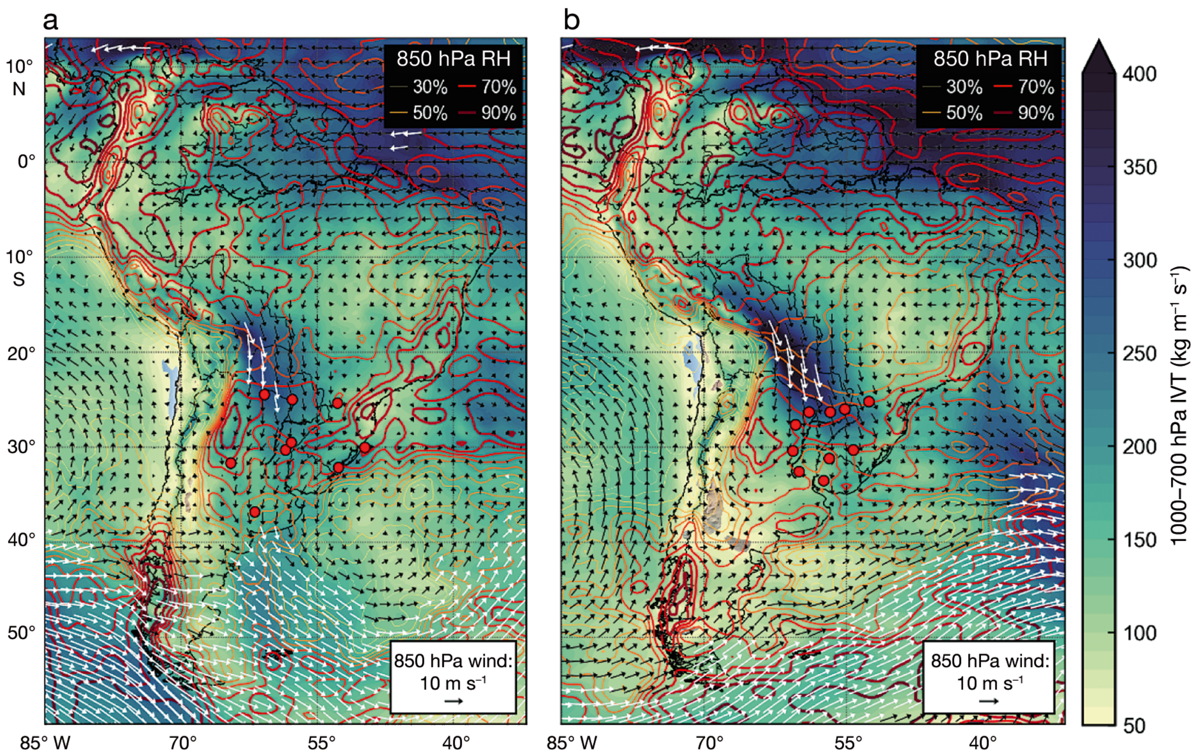

Fig. 4. Mean wind field (zonal and meridional) at 850 hPa (white vectors: regions with wind magnitude ≥10 m s^{-1}), integrated vapor transport (IVT) between 1000 and 700 hPa (kg m^{-1} s^{-1}), and contour lines of relative humidity (RH) at 850 hPa (%) of the 10 mesoscale convective complexes (MCCs, red circles) most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height for the 96 MCCs of southern Brazil

