Anuário do Instituto de Geociências
Universidade Federal do Rio de Janeiro
https://revistas.ufrj.br/index.php/aigeo/

TRABALHO DESTAQUE SIMCLEA 13 A 15 DE OUTUBRO DE 2021 SIMPÓSIO EM CLIMA, ÁGUA, ENERGIA E ALIMENTOS

ISSN 0101-9759
e-ISSN 1982-3908

Mesoscale Cyclonic Vortices Embedded in the South Atlantic Convergence Zone Associated with Natural Disasters in the State of São Paulo, Brazil

Vórtices Ciclônicos de Mesoescala Embebidos na Zona de Convergência do Atlântico Sul associados a Desastres Naturais no Estado de São Paulo, Brasil

João Pedro Rodrigues da Silva & Rita Yuri Ynoue

Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Departamento de Ciências Atmosféricas, São Paulo, SP, Brasil

E-mails: joao.rod@alumni.usp.br; rita.ynoue@iag.usp.br
Corresponding author: João Pedro Rodrigues da Silva; joao.rod@alumni.usp.br

Abstract

Natural disasters (NDs) have been observed more frequently and with increasing intensities in Brazil. The South Atlantic Convergence Zone (SACZ) is identified as one of the main meteorological systems responsible for the NDs, however, intense rainfall does not occur along its entire length but is restricted to some locations within the band of cloudiness that defines it. Thus, the objective of this study is to analyze occurrences of mesoscale cyclonic vortices (MCV) in SACZ events that were associated with NDs in the state of São Paulo from 2013 to 2017 using data from the ERA5 Reanalysis, as well as to analyze one case study. To account for SACZ events, surface synoptic charts, observed and estimated precipitation data were used. ND events were selected from the Integrated Disaster Information System (S2ID) database. The methodology used by Quadro (2012) was adapted to identify MCV. The results showed 62 SACZ events, of which 28 were associated with NDs, and, of these, 10 presented MCV. The MCVs were separated into two groups: 1) MCVs in the SACZ events that showed precipitation at the location of the MCV and NDs and 2) MCVs in the SACZ events that did not show precipitation at the location of the MCV and NDs. Group 1 events were characterized by convergence at low levels and divergence at high levels of the atmosphere, vorticity values lower than -8 x 10^{-4} s^{-1} predominating at low levels (850–900 hPa), demonstrating a relationship with the highest precipitation accumulations and possibly with the occurrence of NDs. In the events of group 2, there was a predominance of negative values of vorticity in medium and high levels, the lack of a pattern in the field of divergence in the atmospheric levels, as well as lower values in the accumulated precipitation compared to the events of group 1. The case study was from January 11 to 15, 2016, associated with NDs in 8 cities. As a result, it was obtained that MCV was coupled in the atmosphere and the precipitation associated with it represented more than 37% of all the precipitation of the SACZ event, making it possible to attribute to the MCV a contribution in the occurrence of NDs caused by precipitation.

Keywords: SACZ; MCV; Natural Disasters

Resumo

Desastres naturais (DNs) têm sido observados com mais frequência e intensidades crescentes no Brasil. A Zona de Convergência do Atlântico Sul (ZCAS) é identificada como um dos principais sistemas meteorológicos responsáveis pelos DNs, porém, chuvas intensas não ocorrem em toda a sua extensão, ficando restritas a alguns locais dentro da faixa de nebulosidade que a define. Assim, o objetivo deste estudo é analisar as ocorrências de vórtices ciclônicos de mesoescala (VCME) em eventos ZCAS associados a DNs no estado de São Paulo no período de 2013 a 2017 utilizando dados da Reanálise ERA5, bem como analisar um estudo de caso. Para contabilizar os eventos da ZCAS, foram utilizadas cartas sinóticas de superfície, dados de precipitação observados e estimados. Os eventos de DN foram selecionados a partir do banco de dados do Sistema Integrado de Informações sobre Desastres (S2ID). A metodologia utilizada por Quadro (2012) foi adaptada para identificar o VCME. Os resultados mostaram 62 eventos ZCAS, dos quais 28 estavam associados a DNs e, destes, 10 apresentavam VCME. Os VCMEs foram separados em dois grupos: 1) VCMEs nos eventos de ZCAS que apresentaram precipitação no local do VCMEs e DNs e 2) VCMEs nos eventos ZCAS que não apresentaram precipitação no local do VCMEs e DNs. Os eventos do Grupo 1 foram caracterizados por convergência em baixos níveis e divergência em altos níveis da atmosfera, valores de vorticidade inferiores a -8 x 10^{-4} s^{-1} predominando em baixos níveis (850-900 hPa), demonstrando uma relação

Received: 19 June 2022; Accepted: 12 January 2023
Anu. Inst. Geociênc., 2023;46:53097 DOI: https://doi.org/10.11137/1982-3908_2023_46_53097

com a maior precipitação acumulações e possivelmente com a ocorrência de DNs. Nos eventos do grupo 2, houve a predominância de valores negativos de vorticidade em níveis médios e altos, a falta de um padrão no campo de divergência nos níveis atmosféricos, bem como valores mais baixos na precipitação acumulada em relação aos eventos do grupo 1. O estudo de caso foi de 11 a 15 de janeiro de 2016, associado a DNs em 8 cidades. Como resultado, obteve-se que o MCV estava acoplado na atmosfera e a precipitação associada a ele representou mais de 37% de toda a precipitação do evento ZCAS, sendo possível atribuir ao MCV uma contribuição na ocorrência de NDs. causados pela precipitação.

Palavras-chave: ZCAS; VCME; Desastres Naturais

1 Introduction

According to the Glossary of National Civil Defense, disaster is the result of adverse events, natural or man-made, on a vulnerable ecosystem, causing human, material and/or environmental damage and consequent economic and social damage. The intensity of a disaster depends on the interaction between the magnitude of the adverse event and the degree of vulnerability of the affected receiving system (Castro 1998).

According to the Brazilian Classification and Codification of Disasters (COBRADE 2012) for an event to be considered a natural disaster (ND), it is necessary that at least one of the following criteria occurs: occurrence of home loss and/or displaced persons, landslide events or river overflows (with or without victims), declaration of emergency or declaration of public calamity and deaths.

Marcelino (2008) portrays the types of DNs that most occurred in Brazil in the period from 1900 to 2006, with the Southeast region having the highest records (40%) and flooding as the main causes (59%). Precipitation is one of the atmospheric elements that most contributes to the occurrence of disasters. One of the most drastic consequences of the occurrence of intense rains in a certain region is floods that can still be aggravated by other phenomena such as strong winds, hail, among others (Teixeira & Satyamurty 2004).

The Southeast region of Brazil is affected by the South American monsoon regime (Zhou & Lau 1998) and has two well-established dry and rainy seasons (Reboita et al. 2010). According to Reboita et al. (2010), precipitation in the Southeast region of South America may be associated with several atmospheric systems, such as the passage of frontal systems (Silva, Reboita & Rocha 2014); circulation of breezes (Pereira Filho, Haas & Ambrizzi 2002); convection due to radiative surface heating; transport of moisture from the ocean to the continent through the South Atlantic Subtropical Anticyclone; transport of moisture from the Amazon region to Southeast Brazil through Low Level Jets (LLJ, Marengo et al. 2001), all factors that contribute to the formation and characterization of the South Atlantic Convergence Zone (SACZ) (Kodama 1992).

