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Extreme Seasonal Droughts and Floods in the Madeira River Basin, Brazil: Diagnosis, Causes, and Trends

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Abstract: The Madeira River, a major tributary of the Amazon River, often undergoes severe flood and drought conditions. This study seeks to investigate the climate processes associated with the opposing extreme precipitation events in the Madeira River basin and to relate them to river discharge variability based on a flood awareness dataset. Despite the uncertainty in the observational datasets, the annual precipitation cycle exhibits a rainy season from November to March. A significant result is the high correlation between the rainy season variability in the Madeira River basin and the sea surface temperature (SST) anomalies in the tropical North Atlantic Ocean and the southwestern South Atlantic Ocean. This result indicates that improving the Atlantic SST representation in climate modeling allows for capturing extreme precipitation events in the region. In addition to this impact, certain Madeira River tributaries present significant climate trends. The river discharge variability reveals an increase in hydrological extremes in recent years in the upper sector, but more significantly, in the lower basin, where it has reduced by more than 400 m³/s per decade. These findings highlight the need to improve in situ data and climate and hydrological modeling, with a focus on describing the intense climate variability and trends in river discharges.

Keywords: extreme precipitation; Amazon rivers; climate change; hydrology



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1. Introduction

The Madeira River basin in southwestern South America spans Brazil, Bolivia, and Peru. The upper part of the river in Bolivia has a highly dense population. In Brazil, the lower part of the river encompasses a complex of hydropower plants, several natural reserves, plantation farms, small communities, and remote indigenous communities. Among the water consumption, most of these activities depend on the river for navigation and transportation. Therefore, the Madeira River contributes significantly to the socio-economic activities in Brazil.

These valuable hydrological conditions in the region are associated with different drivers of extreme precipitation. Whereas the elevated mean annual precipitation is 1834 mm, the basin is highly vulnerable to extreme climate variability, reaching extremes higher than 5000 mm/yr [1,2]. Different studies have focused on the drought mechanisms in the Amazonian region that occurred in 2005 and 2010, as well as the floods of 2009, 2012, and 2014 [3–6]. Specifically for the Brazilian part of the Madeira River basin, ref. [7] classified 1994, 2001, 2008, and 2014 as the rainiest years and 2000, 2005, and 2010 as the driest [5,6]. The most recent and probably the most extreme drought on record was in 2023, which caused the lowest Amazon River level and increased scientific concerns about the

region [8,9]. Historically, the most intense flood occurred in 2014, when the discharge from the Madeira River increased by more than 74% [10].

The discharge from the Amazon River basin has shown linear trends over the last decades [2]. From 1974 until 2004, discharge decreased in different parts of the region, particularly in the southern part, and increased in the northwestern part [2]. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6), warmer climates induce a decrease in the total soil moisture and possibly lead to conflicts over water use in the entire Amazon basin [11].

The precipitation variability in northern South America is often related to remote changes in ocean temperature [12–15]. The variability in the Amazonian region is associated with climate indices, such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), in addition to the tropical Atlantic Ocean temperature [5,6,16]. The warm ENSO phase generally reduces the precipitation in the region, and the cold ENSO phase increases it [17–19]. The 2023 drought was also related to the ENSO, but mainly to its modulation from the warm to the cold phase from 2022 to 2023, which induces a lack of moisture during the rainy season and intensive downward movement during the drought season [9]. The 2023 event's relation to the ENSO was investigated by [8]. However, the severity of the 2023 event surpassed the natural effects of the ENSO and was mainly associated with the increase in global temperatures. In the southwestern Amazon basin, where the Madeira River is located, during the 2014 flood, the high precipitation amounts were associated with abnormal conditions in regard to the tropical Atlantic SST gradient [10], as was the drought in 2005 [6].

Increasing concerns about the region, particularly over the modification in the hydrological conditions, have motivated different studies. Many have focused on different extreme precipitation events [5,6,8–10]. A few climatological diagnoses have been made about the Brazilian part of the basin [7] or the entire Amazonian basin [2,4,16]. Others have integrated hydrological models to understand the dynamics of hydrological processes [1,3,20]. However, there is a need for further exploration and comprehension of the climatological variability and its implications for the Madeira River's regional conditions.

This study aims to contribute to understanding the meteorological features and processes associated with extreme events in the Madeira River basin. The results can help to model the climate in the region more accurately. In addition to increasing the understanding of natural processes impacting seasonal and interannual precipitation variability, this study focuses on the tendencies and impacts of river discharge. In addition, as in [17], precipitation variability is identified using different datasets to provide a more robust picture of the region.

This study is organized as follows: Section 2 describes the study area, methods, and datasets. The results in Sections 3.1–3.3 illustrate the precipitation variability in the basin and how it relates to climate indices. The meteorological patterns during years of extreme precipitation are analyzed using composites to highlight their peculiarities. Lastly, Section 4 focuses on river discharge and characterizes the flow response to precipitation extremes and tendencies. The discussion and conclusions are presented in Section 4.

2. Materials and Methods

2.1. Study Area

The Madeira River basin is a transboundary basin that extends across three countries in South America: Bolivia, Brazil, and Peru (Figure 1). With a drainage area of approximately 1,420,000 km² [21], it is one of the largest sub-basins (23%) of the Amazon basin and is on the right bank of the Amazon River. Most of the basin is found in Bolivia and Brazil, and to a lesser extent in Peru, representing 51%, 42%, and 7% of the total basin area, respectively. The basin presents considerable topographic gradients, from about 25 m in the north to almost 4000 m in the Andes Mountains in the southwestern part. Although the mountain regions remain dry for most of the year, they still exhibit some mountainous features essential to maintaining river discharge.

Due to its location in lower latitudes, the basin suffers from the seasonal variations of the Intertropical Convergence Zone (ITCZ) during austral summer, which is a common feature that occurs during the South American Monsoon System (SAMS) [22]. Studies indicate a rainy period that is established between November and April and a dry period from May to October in the Brazilian portion of the basin [7]. According to [7], using observations from 1988 until 2017 for the Brazilian part of the basin, the ITCZ contributes to establishing the rainy period [7]. The precipitation regime in the region is constrained by the SAMS, whose onset period occurs in November, and its demise occurs in April in the basin [22].

