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Extreme Precipitation and Flooding: Synoptic Analysis in the Taquari-Antas River Basin Region in September 2023

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ABSTRACT

The Taquari-Antas River Basin (TARB), located in the northeastern region of the state of Rio Grande do Sul, southern Brazil, faces recurring extreme meteorological events. One notable event occurred in September 2023, which caused several negative impacts on the economic, social, and environmental sectors due to flooding caused by intense rainfall in the region. In light of this, the objective of this study was to analyze the synoptic environment associated with the event in order to identify the factors that contributed to the excess precipitation and subsequent flooding in the Taquari Valley. For this, the GFS (Global Forecast System) model was used for meteorological fields, and infrared images from the GOES-16 meteorological satellite were considered. It was observed that the event in September 2023 was initially influenced by the transport of heat and moisture from the Amazon, driven by the Low-Level Jet (LLJ) and the subsequent development of the Northwest Argentine Low (NAL), which extended over the days from Paraguay towards Rio Grande do Sul. In addition, dynamic factors associated with instabilities were observed, such as the presence of troughs at mid-levels and diffluence at upper levels. The later arrival of a post-frontal polar air mass dissipated the instability. This study reinforces the need for the analysis of the vertical structure of the atmosphere for diagnosing synoptic patterns related to extreme precipitation events.

Keywords: Extreme Event. LLJ. NAL. CVA.

Precipitação Extrema e Inundações: Análise Sinótica na Região da Bacia do Rio Taquari-Antas em Setembro de 2023

RESUMO

A Bacia Hidrográfica do Taquari-Antas (BHTA), situada na região nordeste do estado do Rio Grande do Sul, sul do Brasil, enfrenta eventos meteorológicos extremos com recorrência. Destaca-se o evento ocorrido em setembro de 2023, que ocasionou diversos impactos negativos no meio econômico, social e ambiental devido às inundações provocadas pelas chuvas intensas na região. Diante disto, o objetivo deste estudo foi analisar o ambiente sinótico associado ao evento, a fim de identificar os fatores que contribuíram para o excesso de precipitação e as inundações subsequentes no Vale do Taquari. Para isso, foram considerados o modelo de previsão GFS (Global Forecast System) para os campos meteorológicos e as imagens em infravermelho do satélite meteorológico GOES-16. Observou-se que o evento ocorrido em setembro de 2023 foi inicialmente influenciado pelo transporte de calor e umidade da Amazônia, impulsionado pelo Jato de Baixos Níveis (JBN) e consequente desenvolvimento da Baixa do Noroeste Argentino (BNOA) que ao longo dos dias se estendeu do Paraguai em direção ao Rio Grande do Sul. Além disso, foram observados fatores dinâmicos associados às instabilidades, como a presença de cavados em níveis médios corrente acima e difluência em altos níveis. A posterior chegada de uma massa polar pós-frontal dissipou a instabilidade. O presente trabalho reforça a necessidade da análise da estrutura vertical da atmosfera para diagnóstico de padrões sinóticos relacionados a eventos extremos de precipitação.

Palavras-chave: Evento Extremo. JBN. BNOA. AVC.

Introduction

Extreme precipitation events are becoming increasingly recurrent in different regions of the world, and here the emphasis is on the state of Rio Grande do Sul (RS), in southern Brazil, which has been facing natural disasters (Dunn et al., 2024; Pereira and Nunes, 2018; Ogassawara et al., 2021; Santos et al., 2022). These events represent a global challenge due to their various impacts on life, material assets, and the economy (Jennrich et al., 2020; Yu et al., 2020).

In addition, due to the uniform distribution of rainfall throughout the year in Rio Grande do Sul, there is a probability of extreme rainfall occurring at any time of the year, with persistence of five or more days (Teixeira and Prieto, 2020).

Extreme precipitation events in RS are associated with atmospheric systems from low, mid, and high latitudes, as well as with continental and maritime air masses (Da Rocha et al., 2024; Nímer, 1989). These occurrences result from climate change, which arises from the complex interaction between natural processes and human actions (Oliveira et al., 2024).

In this context, the Taquari Valley stands out, located in the Taquari-Antas River Basin (TARB), in the northeastern region of Rio Grande do Sul. This area is affected by a variety of extreme meteorological events, such as droughts and intense rainfall, and consequently has an extensive record of these occurrences and their respective impacts in the region (De Souza et al., 2019).

During winter and spring of 2023, the Taquari Valley experienced heavy rainfall, which caused flooding due to the rain falling in a highly concentrated way over short periods, accompanied by strong wind gusts. This combination of factors resulted in multiple flooding events, with particular emphasis on the September episode, which led to the loss of 54 lives, as well as the destruction of infrastructure, the displacement of thousands of people, and economic losses. This episode was considered one of the largest natural disasters in the history of Rio Grande do Sul, with a severe impact on the Taquari Valley (G1 RS, 2024).

Given the above, there is evidence that, in September 2023, a climatic anomaly occurred in the Taquari-Antas River Basin, with emphasis on the municipalities of Muçum, Roca Sales, and Encantado. In this context, the aim of this study is to analyze the synoptic environment associated with the event in question, investigating the atmospheric factors that contributed to the excess rainfall and the subsequent flooding. Understanding the synoptic configuration of this case aims to contribute to the scientific literature regarding the forecasting and mitigation of extreme meteorological events.

Materials and methods

Study Area

The present study was conducted in the Taquari Valley, located in the TARB, in the northeastern part of Rio Grande do Sul State, as shown in Figure 1. The BHTA is part of the hydrographic region of the Guaíba Basin, covers an area of 26,430 km², and has a population of 1,383,442 inhabitants (including urban and rural areas) (SEMA, 2024).

