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Preliminary study on the case of black rain in Rio Grande do Sul, Brazil: A synoptic point of view

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ABSTRACT

Particles of soot from forest fires are transported by the wind, reaching distant locations and being deposited on the soil through precipitation, which clears the atmosphere, taking suspended particulate matter into its drops. The general circulation over South America indicates the possibility of soot from forest fires in the Amazon and Pantanal to be transported to southern Brazil. The event called “black rain” was observed in the period from 11 to 13 September 2020 at São Francisco de Assis City, in Rio Grande do Sul State (RS), and so this work aims to analyze if there were any anomalies of the flow that favored the occurrence of this event, given that there was a large number of fires in this period. Through ERA5 reanalysis data and GOES-16 satellite images, it was observed that on the three days under study low-level flow to the south of Brazil was more intense than normal, with the Low Level Jet occurrences, and on days 12 and 13 such flow to the south was also observed at 500 hPa. The precipitation was due to the instability of an extended trough from the Northwestern Argentinean Low. Thus, it is believed that there was a contribution from circulation at low and mid levels in the occurrence of black rain over RS.

Keywords: Forest Fires, Amazon, Pantanal, ERA5, NAL, LLJ.

Estudo preliminar sobre o caso da chuva negra no Rio Grande do Sul, Brasil: um ponto de vista sinótico

RESUMO

As partículas de fuligem originadas de queimadas são transportadas pelo vento e podem atingir localidades distantes e serem depositadas no solo através da precipitação, que realiza uma limpeza na atmosfera, levando em suas gotas o material particulado suspenso. A circulação geral sobre a América do Sul indica a possibilidade de fuligem das queimadas da Amazônia e Pantanal serem transportadas para o sul do Brasil. O evento denominado de “chuva escura” foi observado no período de 11 a 13 de setembro de 2020 no município de São Francisco de Assis, no estado do Rio Grande do Sul (RS), e assim este trabalho tem como objetivo analisar se houve alguma anomalia do escoamento que favoreceu a ocorrência deste evento, haja vista que ocorreu um grande número de queimadas no período em questão. Por meio de dados de reanálise do ERA5 e imagens de satélite do GOES-16, observou-se que nos três dias em estudo o escoamento em baixos níveis para o sul do Brasil esteve mais intenso que o normal, inclusive com a ocorrência de Jato de Baixos Níveis, e nos dias 12 e 13 tal escoamento para sul também foi observado em níveis médios. A precipitação foi oriunda da instabilidade de um cavado estendido da Baixa do Noroeste Argentino. Desta forma, acredita-se que houve contribuição da circulação em baixos e médios níveis na ocorrência de chuva escura sobre o RS.

Palavras-chave: Queimadas, Amazônia, Pantanal, ERA5, BNOA, JBN.

Introduction

Located in the central region of South America, more specifically in Brazil, Paraguay and Bolivia, the Pantanal biome is the largest tropical

seasonal floodplain on the planet, occupying 1.6% of the Brazilian territory, about 150.355 km². In addition to its ecological and socioeconomic

importance, the biome has a vast biodiversity and peculiar hydrological regime, which makes it the object of studies of works that aim to know and protect its biodiversity (Moraes et al., 2013; Santos et al., 2016; Miranda et al., 2018a; Viganó et al., 2018a; Mendes et al., 2019; Rosseto et al., 2020). Even though it is one of the most preserved ecosystems in Brazil, the Pantanal biome has suffered more and more due to anthropogenic action, mainly the practices of deforestation and burning of biomass for the purpose of a more ostensible agriculture (Araújo and Silva, 2015; Ferreira et al., 2020). According to Macedo et al. (2009) Pantanal suffers from fires regularly, often with the goal of renewing the pasture, usually during the period from September to December.

