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Circulação Atmosférica em Superfície Associada às Friagens no Centro-Oeste do Brasil
Surface Atmospheric Circulation Associated With "Friagens" in Central-West Brazil

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Resumo

O termo friagem é utilizado para definir a queda de temperatura do ar nas latitudes tropicais, entretanto, a maioria dos estudos o associa com a chegada de uma frente fria na região norte do Brasil. Nesse contexto, aqui se tem como finalidade mostrar que na região Centro-Oeste também ocorrem friagens. Para isso, desenvolveu-se uma metodologia baseada na temperatura máxima diária a fim de identificar os eventos de friagem ocorridos entre 1961 a 2012 na cidade de Cuiabá (MT). Por fim, é apresentada a classificação sinótica dos padrões de circulação em baixos níveis associados com os eventos de friagem. Os resultados mostram que os episódios de friagem estão associados com declínios diários da temperatura máxima superiores a 10°C e que podem ocorrer no dia da chegada da frente fria em Cuiabá ou um dia após. No período em estudo, foram identificados 217 casos de friagem que, na maioria, estão associados a quatro padrões sinóticos que representam 74,6% de todos os casos de friagem no Centro-Oeste do Brasil. O padrão sinótico mais frequente mostra um anticiclone pós-frontal que se desloca do oceano Pacífico Sul em direção ao continente, favorecendo uma forte advecção de ar frio sobre a porção central do Brasil. Porém, existem outros três padrões sinóticos importantes para os episódios de friagens no Centro-Oeste do Brasil que estão relacionados com frentes frias, situações de bloqueio sobre o oceano Atlântico e eventos ciclogenéticos no sul do Brasil.
Palavras-chave: classificação sinótica; componentes principais; friagens; Brasil

Abstract

The term "friagem" is used to define the decrease of air temperature in tropical latitudes; however, most of the studies associate it with the arrival of a cold front in the northern region of Brazil. In this context, the study aims to show that in the Central-West region also occur "friagens". For this reason, a methodology based on daily maximum temperature is presented. The frequency of "friagem" episodes (1961-2012) in the city of Cuiabá (MT) was determined, and finally a synoptic classification of the surface circulation associated with these events was presented. The results show that "friagens" are associated with daily maximum temperature declines above 10 °C that can occur on the day of arrival of the cold front in Cuiabá or one day after. During the study period, 217 cases of "friagem" were identified, which are mostly associated with four synoptic patterns, which represent 74.6% of all "friagem" cases in the Central-West of Brazil. The most frequent synoptic pattern shows a post-frontal anticyclone that moves from the South Pacific Ocean toward the continent, favoring a strong cold air advection over the central portion of Brazil. However, three other synoptic patterns are important for the "friagens" in the Central-West of Brazil, which are related with cold fronts, blocking situations on the Atlantic Ocean and cyclogenetic events in southern Brazil, respectively.
Keywords: synoptic classification; principal components; friagens; Brazil

1 Introduction

"Friagens" (locally known term) are defined as cold surges that invade the tropics and affect the Amazon (Marengo *et al.*, 1997) producing a great impact on the population due to the decrease of the air temperature and humidity (Oliveira *et al.*, 2004). Marengo *et al.* (1997) mention that the intensity of the "friagens" is associated with the magnitude of the changes in the weather conditions caused by the penetrating cold air. There is on average between six and eight events of "friagem" per year (Fisch, 1996; Ricarte, 2012) in the North and Central-West regions of Brazil and are frequently observed during the late austral autumn and early spring (Parameter, 1976; Satyamurty *et al.*, 1990; Marengo *et al.*, 1997). Most cold incursions are associated with the passage of mid-latitude waves, which interact with the Andes mountains, and propagate equatorward (Vera and Vigliarolo, 2000; Garreaud, 2000; Lupo *et al.*, 2001; Cavalcanti & Kousky, 2003). According to Pezza & Ambrizi (2005), blocking-like patterns are also observed over the southeastern Pacific Ocean surface at the same time as the cold incursions in Brazil.

Escobar & Bischoff (1999); Müller *et al.* (2003); Escobar *et al.* (2004); Escobar (2007) and Reboita *et al.* (2015) applied Principal Components Analysis (PCA) to obtain an objective synoptic classification of cold air incursions and/or frosts occurrence in central Argentina and southeastern Brazil. The authors showed that the most typical pattern related to cold events in South America is the presence of a large ridge in mid-levels over the Pacific Ocean near the coast of South America and that is associated with an intense surface post-frontal anticyclone favoring cold air advection from the south.

There are different ways to identify cold waves (including "friagens"). However, most of them consider both daily maximum and minimum temperatures (Gonçalves *et al.*, 2002). Ricarte (2012) carried out a 30-year climatology (1979 to 2008) of "friagem" events occurring in the south of the northern region of Brazil from May to September. A total of 202 "friagem" events were identified using an objective method that took into account the climatological information of the minimum temperature, the sea level pressure and the tendency of the minimum temperature decline in the city of Vilhena (Rondônia State). More recently, Lanfredi & Camargo (2018) analyzed the most extreme cold waves in different areas of South America, including the southern part of the northern region of Brazil. The authors used the temperature as the main variable to identify the most extreme cold waves. According to Escobar & Bischoff (2001), in order to define a significant decrease in the air temperature, not only the decreasing of this variable must be considered, but also the temperature value on the previous and post-event days.

Although the literature considers as "friagem" the decrease in air temperature over the Amazon region due to the passage of the cold fronts (e.g. Marengo *et al.*, 1997), in other tropical places of Brazil, these systems also impact the air temperature as in Cuibá, a city located in central latitude of the Central-West region of Brazil (Figure 1). According to the Köppen & Geiger (1928)'s climate classification, Cuiabá belongs to the AW climate type, known as Tropical Wet and Dry Savanna Climate, with high temperatures whole the year and a dry season in the austral winter. As a result of diurnal heating, this city presents high values of maximum temperature every day. However, frontal systems that reach Cuiabá produce a great decrease in air temperature, mainly in the maximum temperature. For this reason, we can consider that in Cuiabá also occurs "friagens". In this context, the purposes of this work are to identify "friagem" events in Cuiabá, with a methodology based on maximum temperature, and the principal modes of atmospheric circulation at surface associated with these events. Our intention is to show the propagation of the cold surges by mean of the different weather systems that lead the cold air into Central-West Brazil. This information will be very useful to improve the weather forecast for this kind of extreme events.

2 Methodology
2.1 "Friagem" Detection Criteria

We initially present the steps that helped to establish the criteria to define the "friagem" events. The goal is to identify the maximum temperature decrease and the magnitude of this decrease associated with the passage of the cold fronts in Cuiabá (Figure 1) to characterize the “friagem” events. For this reason, we selected 23 synoptic charts with cold front occurrence over Cuiabá in the period 2007-2012. The weather charts were obtained from the Center for Weather Forecasting and Climate Studies (CPTEC). This center has elaborated synoptic charts since 2007-year.