According to the Köppen classification, the climate in the basin is predominantly humid subtropical and is subdivided into two varieties: Cfa and Cfb. The Cfa variety, which occurs at altitudes below 600 m, is characterized by well-distributed rainfall throughout the year with an annual total of 1,400 mm, as well as temperatures in the warmest month exceeding 22°C and in the coldest month above 3°C. The Cfb variety, found at altitudes above 600 m, has temperatures in the warmest month below 22°C and an annual total precipitation exceeding 1,600 mm (FEPAM, 2001; SEMA, 2012).

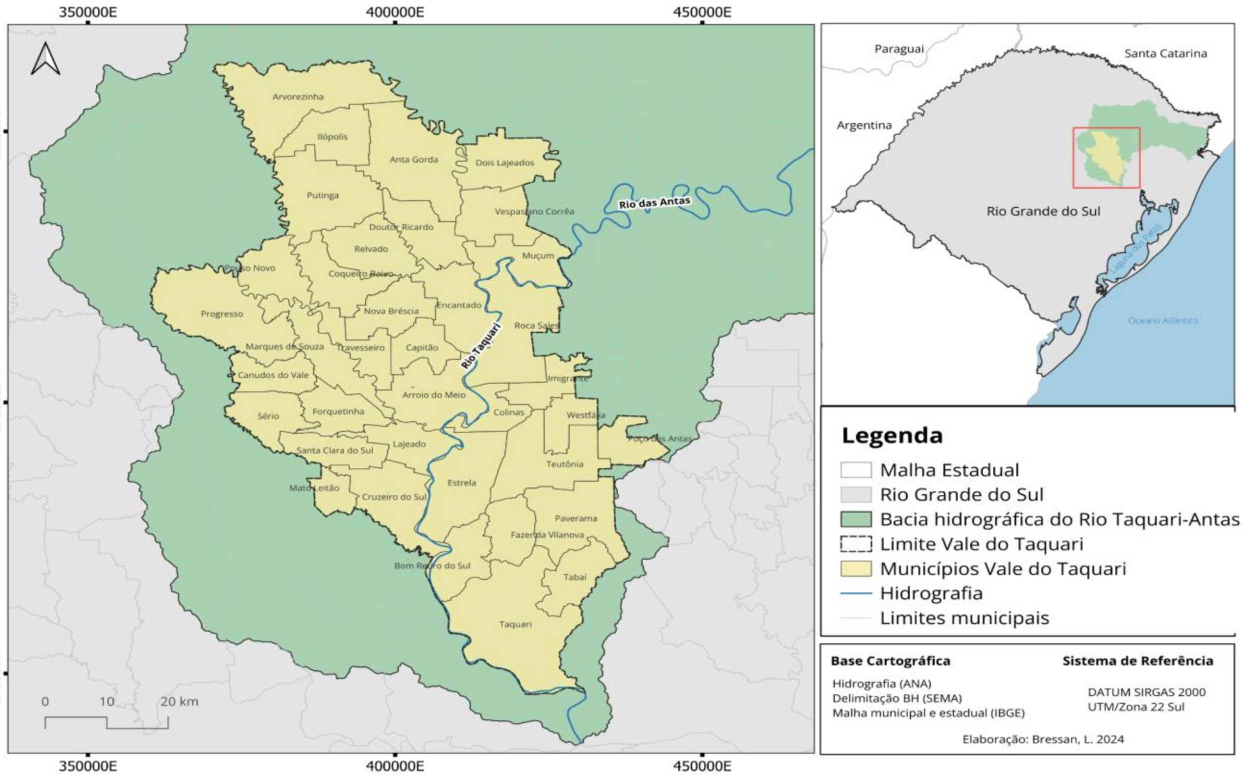

Figure 1. Map and location of the study area.

Hydrological Data Analysis

The analysis period was from September 1 to 6, 2024. According to the technical note from Instituto de Pesquisas Hidrológicas (IPH, 2023), the monitoring station of the Instituto Nacional de Meterologia (INMET, 2023) in the municipality of Serafina Corrêa recorded an accumulated precipitation of 280 mm from September 1 to 4, 2023. Data from Centro Nacional de Monitoramento e Alertas de Desastres Natuais (CEMADEN, 2023) recorded precipitation values above 150 mm in the municipalities of Lajeado and Encantado during this period.

Although the region has evenly distributed precipitation throughout the year, as presented by Mantovani et al. (2024) in Figure 2, October and September show the highest climatological cumulative precipitation volumes, at 193.3 mm and 167.5 mm, respectively. The lowest cumulative precipitation volumes are observed in November, with 131.6 mm, and in March, with 132.4 mm. The authors present data from four INMET meteorological stations located in the municipalities of Cambará do Sul-RS, São Valentim do Sul-RS, Marau-RS, and Taquari-RS. In the first five days of the month, 184 mm of precipitation was recorded across the four monitored municipalities, representing the second-highest value for this period and confirming the positive anomaly. In addition, the basin recorded an accumulated precipitation volume exceeding 400 mm over the course of the month, with particular emphasis on September 4, when precipitation ranged between 200 mm and 250 mm within 24 hours.

Figure 3 presents the analysis of the daily accumulated precipitation for September 2023 carried out by the same authors.