According to the Köppen classification [23], the basin contains tropical forest, tropical monsoonal, and tropical wet and dry climates (types Af, Am, and Aw). These climates are characterized by super humid summers, with monsoon-type rain and a short, dry winter season. Over the Andes, in Bolivia and Peru, the climate is characterized by warmer summers, with mild to cold and relatively dry winters (types Cwb, Cfb, and Cfc).

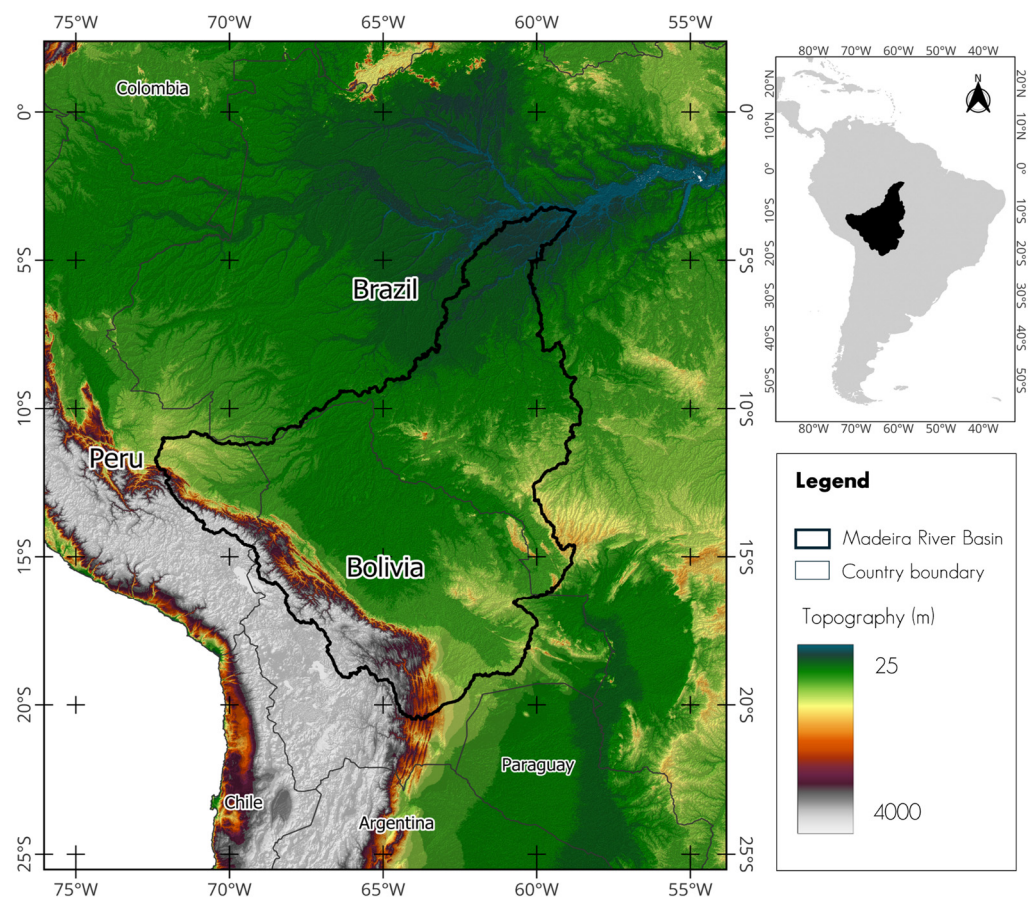


Figure 1. Location of the Madeira River basin. Color-shaded relief originated from a digital elevation model (DEM) derived from Shuttle Radar Topography Mission (SRTM) data, with a 3 arc-second (approximately 90 m) resolution [24].

2.2. Datasets

Different datasets explain the precipitation variability in the Madeira River basin. Initially, this study verifies the consistency between the datasets in the region due to its limited in situ gauge measurements. The two observational precipitation datasets adopted to identify the most extreme precipitation periods of the basin are the MERGE [25] and the Multi-Source Weighted-Ensemble Precipitation (MSWEP) datasets [26]. Both datasets combine gauge stations and satellite observations at a 0.1° horizontal grid resolution from

IMERG. Unlike MSWEP, the MERGE dataset is a dataset produced by the Brazilian National Institute for Space Research (in port., INPE).

Freshwater discharge from the Global Flood Awareness System (GloFAS) reanalysis dataset [27] at a 0.1° grid resolution (version 3.1) is used to diagnose the river flow in the Madeira River basin. The GloFAS derives from the daily hydrological time-series output from a model that is forced by the ECMWF Reanalysis v5 (ERA5) [28].

ERA5 [28] provides the patterns of sea surface temperature (SST), wind at lower and upper levels (850 and 200 hPa), and vertical motion at the mid-level (500 hPa) during extreme precipitation events.

2.3. Methodology

Figure 2 presents a detailed outline of the methodology. In the initial phase, this study compares the representation of seasonal and interannual precipitation variability in the basin for each dataset. Due to the limitations of the MERGE dataset, which includes data from June 2000, the analysis in this study considered 23 years, from 2001 until 2023. Although a more extended period would be desirable, recent studies have considered period lengths of 20 years to describe climatological features [11]. The comparison with other studies on the region over extended periods and using observational data demonstrates its sufficiency.