The synoptic charts helped to identify the magnitude of the decrease in maximum temperature and the moment of the highest fall of this variable, which depends on the cold front velocity. When there is a fast-moving cold front, the temperature decrease occurs on the same day as the cold front reaches Cuiabá. With slower systems, it occurs in the following day. With 23 cold front events, daily maximum temperature decrease was calculated for one day (ΔT_1) and two days (ΔT_2), using the following definition:

$$\Delta T_1 = T_d - T_{d-1}$$

$$\Delta T_2 = T_{d+1} - T_{d-1}$$

where

ΔT_1 = Daily decline of maximum temperature in one day;

ΔT_2 = Daily decline of maximum temperature in two days;

T_{d-1} = Maximum temperature of the day before the cold front arrival;

T_d = Maximum temperature of the day of the cold front arrival;

T_{d+1}= Maximum temperature of the day after the cold front arrival;

The values of the maximum temperature and their respective declines associated with the 23 cases of cold fronts identified in Cuiabá are shown in Table 1.

In most of the cases (Table 1), the maximum temperature of the day before the cold front arrival (T_{d-1}) is higher than 32 °C and their respective daily declines observed in one day (ΔT_1) and two days (ΔT_2) varies from -4 °C to -15.3 °C and from -6.5 °C to -18.8 °C, respectively. The maximum temperature in the cold front arrival day (Td) does not exceed 31.7 °C, whereas on the following day (T_{d+1}) the maximum temperature varies between 13.3 °C and 29.7 °C. Therefore, as higher the decline of the maximum temperature during the day of the cold front arrival (T_d) as greater the probability of the “friagem” occurs on that day. Otherwise, the “friagem” will occur in the next day (T_{d+1}). In this way, the “friagem” date can be that of the day (T_d) of the cold front arrival or that of the day after it (T_{d+1}).

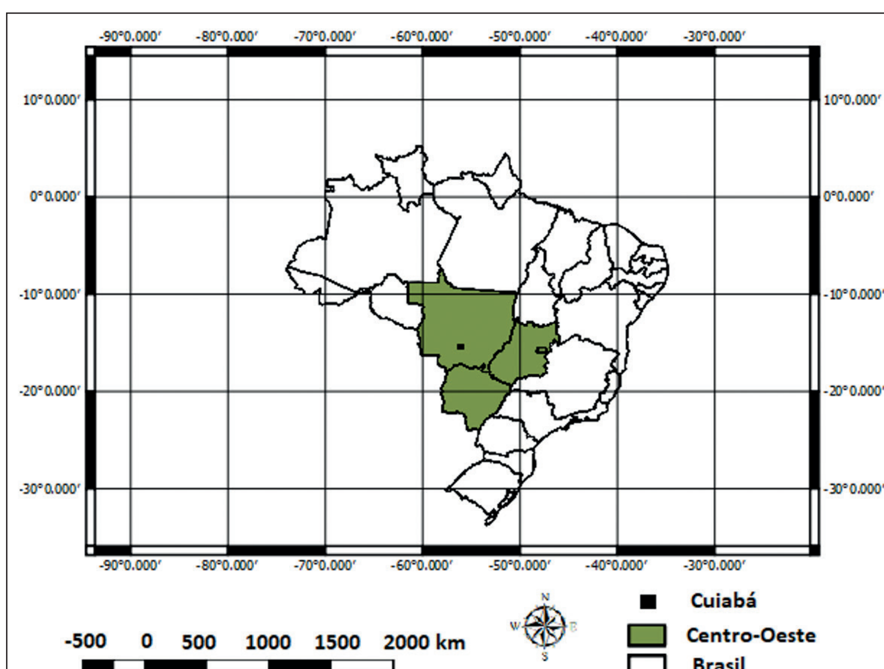

Figure 1 Geographical location of the Central-West Brazilian region (green) and Cuiabá city (black square).

Day	T_{d-1}	T_d	T_{d+1}	ΔT_1	ΔT_2
08/05/2007	35.7	28.2	19.5	-7.5	-16.2
23/05/2007	33.8	26.9	21.1	-6.9	-12.7
02/06/2007	34.1	27.6	22.8	-6.5	-11.3
25/07/2007	34.6	29.0	22.7	-5.6	-11.9
27/08/2007	37.2	25.2	26.5	-12.0	-10.7
12/06/2009	33.0	25.1	22.6	-7.9	-10.4
24/06/2009	33.2	24.5	23.1	-8.7	-10.1
24/07/2009	34.9	21.2	16.1	-13.7	-18.8
09/08/2009	36.7	27.9	24.4	-8.8	-12.3
20/08/2009	38.7	31.7	24.5	-7.0	-14.2
29/09/2009	36.2	25.3	29.7	-10.9	-6.5
08/05/2010	36.0	27.4	21.8	-8.6	-14.2
19/05/2010	36.1	27.8	24.1	-8.3	-12.0
16/07/2010	25.0	15.0	13.3	-10.0	-11.7
02/05/2011	32.7	26.7	21.2	-6.0	-11.5
26/06/2011	32.3	25.3	20.7	-7.0	-11.6
02/07/2011	34.2	26.3	19.7	-7.9	-14.5
02/08/2011	33.4	25.4	21.8	-8.0	-11.6
21/08/2011	32.3	21.1	25.4	-11.2	-6.9
05/06/2012	33.1	23.8	22.4	-9.3	-10.7
07/07/2012	34.5	25.2	21.7	-9.3	-12.8
16/07/2012	32.0	28.0	21.6	-4.0	-10.4
26/08/2012	37.0	21.7	26.1	-15.3	-10.9

Table 1 Maximum temperature and daily decline of maximum temperature occurred in one and two days in the cases associated with cold front occurrences in Cuiabá identified through surface synoptic charts from CPTEC/INPE. Day: cold front event occurrence date, T_{d-1} is the observed maximum temperature in the day before the event, T_d is the observed maximum temperature in the event day, T_{d+1} is the observed maximum temperature one day after the event, ΔT_1 is the daily decline of maximum temperature in one day, and ΔT_2 is the daily decline of maximum temperature in two days.

To verify if the daily decline of the maximum temperature is associated with a cold incursion, the maximum temperature in the "friagem" day must be significantly below the mean climatological maximum temperature ($\overline{T}_{Max}$) for a specific period of the year (Escobar and Bischoff, 2001). For this reason, it was calculated both the mean climatological maximum temperature ($\overline{T}_{Max}$) and standard deviation (σ) for each month from April to November in Cuiabá. These statistical parameters (Table 2) were obtained from daily maximum temperature obtained from a meteorological station in Cuiabá (15.5 °S, 56.0 °W), in the period 1961-2012, belonging to the National Meteorological Institute (INMET).

Variables	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
$\overline{T}_{Max}$	32.7	31.4	31.3	32.0	34.1	34.3	34.4	33.5
σ	2.8	3.7	4.0	4.5	4.2	4.3	3.2	2.7
1.5σ	4.2	5.5	6.0	6.8	6.4	6.4	4.7	4.1
2σ	5.6	7.4	8.0	9.0	8.4	8.6	6.4	5.4
2.5σ	7.0	9.2	10.0	11.2	10.5	10.7	8.0	6.7
$\overline{T}_{Max}$ - σ	29.9	27.7	27.3	27.5	29.9	30.0	31.2	30.8
$\overline{T}_{Max}$ -1.5σ	28.5	25.9	25.3	25.2	27.7	27.9	29.7	29.4
$\overline{T}_{Max}$ -2σ	27.1	24.0	23.3	23.0	25.7	25.7	28.0	28.1
$\overline{T}_{Max}$ -2.5σ	25.7	22.2	21.3	20.8	23.6	23.6	26.4	26.8

Table 2 Mean and standard deviation of the maximum temperature for each month from April to November in Cuiabá in the period 1961-2012.