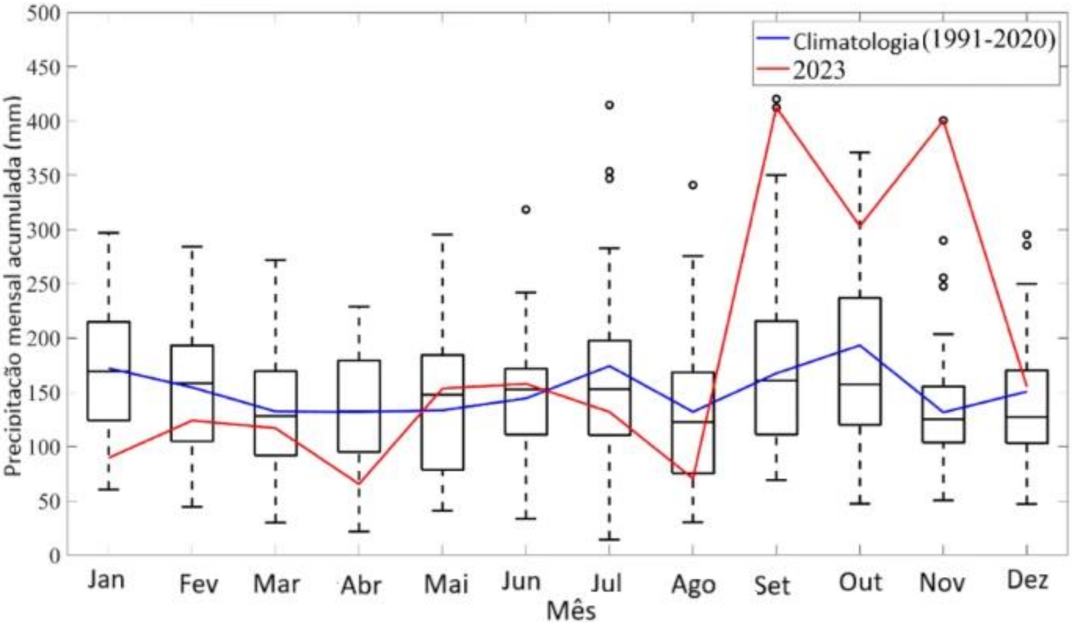

Figure 2. Monthly precipitation from 1981 to 2023 and spatially averaged climatological normal over the Taquari-Antas river basin.
Source: adapted from *MANTOVANI et al*., 2024.

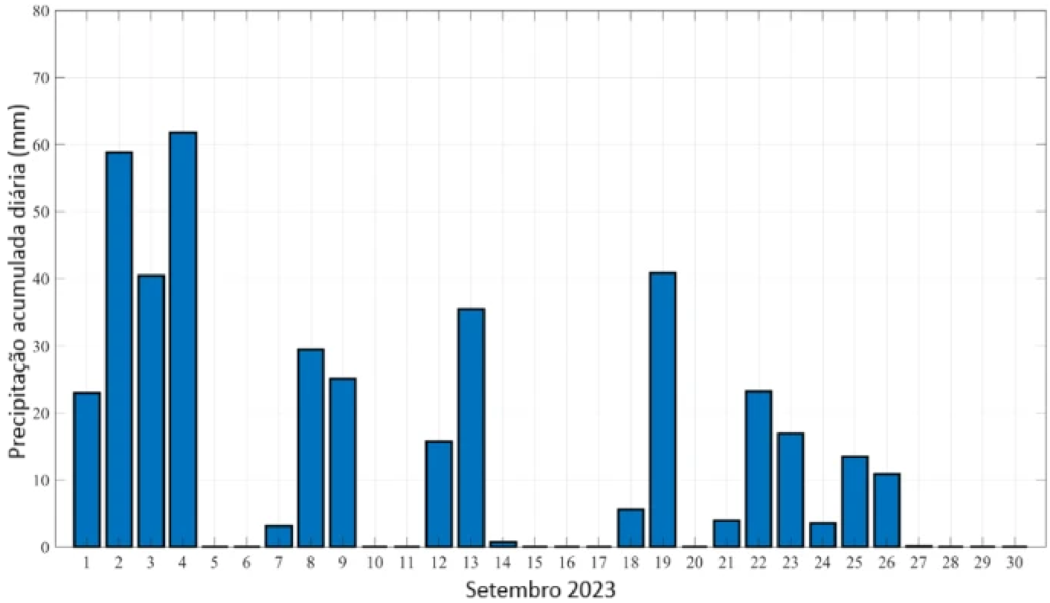

Figure 3. Spatially averaged daily precipitation over the Taquari-Antas River Basin (BHTA) for September 2023.
Source: adapted from *MANTOVANI et al*., 2024.

Synoptic analysis

The synoptic analysis used forecast data from the Global Forecast System (GFS) model, from the National Center for Environmental Prediction (NCEP), linked to National Oceanic and Atmospheric Administration (NOAA). The model provides forecasts at 26 verticals levels, with four daily times (00, 06, 12, and 18 UTC) and a horizontal resolution of 0.5° x 0.5°. The meteorological fields were obtained from the Tropical Tidbits platform, available at https://www.tropicaltidbits.com/. Images from the infrared channels of the GOES-16 meteorological satellite (Geostationary Operational Environmental Satellites) were also used, obtained from the GOES-R Interactive Data Processing and Visualization (DSAT) database of INMET, with a spatial resolution of 2 km and image capture every 15 minutes.