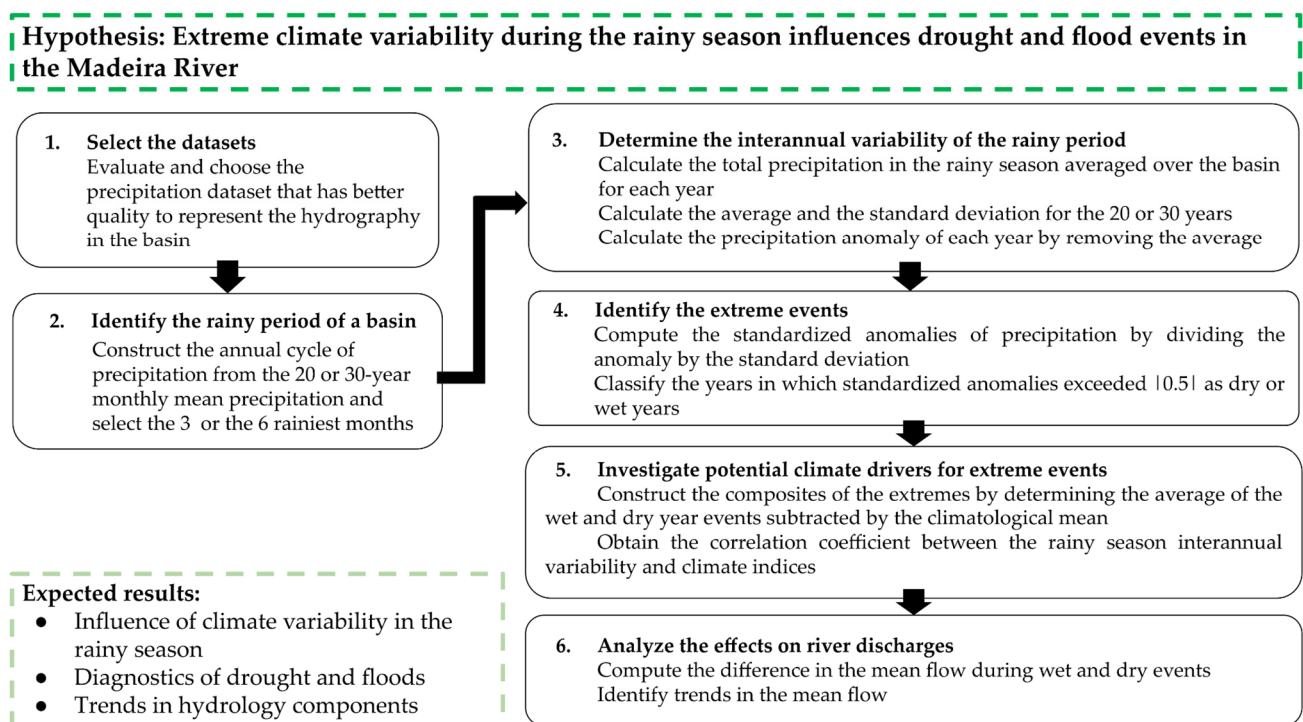


Figure 2. Methodology developed to analyze and identify extreme precipitation events in the Madeira River basin.

Then, the study focuses on observing the most extreme variations in the rainy season in the datasets, considering the seasonal precipitation cycle to determine the rainy season in the basin. The standardized anomalies determine the rainy season variability [29], in which rainy periods presenting deviations of ± 0.5 categorize extremes. The analysis of the rainy periods considers seasonal features contributing to the South American climate that infer the variability in the basin, such as the ITCZ, SACZ, and SAMS [22,30].

After identifying the most extreme events, the study investigates the climatological components that generate these events. Composite anomalies aid in characterizing meteorological variable distributions during extremes. Additionally, Pearson's correlation

analysis between the precipitation variability series and climate indices, representing different variability modes, is carried out to identify their relationship to the occurrence of extremes [29]. The climate indices are a time series of the correlations/standard deviations (STDs) of the SST from the National Oceanic and Atmospheric Administration (NOAA) [31] for the determined regions. Their effects are commonly verified by an STD greater or lower than 0.5 [12]. The analysis comprises the climate indices of interannual and interdecadal variability, such as the Pacific modes Nino12, Nino34, Nino4 (representing different ENSO indices), and the PDO, as well as those for the Atlantic region, the tropical North Atlantic (TNA), the tropical South Atlantic (TSA), and the Atlantic Multidecadal Oscillation (AMO). Additionally, it considers the Quasi-Biennial Oscillation (QBO).

As indicated in Section 1, the extreme rainfall events related to the ENSO phases have different impacts on extreme precipitation in the northern parts of the continent [13]. Some studies have related the cold ENSO phase to the extreme droughts of 2005, 2010, and 2023 in the basin [5,6,9]. Along with the ENSO, different research has suggested a significant role for the TNA variability in the 2005 drought and the 2014 flood [6,10]. Other SST variability modes of interannual variability (TSA) and the interdecadal variability modes, PDO and AMO, also significantly correlate with extreme precipitation in northwestern South America [12,15]. Additionally, the Quasi-Biennial Oscillation (QBO) is considered to relate to extreme precipitation in the region, as confirmed by different models [32]. Pearson's correlation analysis investigates whether the impacts of these indices on South American precipitation influence droughts and flood periods in the Madeira River basin.

After characterizing the precipitation variability in the basin, this study links it to river discharge. In addition to anomalies and comparisons between extreme events, the trends in river discharge from 2001 until 2023 are produced and tested using the Mann–Kendall test [33,34].

3. Results

3.1. Analysis of Precipitation Variability in the Basin

A comparison of the precipitation patterns in the Madeira River basin between the two datasets (Figure 3) shows that the MSWEP dataset contains higher precipitation amounts. The elevated monthly mean precipitation amounts registered by MSWEP appear especially southwest of the basin, where the most populated cities in Bolivia are located, and northeast of the basin, in the lower Madeira basin in Brazil, where it exceeds more than 300 and 150 mm, respectively.

Table 1. The annual mean precipitation for six cities located in the Madeira River basin. The period is from 2001 until 2023.

Location	Coordinates	Annual Mean Precipitation (mm)	
		MERGE	MSWEP
Cochabamba (Bolivia)	66.17° W, 17.41° S	1701	2625
La Paz (Bolivia)	68.12° W, 16.49° S	2321	2123
Rurrenabaque (Bolivia)	67.53° W, 14.44° S	5163	5178
Fazenda Vista Alegre (Brazil)	60.02° W, 4.89° S	5391	6276
Manicoré (Brazil)	61.20° W, 5.82° S	6827	5558
Porto Velho (Brazil)	63.92° W, 8.73° S	5442	7118

The difference in the precipitation amounts in the datasets is less concerning for some of the major cities, as indicated in Table 1. The MSWEP and MERGE estimates demonstrate consistency in the Bolivian cities of La Paz and Rurrenabaque. However, in Cochabamba, the datasets disagree by about 1000 mm, with a higher amount in the MSWEP dataset (as in Figure 3). Similarly, in the Brazilian cities of Porto Velho and Fazenda Vista Alegre, the MSWEP dataset estimates are higher than the MERGE dataset, but in Manicoré, the MERGE dataset has higher amounts.