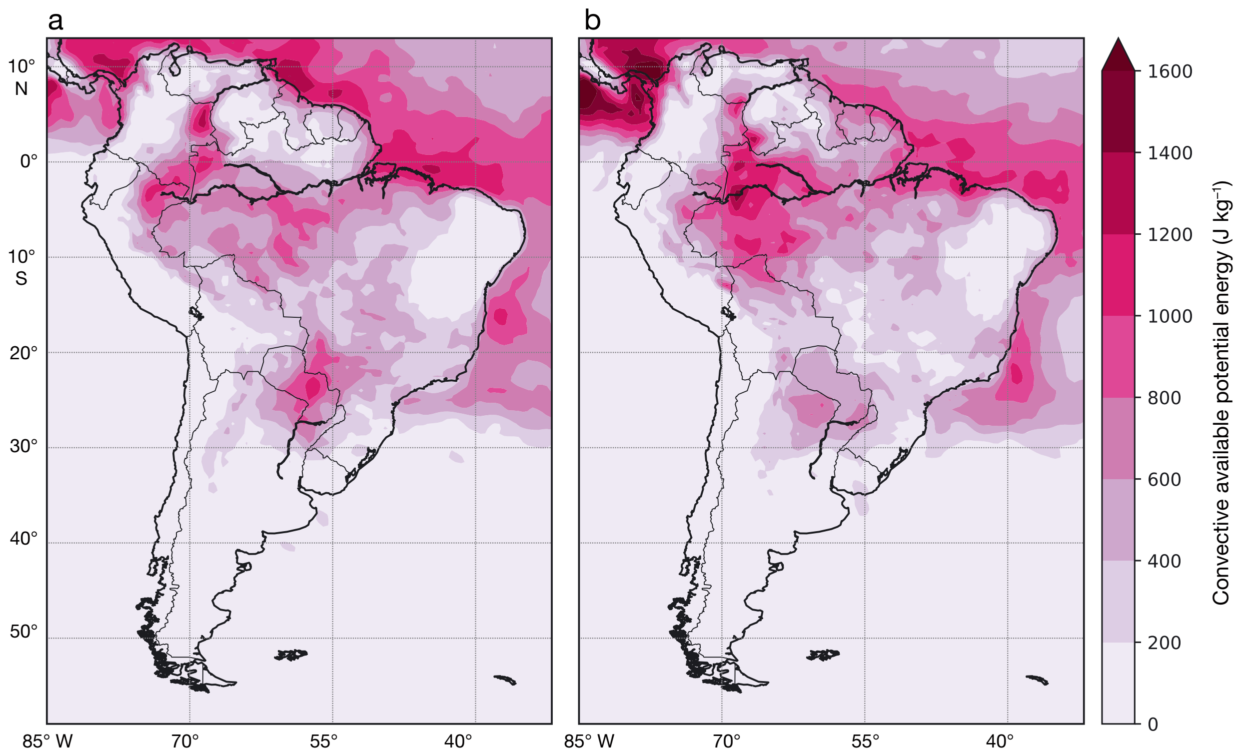

Fig. 5. Mean convective available potential energy for the 10 mesoscale convective complexes (MCCs) most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height of the group of the 96 MCCs of southern Brazil

This component had lower CAPE than the first component, with mean values around 600 J kg^{-1}, reaching 900 J kg^{-1} in only a small area (Fig. 5b). However, these values are within the average indicated for the formation of convective clouds by Laing & Fritsch (2000), Markowski & Richardson (2011), and Tavares & da Mota (2012), who suggest that values greater than 500 J kg^{-1} indicate enough energy available for convection and storm development. On the other hand, the vertical shear (between 1000 and 700 hPa) had the highest magnitude in the genesis region of the MCCs in SB, between 9 and 11 m s^{-1}, which ensured the instability necessary for the MCCs development.

3.2.2. MCCs over other subtropical SA

We extracted the first 2 principal components of 850 hPa geopotential height for MCCs in OSSA, excluding SB. The first principal component accounted for 38.2% of the variance of the 168 MCC group (Fig. 6a). The correlation values of the 10 most highly correlated MCCs ranged from 0.86–0.94.

The synoptic charts corresponding to this principal component showed a trough entering the southern cone of SA with a relatively strong lower-tropospheric pressure gradient. This rapid pressure drop in southern SA shifted low-level flow to the south-central region of Argentina, diverting it to extend to SB (Fig. 7a). The low-level flow of this component was not classified as a LLJ, despite high wind speeds extending to 20 S (Fig. 7a), because its maximum jet streak magnitude was 9 m s^{-1}, which is below the minimum criteria of Bonner (1968). This could be explained by the fact that these MCCs span a larger area than the SB MCCs given the difference in domain size. The vertical shear in the region was also below that established by the criteria, reaching only 4 m s^{-1}.

The MCCs of the first principal component were formed mostly between west-central and southeast Brazil, which is a result of the enhanced winds, stronger IVT and relative humidity patterns (70–90%) at the lower atmospheric levels in these regions. A small part of this low-level flow advanced to north and central Argentina, due to the pressure gradient in these regions, resulting in the formation of the 3 southernmost MCCs in Fig. 7a.

Nevertheless, the average wind field of the 10 most correlated MCCs suggests that the patterns in the lower levels could be classified as the SACZ, with the