Results and discussions

Through the images obtained from the GOES-16 satellite (Figure 4), it is possible to analyze the cloud behavior over the RS region. On September 1, 2023, no significant cloudiness was observed. On September 2, 2023, at 00:00 (Figure

4a), the presence of a large Mesoscale Convective System (MCS) can be observed. This phenomenon is crucial for the occurrence of extreme precipitation events, as highlighted by Salio et al. (2007). On September 3, 2023, at 00:00 (Figure 4b), an area of instability entered the western part of the state and remained active until 12:00 on the same day (Figure 4c). During this period, convective cores were identified, concentrated in the northern half of RS, with particular emphasis on the Taquari-Antas river basin region. On September 4, 2023 (Figure 4d), at 00:00, the image reveals the presence of large convective cores.

On the images from September 6, 2023, no significant cloudiness was observed.

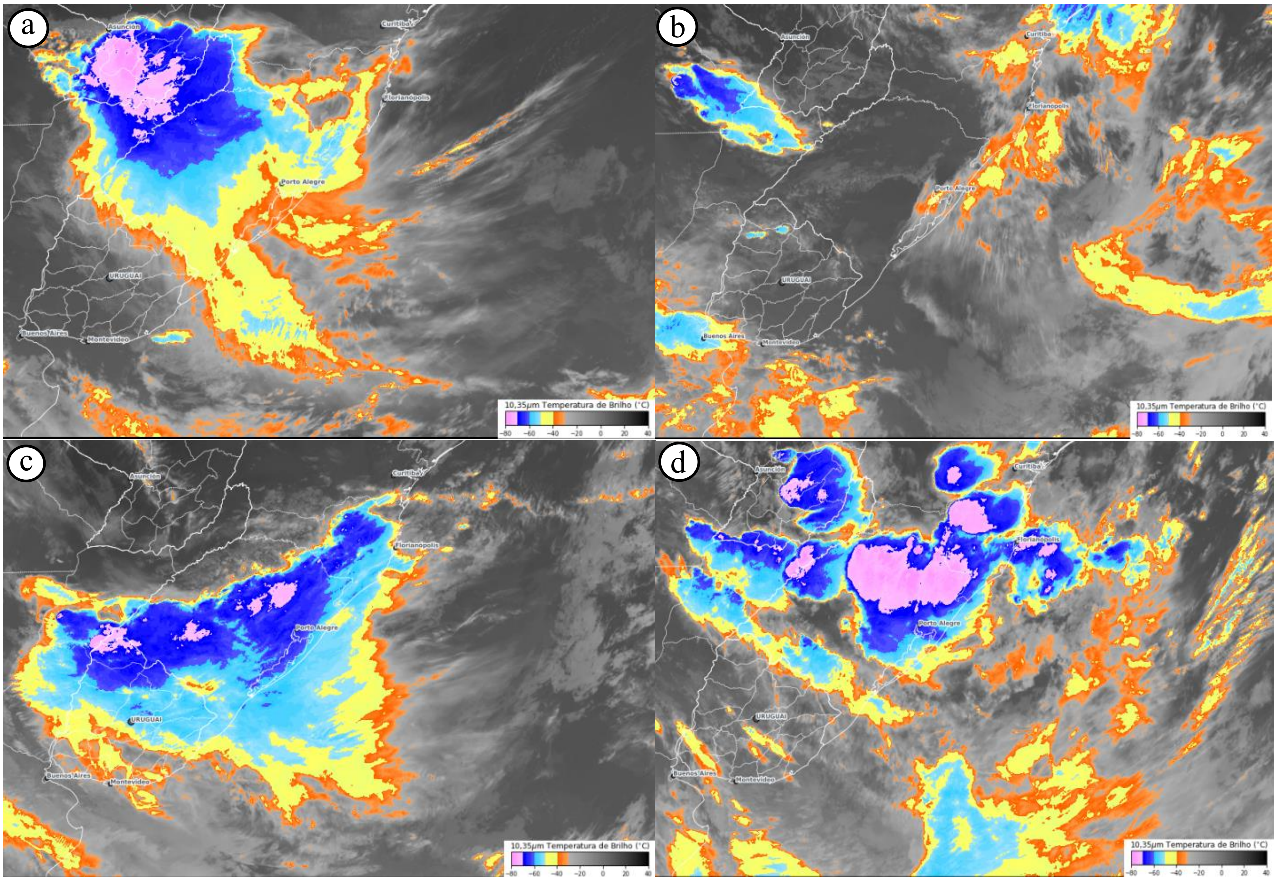

Figure 4. GOES infrared images: (A) September 2, 2023, at 00:00; (B) September 3, 2023, at 00:00; (C) September 3, 2023, at 12:00; (D) September 4, 2023, at 00:00.

From Figure 5, which presents fields at 850 hPa referring to geopotential height, wind magnitude, and mean sea level pressure centers, with low-pressure centers represented by the letter “L” and high-pressure centers by the letter “H”, it is possible to observe, for September 1, 2023 (Figure 5a), the wind flow from north to south over Brazil, passing through northern Argentina. On the following day, September 2, 2023 (Figure 5b), an intensification of a possible the Low-Level Jet (LLJ) was observed over Paraguay towards southern Brazil, transporting heat and moisture from the Amazon with wind flows exceeding 34 kt, a condition characteristic of surface instability and favorable for the occurrence of extreme events in southern Brazil (Nascimento, 2005; Salio et al., 2007; Bork et al., 2017; Sanches et al., 2019; Ribeiro et al., 2023; Santiago et al., 2025). This synoptic feature agress with the cloudiness observed in Figure 4b.

On September 3 and 4, 2023 (Figures 5c and 5d), the wind flow conditions remained, with the system approaching even closer to the northern part of the RS state, as shown in Figures 4c and 4d.