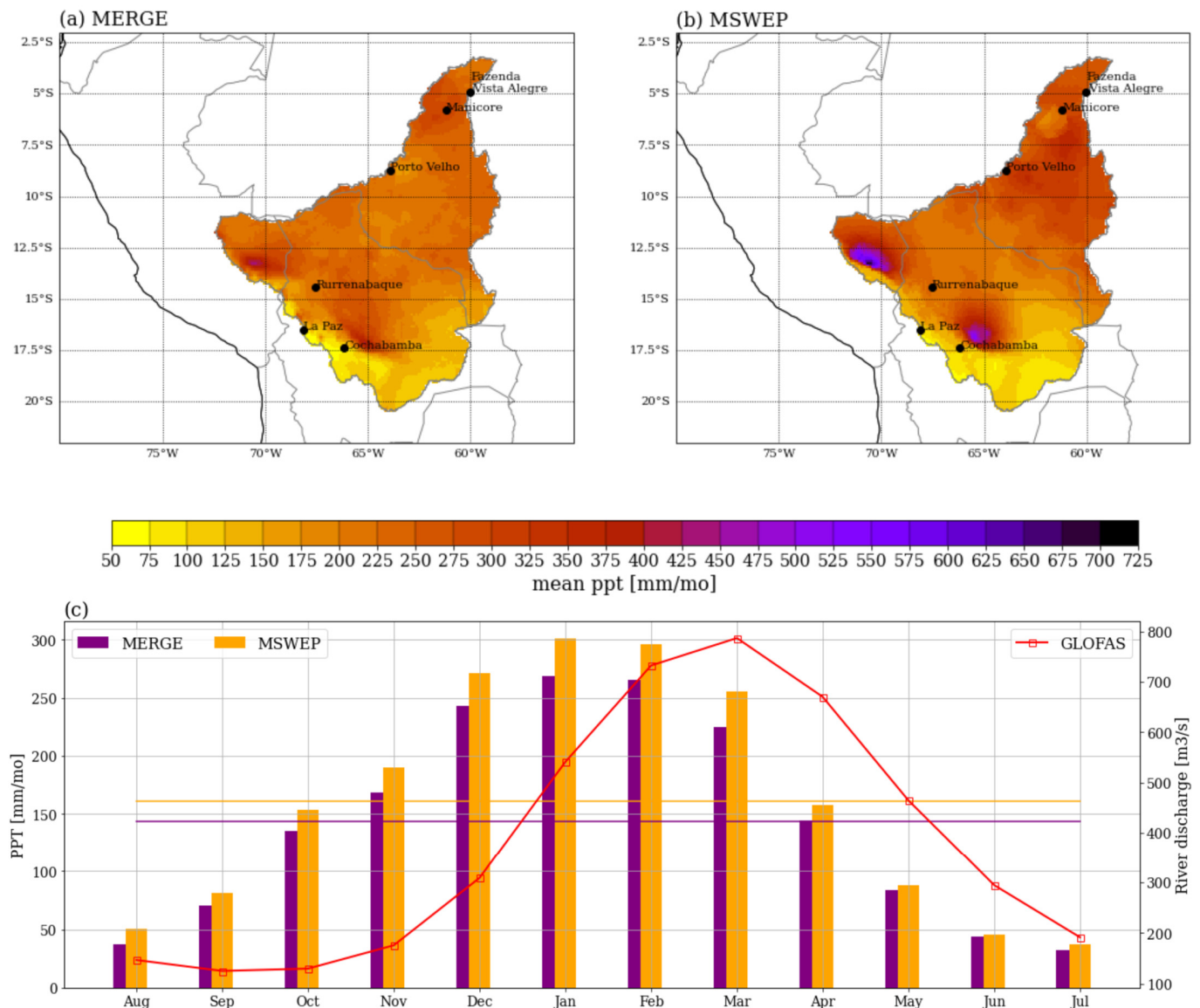


Figure 3. Monthly mean precipitation (mm/month) pattern from (a) MERGE and (b) MSWEP datasets. (c) Annual cycle of precipitation in the Madeira River basin averaged from 2001 until 2023. The GloFAS river discharge is the red curve. Black dots show the location of the cities listed in Table 1. The horizontal-colored lines are the annual mean for the corresponding precipitation dataset.

The datasets share the same horizontal resolution and consider IMERG satellite data, which does not explain the precipitation differences. As they come from different sources, their methodological approach differs. Moreover, the MSWEP dataset incorporates additional satellite observations from CHLSA (0.01° grid resolution) and GridSat (0.07°) and reanalysis data from ERA5 [26]. The assembly of different products in regions with reduced in situ data increases the discordance. Therefore, the disparities derive from the different estimation methods and/or data availability within each dataset.

The disparities in the datasets result in the mean precipitation being 20 mm higher for the MSWEP dataset, reaching 160 mm (Figure 3). Despite the differences, the estimated annual precipitation of 1717 mm for the MERGE dataset and 1926 mm for the MSWEP dataset are close to the 1834 mm in ref. [1]. The seasonal cycle of the two datasets agrees that the rainiest months in the basin occur from November to April [7].

The annual cycle of the GloFAS river discharge in the basin peaks in March and lags behind the precipitation peak by about two months. Most of the river flow in the Madeira River depends on the rainy season. The onset of the rainy season in October contributes to

the flow increase in October, but with a more significant contribution in January, after three months of monsoonal precipitation. The GloFAS mean monthly discharge of $380 \text{ m}^3/\text{s}$ and an annual mean of $4565 \text{ m}^3/\text{s}$ are close to the values observed at some stations, such as the Bolivian station of Rurrenabaque and the Brazilian stations of Porto Velho and Fazenda Vista Alegre [7].

The observed precipitation in the Brazilian sector of the Madeira River basin indicates the rainiest trimester is January–February–March, and the rainy season is from November until April, characterized by precipitation above the annual average [7]. Based on the same criterion, in Figure 3, April shows precipitation below the average. Although excluding April from the rainy season disagrees with [7], the rainy season from November until March agrees with the SAMS period in the region [22]. Thus, the period from November to March defines the rainy season in the basin from now on.