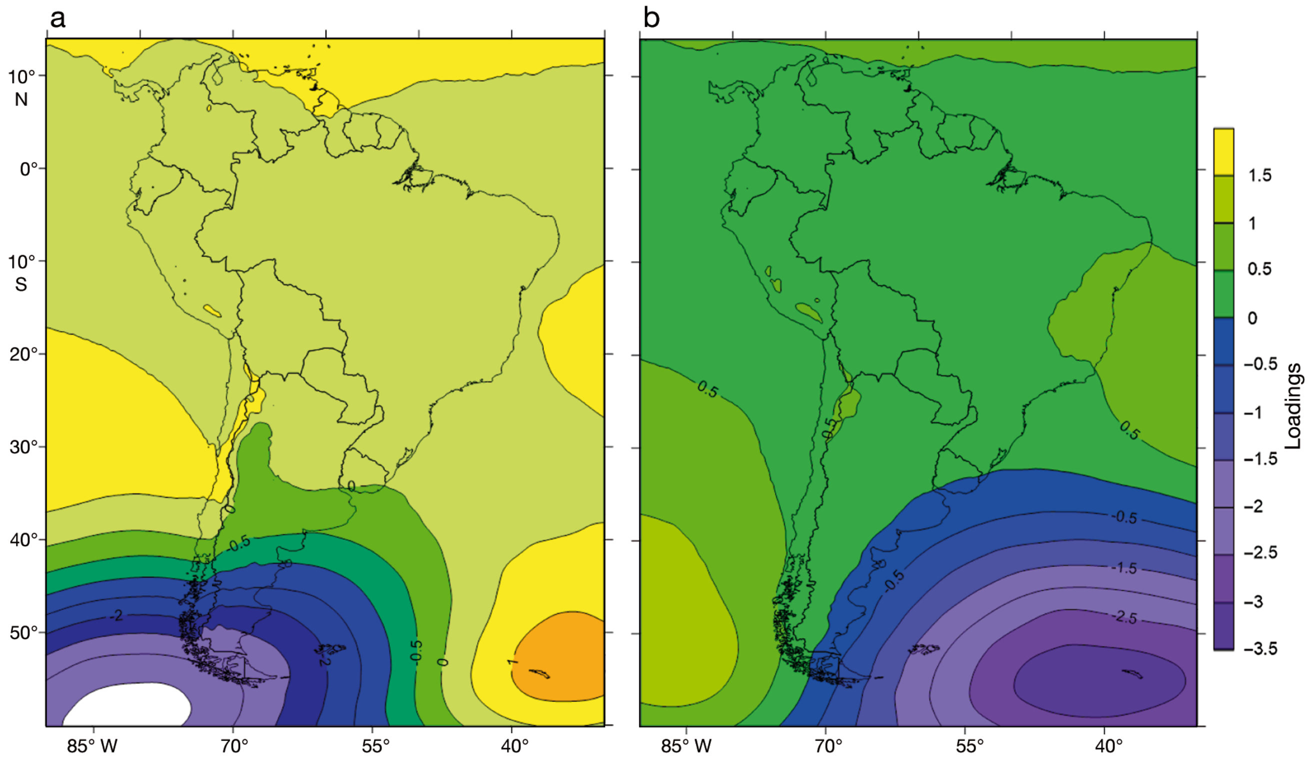

Fig. 6. Loading patterns of the (a) first and (b) second principal components of geopotential height (850 hPa) for other subtropical South America mesoscale convective complexes

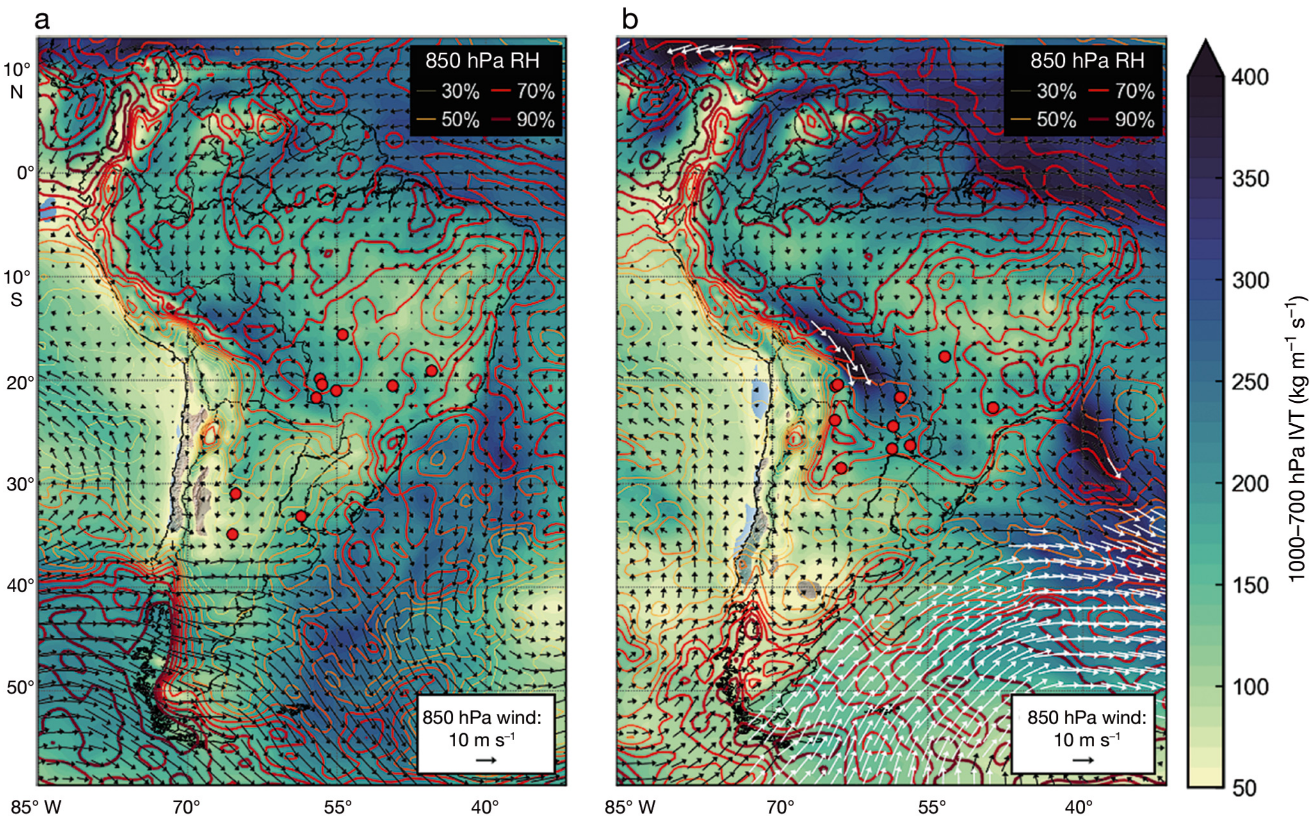

Fig. 7. Mean wind field (zonal and meridional) at 850 hPa (white vectors: regions with wind magnitude ≥10 m s^{-1}), integrated vapor transport (IVT) between 1000 and 700 hPa (kg m^{-1} s^{-1}), and contour lines of relative humidity (RH) at 850 hPa (%) of the 10 mesoscale convective complexes (MCCs, red circles) most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height for the 168 MCCs of the other subtropical South America region