In order to define a "friagem" event, not only the magnitude of the maximum temperature decline must be considered, but also the maximum temperature value in the "friagem" day. Through the information shown in Tables 1 and 2, it can be observed that when the maximum temperature after the cold front passage (T_d or T_{d+1}) is lower than the mean climatological maximum temperature minus two standard deviations ($\overline{T}_{Max}$ -2σ), the daily maximum temperature declines (Δ_{T1} or Δ_{T2}) are in general higher than 10 °C.

Using the previous information, the established criteria to detect "friagem" events are:

To each month, the daily decline of maximum temperature in one day (ΔT_1) or in the following day (ΔT_2), must be greater than 10 °C ($|\Delta T_1| \geq 10$ °C or ($|\Delta T_2| \geq 10$ °C.

To each month, the daily maximum temperature observed in the day of the cold front arrival (T_d) or in the following day (T_{d+1}) must be below of the mean climatological maximum temperature ($\overline{T}_{Max}$) minus two standard deviations (σ) ($Td \leq \overline{T}_{Max} - 2\sigma$ or $T_{d+1} \leq \overline{T}_{Max} - 2\sigma$).

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The developed criteria (a) and (b) were applied in the maximum temperature obtained from INMET in the period 1961-2012 (from April to November) to obtain a climatology of "friagem" events in Cuiabá.

With the occurrence date of "friagens" was possible to carry out a synoptic classification. For this analysis, we used daily mean sea level pressure at 12 Z, from the JRA-55 Reanalysis from the Japan Meteorological Agency (JMA) (Kobayashi *et al.*, 2015), also to the period 1961-2012. These data are available at a spatial resolution of 1.25 ° latitude x 1.25 ° longitude.

2.2 Principal Component Analysis (PCA)

In the present study, the PCA in T-Mode using correlation input matrix (Green & Carroll, 1978; Richman, 1983; Compagnucci & Salles, 1997; Escobar & Bischoff, 1999; Escobar, 2014) was applied to synthesize, classify and reproduce surface synoptic circulation patterns associated with "friagem" events in Cuiabá, previously identified through detection criteria described in 2.1.

In order to analyze the trajectory and behavior of the synoptic systems associated with the "friagem" events, the Principal Sequence Patterns (PSP) of the surface were also obtained. According to Compagnucci *et al.* (2001) Escobar *et al.* (2004) and Escobar (2007), this approximation is considered an extension of the traditional PCA, with a correlation matrix in T-Mode, whose main objective is to obtain the evolution of the main dominant modes of atmospheric circulation for specific meteorological situations. Thus, in this application, each variable is a sequence of the consecutive spatial mean sea level pressure patterns, and the correlation matrix represents the correlation between sequences. Then, a varimax rotation retaining eight principal components (PCs) was applied to separate signal from noise on real data. According to Richman (1986), this methodology is useful to redistribute the total variance of the data in order to emphasize the physical meaning of the PCs obtained. To determine these numbers of components, the eigenvalue 1.0 rule was used (Richman *et al.*, 1992).

3 Results and Discussion

3.1 Identification of "friagens"

The application of the "friagem" detection criteria to the historical series of daily maximum temperature in Cuiabá detected 217 cases for the period 1961-2012. Here, we exemplified two synoptic situations associated with "friagem" events in Cuiabá: one related with the daily decline of maximum temperature in one day (ΔT1) and other in the following day (ΔT2) (Figure 2 and Figure 3).

The Figure 2 (left) shows the surface chart at 1200 Z 23 July 2009 corresponding to the day before the "friagem" event (that is considered the day that the a-b criteria are satisfied). There is a cold front extending from northern Bolivia to the Atlantic Ocean with an associated extratropical cyclone with a central pressure of 968 hPa around 47 °S, 46 °W. The post-frontal anticyclone is located over a wide zone elongated over Chile, Argentina, Uruguay, south of Bolivia, Paraguay, south of Mato Grosso do Sul, São Paulo and southern region of Brazil. This anticyclone is associated with the Semipermanent Subtropical Anticyclone of the South Pacific Ocean, whose center of 1040 hPa is located approximately at 44 °S, 85 °W.

The "friagem" day (1200 Z 24 July 2009) is shown on the right side of Figure 2. Regarding the previous day, the cold front advanced to lower latitudes over the continent reaching southern Rondônia and the central portion of Mato Grosso, including Cuiabá city. The extratropical cyclone associated with this frontal system displaced to the southeast over the Atlantic Ocean and locates around 52 °S, 37 °W. The post-frontal migratory anticyclone presents central pressure of 1028 hPa and is centered over the northeast Argentina, around 27 °S, 61 °W. The cold front passage over Cuiabá produced a daily maximum temperature decline of 13.7 °C, decreasing from 34.9 ° C (T_{d-1}) to 21.2 ° C (T_d) (Table 1).

Figure 3 shows the surface charts associated with a "friagem" when the daily maximum temperature decline occurred one day after the cold front arrival (ΔT_2). Two days before the "friagem" (1200 Z 01 July 2011), Figure 3 (left), a frontal wave develops in southern Mato Grosso do Sul, with the cold