The time series of the standardized anomalies of precipitation and river discharge for the rainy season reveal that the river discharge has higher interannual variability than the precipitation in the basin (Figure 4). As the river fluctuations occur four months later, the drought discharge extremes detected for the rainy season are further enhanced in the dry season (with a peak in August, Figure 3). In addition, recurrent drought events can aggravate the impact in the following seasons. For instance, the precipitation anomalies for the 2022 drought could significantly contribute to the river discharge anomalies in 2023 (Figure 4).

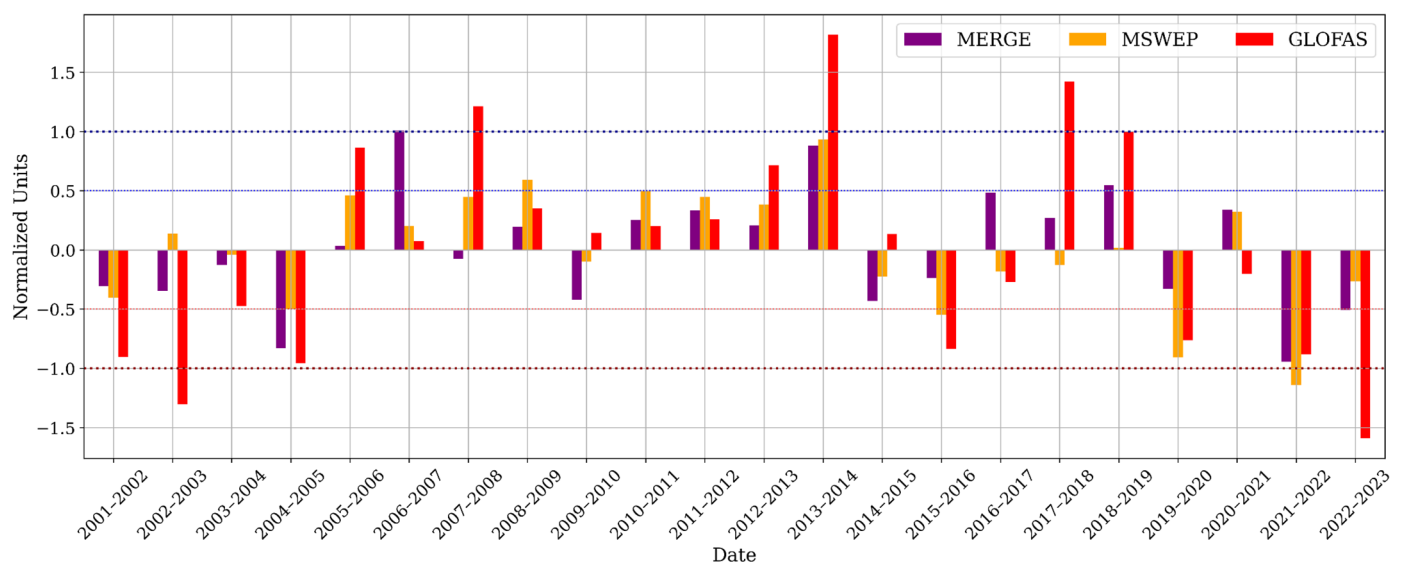


Figure 4. Time series of the standard deviations of precipitation and river discharge in the Madeira River basin. The rainy season starts in November of one year and ends in March of the following year.

Although GloFAS derives from a model, comparing river discharge with the precipitation datasets indicates a possible consistency in terms of characterizing droughts and floods in the Madeira River basin. In Figure 4, the MSWEP dataset shows better alignment with GloFAS. The MERGE dataset has shown more discrepancy in several years, such as 2006, 2007, 2008, 2010, 2015, 2017, and 2020, while the MSWEP dataset deviates during 2003 and 2018. Thus, the MSWEP dataset better characterizes extreme precipitation events in the Madeira River basin, confirming the superior performance of the MSWEP dataset compared to other satellite products and in situ data, as demonstrated in previous research [35,36].

3.2. Correlation with Climate Forcing

South American climate variability is highly related to climate indices [12–14]. Figure 4 shows the time series of the standard deviations of the MSWEP dataset precipitation in the basin, in comparison to the variability of the various climate forcing data represented by the

indices: Niño12, Niño34, Niño 3, PDO, AMO, QBO, TSA, and TNA [31]. The outstanding extremes agree with the records in the literature, pointing out extreme rain events in 2009 and 2014 and extreme droughts in 2005, 2016, 2020, and 2022.

The correlation coefficients between the precipitation anomalies and the indices reveal that the basin variability is strongly modulated by the TNA SST and the AMO, with significant correlation coefficients of 0.44 and 0.27, respectively. Although earlier findings indicate a relationship between the Pacific SST and the precipitation in the Amazon region [4,9,16], the subregion covering the Madeira River basin exhibits a different relationship. The correlation coefficient with different ENSO indices, such as Niño1.2, Niño3, and Niño3.4, is low, as is the correlation with the PDO. Some drought events, such as in 2005, occurred during the ENSO warm phase (Figure 5, positive Niño indices), but the same warming occurred in the 2009 rainy event. In more recent years, the ENSO cold phase happened in the 2014 rainy event (Figure 5, negative Niño indices), but the same characteristic resulted in the 2020 drought. The absence of alignment during the extremes, as verified by the ENSO and PDO, explains the low correlation coefficients.