In South America, the Amazon biome also stands out, which consists mainly of a large tropical forest (Amazon rainforest) and occupies an area of 4,196,943 km² (about 40% of the Brazilian territory) (Richter, 2020). Studies such as Nobre (2014) and Rufino (2020), show the great relevance of this biome in regulating the climate on the continent. As Pantanal, the Amazon has also been suffering from the increase in deforestation and fires rates that have become more frequent, which are directly related to the process of deforestation, management of agricultural and livestock areas (Aragão et al., 2016; Arima et al., 2016; Copertino et al., 2019; Fuchs, 2020).

As pointed out by Abreu and Souza (2016) and Miranda et al. (2018b), fires occur in almost the entire Brazilian territory and can be caused by anthropic and / or natural processes, such as actions that use fire as a tool for cleaning pastures and crop remains, expanding borders occupation, pest control, among others. According to Ichoku et al. (2012), Loureiro e Dos Santos (2018), Zanin et al. (2018) and Pardini (2020), the burning of plant biomass through fires represents one of the main sources of emissions and releases of trace gases and aerosols into the atmosphere, influencing the climate (mainly on a regional scale), the chemistry of the atmosphere, the properties of clouds, besides being an introductory factor of changes in the local and regional landscape.

Data from the Instituto Nacional de Pesquisas Espaciais (INPE) on burned areas (or heat points) in South America indicate that in 2020 there was the largest number of fires in the Pantanal since 1998, beginning of measurements, totaling 21994 until December 19, 2020. It is worth noting the September 2020, which has the largest number of outbreaks (8106) compared to the same month in previous years (INPE, 2020).

According to Machado et al. (2014), specific meteorological conditions such as precipitation deficit, high wind speed and low relative humidity are aggravating factors for fires. In addition, it must be known that the impacts of increased fires not only affect the areas of the fires, but can also affect locations thousands of kilometers from the place of origin (Corrêa et al., 2020a). The heat from fire flames forms upstreams that carry ash, soot and smoke from miles away, where it can subsequently precipitate (Lenzi and Favero, 2014). These particles are complex mixtures suspended in the air containing inorganic salts and numerous carbon compounds in its composition. Among them is the soot aerosol, which is characteristic of coal and diesel combustion emissions and burning biomass (Santos et al., 2016).

This particulate material present in the atmosphere can exhibit different physical or chemical behaviors. Between them is sweeping, which is the phenomenon that occurs when the rain dissolves and drags the existing particles to the surface, leading to a cleaning of the atmosphere through the removal of these substances (Lenzi and Favero, 2014). In this context, "black rain" is a phenomenon that can happen when precipitation occurs and the air is polluted with soot from, for example, forest fires (Evangelista, 2020). Black rain is not a new phenomenon, records can be found in the American Meteorological Society's Monthly Weather Review since 1873 (available at https://journals.ametsoc.org/view/journals/mwre/1/12/1520-0493_1873_112_3b_cs_2_0_co_2.xml?rskey=Ch3H40&result=8&tab_body=pdf).

Silva (2020) says that air pollution studies are carried out exclusively with subjects related to the emission from urban centers. On the other hand, studies on burning aerosols indicate that there are other mechanisms that influence the dynamics of air pollution, such as rain and the balance of solar radiation.

The South Region of Brazil, where the State of Rio Grande do Sul (RS) is located (Figure 1), is affected by synoptic-scale atmospheric systems that are influenced both by factors associated with large-scale circulation and local circulation, whether of tropical or extratropical origin (Grimm, 2009; Reboita et al., 2010). An example is the Chaco Low, which consists of a low-pressure surface system located on the Chaco plain close to Paraguay, Bolivia and northern Argentina and it is a typical system of the warmer seasons, different from Northwestern Argentinean Low, located further south, which is associated

with transient systems, occurring in all seasons (Saulo et al., 2004; Seluchi and Saulo, 2012).