The SACZ is characterized by a persistent band of cloud cover and precipitation oriented in a northwest-southeast direction from the south/southeast of the Amazon region to the southwest of the South Atlantic Ocean (Carvalho, Jones & Liebmann 2004; Kousky 1988). In the presence of the SACZ there is also an anticyclone at high levels, known as Bolivian High (BH). According to Lenters and Cook (1999), the release of latent heat in the Amazon contributes to the formation of the BH and downwind there is the formation of a trough between the Northeast of Brazil and the Atlantic Ocean. Closed vortices can often appear inside the trough, which are called High Level Cyclonic Vortices (HCVs). In the presence of SACZ and BH, in general, there is a trough over southern Brazil and a ridge over the Southeast region. BH also contributes to intensifying the subtropical high-level jet, a feature of the global atmospheric circulation.

Quadro (1994) defined some meteorological parameters that characterize the presence of SACZ over Brazil, during the summers from 1980 to 1989, analyzing 28 episodes of SACZ over South America. Visual analysis of geostationary satellite images showed organized tropical convection, in terms of a band with northwest/southeast orientation, associated with the presence of frontal systems at the southeast of the South American continent. The analyzes suggest that an episode of SACZ must occur associated with the following meteorological patterns: (i) convergence of humidity in the lower and middle troposphere; (ii) band of upward movement of the air with northwest/southeast orientation; (iii) a semi-stationary trough over the east coast of South America at 500 hPa; (iv) intense potential temperature gradient in the middle troposphere and (v) an anticyclonic relative vorticity range at high levels (200 hPa). The Weather Forecast Group (GPT) of the Weather Forecast Center for Climate Studies (CPTEC-INPE) defined as criteria for the daily identification of this system in the operational environment: 1) a well-established 850 hPa moisture flow from the Amazon region to the Atlantic Ocean through the Midwest and Southeast regions of the country; 2) the upward vertical velocity field (negative values of omega) at 500 hPa in phase with the converging humidity flux at 850 hPa; 3) the BH and the northeast trough, generally well defined; and 4) persistence of a convergence zone at low levels and cloudiness for at least 3 consecutive days. (Escobar 2019; Sacramento Neto, Escobar & Dias Da Silva 2010).

Barcellos et al. (2016) used COBRADE to identify 35 NDs, divided between floods and landslides, which occurred between 1996 and 2015 in the city of Duque de Caxias in the state of Rio de Janeiro. The authors associated these NDs to meteorological systems, using CPTEC analyzes and verified the spatial distribution of precipitation with 116 rain gauges spread throughout the state of Rio de Janeiro. As a result, 57% of the disasters were associated with SACZ, 29% with the passage of frontal systems and 14% with areas of local instability.

Despite the studies mentioned above identifying the SACZ as the meteorological system responsible for the NDs, it is noted that such disasters do not occur all over its extension but are restricted to some locations within the cloud band that defines it. It can be seen, therefore, that analyzes on the synoptic scale are not enough to understand the phenomena that lead to more intense rains.

According to James and Johnson (2010), mesoscale cyclonic vortices (MCV) have become a topic of increasing interest in mesoscale meteorology, largely due to the recognition of their influence on the initiation, organization, and evolution of wet deep convection. Mesoscale cyclonic vortices form both in the tropics and in mid-latitudes, with diameters between 50 and 300 km. They are quasi-stationary and generally form in the lower and middle troposphere, developing together with mesoscale convective systems (MCS) in its mature and dissipating stages. MCVs are characterized by concentrating cyclonic relative vorticity in the lower and middle troposphere and persist after the dissipation of the convective system. This persistence concentrates large volumes of precipitation over the region of influence with subsequent floods. A MCV in the stratiform region of an MSC is characterized by having a hot core, where rising warm air induces convergence at low levels and further contributes to the amplification of the cyclonic vorticity. (Bosart & Sanders 1981; Chen et al. 1998; Davis et al. 2004; Quadro, Silva Dias & Herdies 2016).

MCVs can be associated with SACZs through a feedback process, being generated in a stratiform SACZ environment, intensifying upward movements and transporting moisture to high altitudes. Quadro (2012) identified MCVs embedded in the SACZ cloudiness band, following the detection criteria: a minimum relative vorticity (ζ) around a grid point at a given vertical level, a closed clockwise circulation around the central point of the minimum relative vorticity and an average cloud cover value above 90% which would indicate the presence of cloudiness in the region of vortex formation. In the period from 2000 to 2009, a total of 300 MCVs were found in the lower troposphere and 277 in the middle and upper troposphere. The author identified these MCVs in three different regions: Continental Amazon SACZ; Continental Coastal SACZ, which would be the portion of SACZ in the Center-West/Southeast region of Brazil, and Oceanic SACZ. The most intense eddies, which have cyclonic rotation and relative vorticity minima, are located above the Planetary Boundary Layer (PBL) up to approximately 700hPa, in the Continental Coastal SACZ region, possibly related to topographic effects and local instability generated by transient systems that penetrate the SACZ region. Therefore, the most intense events occur in the lower troposphere, making it possible to verify the agreement between the MCVs and the extremes of precipitation.

2 Methodology and Data

2.1 Region and Period of the Study

The study region is the state of São Paulo, located in the Southeast region of Brazil, with an area of approximately 248 thousand km². São Paulo is the most populous state in the country with 46.6 million inhabitants, concentrating 21.9% of the total Brazilian population. Its relief is composed of mountains, plateaus, and plains. The lowest altitudes are observed in the coastal regions, which is surrounded by the Serra do Mar, and the highest altitudes are found in the Serra da Mantiqueira with values close to and even higher than 2000 m (IBGE - Brazilian Institute of Geography and Statistics 2021). For the study period, the years 2013 to 2017 were chosen, due to the availability of NDs data.

2.2 Observed Precipitation Data

Daily precipitation data were obtained from 206 rain gauges provided by the Department of Water and Electricity (DAEE) of the state of São Paulo from January 1990 to December 2017 and hourly rainfall data from 33 rain gauges in the state of São Paulo available from the website of the National Institute of Meteorology (INMET) from January 2013 to December 2017. Such data were quality control, aiming to identify errors occurred in the process of registration, formatting, transmission and archiving of data (WMO - World Meteorological Organization 2003). Initially, erroneous data in the daily precipitation time series were filtered out using the methodology described by Sugahara et al. (2012), the Interquartile Range (IQR), represented in Equation 1.

$$N = P_{98\%} + 3 * IQR \quad (1)$$

Where P98% is the 98% percentile and IQR is the difference between the 75% and 25% percentile (Sugahara et al. 2012)

Days with values greater than N were only considered when nearby stations measured values close to N, otherwise this data was discarded.

For the hourly data, it was not possible to use the Interquartile Variation methodology because the data period is very short, therefore, only gross errors, such as negative values of precipitation, were discarded.

To complement the observed precipitation, as they present temporal and spatial gaps, daily precipitation data from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) were used. They are precipitation estimates with 0.05° resolution satellites data combined with rainfall stations. Subsequently, the daily rainfall is produced using interpolation techniques to create a unified dataset, being provided in grid points of 0.05° x 0.05° from 1981 to the present (Funk et al. 2015).

For comparison of results, hourly data from INMET stations were accumulated to daily data.

2.3 Identification of SACZ

Surface synoptic maps provided by the Weather Forecast Group (GPT/CPTEC/INPE) produced according to the operational criteria used by the GPT (Escobar 2019) were used to identify the days of SACZ occurrences, which were also compared with the SACZ events used in Silva, Reboita and Escobar (2019).

ERA5 reanalysis, which is derived from the global model of the European Center for Medium-Range Weather Forecast (ECMWF), with spatial resolution of 0.25° latitude by 0.25° longitude and temporal resolution of 1 hour (Herbash et al. 2020) was used to characterize the SACZ events. The selected variables were Pressure at Mean Sea Level; Specific humidity and wind at 850 hPa, for the identification of convergence regions and moisture transport; Vertical velocity (omega) and geopotential height at 500 hPa; Divergence and current lines at 250 hPa.