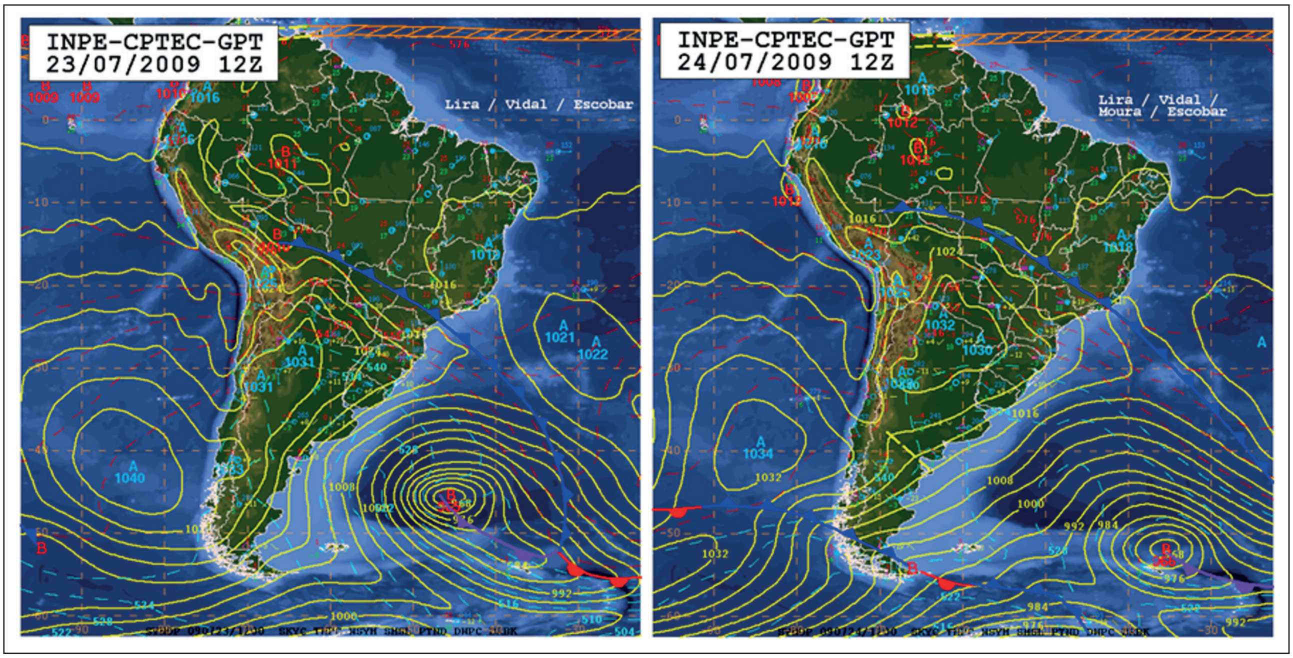

Figure 2 Surface synoptic charts from GPT/CPTEC at 12 Z: (left) 23 July 2009 and (right) 24 July/2009. Yellow lines represent the mean sea level pressure, red dashed lines are the layer thickness and the blue line indicates the cold fronts.

front extending to the north of Bolivia. This frontal system is coupled to the main cold front, which is associated with an extratropical cyclone with a central pressure of 998 hPa located around 50 °S, 47 °W. The high pressure area extends over a large part of Argentina and the central and southern Chile. The surface atmospheric circulation associated with this synoptic pattern allows the identification of cold air mass entering in the southern part of Mato Grosso do Sul and northern Bolivia. In the day before of the "friagem" (1200 Z 02 July 2011), Figure 3 (middle), we can observe that the frontal system slowly advances regarding the previous day, appearing stationary between Santa Catarina state and the northern Bolivia.

The day of the "friagem" in Cuiabá (1200 Z 03 July 2011), Figure 3 (right), shows the cold front along the continent reaching the southern part of the Northern region of Brazil and the southern and western part of Mato Grosso State. The frontal system is

Figure 3 Surface synoptic charts elaborated by GPT/CPTEC at 12 Z. (left) 01 July 2011, (middle) 02 July 2011 and (right) 03 July 2011.

associated with an intense extratropical cyclone of 1006 hPa located over the Atlantic Ocean to the east of Buenos Aires Province (Argentina) around 40 °S, 40 °W. In this "friagem" event, due to the slow advance of the cold front, the decline of the maximum temperature is observed one day after (T_{d+1}) the cold front passage over Cuiabá. Between day -2 and day -1, the daily maximum temperature decreased 7.9 °C, and then between day -1 and the "friagem" day, the daily maximum temperature reached 6.6 °C, that is a decline with a magnitude of 14.5 °C. In this way, the maximum temperature decreased from 34.2 °C (T_{d-1}) to 19.7 °C (T_{d+1}) (Table 1). In both analyzed synoptic situations, the daily maximum temperature observed in the day of the "friagem" arrival was below the mean climatological maximum temperature (T_{Max}) minus two standard deviations (σ).

The analysis of the absolute frequency distribution of "friagem" events (Figure 4), detected with the criteria presented in section 2.1, indicates that theses cold episodes are more frequently in winter (June, July, and August), with a peak in July (47 cases). However, considerable frequencies also occur in May and September. The lowest frequency of "friagem" events occur in November (6 cases).

Figure 4 also shows higher frequency of "friagem" events related to the daily decline of maximum temperature occurred in two days (ΔT_2) than those occurred in one day (ΔT_1), except during September and November when the frequencies were similar for both types of declines. In October, the daily declines occurred in one day (ΔT_1) were more frequently (five cases) than those that occurred in two days (ΔT_2) (two cases). Thus, approximately 63% of the "friagem" events occur in two days (ΔT_2), while 37% occur in one day (ΔT_1).

3.2 Synoptic Classifications

The application of PCA indicated seven patterns of sequences that explained 82.4% of the total variance of the time series and the first four components represented 74.6% of the total variance (Table 3). The analysis of the component loadings (figures not shown) allowed evaluating the representative patterns (obtained from PCA) as real synoptic situations (registered in the reanalyses). Values of component loadings closer to 1 represent sequences of surface meteorological situations similar to the obtained pattern sequence (Harman, 1976; Cattell, 1978). The first four components loadings presented values greater than 0.7.

PC	PER.VAR. (%)	PER. ACUM. VAR. (%)
1º	31.6	31.6
2º	22.2	53.8
3º	10.6	64.4
4º	10.2	74.6
5º	3.0	77.6
6º	2.6	80.2
7º	2.2	82.4

Table 3 Percentages of explained variance and cumulative percentage explained by the seven principal components.

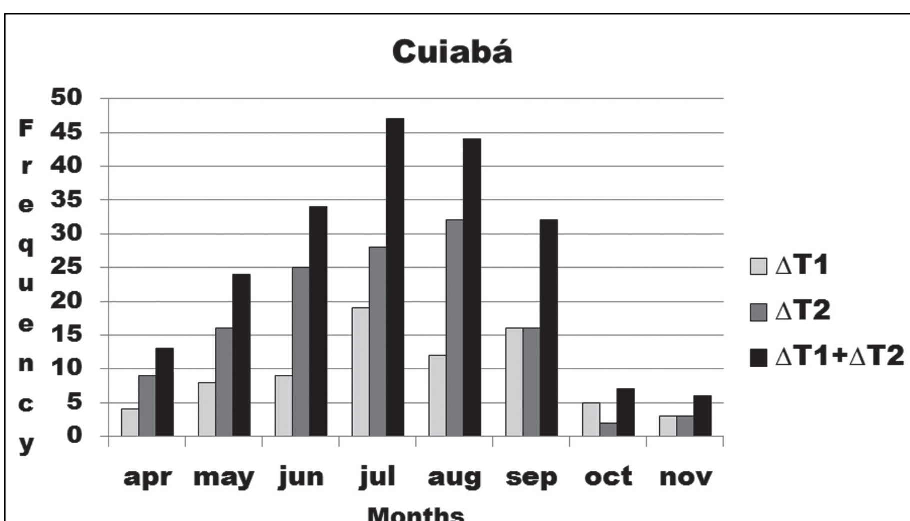

Figure 4 Absolute frequency of "friagem" events in Cuiabá in the period 1961-2012. ΔT1 and ΔT2: number of daily declines of maximum temperature occurred in one and two days, respectively. Total number of daily declines of maximum temperature ($\Delta T_1 + \Delta T_2$).

It means that the theoretical patterns (PSP) have similar configurations to the real meteorological situations. The remaining PSP were not considered in this study since they explained less than 4% of the total variance. These patterns also represented real meteorological situations, however less frequent.