absence of the meridional LLJ and with the location of MCC formation in southeast and west-central portion of Brazil. Carvalho & Jones (2009) defined this zone of convergence as a band of cloudiness and precipitation that occurs during the summer in SA, ranging from the Amazon to southeast Brazil (northwest–southeast), toward the South Atlantic Subtropical Ocean. Durkee (2008) indicated that during periods in which the SACZ region is active, MCCs are positioned farther to the northeast of their preferential region of formation (which is SB and Paraguay, and central and northern Argentina), and the moisture advection from the Amazon basin also leads to a dislocated area of moisture (Fig. 7a). This change of MCC development area is indicative of the change of direction and position of the heat and humidity advection at lower levels (Durkee 2008). Thus, this indicates that the presence of the SACZ can influence the area of development and frequency of MCCs in OSSA.

The CAPE value from this group was the lowest found in all the principal components analyzed in this study (i.e. 450 J kg^{-1}; Fig. 8a), which is also below the average value found by other studies (Laing & Fritsch 2000, Tavares & da Mota 2012). This can be related to the spatial distribution of the MCCs in this group, or it may indicate that the role played by other variables was more important for convection and MCC development in this case. Characteristics such as the coupling between low- and upper-level flows and the vertical shear between 700 and 1000 hPa, which ranged from 6–12 m s^{-1} in the genesis region, likely led to MCC development (Barboza & Fedorova 1998b, Laing & Fritsch 2000, Tavares & da Mota 2012).

The second principal component represented 36.4% of the variance of the 168 MCCs in OSSA (Fig. 6b), with correlation values of the 10 most highly correlated MCCs ranging from 0.89–0.98. The negative loading patterns of this principal component indicate a low-pressure system in the southwest South Atlantic Ocean, which can be confirmed by a cyclonic circulation shown in the mean wind field (Fig. 7b). Such a sharp pressure gradient may be the reason for the direction the LLJ followed, to the Southwest Atlantic. However, 50% of these events had a high-pressure system in southern SA, which was confirmed by the anticyclonic circulation located in the continent in the composite maps (Fig. 7b).

Therefore, it is possible that the MCCs developed in central SA suggest a similar situation indicated by Marengo et al. (2009); the intensification of trade winds and moisture advection from the Amazon to

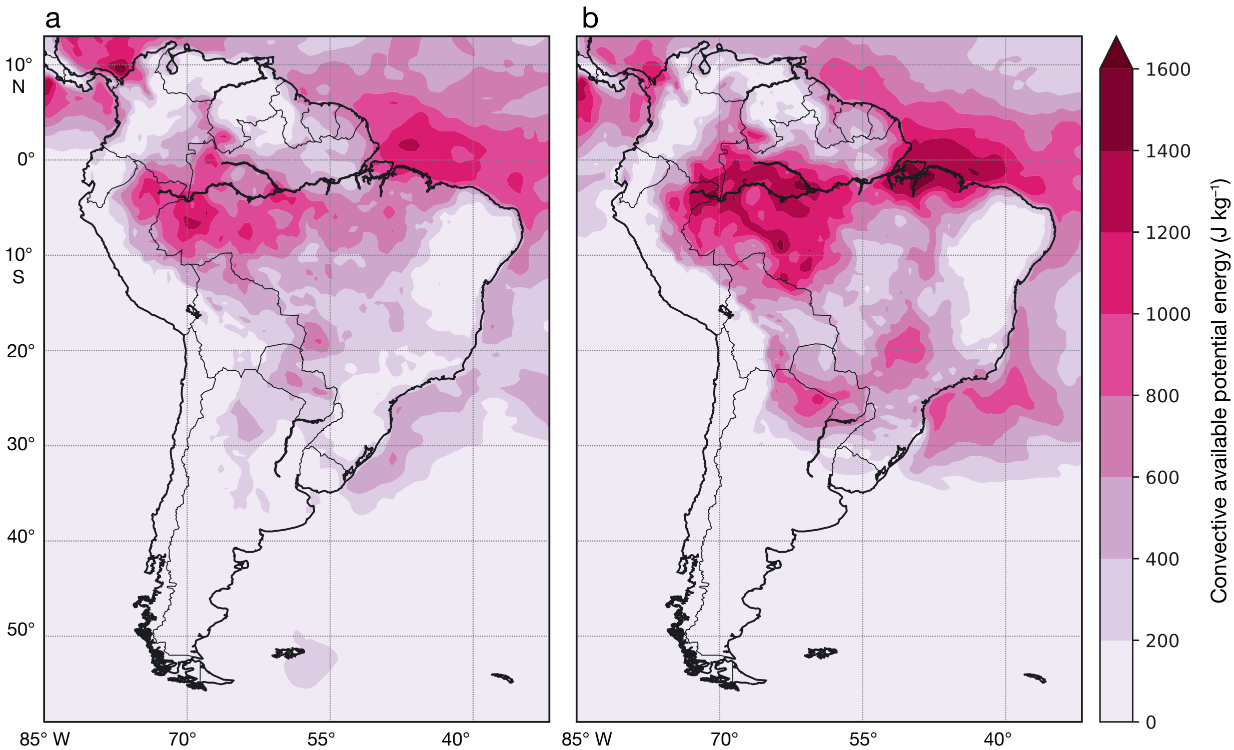

Fig. 8. Mean convective available potential energy for the 10 mesoscale convective complexes most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height for the 168 MCCs of the other subtropical South America region

SB at the exit region of this north–south flow meets a low-level flow coming from the South Atlantic, providing sources of moisture and convergence to the MCC genesis area (with relative humidity exceeding 70% and IVT >300 kg m^{-1} s^{-1}).