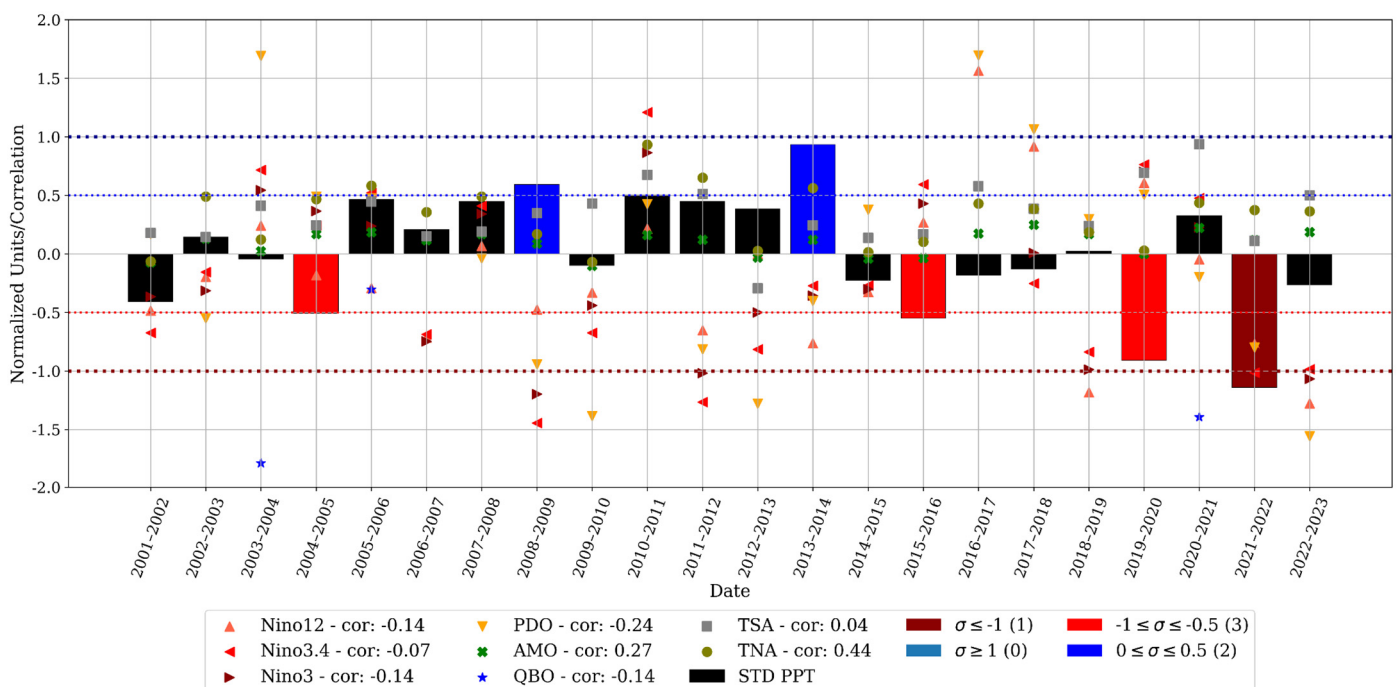


Figure 5. Time series of the standard deviations of the rainy season precipitation in the Madeira River basin. The bars (STD PPT) correspond to the November–March standardized anomalies from the MSWEP dataset. Red/darker red displays the most extreme drought events, and the extreme rainy events are blue/darker blue. The climate indices are monthly values derived from the NOAA [31].

3.3. Composites of Extremes

Composite anomalies of the SST confirm the relation between the precipitation variability in the basin and the TNA variability (Figure 6). Some studies have indicated this relationship during dry and rainy extremes in the Madeira River basin [5,6,10]. The SST in tropical Atlantic waters modifies the latitudinal displacement of the ITCZ [10,14]. In drier years (Figure 6b), the SST is warmer in the TNA region, indicating a northern ITCZ. At the same time, the opposite occurs in rainier years, with negative SST anomalies in the TNA (Figure 6c). The SST anomaly pattern also shows opposite signs in the southwestern South Atlantic Ocean, around 30°S. Negative SST anomalies in the southwestern South Atlantic (Figure 6b) suggest that a cooler ocean surface occurs during the drier years in the Madeira River basin. In contrast, positive SST anomalies, suggesting a warmer ocean, are associated with rainier years (Figure 6c).

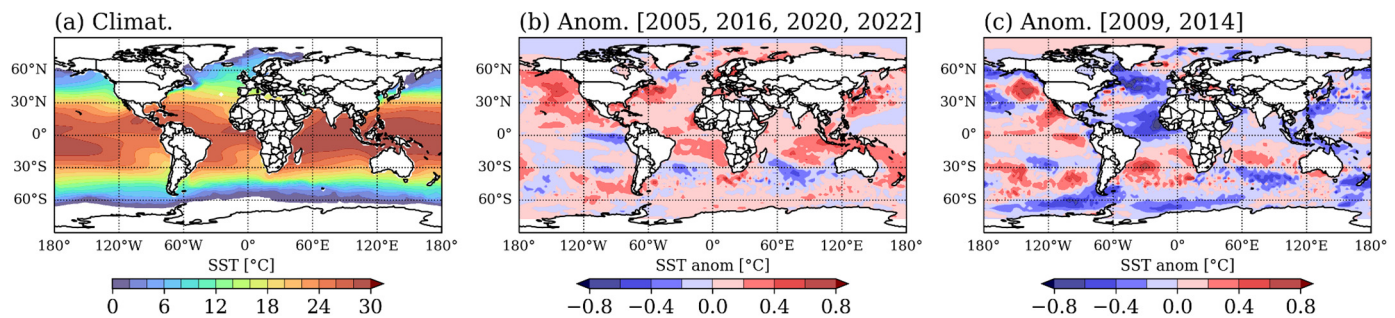


Figure 6. Sea surface temperature (°C): climatology (a) and mean anomalies during dry (b) and wet (c) years. The plots consider ERA5 data on the yearly means for the rainy season from November to March.

The lower-level winds in the 850 hPa layer (Figure 7) indicate the effects of the TNA's contribution to the precipitation variability in the basin. During drought events, the winds from the North Atlantic are weaker, revealing wind anomaly vectors in opposite directions (Figure 7c), and the southeasterly trade winds reduce their flow over northern South America (Figure 7b). The amount of moisture that the region receives from the Amazon region is related to the maintenance of this flow [10,37]. The anomalies show an average wind speed reduction of more than 1 m/s, which will contribute significantly to less moisture and precipitation in the basin. In contrast, the opposite relates to rainy events registered in the basin, and the wind patterns indicate enhanced trade winds (Figure 7e). This wind that blows out of the basin is a component of the low-level jet (LLJ) [30], and its modulation is crucial to the distribution of precipitation across the continent.