Over RS, precipitation is fairly well distributed throughout the year, but it presents spatial and temporal variability conditioned to the interactions of different climatic mechanisms (Grimm, 2009; Alvares et al., 2013; Forgiarini et al., 2014). Studies such as Forgiarini et al. (2014) indicate that the state's climate is controlled by the advancement of polar air masses, with the direction most often southwest-northeast, however, at the same time there is the invasion of subtropical air masses, even equatorial ones, originating of the Amazonian humidity channel that reaches the state from the northwest. This factor, associated with the relief (local factor), is responsible for the spatial inhomogeneity of the rains in the state.

Grimm (2009) and Cataldi et al. (2010) pointed out in their studies large time-scale atmospheric factors that affect the rainfall regime in RS, that is, factors that indicate a high climatic variability of precipitation in the state, such as El Niño - South Oscillation (ENSO). Several scientific studies have shown that ENSO plays a relevant role in the climatic anomalies of precipitation in RS. In El Niño years the chances of rains above normal are greater in southern Brazil, while in La Niña years negative deviations are more common (Britto et al., 2008).

In the period from 11 to 13 September 2020, residents of the municipality of São Francisco de Assis (Figure 1), located in the *Missões* region, in RS, observed a black colored rain, which can be better seen by residents when they stored in clear receivers. This fact was widely reported in digital and visual media, and then speculation was raised about the factors that may have caused the event, such as the large areas burned in the Pantanal (Ely, 2020; Correio do Povo, 2020; Soares, 2020). Thus, this work aims to assess the large-scale factors (moisture, wind, pressure and column of water vapor) that may have influenced the event of "black rain" observed in RS in the period from 11 to 13 September 2020.

Data and methods

The figure below shows the extension of the Amazon and Pantanal biomes in Brazil, as well as the location of the State of RS in the extreme south of the country (Figure 1).

Figure 1. Location of Brazilian biomes.

To identify the number of fires in the Pantanal and the Amazon, a preliminary treatment was carried out with the data available on the INPE website (<http://queimadas.dgi.inpe.br/queimadas/portal>). The preliminary treatment is the filtering provided by the platform, enabling the selection of data by country, time period, biome and satellite. Basically the filtering of the fire spots in GOES-16 location or satellite was carried out for all biomes, thus obtaining the quantity and also the percentage of outbreaks that occurred in the biomes compared to South America in this study.

In order to verify if on the period under study fires occurred in the Amazon and in the Pantanal, the map of burned areas (available on the website from INPE <http://queimadas.dgi.inpe.br/queimadas/bdqueimadas>) was obtained. Such a map is made by means of estimates of satellite images, in this work, the GOES-16.

Subsequently, a major search on news sites that reported the occurrence of black rains in the period was made. Thus, reports were found on reputable sites such as G1 (Ely, 2020), GaúchaZH (Soares, 2020) and Correio do Povo (2020), which reported the occurrence of black rains in the city of São Francisco de Assis - RS from 11 to 13 September 2020. Since there are no official

weather stations in São Francisco de Assis, accumulated precipitation data was observed at stations in the cities of Alegrete, Caçapava do Sul, Santa Maria, São Gabriel and São Sepé (Figure 2). Such stations belong to the Instituto Nacional de Meteorologia (INMET) and to Agência Nacional de Águas e Saneamento Básico (ANA).

For the synoptic analysis of the period, meteorological fields obtained from the hourly ERA5 reanalysis data (Hersbach et al., 2020), from the European Center for Medium-Range Weather Forecasts (ECMWF), were used, with spatial resolution of 0.25° and 137 vertical levels. The fields of the following variables were generated: streamline and speed of the wind at 500 hPa, 700 hPa and 850 hPa; sea level pressure and total column of water vapor. Wind anomalies were

generated from each of these fields by the difference between the field on the day of the event and the September climate normal (1991-2020). Satellite images from GOES-16, channel 1 ($0.47 \mu\text{m}$), available on Divisão de Satélites e Sistemas Ambientais (DSA) of INPE website, were used to observe the cloudiness of the system that caused precipitation over RS, and the possible transport of soot from the Amazon and Pantanal to the south of Brazil, given that the visible channel shows the reflectivity of the particles suspended in the air.