This was the only group among the 168 MCCs in OSSA in which the northerly flow met the criteria to be classified as LLJ. The maximum magnitude of the jet streak was ≥12 m s^{-1} (white vectors in Fig. 7b) and the vertical shear was 5.7 m s^{-1}, meeting criterion 0 of Bonner (1968). The LLJ exit region, at 25° S, also characterizes it as a CJE type (Nicolini et al. 2002). Furthermore, this was also the principal component for which CAPE values were highest in this group of 168 MCCs in OSSA, at 800–1000 J kg^{-1} (Fig. 8b). This indicates that there was convective energy available for deep convection, making MCC development less dependent on the coupling between LLJ and ULJ (Williams & Renno 1993, Barboza & Fedorova 1998a, Tavares & da Mota 2012). The value of vertical shear in the MCC development region also corresponded to that indicated for SA events by Laing & Fritsch (2000), at 6–8 m s^{-1}.

3.2.3. 850 and 200 hPa winds

For the comparative analysis between mean fields of high- and low-level winds, composite fields were created using the *u* and *v* wind components at 850 and 200 hPa atmospheric levels, which correspond closely to the vertical position of LLJ and ULJ circulations, respectively. The maps presented here also refer to the 10 MCCs most correlated with each of the principal components discussed above. In order to evaluate the relationship between the jets, their respective couplings — between zones of convergence at lower levels and divergence at higher levels — and the development of MCCs, the initial position (genesis) of each of the 10 events was plotted.

First, it is relevant to discuss the coupling between the LLJ and the ULJ analyzed here, which is important for the development of severe storms. According to Newton (1967) and Uccellini & Johnson (1979), this dynamic mechanism of coupling between the jets is responsible for the genesis and intensification of severe storms, because the convective activity is favorable when the axes of the 2 jets tend to meet orthogonally. This is due to the difference in wind direction and speed (i.e. wind shear) at lower and higher levels (here calculated as the difference in wind speed between the 850 and 200 hPa levels), and the consequent vertical gradient in humidity and temperature between these heights which develops convective instability within this layer. Therefore, in the exit region of the LLJ there is a moisture and warm air convergence, while at in the northern and left portions of the ULJ jet streak (in the Southern Hemisphere) there is typically a region of divergence. These 2 regions, when acting together, favor convection and the development of organized convective systems, including MCCs (Trewartha 1954, Uccellini & Johnson 1979, Vasquez 2011).

Following the analysis of the mean wind fields at 850 and 200 hPa, both SB and OSSA MCCs groups presented an ULJ with vertical shear between 5 and 11 m s^{-1} km^{-1} and have a jet streak of at least 32 m s^{-1}, as established by Maddox (1983) and Guedes (1985). Even in events in which the north–south flow did not fulfill all the criteria to be classified as a LLJ, it is possible to suggest the coupling between that lower-level flow and the ULJ in the atmospheric environment prior to the development of the MCCs of all the principal components detailed above (Figs. 9 & 10).

Of the group of 96 MCCs that occurred in SB, both principal components met the LLJ and ULJ criteria, and visual inspection of both wind fields suggests the coupling between these jets was within the expected patterns (Fig. 9a,b). In these events, as in Maddox (1983), the ULJ, with a jet streak ≥32 m s^{-1}, indicates that the initial development of the MCCs occurred in the left entrance of the jet. Together with the low-level forcing, this may be responsible for the vertical circulation associated with this ULJ in the region where its flow is divergent.

In the 168 MCCs of OSSA, the case of the wind field that did not present a defined LLJ (Fig. 10a) was also found in other studies, like Guedes & Silva Dias (1984) and Barboza & Fedorova (1998a). Even so, these low-level circulations were apparently sufficient to transport heat and moisture to the region where divergence was occurring at higher levels, a condition that favored upward vertical motion, cloud development, and the genesis of MCCs. However, it is important to note that both principal components had the ULJ characteristics, with jet streak velocities between 32 and 50 m s^{-1} (Fig. 10a,b).

4. DISCUSSION AND CONCLUSIONS

Between 1998 and 2007, one-third of the SA MCCs occurred in SB. In addition, the events in SB were larger and of longer duration, indicating that this could be considered a preferential area of occurrence