On September 5, 2023 (Figure 5e), the northward moisture transport reached only the State of Santa Catarina (SC) and northern regions of Rio Grande do Sul (RS), while in the southern region of RS, the southerly winds indicated the approach of a polar air mass. This spatial feature of low levels winds indicates a possible decrease in atmospheric instability, common after the passage of cold fronts, a pattern observed during winter, according to Escobar et al. (2016), leading to lower precipitation in the southern region of RS. Furthermore, the cold fronts typically come from the southern continente, with higher frequency between May and September, as described by Foss et al. (2013), among others.

Oliveira et al. (2024) also observed that, in the period from 1991 to 2020, the highest frequency of cold fronts in central-southern South America occurred in spring (September, October, and November), followed by winter (June, July, and August). This pattern coincides with the analyzed period and reinforces that the specific conditions of the day play a crucial role in the intensity of the associated rainfall. Two days after the event, on September 6, 2023 (Figure 5f), RS again presented a predominance of northerly winds, however, not originating from the Amazon, but rather due to the approach of a post-frontal High-Pressure center coming from Uruguay, which can be verified more clearly in Figure 6f.

In Figure 6, the presence of a low-pressure center north of Argentina and Paraguay can be observed, extending towards RS on September 1, 2023 (Figure 6a). This low-pressure system is one of the main factors responsible for inducing moisture transport in the region and presents characteristics of the Northwestem Argentinean Low (NAL) (Seluchi and Saulo, 2012). Such a system is associated with the large MCS, evidenced in the satellite image (Figure 4a). In the presented context, the northwest of RS is under the influence of this surface low-pressure center, while the southeast of the state is influenced by an anticyclone over the ocean. Additionally, to the west of RS, at mid-levels, there is an almost zonal flow with few undulations, suggesting that Cyclonic Vorticity Advection (CVA) is absent or weak at this time.

From September 2, 2023 (Figure 6b), an intensification of the low-pressure center over northern Argentina towards southeastern RS was observed, and on September 3, 2023 (Figure 6c), the presence of a trough at 500 hPa was observed to the west of the continent, but due to its considerable distance from RS, it was not possible to affirm a dynamic influence on the state. However, the intensification of the surface low-pressure center over northern Argentina is noted, due to the northward transport of heat and moisture, as already mentioned. This resulted in the instability observed in Figure 4c, which moved to the western region of the state and remained active until 12:00 on the same day. According to Pereira and Nunes (2018) and Rodrigues et al. (2021), this instability, when interacting with the LLJ, enhances convergence, generating significant precipitation. This environment favors the ascent of warm, moist air, resulting in cloud formation and an increase in precipitation.