2.4 Data Collection on Natural Disasters

The database of the Integrated Disaster Information System (S2ID), a system developed by the National Secretariat for Civil Defense and Protection, together with the University Center for Studies and Research on Disasters of the Federal University of Santa Catarina (CEPED – UFSC), was used to identify the NDs providing their locations, dates, and classification according to COBRADE, as well as the number of home losses, displaced, injured and dead victims.

2.5 Identification of the Mesoscale Cyclonic Vortex

With the dates of occurrence of SACZ events that were associated with DNs, it was possible to seek if these events were influenced by a mesoscale cyclonic vortex.

The variables used in this step are relative vorticity, divergence, horizontal and vertical wind components, from 950 to 100 hPa with 50 hPa variation of the ERA5 reanalysis. Images from the infrared channel of the GOES - 13 satellite (Division of Environmental Satellites - INPE) were also used, following a subjective methodology. The criteria established by Quadro (2012) were used to develop an objective system to detect the cyclonic vortices: a minimum relative vorticity (ζ) enclosed by a cyclonic circulation. The algorithm did not consider the presence of clouds.

The detection system scans all grid points at all available vertical levels and outputs the minimum value of relative vorticity, latitude, longitude, and pressure level for each time of the period of occurrence of SACZ. Then it was possible to plot the vertical profiles of relative vorticity and divergence in the center of the vortex.

In this study, the time when the vortex was most intense was chosen, considering the lowest relative vorticity, and the system radius was calculated, adapting the methodology of James and Johnson (2010), where the radius of the MCV is defined where the average relative vorticity between 600 and 500hPa falls below 10% of the minimum relative vorticity of the MCV, however for this study the methodology was applied to all available vertical levels.

After the identification and analysis of the MCVs, the SACZ events were separated into two groups: the events that presented precipitation at the sites of the MCVs and NDs and those that did not.

3 Results

3.1 Counting of SACZ Events, Natural Disasters and Mesoscale Cyclonic Vortices

There were 62 SACZ events in the period 2013 - 2017, with an average of approximately 12 cases per year. Except for two events characterized in May, all events occurred between October and April, as also indicated by Rosa et al. (2020) and Silva, Reboita and Escobar (2019).

The month with the highest frequency of occurrence is February with 12 cases, representing 18% of the total cases and the month with the lowest frequency is May with only two cases, representing 3% of the total. In general, with the ERA5 dataset, it was possible to represent and characterize the events of SACZ, observing the criteria of Escobar (2019): 1) a well-established humidity flow at 850 hPa from the Amazon region to the Atlantic Ocean, passing through the Center-West and Southeast of Brazil; 2) The upward (negative) omega vertical velocity field at 500 hPa in phase with the converging moisture flow at 850 hPa; 3) The presence of the BH and the Northeast trough and in some cases the high level cyclonic vortex.; 4) Persistence of a convergence zone at low levels and cloudiness for at least 3 consecutive days. Despite the characteristics presented, the cloud band associated with SACZ did not always appear well defined and homogeneous, in some cases there was a break in the organization of the cloud band.

Out of the 62 SACZ events, 28 presented NDs in the state of São Paulo and, of these 28, 10 cases with MCVs were found (Table 1). In this study, these 10 SACZ cases with ND and MCVs will be analyzed in detail. For the 34 remaining events that did not present DLs, 31 MCVs were found, but with lower intensities and duration. Finally, 3 SACZ events were not associated with neither NDs nor MCV.

Table 2 shows the characteristics of the NDs that occurred in each of the 10 SACZ+ND+MCV events provided by the S2ID, showing the number of affected cities, the classification of the natural disaster according to COBRADE, the number of deaths, injured, home losses and displaced people. Most of the classifications of natural disasters made by COBRADE showed local and convective storms that were possibly responsible for flooding. Despite the SACZ 1 event presenting the largest number of affected cities, it was not possible to verify the number of deaths. The SACZ event number 41 had the second largest number of affected cities and expressive numbers in terms of home losses and displaced people. Due to these impacts and cyclonic vortex present the most intense vorticity among all cases (Table 3), this number 41 event was chosen for case study.

Table 1 Dates of SACZ events in the period 2013 – 2017 indicating events of NDs and MCVs. The date of the case study is highlighted.

N°	System	Start	End	N°	System	Start	End
1	ZCAS	10/01/2013	17/01/2013	36	ZCAS	17/03/2015	20/03/2015
3	ZCAS	26/01/2013	28/01/2013	**41**	**ZCAS**	**11/01/2016**	**15/01/2016**
13	ZCAS	11/12/2013	13/12/2013	51	ZCAS	13/01/2017	16/01/2017
18	ZCAS	15/02/2014	19/02/2014	52	ZCAS	17/01/2017	23/01/2017
35	ZCAS	09/03/2015	15/03/2015	54	ZCAS	25/02/2017	01/03/2017

Table 2 Characteristics of NDs provided by S2ID in SACZ events. *Indicates missing data. F – Floods; CS – Convective Storms; LA – Landslides; HR – Heavy Rains.

	Events				
S2ID	**SACZ 1**	**SACZ 3**	**SACZ 13**	**SACZ 18**	**SACZ 35**
Number of cities affected	45	5	2	1	1
COBRADE	F; CS; LA	F	CS	F	HR
Dead	*	0	0	0	0
Injured	43	3	64	1	0
Homeless	0	0	24	0	6
Displaced	14	6	152	9	249
S2ID	**SACZ 36**	**SACZ 41**	**SACZ 51**	**SACZ 52**	**SACZ 54**
Number of cities affected	6	8	1	4	1
COBRADE	HR, F	F, CS, LA	F	HR	F
Dead	0	1	0	1	0
Injured	0	14	0	0	0
Homeless	19	27	4	27	8
Displaced	305	721	10	270	18

MCVs' characteristics in the SACZ events that showed (Table 3) and did not showed (Table 4) precipitation at the MCVs and NDs locations are discussed below. All events in Table 3 showed negative divergence at low levels, that is, convergence at low levels; high negative values of vorticity, representing the cyclonic vorticity of these systems and high values in the accumulated precipitation. In the events in Table 4, it can be seen a predominance of negative values of vorticity in medium and high levels, the lack of a well-established divergence field at atmospheric levels, as well as lower values in the accumulated precipitation compared to the events from Table 3.

Table 3 Characteristics of MCVs in SACZ events that presented precipitation at the location of MCVs and NDs. *Indicates that there were no MCVs at this level and **Indicates that it was not possible to identify the radius of the MCVs due to their more elongated shape.

		EVENTS			
		SACZ 1	**SACZ 18**	**SACZ 41**	**SACZ 52**
Maximum convergence found (10^{-4} s^{-1}) and the respective vertical level		-0.6 (500 hPa)	-3.6 (900 hPa)	-4.3 (850 hPa)	-3.5 (700 hPa)
Minimum vorticity found (10^{-4} s^{-1}) and the respective vertical level		-2.5 (500 hPa)	-7.9 (900 hPa)	-8.9 (850 hPa)	-8.9 (700 hPa)
MCV duration (hours)		17	12	52	8
DAEE station with the highest accumulated precipitation in the SACZ occurrence period (mm)		Barbosa 305.9	Pedro de Toledo 268.3	Bebedouro 377.8	Embura 348.9
MCV Radius (km)	**250 hPa**	*	*	50	**
	500 hPa	110	100	70	90
	700 hpa	**	70	140	160
	850 hPa	70	110	110	70

Table 4 Characteristics of MCVs in SACZ events that did not show precipitation at the location of MCVs and NDs. *Indicates that there were no MCVs at this level and **Indicates that it was not possible to identify the radius of the MCVs due to their more elongated shape.