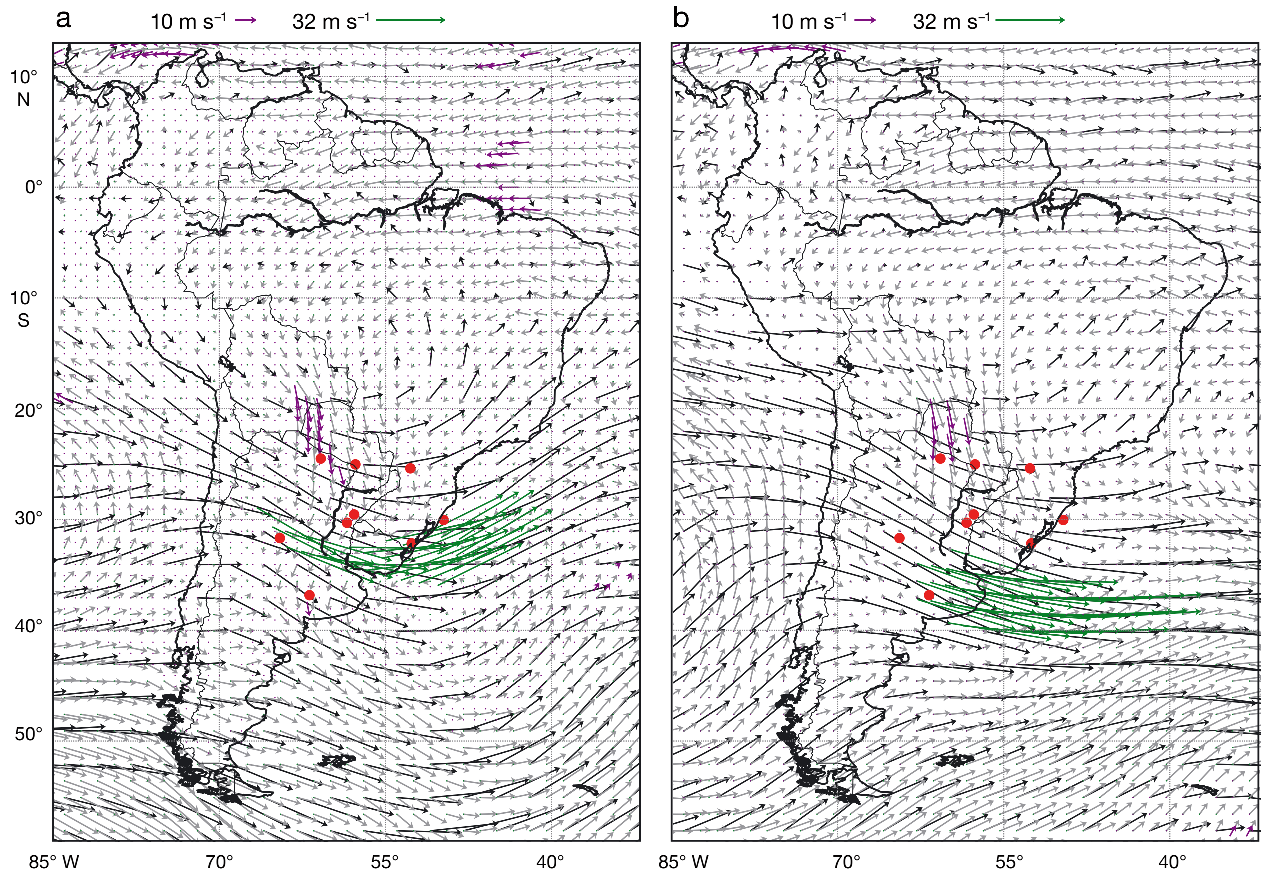

Fig. 9. Zonal and meridional wind components, at 850 hPa (gray) and 200 hPa (black), referring to the 10 mesoscale convective complexes (MCCs, red circles) most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height for the 96 MCCs of southern Brazil. Purple arrows: jet streak of the low-level jet — ≥10 m s^{-1} in (a), ≥12 m s^{-1} in (b); and green: upper-level jet — ≥45 m s^{-1} in (a), ≥48 m s^{-1} in (b)

for convective systems in SA (Table 2). December was the most common month for MCCs, with 22 of the 96 cases (Fig. 2). This result is consistent with that of Durkee et al. (2009), which showed December as the month with the greatest amount of rainfall in subtropical SA related to the occurrence of MCCs (30–50 %).

When comparing the mean wind fields presented in Figs. 4 & 7b, we suggest that there is a similarity between the SB MCCs group and the second principal component of the OSSA MCCs group, with a clearly defined LLJ. Prior to MCC formation, the north–south flow can be classified as a LLJ, based on Bonner (1968), and was also a CJE type, with the LLJ exit at latitudes south of 25° S (Figs. 4 & 7b). This type of LLJ, according to Nicolini et al. (2002), was related to the greatest amounts of precipitation over Uruguay, part of Argentina, and the Brazilian State of Rio Grande do Sul between 2000 and 2006, which corroborates our findings of the occurrence of MCCs in SB and in Argentina and Uruguay. The behavior of the LLJ at 850 hPa also matches the wind fields analyzed by Guedes (1985), indicating that to the north and in the region of MCC development, the wind originates in northern SA and has a larger *v* component (poleward predominance).

The relationship between the presence of the LLJ, the concentration of relative humidity in its exit region, and the strong IVT patterns is one of the factors that contributes to deep convection (Figs. 4 & 7b). According to Nascimento (2008), the moisture advection from the tropical region to the higher latitudes by the LLJ is one of the main reasons for the increase in humidity and the consequent destabilization of the atmosphere for the storms' development.