The relationship between burned areas and synoptic flow at different vertical levels may indicate the role of large-scale circulation in the occurrence of black rain on RS.

Figure 2. Location of São Francisco de Assis and neighboring cities with INMET and / or ANA stations.

Results and discussion

According to the INPE database for the period from 10 to 13 September 2020, 16097 burned areas were found on the Pantanal and 28461 on the Amazon, representing, respectively, 19.32% and 34.16% of all forest fires in South America in that period. The two biomes mentioned above are the focus of several studies on the most diverse

themes (Palácios et al., 2018; Viganó et al., 2018b; Chaves et al., 2020; Bolwerk and Ertzogue, 2021; Dias et al., 2021; Ferro, 2021). Figure 3 shows the spatial distribution of the burned areas in South America according to the GOES-16 satellite between September 11th and 13th.

Figure 3. Location of estimates of burned areas between September 11 and 13, 2020 according to the GOES-16 satellite, obtained from INPE (2020).

Figure 3 shows an enormous number of burned areas in the period, with high concentration in the Amazon and Pantanal biomes. It is noted that a great part of the heat points are located outside the Brazilian territory.

Figure 4 shows the climate normal flow for September. At mid levels (Figure 4a) there is a large-scale anticyclonic circulation, centered on the state of Mato Grosso, resulting from continental warming. Such an anticyclone was also observed, albeit with a different aspect, at 250 hPa (not shown here), which is normally expected for the summer, characterizing the so-called Bolivian High (Satyamurty et al., 1998). At 700 hPa (Figure 4b), about 3000 m high, the flow from the northern region to the southern region of Brazil is observed. This flow has a meridional component (towards the south) that is even more intense and clear at the 850 hPa (Figure 4c). That is, at low levels (700 and 850 hPa) a northerly flow from north and central-west regions is expected, while at 500 hPa the flow over the RS is zonal (westerlies). It is known that flow at low levels (mainly 850-700 hPa) is quite significant in transporting quantities such as heat and humidity. At first it is assumed that it is also for the case of soot from forest fires as suggested in Lemes et al. (2020).

On September 11, 2020 (Figure 5) the flow presented a direction similar to the climate normal (Figures 5a-c). However, at low levels the flow was more intense (Figures 4e-f) - at 850 hPa (Figure 5b) the Low Level Jet (LLJ) is observed, although subtly, with its core over the border between Bolivia and Paraguay - which enhances the transport of particles from the Amazon and Pantanal to the south of Brazil. The LLJ is part of the northerly flow from Amazon region to the southern Brazil, intensifying transport of moisture to the region, increasing the chances of precipitation in RS (Marengo and Soares, 2002; Teixeira and Satyamurty 2007; Santos and Reboita, 2018). Martins et al. (2018) indicate that LLJ directly influences the transport of aerosols from the central region to the southern Brazil, contributing to the concentration of particulate material on South region. Situation (transport of particles from Amazon) is present in Corrêa et al. (2020b) too.

Figure 6 shows that on September 12, the low-level flow was similar to 11th, but with the southward flow at 850 hPa more intense, indicating LLJ. However, differently from the previous day, the southward flow was also observed at 500 hPa. Artaxo et al. (2005) indicates that aerosols (such as soot) may also be present in cumulonimbus clouds that reach up to 10 km or 15 km in height, implying that mid-level winds may have contributed to the transport of smoke towards RS. This scenario also occurred for the 13th (Figure 7), that is, intense and anomalous southward flow at low and mid levels. Intense northerlies at low levels, including LLJ, are common, mainly associated with events of intense rain. This flow causes warm advection, resulting in a ridge at mid and upper levels, over the southward flow. In other words, some lag is expected between the southward flow at low and mid levels. Therefore, the fact that the southward flow is observed up to 500 hPa must have influenced the transport of soot from the Pantanal and Amazon to RS.

Figure 4. a) Streamlines and wind speed (m s^{-1}) (shaded) climate normal (1991-2020) for September at 500 hPa; b) at 700 hPa; c) at 850 hPa.