		EVENTS					
		SACZ 3	**SACZ 13**	**SACZ 35**	**SACZ 36**	**SACZ 51**	**SACZ 54**
Maximum convergence found (10^{-4} s^{-1}) and the respective vertical level		-2.1 (750 hPa)	-0.5 (900 hPa)	-1.4 (300-250 hPa)	-1.1 (600 hPa)	-2.3 (450-600 hPa)	-0.8 (600 hPa)
Minimum vorticity found (10^{-4} s^{-1}) and the respective vertical level		-5.1 (750 hPa)	-1.5 (900 hPa)	-3.3 (300-250 hPa)	-3.4 (600 hPa)	-5.9 (450-600 hPa)	-2.4 (600 hPa)
MCV duration (hours)		31	8	37	25	28	38
DAEE station with the highest accumulated precipitation in the SACZ occurrence period (mm)		Praia Grande 121.1	Bertioga 194.1	Pedro de Toledo 190.3	Mongaguá 242.2	Guararapes 157.9	Altinopolis 143
MCV Radius (km)	**250 hPa**	70	*	**	**	70	70
	500 hPa	70	**	**	90	110	70
	700 hpa	80	**	**	70	70	80
	850 hPa	80	**	**	**	**	**

The most intense MCVs events in cyclonic vorticity shown in Table 3 occurred at low levels (800 – 850 hPa), demonstrating a relationship with the highest precipitation accumulations and consequently with the occurrence of NDs. The systems presented radius between 50 and 160 km in the analyzed vertical levels, being smaller than those found by Davis et al. (2004) and James and Johnson (2010), who detected mean radius around 185 km and 224 km, respectively. On average, the MCVs in Table 3 were larger than the MCVs in Table 4, the more intense systems tended to be located at lower levels, had larger radius, and tended to be more circular. SACZ 13 is an exception in this case. Despite being at low levels, the MCV presented low vorticity, making it difficult to identify the radius when applying the proposed methodology.

The MCVs were separated into two groups: MCVs in the SACZ events that 1) showed and 2) did not show precipitation at the site of the MCVs and NDs. The general characteristics of the events are highlighted in Table 5, thus, the events of group 1 were characterized by convergence at low levels and divergence at high levels of the atmosphere; high negative values of vorticity (the most intense values were below -8 x 10-4 s-1) and high values of accumulated precipitation (greater than 300 mm). The most intense MCV events had the lowest cyclonic vorticity values at low levels (850 – 900 hPa), demonstrating a relationship with the highest precipitation accumulations and possibly with the occurrence of NDs. In the events of group 2, a predominance of negative values of vorticity in medium and high levels were observed, the lack of a well-established divergence field in the atmospheric levels, as well as lower values in the accumulated precipitation compared to the events of the group 1.

Table 5 Comparison between group 1 and group 2 SACZ events.

Group 1 – MCV in SACZ events with precipitation at the ND site	Group 2 – MCV in SACZ events without precipitation at the ND site
Convergence at low levels and divergence at high levels;	Overall, there is no pattern of convergence at low levels and divergence at high levels;
Upward movement throughout the atmospheric column;	Upward movement (does not occur throughout the atmospheric column);
Vertically coupled systems;	Vertically coupled systems (less intense);
Circular MCV with a radius between 50 – 160 km;	Elongated MCV (difficulty in identifying the radius);
High negative values of relative vorticity (< -8×10^{-4} s^{-1}) at low levels (850 – 900 hPa);	Negative values of relative vorticity at medium (500 hPa) and high levels (250 hPa);
High accumulated precipitation (>300 mm).	High precipitation accruals, but lower than group 1 events.
Relation between low level MCV x high precipitation x occurrence of ND.	There is no relationship between MCV at high levels with precipitation.

3.2 Case Study of the SACZ 41 Event

The SACZ 41 episode occurred between January 11 and 18th, 2016. However, it only affected the state of São Paulo until the 15th. This event affected 8 cities with DNs in the state of São Paulo, being recorded by COBRADE as floods, local convective storm, landslides. The SACZ started between the 11th and 12th with a dynamical support of a cyclone over the Subtropical Atlantic Ocean (Figure 1A) where it is possible to notice a confluence of the winds close to the surface and at the level of 850 hPa. In the initial phase of the SACZ a frontal system was acting over the South Atlantic Ocean (Figures 1A, 1E, 1I and 1M, light blue line), and it is coupled to the SACZ on the 14th. Over the North and Northeast regions of Brazil, the trade winds transported moisture from the tropical Atlantic Ocean to the interior of the continent towards the center of South America. Part of this moisture precipitated in the Amazon region. The evapotranspiration of the forest added to the oceanic moisture is deflected by the Andes Mountains and transported to the Central-West and Southeast regions of Brazil, joining the winds of the Subtropical High of the South Atlantic (Figure 1B). In the field of vertical velocity and geopotential height at 500 hPa (Figure 1C) there is a trough associated with the cyclone on the surface over the Atlantic Ocean, however, negative values of omega stand out over the Southeast region of the country, mainly over the state of São Paulo, indicating an upward movement, which associated with high values of specific humidity at low levels supports the convective cells start and, consequently, the occurrence of precipitation in this event. The divergence field and streamlines at 250 hPa (Figure 1D) show the typical high-level flow in SACZ events, with the presence of BH, a trough east of northeastern Brazil, associated with the cyclonic vortex of high levels, and the presence of divergence at this level, mainly over the state of São Paulo, providing support for convergence at low levels.

When analyzing a more regional environment, focusing on the state of São Paulo, characteristics of meteorological systems that act on smaller spatial scales, such as mesoscale cyclonic vortices, are observed. Figure 2 shows the same meteorological fields as Figure 1, except for the surface pressure field. A cyclonic circulation at 850 hPa at the north of the state stands out (Figure 2A), associated with a maximum vertical movement at 500 hPa (Figure 2B) described by negative values of omega and a maximum divergence at 250 hPa (Figure 2C), thus representing the formation and evolution of a mesoscale cyclonic vortex in a synoptic SACZ environment. Satellite images (Figure 3) highlight the most intense convections during the 13th with the occurence of an MCS, with temperatures at the top of the clouds around -80°C and the formation of the MCV on the 14th, still showing intense convections, however weaker than those that occurred on the 13th.