The wind anomalies observed in the ocean are consistent with the SST patterns and are related to the precipitation patterns [30]. During rainy events (Figure 7e), the anomalies intensify the northwest flow of the South Atlantic Subtropical High. Conversely, the drought events (Figure 7c) display wind anomalies from the opposite direction of the climatological flow (Figure 7a). This structure and its confluence with the LLJ are necessary to maintain the South Atlantic Convergence Zone (SACZ) activity, as observed by others [30,38]. Stronger southward winds increase precipitation over southern Brazil, while weaker southward winds increase precipitation over central–east Brazil. The relationship between precipitation and near-surface winds results in SST anomalies in the southwestern Atlantic Ocean [30,39].

The mid-level (500 hPa) mean vertical motion reveals the presence of a semi-permanent area of rising air over the Amazon basin. The negative sign indicates upward air motion as an indicator of the Walker cell circulation (Figure 8a,b,d). The extreme years modify this circulation, with interactions explained by the wind anomalies. During drought periods, the winds are weaker (Figure 7b), and, as a consequence, less moisture is transported to the region, reducing the convection and upward motion in the basin. The impact of reduced convection leads to an increase in the mean vertical velocity in the midwest of the basin (Figure 8b), and furthermore, the anomalies reveal that the entire region is affected, increasing by at least 1% of its value, with a greater contribution in the central–west and northern part of the basin (Figure 8c). This effect indicates that the wind impacts in the basin are not fully suppressing the convection activities in the region. However, it suggests a higher capability to reduce the volumes of moisture transport. Similar aspects, but opposite signs, occur during rainy periods (Figure 8d,e), and enhanced vertical motion appears in the center to the north of the area. Nevertheless, more intense vertical motion anomalies are observed northwest of the basin during extreme events. These anomalies suggest that the extremes in the Madeira River basin relate to the same system that suppresses convection in northwestern Brazil, mainly due to the modulation of SST in the TNA.

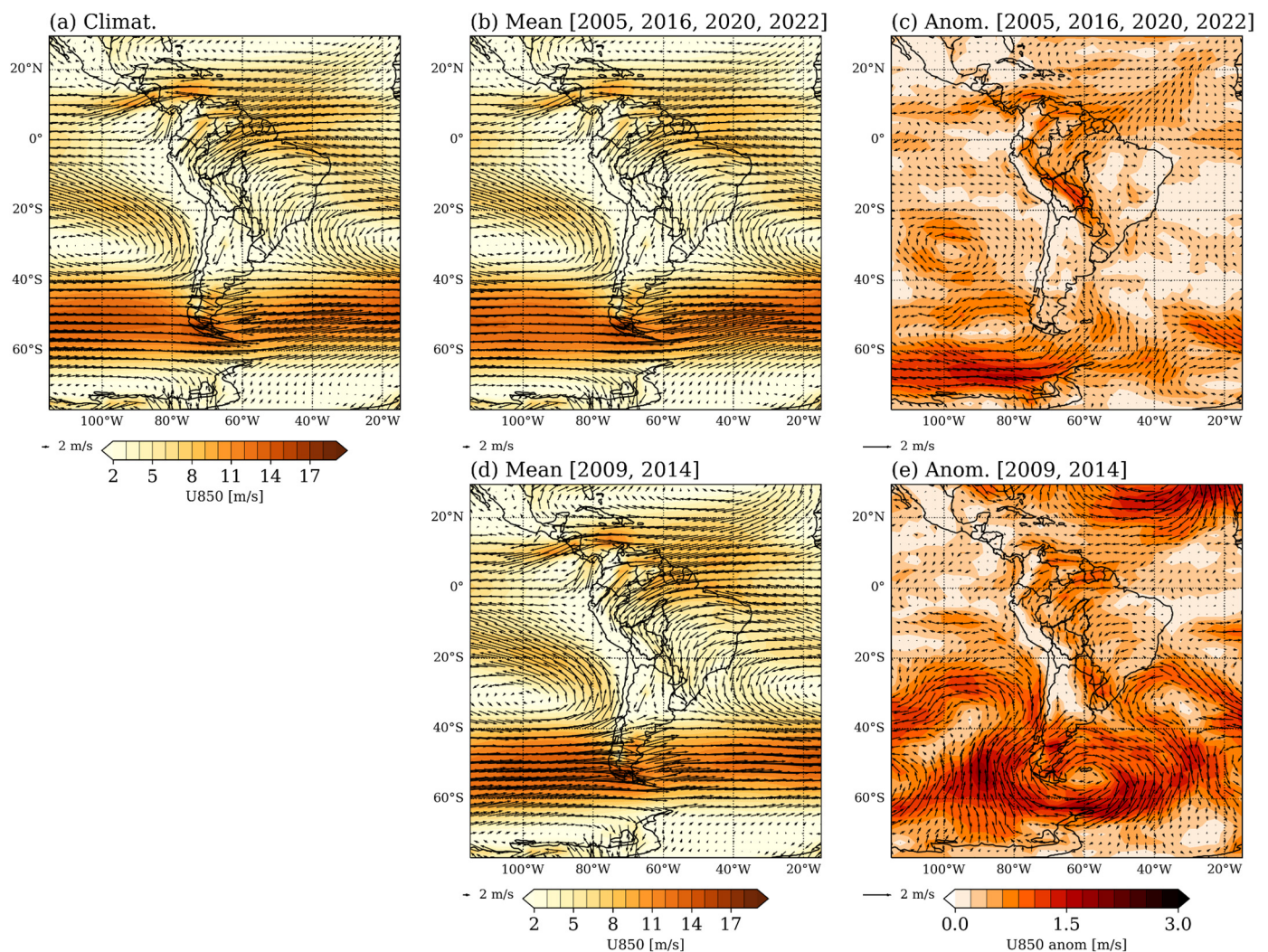


Figure 7. Plots of 850 hPa winds (m/s): climatology (a), mean (b), and anomalies (c) during dry years, and mean (d) and anomalies (e) during wet years. The plots consider ERA5 data on the yearly means for the rainy season from November to March.