In addition to moisture advection by the LLJ, the group of MCCs in SB indicates the presence of an anticyclone in the southwestern portion of the South Atlantic Ocean, a relatively strong IVT pattern on the coast of SB, and corresponding high relative humidity in the composite fields (Fig. 4a). This suggests

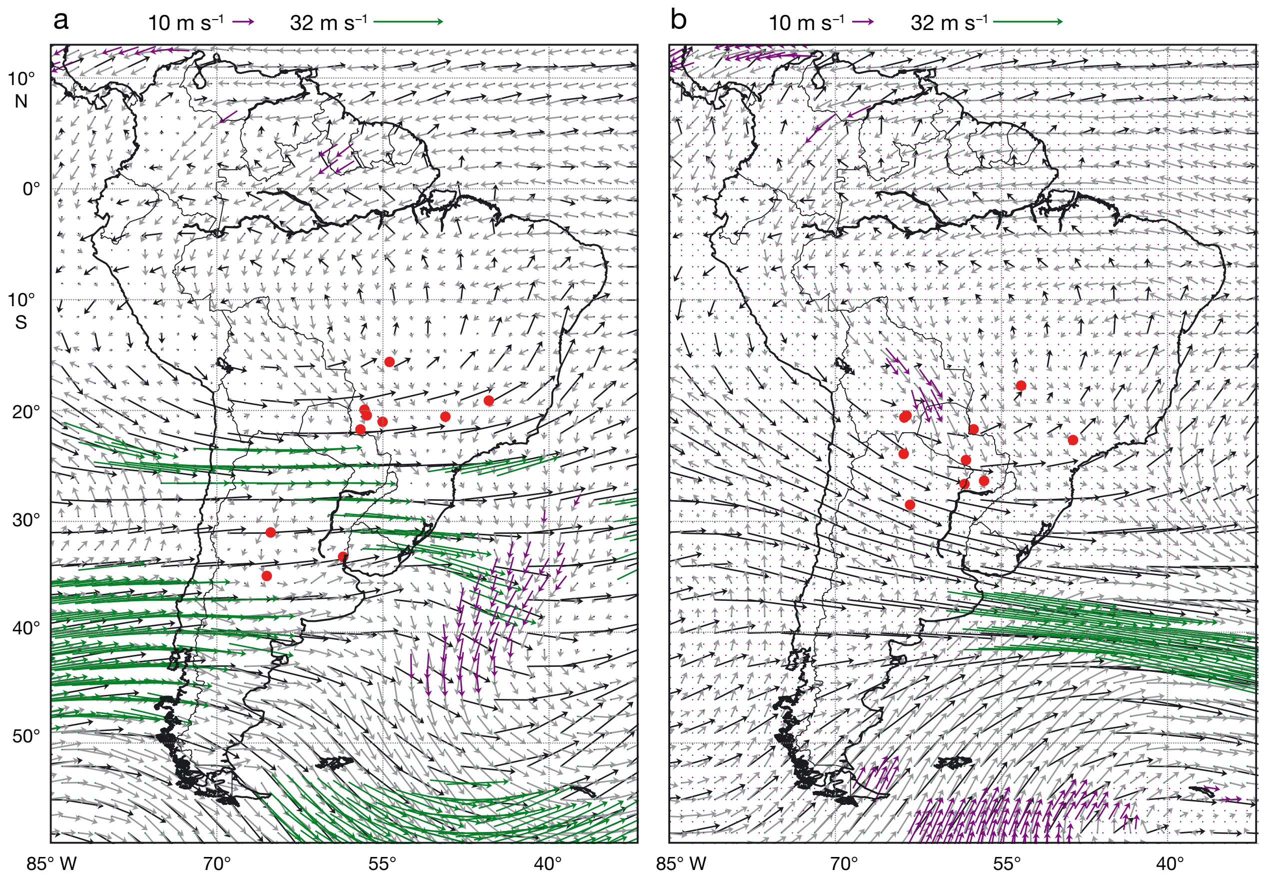

Fig. 10. Zonal and meridional wind components, at 850 hPa (gray) and 200 hPa (black), referring to the 10 mesoscale convective complexes (MCCs, red circles) most correlated with the (a) first and (b) second principal components of 850 hPa geopotential height for the 168 MCCs of the other subtropical South America region. Purple arrows: jet streak of the low-level jet — no low-level jet in (a), ≥12 m s^{-1} in (b); and green: upper-level jet — ≥32 m s^{-1} in (a), ≥50 m s^{-1} in (b)

moisture advection from the South Atlantic Ocean to the continent prior to the formation of MCCs. Velasco & Fritsch (1987) suggested that because the Amazon Basin is the main source of moisture for the MCCs' genesis area in SA (transported by the LLJ), this region has larger and longer lasting MCCs than the USA. However, SB MCCs not only have the source of moisture from the Amazon Basin but also from the South Atlantic Ocean, which could help explain the greater MCC dimensions in SB relative to the others in the OSSA and USA (Table 2).

Of the MCCs that occurred in OSSA, 3 characteristics differentiate them from those that occurred in SB. First, the 2 principal components (Fig. 6) had negative component loadings for southern SA, instead of positive loadings as shown in the SB principal components (Fig. 3). The corresponding wind field composites suggest that the OSSA MCCs are normally related to cyclonic circulation and cold fronts, while the SB MCCs depend on anticyclonic circulation advecting moisture from the South Atlantic and/or strong moisture advection by the LLJ to the MCC genesis area. Second, the wind field of the first principal component cannot be classified as a LLJ, as it does not meet the criteria widely used in the literature. In addition, it does not have a low-level flow with an exit area south of 25° S, instead forming an atmospheric condition similar to the SACZ. Therefore, when there is no LLJ activity the region of the La Plata Basin, SB in particular has weak convective activity, resulting in no MCCs in SB (Fig. 7a). On the other hand, the southeast, west-central, and northern regions of Brazil have convective activity similar to the SACZ regions, and, consequently, MCCs (Durkee 2008).