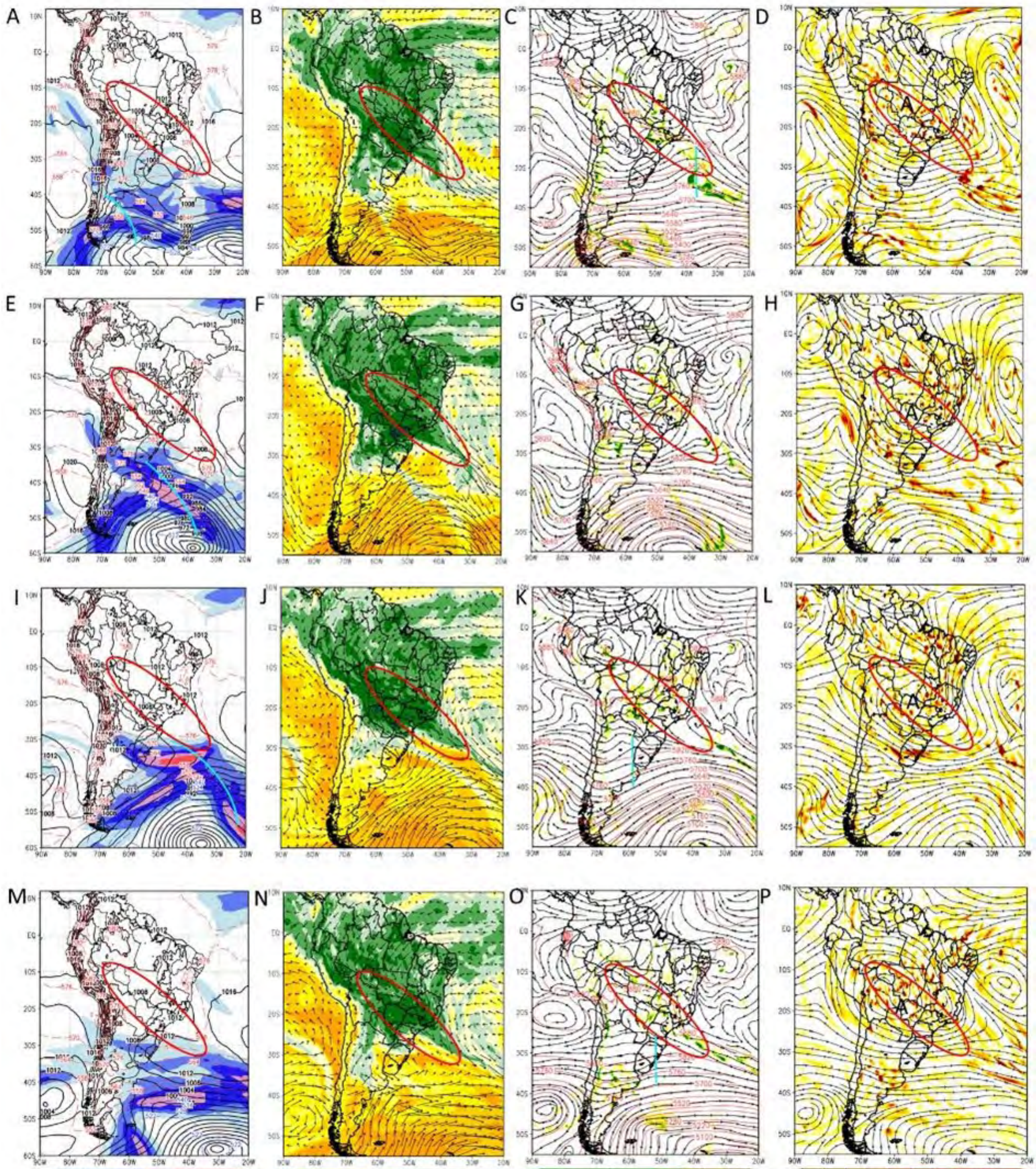

Figure 1 Synoptic Fields: A-E-I-M. Pressure at sea level (hPa, solid lines in black), 500 and 1000 hPa thickness (dam, dashed lines in blue and red) and wind speed at 250 hPa (m s^{-1}, colored); B-F-J-N. Specific Humidity (g kg^{-1}, colored) and wind vectors (m s^{-1}) at 850 hPa; C-G-K-O. Omega (Pa s^{-1}, colored), geopotential height (m, red lines) and streamlines at 500 hPa; D-H-L-P. Divergence (10^{-5} s^{-1}, colored) and streamlines at 250 hPa at 00Z for January 12, 13, 14 and 15, 2016. Red ellipse indicates the SACZ region.

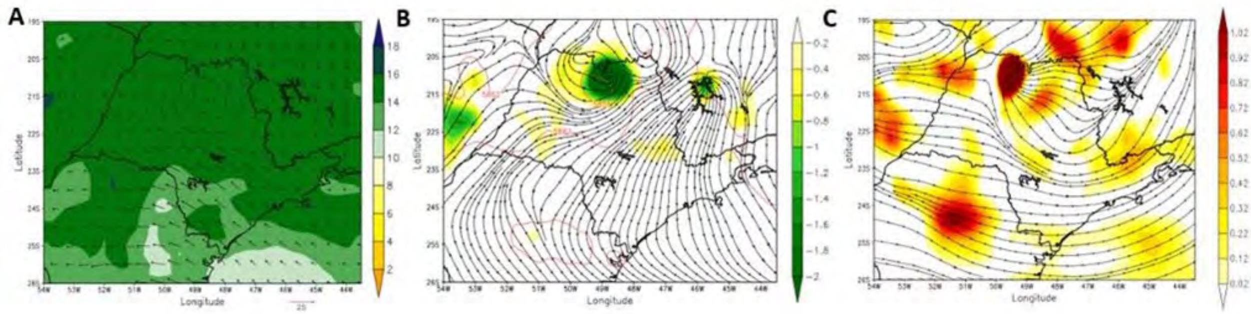

Figure 2 Synoptic Fields: A. Specific Humidity (g kg^{-1}, colored) and wind vectors (m s^{-1}) at 850 hPa; B. Omega (Pa s^{-1}, colored), geopotential height (m, red lines) and streamlines at 500 hPa; C. Divergence (10^{-5} s^{-1}, colored) and streamlines at 250 hPa at 04Z for January 14, 2016.

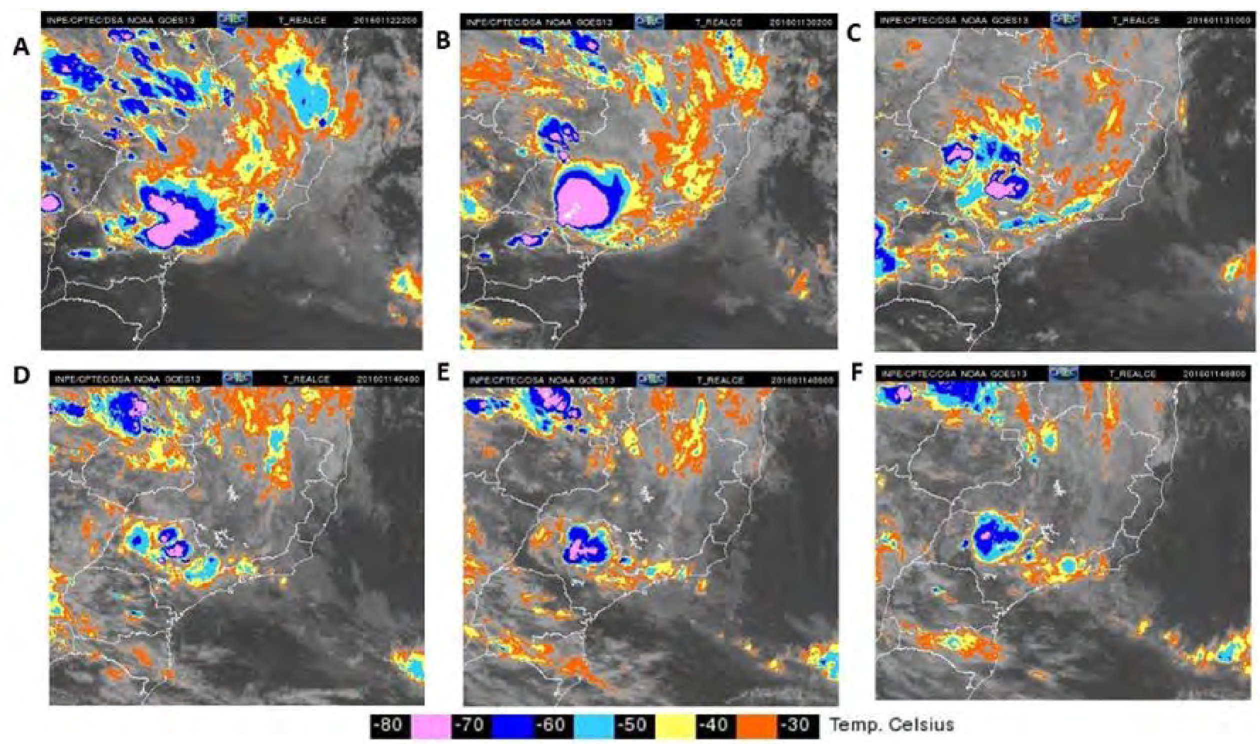

Figure 3 Images from the Infrared Channel of the GOES Satellite – 13 for the days: A. 12th at 22Z; B. 13th at 02Z; C. 13th at 10Z; D. 14th at 4Z; E. 14th at 6Z; F. 14th at 8Z.