The first four PSP and examples of real circulation fields sequences are shown in Figures from 5 to 8. PSP 1 is shown in the top panels of Figure 5 where the three frames corresponding to day -2 in the left, day -1 in the middle and day 0 (related to the day of "friagem" in Cuiabá) in the right. This PSP explains 31.6% of the total variance and represents the most frequent temporal evolution of the synoptic situations associated with "friagem" episodes in Cuiabá. Two days before (day-2) the "friagem" in Cuiabá, there is a cold front in southern Brazil extending to Paraguay and the southern part of Bolivia. This frontal system is connected to an intense extratropical cyclone located over the Atlantic Ocean around 57 °S, 45 °W. In the following days, the cold front displaced to northeast acting over Southeastern and Central-West Brazil, which represented the "friagem" day (day 0). The sequence of patterns also showed a post-frontal anticyclone, behind the frontal system, moving from the Pacific Ocean to the continent.

PSP1 is the pattern obtained in with the PCA. To represent it with a real situation, we choose one event occurred from 1200 Z 25 May 1971 to 1200 Z 27 May 1971 (bottom panels in Figure 5). Two days (1200 Z 25 May 1971) before the "friagem" reaches Cuiabá, the cold front is located between Santa Catarina and Paraná states and in the southern part of Bolivia. Behind this frontal system, it can be noticed a post-frontal anticyclone over the central and northern part of Argentina. In the day -1 (1200 Z 26 May 1971), the cold front reaches the coast of São Paulo state and extends to the continent towards northern Bolivia. In this surface chart, a migratory high system of 1029 hPa located around 40°S, 75°W is also observed. However, in the day 0 ("friagem day"), this anticyclone enters the continent, pushing the cold front to the southern part of Mato Grosso, leading to south and southeasterly winds over Cuiabá. In the South Atlantic Ocean, there are two extratropical cyclones with a central pressure of 981 hPa and 969 hPa and located around at 56 °S, 55 °W, and 53°S, 30°W, respectively. At the upper levels, this surface pattern circulation is usually associated with a north/south ridge over the Pacific Ocean close to the coast of Chile and a trough over the Atlantic Ocean (figures not shown). The upper level configuration favors driving the migratory surface systems associated with cold air masses to lower latitudes, including the Central-West of Brazil. Thus, the atmospheric circulation related to this surface synoptic pattern produces south and southeasterly flow over southern Mato Grosso with a cold horizontal advection in Cuiabá that determines a "friagem" episode. This synoptic pattern is similar to those found by Girardi (1983), Garreaud (2000), Müller *et al.* (2003), Escobar *et al.* (2004), Escobar (2007), Ricarte (2012) and Reboita *et al.* (2015), when they performed a synoptic climatology of cold air incursions in South America, frost events in the Argentinean Pampa, cold waves in São Paulo, "friagem" episodes in the south of the Amazon region and cold waves on the southern part of Minas Gerais state, respectively. This synoptic pattern was also found by Lanfredi & Camargo (2018) when they studied the extreme cold waves over the southern part of the northern region of Brazil.

PSP2 (top panels in Figure 6) with 22.2% of the total variance shows a wide and intense anticyclone covering the southern part of the continent and centered around the 35 °S, 63 °W two days (day -2) before the "friagem" event. This high pressure slowly displaces eastward along the next days, indicating a possible blocking situation in the Southern Hemisphere (Sinclair, 1996). In the day -1, the cold front appears over Rio de Janeiro state, and the surface pressure configuration related to this synoptic pattern contributes to the cold outbreak over São Paulo, Rio de Janeiro, the southern part of Minas Gerais, Mato Grosso do Sul and southern part of Mato Grosso. In the day of the "friagem" occurrence (day 0), the frontal system appears stationary over the southern part of Espírito Santo state and the blocking anticyclone appears in the Atlantic Ocean around 40 °S, 45 °W.

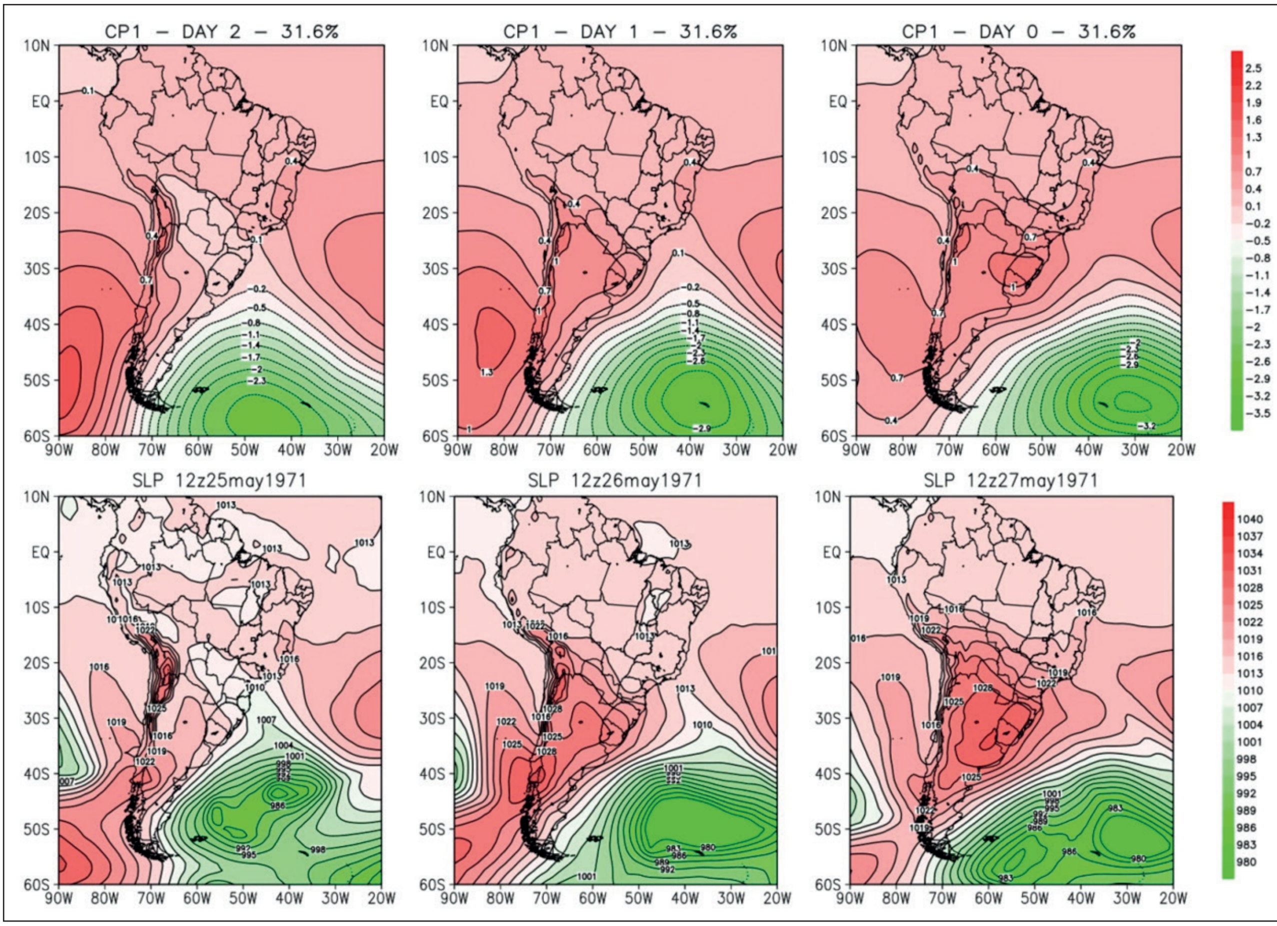

Figure 5 Top: first main sequence patterns (PSP1). Bottom: real sequence of Sea Level Pressure (SLP) fields for 25 May 1971 – 27 May 1971.