When comparing the 850 and 200 hPa wind fields, the SB MCC environment showed evidence of a well defined LLJ and ULJ. The 2 principal components also suggest coupling between these jets (Fig. 9a,b). In these events, as in Maddox (1983), the ULJ with a jet streak ≥32 m s^{-1} indicates that the initial development of the MCCs is occurring in the left entrance area of the jet. The divergent flow associated with the ULJ streak, together with the low-level forcing, could be responsible for the upward vertical circulation that sustains MCC development. Furthermore, the geographic concentration of the MCC development region for the group of SB MCCs (i.e. equatorward of the ULJ) also agrees with the findings of Velasco & Fritsch (1987) in SA.

In the group of MCCs that occurred in OSSA outside of SB, the composite presenting SACZ circulation (Fig. 10a) did not have a strong and defined north wind, but rather a northwest flow toward the South Atlantic Ocean. Nonetheless, this group had ULJ characteristics, with a jet streak magnitude between 32 and 50 m s^{-1}. Another peculiarity of this group, in comparison to the SB MCCs, is that the composite CAPE of the 10 MCCs associated with the first principal component had low values (450 J kg^{-1}), which makes this group more dependent on the coupling between LLJ and ULJ to support the development of MCCs. On the other hand, the second principal component had a defined LLJ and higher CAPE values (between 800 and 1000 J kg^{-1}), which would favor MCC development. In addition, the positioning of their LLJ and ULJ also suggests coupling (Fig. 10b), which also favors the development of MCCs.

MCCs developed north of the 2 jet streaks of the ULJs in the OSSA MCCs first principal component (Fig. 10a). In this case, the mean wind field indicates that there was a contribution of the subtropical jet coupled with the polar jet. Escobar (2009) already described this coupling between the 2 ULJs in SA during cold and transition seasons. Consequently, the northward displacement of the polar jet indicates its association with cold fronts at lower levels, with the jet being located behind the cloud system and above the frontal surface (Escobar 2009). This description corresponds to the case of this principal component, for which 80% of the associated synoptic charts showed the presence of cold fronts, and the positioning of the MCCs (located north of the polar jet) reveals the location of the cloud development area.

Moreover, the MCCs that developed in between the subtropical and polar jets are located near the region where the polar jet passes from trough to ridge, a region where previous studies have indicated that upper-troposphere divergence favors convergence at lower levels (Barboza & Fedorova 1998b). Although the polar ULJ and LLJ do not appear coupled in this case, the flow of this polar ULJ, from equatorward to poleward, contributes to MCC convection and development in this region (Fig. 10a).

The SB MCCs last longer than OSSA MCCs (+3 h) and are at least 50000 km^2 larger on average than the maximum extent in the other regions. Additionally, the characteristics of the atmospheric environment prior to the development of SB MCCs are more easily identifiable than the OSSA MCCs. That is, the characteristic atmospheric environment to indicate occurrences of MCCs in SB are: ≥10 m s^{-1} LLJ (Bonner 1968); a ULJ with a ≥32 m s^{-1} jet streak (Maddox 1983, Guedes 1985); the mean wind field in 850 and 200 hPa in orthogonal position (indicating coupling between LLJ and ULJ) (Trewartha 1954, Uccellini & Johnson 1979); CAPE values >600 J kg^{-1} (Williams & Renno 1993, Barboza & Fedorova 1998a, Tavares & da Mota 2012); vertical shear between 7 and 12 m s^{-1} in the first 3 km of the atmosphere (Laing & Fritsch 2000); moisture advection, represented by IVT patterns >250 kg m^{-1} s^{-1}, and relative humidity concentrated near the SB region with values greater than 80% (Marengo et al. 2009).

Additionally, there are differences in the behavior of the LLJ and ULJ between the MCC groups that occurred in SB from those operating in OSSA, as well as differences in their atmospheric stability. The difference in the direction and the exit region of the LLJ of the OSSA group, in relation to the group from SB, may be useful from an operational forecasting perspective for MCC development. For example, in the first principal component of the MCCs of OSSA, the northerly flow advects moisture from the tropical region to north-central Argentina and to west-central and southeast of Brazil, instead of to SB and its surroundings. Consequently, the MCCs develops to the south (in Argentina) or farther north (in the west-central and southeastern Brazil) of the region of interest (i.e. SB), and moves (from west to east) without crossing SB during its lifecycle.

Finally, it is important to emphasize that the 2 principal components of the SB MCCs indicated the presence of high-pressure systems located in the southwestern South Atlantic and southeastern Pacific, while the 2 principal components of the OSSA MCCs indicated low-pressure systems in southern SA. This suggests that the OSSA MCCs are related to cyclonic circulation and low-level moisture advection mainly from the Amazon Basin, while the majority of SB MCCs have 2 main atmospheric circulation systems responsible for moisture advection to its genesis area: the LLJ (moisture advection from the Amazon Basin), and the anticyclonic circulation (moisture advection from the South Atlantic Ocean).

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