The mesoscale cyclonic vortex is represented in the relative vorticity field and streamlines (Figure 4). The system starts on the 13th over the south-central region of the state of São Paulo and reaches its maximum size and intensity during the 14th, with values around -8 x 10^{-4} s^{-1} of relative vorticity (Figure 5A), over the northern portion of the state. The system is vertically coupled, however, the predominance of the lowest relative vorticities occurs at low levels, between 850 and 900 hPa, with a maximum upward movement in the entire atmospheric column hours before the minimum of cyclonic vorticity. This maximum upward movement occurs concomitantly with the convergence at low levels and divergence at high levels, favoring the rise of air for the maintenance of the MCV itself. The system weakens as it moves to the east of the state, persisting in the form of a trough, both at low and medium levels, however without the signature of a cyclonic vortex.

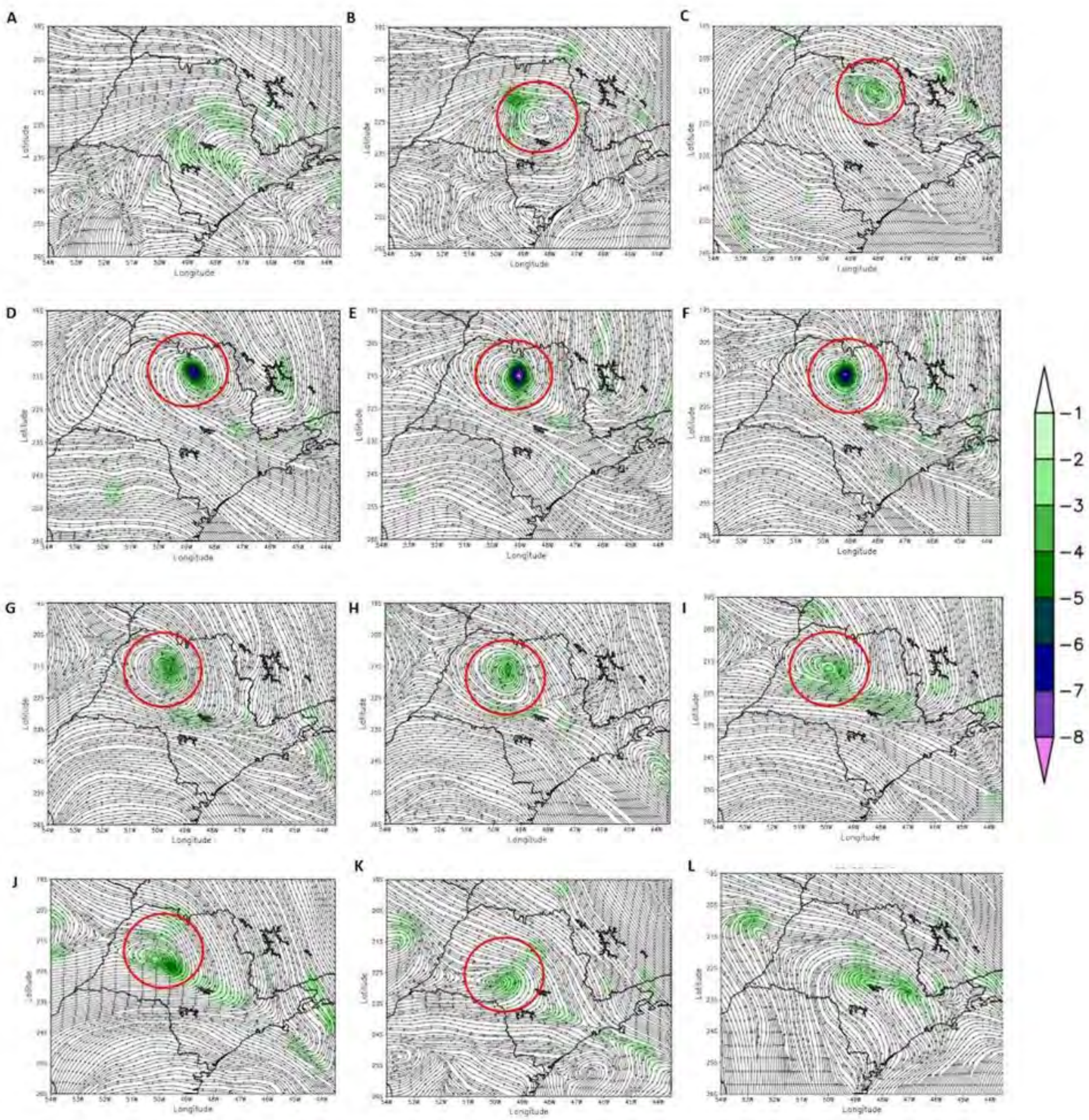

Figure 4 Relative vorticity (10^{-4} s^{-1}, colored) and streamlines at: A. 850 hPa on the 13th at 10Z; B. 850 hPa on the 13th at 13Z; C. 850 hPa on the 14th at 00Z; D. 850 hPa on the 14th at 04Z; E. 850 hPa on the 14th at 08Z; F. 850 hPa on the 14th at 10Z; G. 850 hPa on the 14th at 16Z; H. 850 hPa on the 14th at 19Z; I. 850 hPa on the 15th at 01Z; J. 850 hPa on the 15th at 07Z; K. 850 hPa on the 15th at 14Z; L. 850 hPa on January 15th to 19th, 2016.

When accumulating precipitation in the 5 days of the SACZ event (Day 11, 12, 13, 14 and 15, Figure 6), values close to 300 mm are observed in the CHIRPS dataset (Figure 6B) and 350 mm at INMET and DAEE stations (Figure 6A), a value that approximates and even exceeds the precipitation climatology of January for some locations of ND occurrences, that are around 260 – 280 mm (Ruv Lemes, Reboita & Torres 2019). When comparing the precipitation for the days of occurrence of the MCVs (January 14, 15) with the precipitation of the entire SACZ event in the INMET, DAEE and CHIRPS sets, the MCV contributed with 50%, 37% and 40.8% of the precipitation, respectively. Thus, except for the MCS that acted on the state of SP on the 13th, the precipitation associated with the cyclonic vortices represented an expressive percentage of all the precipitation of the SACZ event. And when observing the regions with the highest accumulated precipitation, it appears that they were located close to 3 of the 8 cities (represented by red triangles inside the circles in Figure 6) where there were records of NDs, making it possible to attribute to the MCV a contribution in the occurrence of DNs caused by precipitation.

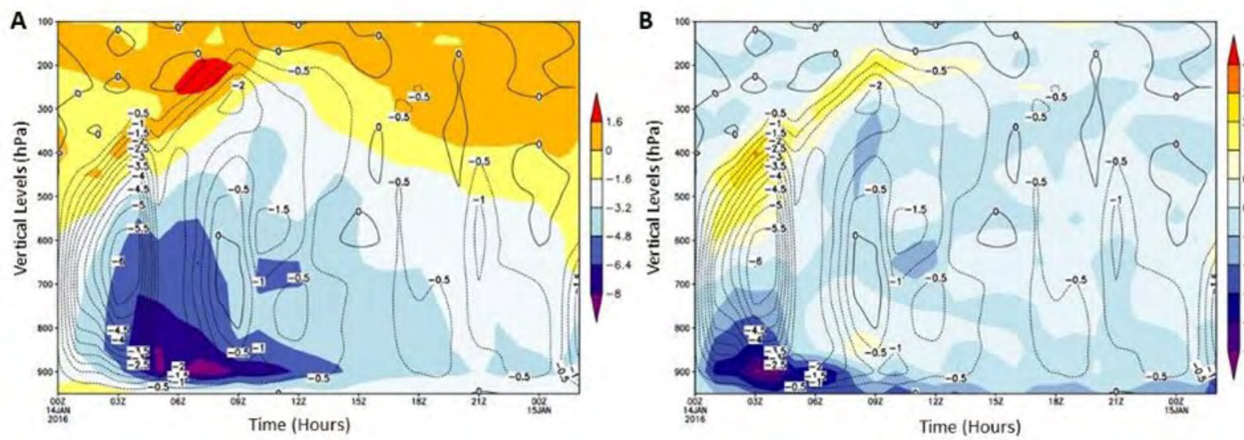

Figure 5 Vertical profile at the center of the MCV: A. Relative vorticity (x 10^{-4} s^{-1}, colored) and Omega (Pa s^{-1}, negative values in dashed lines); B. Divergence (x 10^{-4} s^{-1}, colored) and Omega (Pa s^{-1}, lines).