A real sequence of surface charts (bottom panels in Figure 6) shows the slow movement of a cold front during 1200 Z on 8-10 July 1979. This meteorological situation shows an intense migratory high pressure system slowly propagating toward the east with its associated ridge entering the continent and producing cold air advection in Cuiabá during the "friagem" event (1200 Z 10 July 1979). This type of surface circulation pattern is usually associated with a blocking anticyclone at upper levels that is located over the South Atlantic Ocean with a slowly eastward shift. A similar synoptic pattern was identified by Reboita *et al.* (2015) in a synoptic climatology of cold outbreaks in the southern part Minas Gerais state.

PSP3 (top panels in Figure 7) explains 10.6% of the total variance and shows a cyclogenesis process over the Atlantic Ocean, close to the east of Uruguay, Argentina and the coast of Rio Grande do Sul. The day when the cold air reaches Cuiabá, the cold front associated with the extratropical cyclone is located between São Paulo state and the southern Mato Grosso. The migratory high pressure related to the cold front enters the continent near 40 °S with zonal displacement. It is interestingly highlighted, during the sequences of synoptic charts, the presence of an intense baroclinic zonal flow located to the south of 50 °S. The bottom panels in Figure 7 show real sequences of surface charts from 1200 Z 9 July 1965 to 1200 Z 11 July 1965, when a "friagem" event reached Cuiabá. Two days before (day -2) the "friagem" occurs in Cuiabá, there is an inverted trough over Paraguay, and the northern Rio Grande do Sul. At day -1, an extratropical cyclone of 1011 hPa central pressure develops over the Atlantic Ocean around 33 °S, 47 °W and the cold front related to it extends

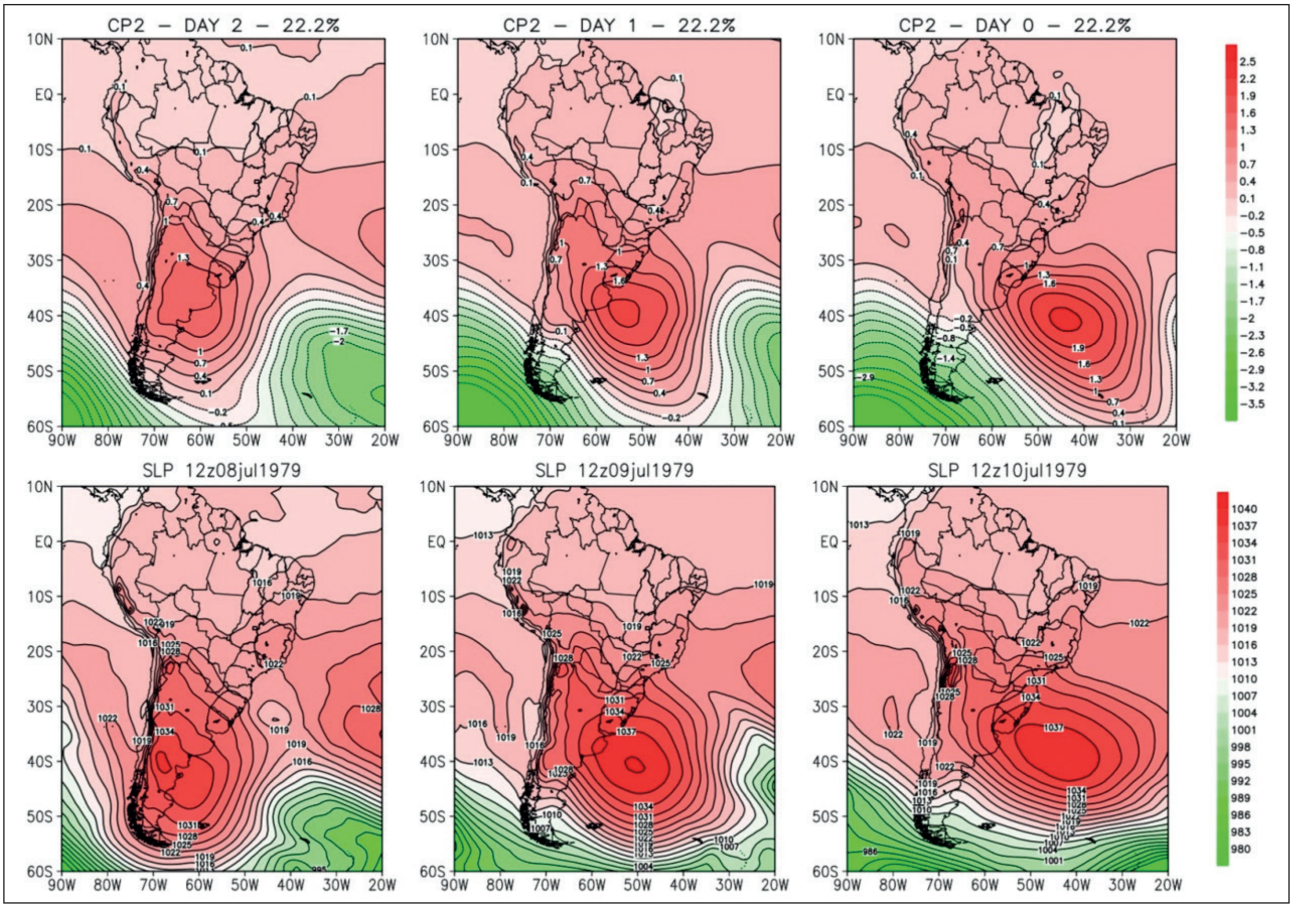

Figure 6 Top: second main sequence patterns (PSP2). Bottom: real sequence of Sea Level Pressure (SLP) fields for 8 July 1979 – 10 July 1979.

from the eastern part of Santa Catarina state to the southern part of Mato Grosso state. In the "friagem" day (day 0), the cold front advances through the continent towards the southern part of the northern region of Brazil and behind this system, a wide area of high pressure with values greater than 1026 hPa is observed. A similar synoptic pattern was obtained by Escobar (2007) in a synoptic classification associated with cold waves in the city of São Paulo.

PSP4 (top panels in Figure 8) explains 10.2% of the total variance showing a cyclogenesis near the southeast of Rio Grande do Sul, with displaced towards the southeast over the Atlantic Ocean during the three days in the analysis. In addition, an anticyclone over the South Atlantic Ocean is observed to the east of the Argentine Patagonia, around 50 °S, 65 °W remaining practically stationary during the three days. In the day -2, an inverted trough extending from Mato Grosso do Sul state towards the Rio Grande do Sul state is observed, showing the first stage of the extratropical cyclone formation. The cyclone appears well configurated in the day -1 near the southern Brazilian coast (35 °S, 45 °W). At this same time, the cold front associated with the low pressure system extends towards southeastern Mato Grosso. During the day of the "friagem" episode (day 0), the low pressure system moves to the east and its associated cold front advances over the continent to the south of the northern region of Brazil.