Figure 5. Streamlines and wind speed (m s^{-1}) (shaded) for September 11, 2020 at 00z. a) at 500 hPa; b) at 700 hPa; c) at 850 hPa; d) wind anomaly at 500 hPa; e) wind anomaly at 700 hPa; f) wind anomaly at 850 hPa.

Figure 6. Same as Figure 4, but for September 12, 2020.

Figure 7. Same as Figure 4, but for September 13, 2020.

Satellite imagery in the visible channel shows the reflectivity not only of the cloudiness but also of the plume of smoke. Figure 8 shows the transport of soot from the north and central-west of Brazil to the south, as well as the cloudiness of the system that caused precipitation in RS. On 11th (Figure 8a and 8b) and 12th of September (Figure 8c and 8d) there is the greatest flow of smoke to RS, with an apparent decrease on 13th of September (Figure 8e and 8f). The images show plumes over the Amazon region on the 11th, 12th and 13th, indicating that the region apparently contributed as a source of smoke.

Cloudiness over the RS was an instability due to a surface low pressure system on the continent (Figure 9). Such a system is known as Northwestern Argentinean Low (NAL) (Seluchi

and Saulo, 2012; Escobar and Seluchi, 2012). The total column of water vapor field shows the association of NAL with the frontal system to the south, over the ocean. The trough extended from the NAL towards RS is a pattern easily found in cases of heavy rain over the State (Riquetti et al., 2018; Dorneles et al., 2020; Ogassawara et al., 2021). Even with the intrusion of a post-frontal anticyclone in RS on the 12th (Figure 8b), the northern moisture flow was maintained and driven by mid-levels flow. Table 1 shows the precipitation generated by this instability observed in the cities neighboring São Francisco de Assis.

Figure 8. GOES-16 satellite imagery, channel 1. a) 09/11/2020, 12z, b) 09/11/2020, 18z, c) 09/12/2020, 12z, d) 09/12/2020, 18z, e) 09/13/2020, 12z, f) 09/13/2020, 18z. The red polygon is a zoom over the area under study.

Figure 9. Sea level pressure (hPa) (dark) and total column of water vapor (kg m^{-2}) (colored). a) 09/11/2020, 12z, b) 09/12/2020, 12z, c) 09/13/2020, 12z.

Table 1. Precipitation generated by this instability observed in the cities neighboring São Francisco de Assis.

Operator	City	Precipitation (mm)		
		11/09	12/09	13/09
ANA (2020)	Alegrete	0	6,7	27,7
	Caçapava do Sul	0	30,3	14,8
	São Gabriel	25	25	20
	São Sepé	0	24,9	24,3
INMET (2020)	Caçapava do Sul	0	21,4	28,2
	Santa Maria	0,2	5	24,8
	São Gabriel	0	21,2	24,2

Conclusions

From September 11 to 13, 2020, black rain was observed on the city of São Francisco de Assis-RS, extreme south of Brazil. This work analyzed large-scale flow, given that this period coincided with a large number of fires in the Amazon and Pantanal biomes, as identified by the map of fires from INPE. The analysis was performed using ERA5 reanalysis data and satellite images.

It is known that the flow at low levels is more significant in the transport of heat and humidity. It is assumed that this is also the case for soot from forest fires. The analysis showed that on the three days under study there was a more intense flow than normal at low levels. As from 12th, the flow at 500 hPa also turned southward, which must have contributed to a greater soot transport to RS.

The satellite images show the plume of smoke from the Amazon and Pantanal towards the south of Brazil, in addition to the instability that caused the rain in RS. Such instability was due to the association of a trough, extended from Northwestern Argentinean Low, with a frontal system over the ocean to the south.

For a more advanced study to determine the role of the Pantanal and Amazon fires in the black rain over RS it is suggested, as future work, the analysis of the spatial and temporal variability of the points of fires and the modeling of the dispersion of the aerosols emitted from the fires.

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