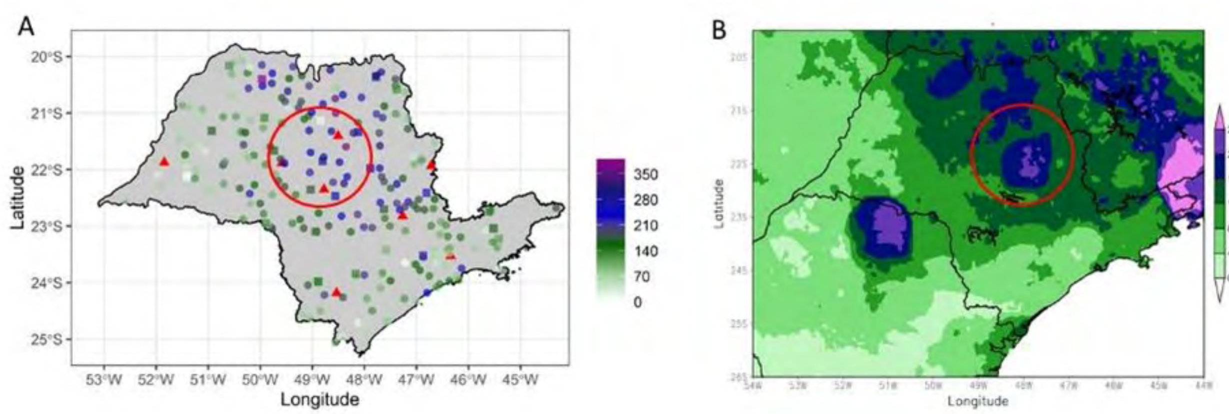

Figure 6 Accumulated precipitation during SACZ (January 11 - 15): A. Daily precipitation (mm) from INMET (squares) and DAEE (circles); B. Daily precipitation (mm) from CHIRPS. The red triangles in A. identify the locations with NDs.

4 Conclusion

This study analyzed the occurrences of mesoscale cyclonic vortices in SACZ events that were associated with DNs in the state of São Paulo from 2013 to 2017 using the ERA5 reanalysis dataset. 62 SACZ events were recorded in this period. The month with the highest frequency of occurrence was February with 12 cases, representing 18% of the total cases and the month with the lowest frequency was May with only two cases, representing 3% of the total. Of the total number of cases, 28 presented DNs in the state of São Paulo and, of these 28, 10 cases were found with MCVs. Out of the 34 remaining events that did not present DNs, 31 MCV were found, but with lower intensities and duration. Finally, 3 SACZ events were not associated with neither DN nor MCV. In general, with the ERA5 dataset, it was possible to represent and characterize the events of SACZ, observing the criteria of Escobar (2019).

The event from January 11 to 15, 2016 was selected, which was associated with high values of observed precipitation, in the three data sets used, and 8 cities with DNs throughout the state of São Paulo. The highest precipitation accumulations and the highest convective activities were observed on the 13th and 14th, days in which the performance of an MCS stands out and as also a later MCV with minimum relative vorticity at 900 and 850 hPa. From the vertical profile of relative vorticity, it is possible to affirm that the cyclonic vortex remains vertically coupled during the study period and through the vertical profile of divergence and vertical velocity of these systems, there is a behavior of convergence at low levels and divergence at high levels, supporting upward movement throughout the atmospheric column. The precipitation associated with cyclonic vortices represented more than 37% (considering the lowest percentage among the three datasets) of all precipitation from the SACZ event, with the highest precipitation accumulations located near 3 of the 8 cities with records of NDs, being possible to attribute to the MCVs a contribution in the occurrence of the NDs caused by precipitation. Thus, it is important to highlight the contribution of the SACZ at the synoptic scale, through the transport of moisture from the Amazon region and the Atlantic Ocean to Southeast Brazil, the persistence of a band of cloudiness and precipitation, which ends up favoring the occurrence of precipitation events and later, possible NDs. However, only analyzes on the synoptic scale are not enough to understand the phenomena that lead to more intense rains, the analysis of mesoscale atmospheric systems becomes relevant, as it is possible to verify the causes of precipitation on a regional and even local scales.

5 References

Barcellos, P.C.L., Silva, F.P., Vissirini, F.S.B., Magalhães, C.A., Terra, J.M., Dutra, M.R.F. & Amaral, I.C.F. 2016, 'Diagnóstico Meteorológico dos Desastres Naturais Ocorridos nos Últimos 20 Anos na Cidade de Duque de Caxias', *Revista Brasileira de Meteorologia*, vol. 31, no. 3, pp. 319-329, DOI:10.1590/0102-778631320150146.

Bosart, L.F. & Sanders, F. 1981, 'The Johnstown flood of July 1977: A long-lived convective system', *Journal of Atmospheric Science*, vol. 38. pp. 1616–42, DOI:10.1175/1520-0469(1981)038<1616:TJFOJA>2.0.CO;2.

Carvalho, L.M.V., Jones, C. & Liebmann, B. 2004, 'The South Atlantic convergence zone: Intensity, form, persistence, and relationships with intraseasonal to interannual activity and extreme rainfall', *Journal of Climate*, vol. 17, pp. 88–108, DOI:10.1175/1520-0442(2004)017<0088:TSACZI>2.0.CO;2.

Castro, A.L.C. 1998, *Glossário de defesa civil: estudo de riscos e medicina de desastres*, MPO/Departamento de Defesa Civil, Brasília, viewed 19 August 2022, <http://www.defesacivil.mg.gov.br/images/documentos/Defesa%20Civil/manuais/GLOSSARIO-Dicionario-Defesa-Civil.pdf>.

COBRADE – Classificação e Codificação Brasileira de Desastres 2012, *COBRADE*, viewed 20 August 2022, <https://www.defesacivil.pr.gov.br/sites/defesa-civil/arquivos_restritos/files/documento/2018-12/Cobrade_comsimbologia.pdf>.

Chen, S.J., Kuo, Y.H., Wang, W., Tao, Z.Y. & Cu, B. 1998, 'A modeling case study of heavy rainstorms along the Mei-Yu front', *Monthly Weather Review*, vol. 126, pp. 2330–51, DOI:10.1175/1520-0493(1998)126<2330:AMCSOH>2.0.CO;2.

Davis, C., Atkins, N., Bartels, D., Bosart, L., Coniglio, M., Bryan, G., Cotton, W., Dowell, D., Jewett, B., Johns, R., Jorgensen, D., Knievel, J., Knupp, K., Lee, W.C., Mcfarquhar, G., Moore, J., Przybylinski, R., Rauber, R., Smull, B., Trapp, R., Trier, S., Wakimoto, R., Weisman, M. & Ziegler, C. 2004, 'The Bow Echo and MCV Experiment: Observations and opportunities', *Bulletin of American Meteorologycal Society*, vol. 85, pp. 1075-93, DOI:10.1175/BAMS-85-8-1075.