The bottom panels in Figure 8 show an example of a real situation related to a "friagem" episode from 10 July 2000 (left panel) to 12 July 2000 (right panel). Two days before (day -2) the "friagem" reaches Cuiabá, an extratropical cyclone with a center of 1011 hPa can be observed over great part of Rio Grande do Sul state, around 30 °S, 55

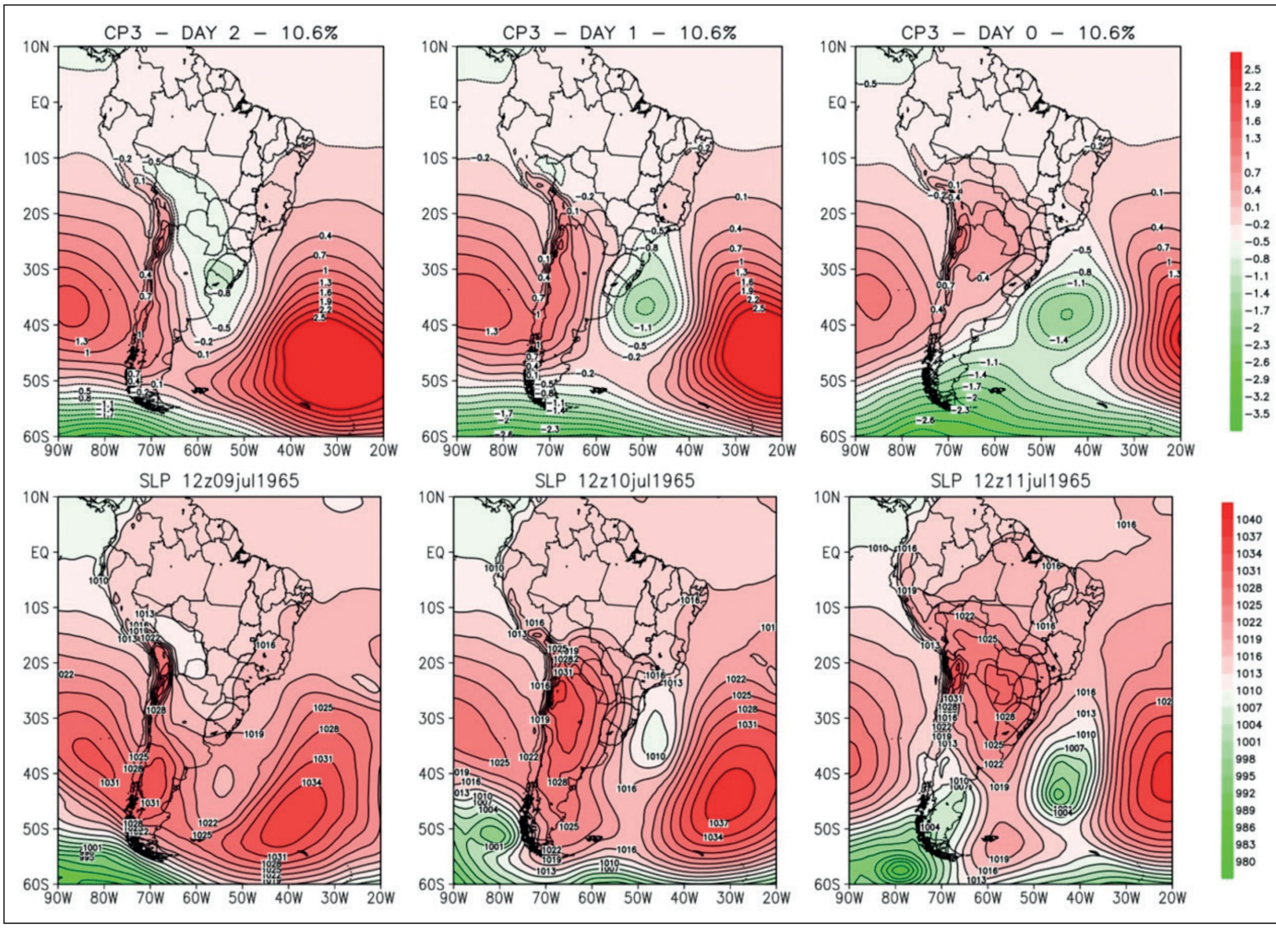

Figure 7 Top: third main sequence patterns (PSP3). Bottom: real sequence of Sea Level Pressure (SLP) fields for 9-11 July 1965 (Bottom).

°W. The cold front associated with this low pressure system extends from the western part of Rio Grande do Sul towards eastern Bolivia. Southward of the extratropical cyclone, a wide and intense anticyclone with a central pressure of 1044 hPa is observed centered in the southern part of Argentina (around 52 °S, 70 °W). In the day -1, the extratropical cyclone intensifies reaching 1005 hPa over 34°S, 52°W and slightly moves to the southeast. In this day, the cold front is extended from the Atlantic Ocean toward the northwest reaching the center part of São Paulo state and the southern part of Mato Grosso state. The atmospheric surface circulation associated with this synoptic situation allows identifying the cold air advance to Paraguay, Uruguay, the west part of the southern region of Brazil, Mato Groso do Sul, the southern and western portion of São Paulo and the southern part of Mato Grosso. In the "friagem" day (day 0), the frontal system can be observed extended from Rio de Janeiro state towards the southern part of the northern region of Brazil, reaching Mato Grosso state and including the Cuiabá city. The extratropical cyclone of 991 hPa associated with this cold front slowly moves towards the southeast and locates around 37 °S, 48 °W. Through this real sequence of surface charts, it can also be observed the propagation of a ridge from Argentine Patagonia towards the north, reaching the southern and western portions of Brazil. This surface synoptic pattern is usually related to the presence of a cyclonic perturbation observed at the 500 hPa level over the Pacific Ocean that crosses the Andes toward the subtropical region of South America. The configuration at upper levels is associated with cyclogenetic processes in the Atlantic Ocean, near the east coast of the south region of Brazil (figures not shown). PS4 is a synoptic pattern associated with a cyclogenesis in the southeastern of South America that was also identified by Escobar (2007), Reboita *et al.* (2015) and Viana & Herdies (2018).

In summary, the synoptic patterns PSP1, PSP2 and PSP4 are similar to those found by Escobar (2007) when studied cold waves over the city of São Paulo. That means that around 60% of the “friagens” in Cuiabá occur simultaneously with cold waves in the city of São Paulo. On the other hand, the synoptic patterns PSP1, PSP3 and PSP4 are similar to those identified by Reboita *et al.* (2015) when they performed a synoptic classification of cold waves in the southern region of Minas Gerais (MG). This result shows that 50% of the “friagem” events in Cuiabá also occur simultaneously with cold waves in the southern region of Minas Gerais.