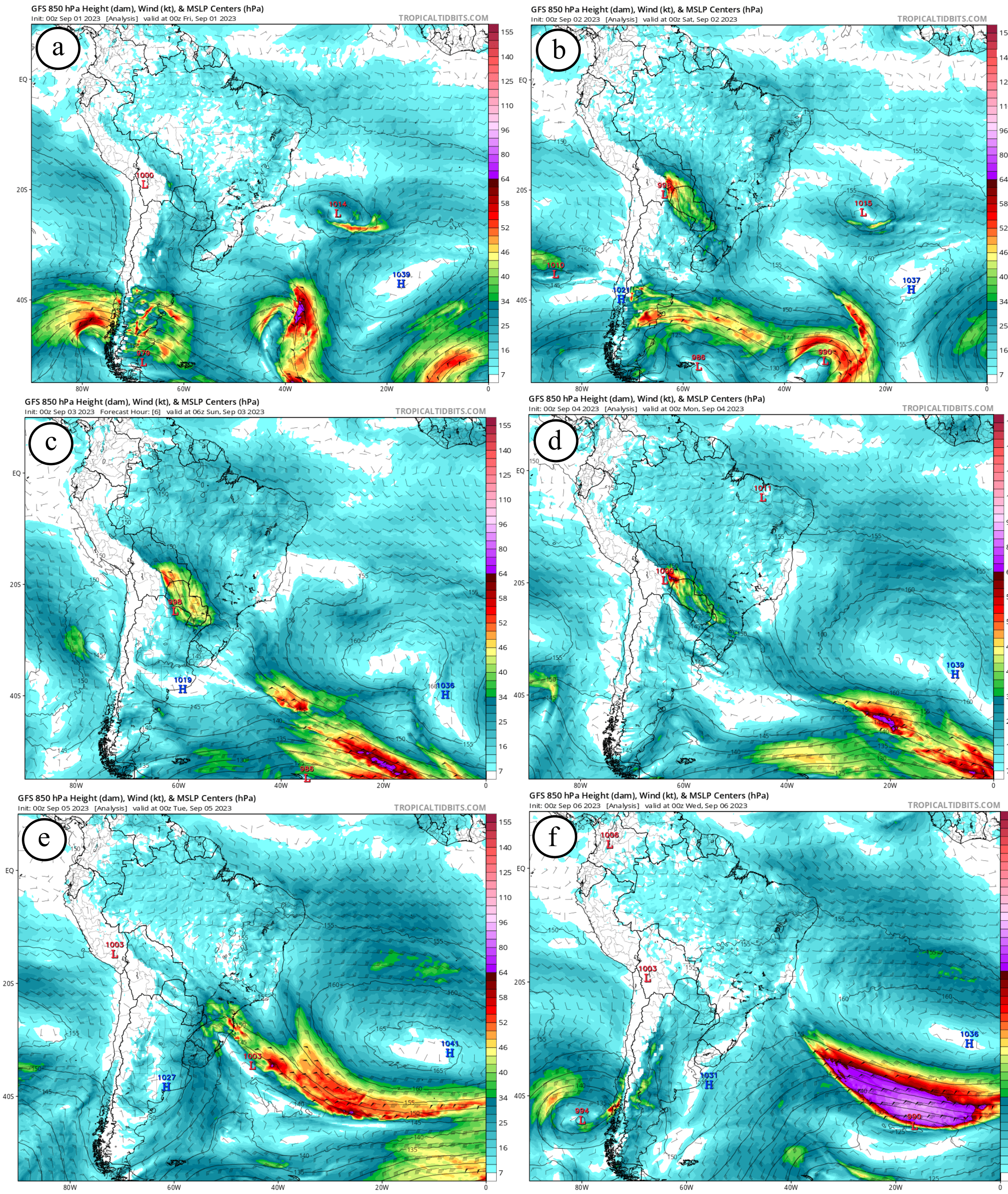

Figure 5. Geopotential height (contours) and wind magnitude in kt (colored shading) at 850 hPa and indication of surface pressure centers in mb, at 00Z on the days: (A) September 1, 2023; (B) September 2, 2023; (C) September 3, 2023; (D) September 4, 2023; (E) September 5, 2023; (F) September 6, 2023.

Previous studies, such as those by Zhang and Meng (2018), verified the presence of mid-level troughs associated with persistent rainfall events in the United States. Teixeira and Pietro (2020), Dornelles et al. (2020), among others, also identified mid-level troughs associated with surface low-pressure systems over the state of Rio Grande do Sul during intense rainfall events.

On September 4, 2023 (Figure 6d), the precipitation recorded in the TARB can be partially explained by the 500 hPa trough located over Argentina, which was moving towards the continent, with the RS state on the lee side (downstream), suggesting the influence of CVA. Moreover, the surface low-pressure center, originating in northern Argentina and extending to the ocean, covering the entire Gaúcho (RS) territory, indicates the presence of a large area of instability over the state.

On September 5, 2023 (Figure 6e), a weakening of the 500 hPa trough and the displacement of the surface low-pressure center towards the Atlantic is observed, which reduces its influence over Rio Grande do Sul. This behavior of a continental low pressure progressing over RS until developing a low-pressure center in the Atlantic is trivial, and is often associated with intense rainfall events in RS, as presented, for example, in Caballero et al. (2018). On the following day, September 6, 2023 (Figure 6f), as already verified in the low-level wind field (Figure 5f), the state is under the influence of a post-frontal high-pressure center, indicating atmospheric stability.

In the upper-level analysis on September 1, 2023 (Figure 7a), a zonal flow over the region is observed. On September 2, 2023 (Figure 7b), significant diffluence occurs over RS, indicating the intensification of the surface low-pressure center and instability (Sanders, 1993; Santos et al., 2022). On September 3, 2023 (Figure 7c), the presence of the subtropical jet core southern RS is noted, indicating baroclinic instability conditions.

As observed at mid-levels (Figure 5d), on September 4, 2023 (Figure 7d), at the peak of the event, the entry of the trough over the continent is observed, indicating Cyclonic Vorticity Advection and instability over RS, as well as at 500 hPa (Figure 6d), in addition to the presence of the subtropical jet, signaling an increase in the meridional temperature gradient (baroclinic instability) at the surface. On September 5, 2023 (Figure 7e), the presence of the jet core over RS is observed, referring to a probable intensification of the surface temperature gradient, indicating cyclogenesis. The continuity of the upper-level trough suggests the presence of a dry and stable polar air mass, due to the entry of the polar high observed in Figure 6e. Finally, on September 6, 2023 (Figure 7f), the confluence over RS indicates stability, signaling the weakening of the atmospheric systems that previously caused instability in the region.