Escobar, G.C.J. 2019, *Zona de Convergência do Atlântico Sul (ZCAS): Critério de detecção para uso em centros operacionais de previsão de tempo*, Instituto Nacional de Pesquisas Espaciais – INPE, São Jose dos Campos, viewed 20 August 2022, <http://urlib.net/8JMKD3MGP3W34R/3SGMUDP>.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shraddhanand, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. 2015, 'The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes', *Scientific Data*, vol. 2, no. 150066, DOI:10.1038/sdata.2015.66.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. & Thépaut, J.N. 2020, 'The ERA5 global reanalysis', *Quarterly Journal of the Royal Meteorological Society*, vol. 146, pp. 1999–2049, DOI:10.1002/qj.3803.

IBGE – Instituto Brasileiro de Geografia e Estatística 2021. *Área Territorial Brasileira*, IBGE, Rio de Janeiro, viewed in 20 August 2022, <https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial/15761-areas-dos-municipios.html?t=acesso-ao-produto&c=1>.

James, E.P. & Johnson, R.H. 2010, 'Patterns of precipitation and mesolow evolution in midlatitude mesoscale convective vortices', *Monthly Weather Review*, vol. 138, pp. 909–31, DOI:10.1175/2009MWR3076.1.

Kodama, Y. 1992, 'Large-scale common features of Sub-tropical Precipitation Zones (the Baiu Frontal Zone, the SPCZ, and the SACZ). Part I: characteristics of Subtropical Frontal Zones', *Journal of Meteorological Society of Japan*, vol. 70, no. 4, pp. 813-35, DOI:10.2151/jmsj1965.70.4_813.

Kousky, V. E. 1988, 'Pentad outgoing longwave radiation climatology for the South American sector', *Revista Brasileira de Meteorologia*, vol. 3, pp. 217-31.

Lenters, J.D. & Cook, K.H. 1999, 'Summertime precipitation variability over South America: Role of the large-scale circulation', *Monthly Weather Review*, vol. 127, pp. 409-

31, DOI:10.1175/1520-0493(1999)127<0409:SPVOSA>2.0.CO;2.

Marcelino, E.V. 2008, *Desastres Naturais e Geotecnologias: Conceitos Básicos*, INPE/CRS, Santa Maria, viewed 19 August 2022, <http://mtc-m16c.sid.inpe.br/col/sid.inpe.br/mtc-m18@80/2008/07.02.16.22/doc/publicacao.pdf>.

Marengo, J.A., Liebmann, B., Kousky, V., Filizola, N. & Wainer, I. 2001, 'On the onset and end of the rainy season in the Brazilian Amazon Basin', *Journal of Climate*, vol. 14, pp. 833-53, DOI:10.1175/1520-0442(2001)014%3C0833:OAEOTR%3E2.0.CO;2.

Pereira Filho, A.J., Haas, R. & Ambrizzi, T. 2002, 'Caracterização de eventos de enchentes na bacia do Alto Tietê por meio do radar meteorológico e da modelagem numérica de mesoescala', *Congresso Brasileiro de Meteorologia*, vol. 12, Foz do Iguaçu, PR.

Quadro, M.F.L. 1994, 'Estudos de episódios de Zona de Convergência do Atlântico Sul (ZCAS) sobre a América do Sul', Master's dissertation, Instituto Nacional de Pesquisas Espaciais, São José dos Campos.

Quadro, M.F.L. 2012, 'Estudo de Vórtices Ciclônicos de Mesoescala associados à Zona de Convergência do Atlântico Sul', PhD thesis, Universidade de São Paulo.

Quadro, M.F.L., Silva Dias, M.A.F. & Herdies, D.L. 2016, 'Análise de um Vórtice Ciclônico de Mesoescala Associado à ZCAS em Janeiro de 2009', *Revista Brasileira de Meteorologia*, vol. 31, no. 3, pp. 273-87, DOI:10.1590/0102-778631320150141.

Reboita, M.S., Gan, M.A., Rocha, R.P. & Ambrizzi, T. 2010, 'Regimes de precipitação na América do Sul: uma revisão bibliográfica', *Revista Brasileira de Meteorologia*, vol. 25, no. 2, pp. 185-204, DOI:10.1590/S0102-77862010000200004.

Rosa, E.B., Pezzi, L.P., Quadro, M.F.L & Brunsell, N. 2020, 'Automated Detection Algorithm for SACZ, Oceanic SACZ, and Their Climatological Features', *Frontiers In Environmental Science*, vol. 8, e18, DOI:10.3389/fenvs.2020.00018.

Ruv Lemes, M.C., Reboita, M.S. & Torres, R.R. 2019, 'Elementos Fisiográficos e a Precipitação no Estado de São Paulo', *XVIII Simpósio Brasileiro de Geografia Física Aplicada*, vol. 18, Fortaleza, CE.

Sacramento Neto, O.B., Escobar, G.C.J. & Dias Da Silva, P.E. 2010, 'Método objetivo para identificar episódios de Zonas de Convergência de Umidade (ZCOU) no ambiente operacional do Centro de Previsão de Tempo e Estudos Climáticos – CPTEC', *Congresso Brasileiro de Meteorologia,* Belém, PA.

Silva, L.J., Reboita, M.S. & Rocha, R.P. 2014, 'Relação da Passagem de Frentes Frias na Região Sul de Minas Gerais (RSMG) com a Precipitação e Eventos de Geada', *Revista Brasileira de Climatologia*, vol. 14, no. 10, pp. 229-46, DOI:10.5380/abclima.v14i1.36314.

Silva, J.P.R., Reboita, M.S. & Escobar, G.C.J. 2019, 'Caracterização da Zona de Convergência do Atlântico Sul em campos atmosféricos recentes', *Revista Brasileira de Climatologia*, vol. 25, pp. 355-77, DOI:10.5380/abclima.v25i0.64101.

Sugahara, S., Da Rocha, R.P., Ynoue, R.Y. & Da Silveira, R.B. 2012, 'Homogeneity assessment of a station climate series (1933-2005) in the Metropolitan Area of São Paulo: instruments change and urbanization effects', *Theoretical and Applied Climatology*, vol. 107, no. 3-4, pp. 361-74, DOI:10.1007/s00704-011-0485-x

Teixeira, M.S. & Satyamurty, P. 2004, 'Episódios de chuvas intensas na região sul do Brasil. Parte I: configuração sinópticas associadas', *Congresso Brasileiro de Meteorologia*, Fortaleza.

WMO - World Meteorological Organization 2003, *Guidelines on Climate Metadata and Homogenization*, Secretariat of the World Meteorological Organization, Geneva, viewed 19 August 2022, <https://library.wmo.int/doc_num.php?explnum_id=10751>.

Zhou, J. & Lau, K.M. 1998, 'Does a Monsoon Climate Exist Over South America', *Journal of Climate*, vol. 11, no. 5, pp. 1020-40, DOI:10.1175/1520-0442(1998)011%3C1020:DAMCEO%3E2.0.CO;2.

Author contributions

João Pedro Rodrigues da Silva: conceptualization; formal analysis; methodology; validation; writing - original draft; writing review and editing; visualization. **Rita Yuri Ynoue:** writing review and editing; supervision.

Conflict of interest

The authors declare no potential conflict of interest.

Data availability statement

All data included in this study are publicly available in the literature.

Funding information

CNPq, Process Nº 130631/2019-1.

Editor-in-chief

Dr. Claudine Dereczynski

Associate Editor

Dr. Fernanda Cerqueira Vasconcellos

How to cite:

Silva, J.P.R & Ynoue, R. Y. 2023, 'Mesoscale Cyclonic Vortices Embedded in the South Atlantic Convergence Zone Associated with Natural Disasters in the State of São Paulo', *Anuário do Instituto de Geociências,* 46:53097. https://doi.org/10.11137/1982-3908_2023_46_53097