4 Conclusions

This study presented a methodology to identify “friagem” events in Cuiabá, the frequency of these events and the main surface circulation patterns associated with them. From 1961 to 2012, 217 cases of “friagens” were identified, which indicates an annual average of 4 events. This number is lower than those obtained in others studies (Fisch, 1996; Ricarte, 2012) for the northern Brazilian region due to the more restrictive methodology. In Cuiabá, “friagens” are more frequent in July.

Four main synoptic patterns of sequences, which explained 75.6% of the total variance, represent the environment associated with the “friagens” in Cuiabá. It was observed that, approximately, 70% of the “friagens” events are associated with cold fronts coming directly from the south of the conti-

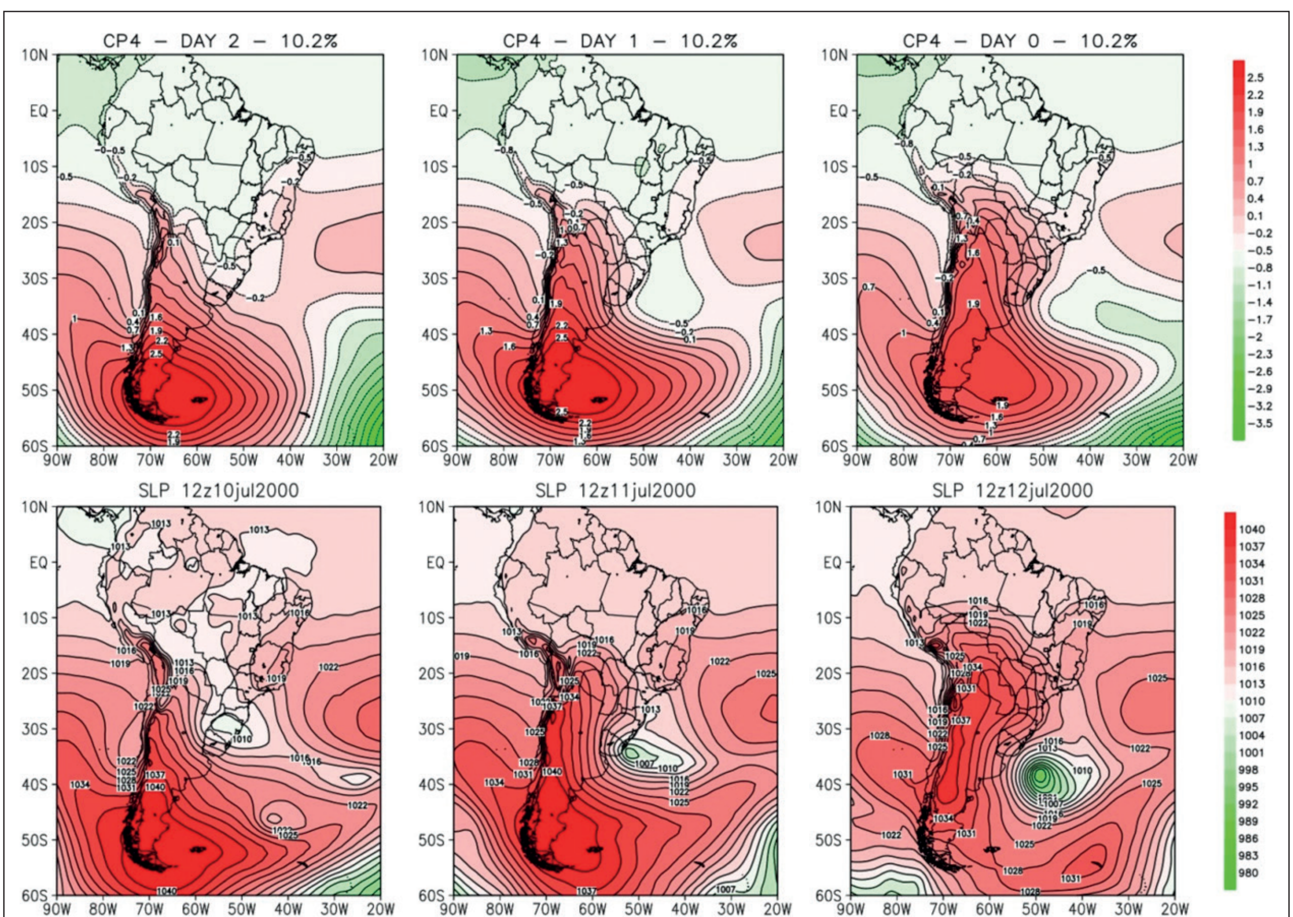

Figure 8 Top: fourth main sequence patterns (PSP4). Bottom: real sequence of Sea Level Pressure (SLP) fields for 10-12 July 2000 (Bottom).

nent. The remaining cases are associated with cyclogenesis in the Atlantic Ocean, mainly east of the Brazilian southern coast.

The PSP1 showed the most frequent synoptic pattern associated with cold waves in South America: a migratory anticyclone that displaces over the continent to lower latitudes. This pattern represents the most frequent circulation model associated with cold surges in the South American continent (Girardi, 1983; Garreaud, 2000; Müller *et al.*, 2003; Escobar *et al.*, 2004; Escobar, 2007; Ricarte, 2012; Reboita *et al.*, 2015 and Lanfredi & Camargo, 2018). The PSP2 showed a synoptic pattern similar to blocking situation in the Southern Hemisphere. In this pattern, there is a large and intense postfrontal anticyclone located on the center-south of the continent and that slowly moves with a zonal displacement and its associated circulation allows the cold air penetrating on the southern and southwestern part of Mato Grosso, including Cuiabá. PSP3 is related with a frontal wave formation over Uruguay and Rio Grande do Sul, near the Atlantic Ocean, with its anticyclone detached from the semi-permanent subtropical anticyclone of the South Pacific Ocean moving with a preferably zonal displacement over Argentina, Uruguay, southern Bolivia and Paraguay. Later, the frontal wave cold front advances over the continent, eventually reaching Cuiabá in day 0. As a result of the zonal movement of the system, this pattern shows a surface circulation with lower temperature advection than PSP1. Finally, the PSP4 shows a synoptic pattern related to a typical cyclogenesis in southeastern South America, with a frontal wave formation over Rio Grande do Sul and border with Argentina and Uruguay, whose cold front moves to the northeast and produces a "friagem" episode in Cuiabá. To the south of the extratropical cyclone, it can be observed an intense anticyclone located in the South Atlantic Ocean and southern Argentina, remaining practically stationary during the analyzed period. Thus, as the extratropical cyclone intensifies, the pressure gradient between the ocean and the continent increases, intensifying the cold air advection over the continent, including a large part of Mato Grosso.

Approximately 60% of the "friagem" events in Cuiabá are related with the synoptic patterns PSP1, PSP3 and PSP4 and occur simultaneously with cold surges in the city of São Paulo (Escobar, 2007). On the other hand, 50% of the "friagem" episodes in Cuiabá are associated with the synoptic patterns PSP1, PSP2 and PSP4 and occur simultaneously with cold surges in the southern region of Minas Gerais (Reboita *et al.*, 2015). Finally, it should be noted that the results obtained from this study are very useful for forecasters that work in operational centers for weather forecasting.

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