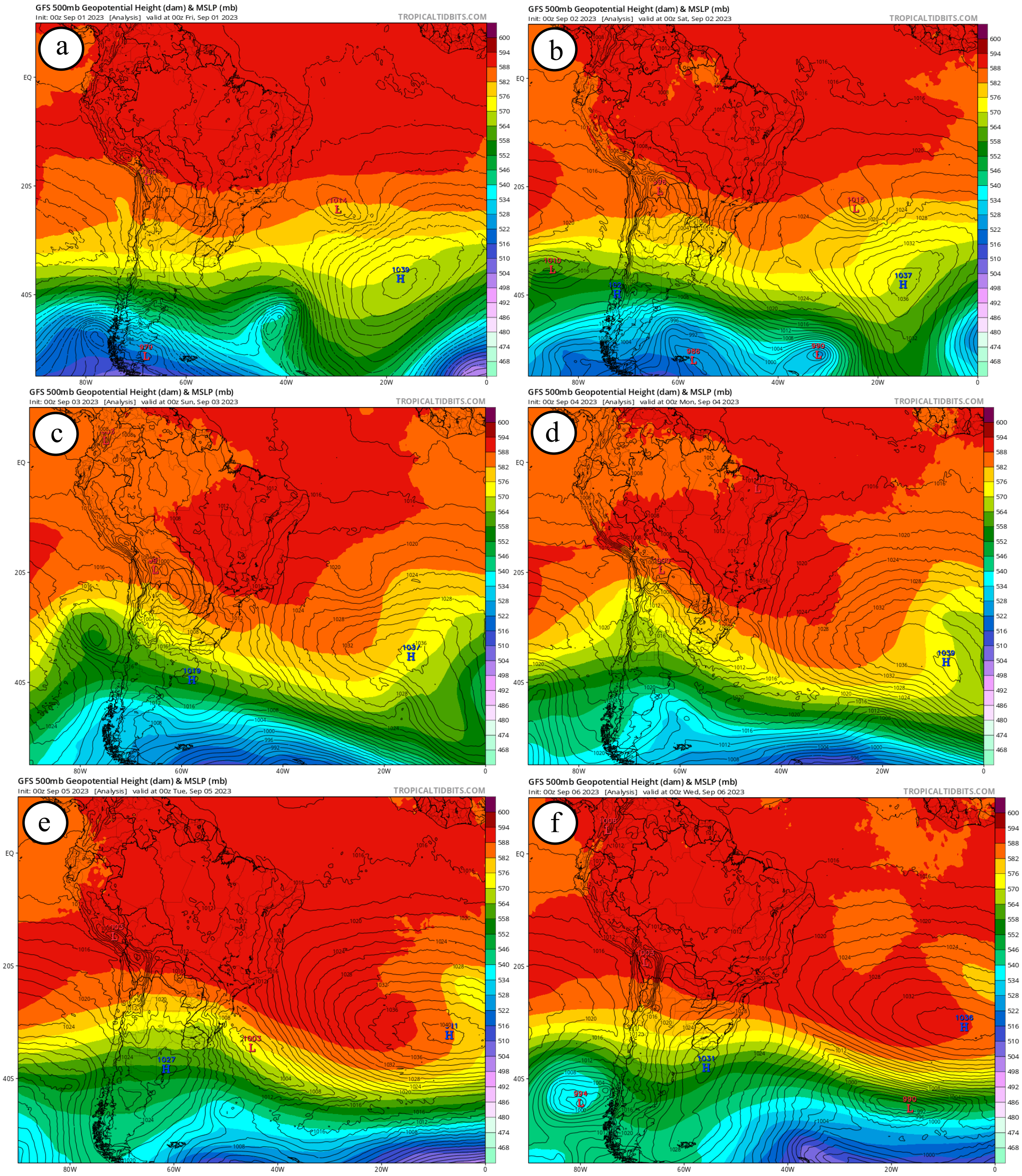

Figure 6. Geopotential height at 500 hPa in dam (colored shading) and mean sea level pressure in hPa (contours), at 00Z on the days: (A) September 1, 2023; (B) September 2, 2023; (C) September 3, 2023; (D) September 4, 2023; (E) September 5, 2023; (F) September 6, 2023.

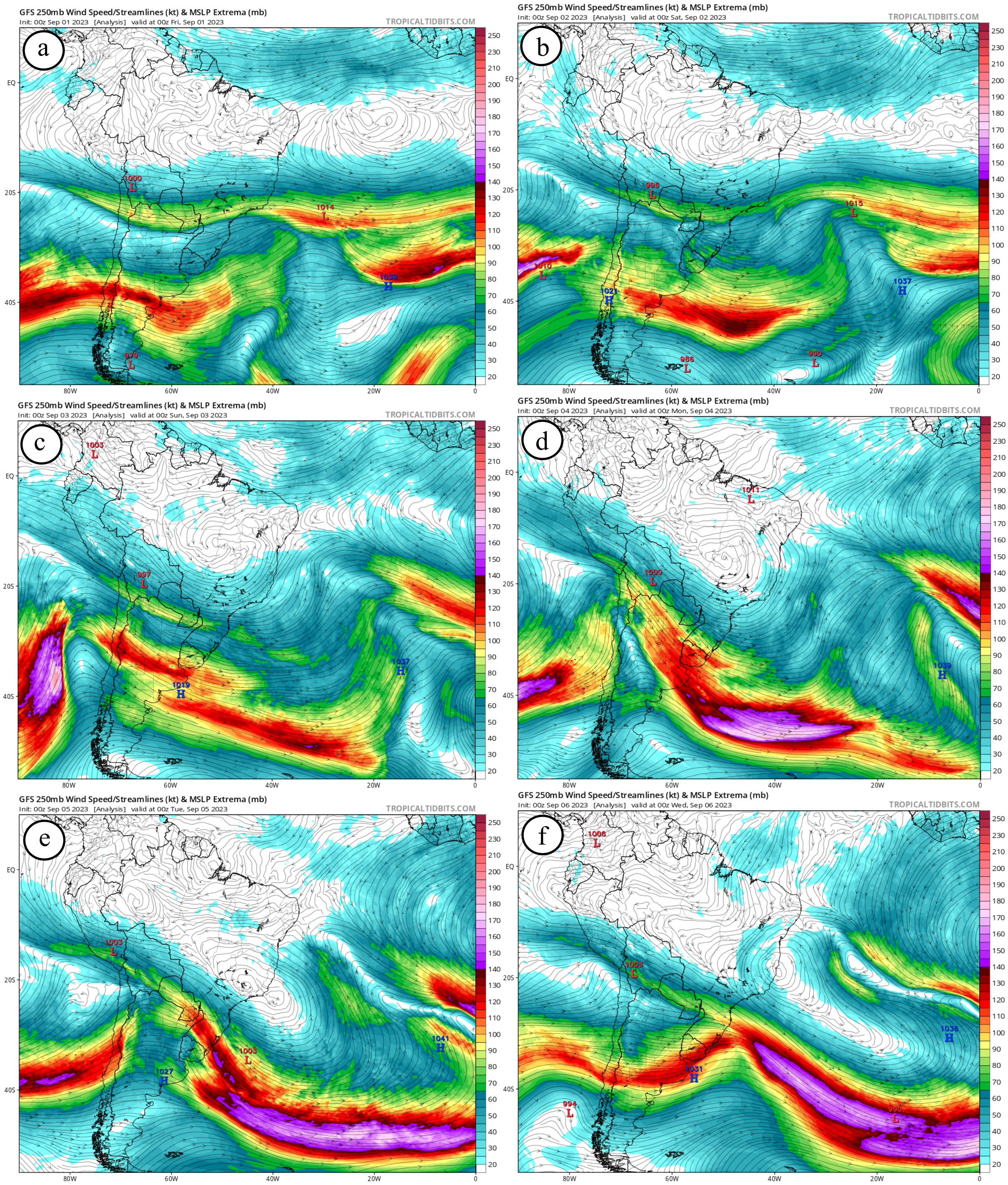

Figure 7. Streamline and wind speed (shaded in kt) at 250 hPa and representation of surface pressure centers (hPa) at 00Z on the days: (A) September 1, 2023; (B) September 2, 2023; (C) September 3, 2023; (D) September 4, 2023; (E) September 5, 2023; (F) September 6, 2023.

In order to organize and highlight the most relevant aspects of the extreme event that occurred in September 2023 in the Taquari-Antas River Basin, Table 1 was presented. In it, the observed precipitation volumes, the predominant atmospheric systems on each day, and the most significant effects recorded are presented in chronological order. This analysis, in summary, contributes to a clearer and more structured understanding of the synoptic evolution of the event throughout the studied period, allowing an integrated view of the large scale development.

Table 1. Summary of the synoptic development of the event

Analysis Day	Precipitation	Acting System	Consequences
01/09/2023	No significant record	Pre-instability	None
02/09/2023	Observed cloudiness, no significant record	MCS; LLJ; NAL	Beginning of instability
03/09/2023	200-250 mm	500 hPa Trough; LLJ	Intense rainfall
04/09/2023	200-250 mm	CVA; Convective cores	Severe floods
05/09/2023	Gradual reduction	Entry of polar air mass	Reduction of instability
06/09/2023	No significant record	High-Pressure Center	Atmospheric stability

Precipitation (mm); MCS – Mesoscale Convective System; LLJ – Low-Level Jet; NAL – Northwestern Argentinean Low; CVA – Cyclonic Vorticity Advection.

According to the summary of the synoptic development of the event under analysis, the extreme precipitation event began on September 2, 2023, driven by the MCS, the LLJ, and the NAL. These systems, characteristic of surface instability, favor the occurrence of extreme events (Ogassawara et al., 2021) due to moisture transport and the intensification of convergence areas.

Although the presence of a 500 hPa trough was recorded on September 3, 2023, it was located to the west of the continent, making it impossible to affirm its direct dynamic influence on the event. The precipitation observed on this day was due to the action of the low-level jet, responsible for transporting heat and moisture from the northern region to the south of the country (Da Rocha et al., 2024; Santiago et al., 2021 and 2025), in addition to contributing to the intensification of the low-pressure center.

The situation intensified on September 4, 2023, when the 500 hPa trough moved over Argentina, generating a CVA area that promoted the formation of large convective cores. This process resulted in severe floods in the basin, with extreme precipitation, accumulating between 200 and 250 mm.

On September 5, 2023, the intensification of precipitation began to gradually decrease due to the entry of a polar air mass. Finally, on September 6, 2023, the arrival of a high-pressure center from Uruguay completely dissipated the convective cloudiness, resulting in atmospheric stability and the absence of significant rainfall.

In general, the synoptic analysis demonstrates that the extreme precipitation event was the result of a complex and interconnected sequence of atmospheric systems. The initial action of the LLJ and the NAL created a favorable environment for the formation of instability, which was subsequently intensified by CVA associated with the mid-level trough. The instability was completely dissipated only with the arrival of a polar air mass and the low-pressure center, marking the end of the period of intense rainfall in the TARB. This dynamic reinforces the importance of analyzing the vertical structure of the atmosphere for the understanding and diagnosis of extreme precipitation events, as also pointed out by Bartolomei et al. (2023), who investigated the role of synoptic-scale systems and extratropical cyclones in the genesis of intense precipitation in southern Brazil.

Conclusions

It is concluded that the precipitation events recorded in September 2023 over the Taquari-Antas River Basin were significantly influenced by the transport of heat and moisture from the Amazon towards southern Brazil, a process strongly driven by the action of the Low-Level Jet. This moisture advection system is well known as one of the main drivers for the formation of convective systems and the intensification of atmospheric instability in the southern region of the country.

At the same time, the presence of the Northwestern Argentinean Low, which moved from Paraguay towards Brazil, played a fundamental role by favoring low-level moisture convergence, creating an unstable environment conducive to the formation of intense convective cores. This interaction between the LLJ and the NAL highlights the complexity of atmospheric behavior during the event.

At mid-levels of the atmosphere, the dynamic action of a trough was observed, contributing to the occurrence of extreme precipitation. In addition, some episodes of upper-level diffluence were recorded, reinforcing the presence of mechanisms favorable to the ascent of moist air masses and contributing to the development of convection.

The arrival of a cold front in southern Brazil, accompanied by a change in wind direction, with predominance of southerly winds, promoted the dissipation of instability over Rio Grande do Sul at the end of the extreme episode under study, subsequently resulting in atmospheric stabilization.

As discussed and observed throughout this study, the extreme precipitation event was the result of the combination of thermal and dynamic forcings that interacted at different levels of the troposphere. The recorded atmospheric behavior corroborates the literature, which highlights the importance of analyzing the atmosphere at different vertical levels as a fundamental element for the diagnosis and prediction of extreme events.

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