3.4. Response of Madeira River Tributaries to Extremes

The impact of extremes in the main Madeira River regions and its tributaries varies as land use and topography diverge. Figure 9 shows the differences in precipitation and river discharge between the extreme rainy and drought events in the basin. The main river course is highly susceptible to precipitation variations, and the river flow can deviate more than $20,000 \text{ m}^3/\text{s}$ from rainy to dry events. Such variations could have severe consequences for the population that depends on the river for their daily activities, such as in Manicoré and Fazenda Vista Alegre, located inside the Madeira River Sustainable Development Reserve, and the city of Porto Velho, as seen in Figure 3.

The river discharge pattern in the basin and its tributaries appears unrelated to the precipitation pattern. Considering the narrowness of the tributaries, the main Madeira River naturally shows more prominent river discharge anomalies. Nevertheless, the differences for the extremes reveal roughly homogeneous positive precipitation anomaly patterns in the southwestern Basin, consistent with a symmetrical response to the rainy and drought signals. Some northeast regions present negative anomalies, indicating the persistence of reduced precipitation, even during rainy events. Even though the precipitation varies between the different sources, their distribution is similar north of the domain, which looks unrelated to the diagnostics of the flow anomalies in Figure 9c. While the main Madeira

River path, in the northeastern region of the basin, presents a difference of more than $15,000 \text{ m}^3/\text{s}$ in terms of the river flow during extreme events, the changes nearly reach $2500 \text{ m}^3/\text{s}$ in other regions.

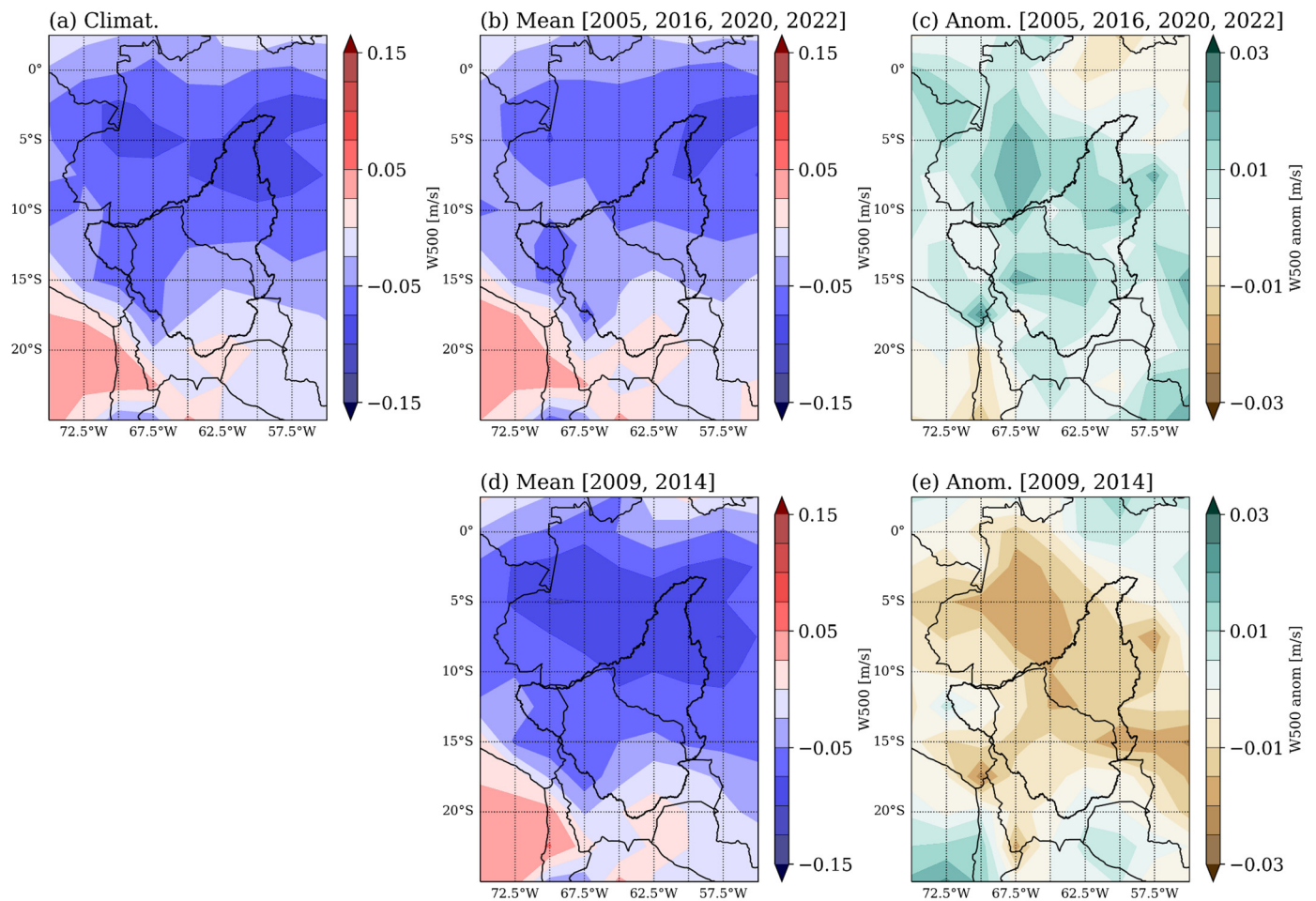


Figure 8. Plots of 500 hPa vertical motion: climatology (a), mean (b), and anomalies (c) during dry years, and mean (d) and anomalies (e) during wet years, in the Madeira River basin. The plots consider ERA5 data on the yearly means for the rainy season from November to March.

The apparent uncorrelated patterns of precipitation and river discharge during extreme events may be affected by events that present an uneven distribution of precipitation in the basin. Figure 10a,b shows the relative difference in the river discharge between more recent and older extreme events. The events are the most contrasting records and show a high variation in the precipitation amount (more than 0.5 standard deviations, as observed in Figure 4). Nevertheless, the resulting river discharge remains relatively similar in the course of the main Madeira River. Instead, the events produced different river discharge in the tributaries.

In the southern Madeira River basin, the difference between the 2014 and 2009 events is almost two (Figure 10a), which indicates that the amount of precipitation during 2014 doubled the river flow in this location. That significantly contributed to the floods registered in 2014 in northwestern Brazil and northern Bolivia [3,10,40]. Other regions experienced fewer discharges in 2014 than in 2009, with the negative values in the north, midwest, and southeast parts of the basin standing out.

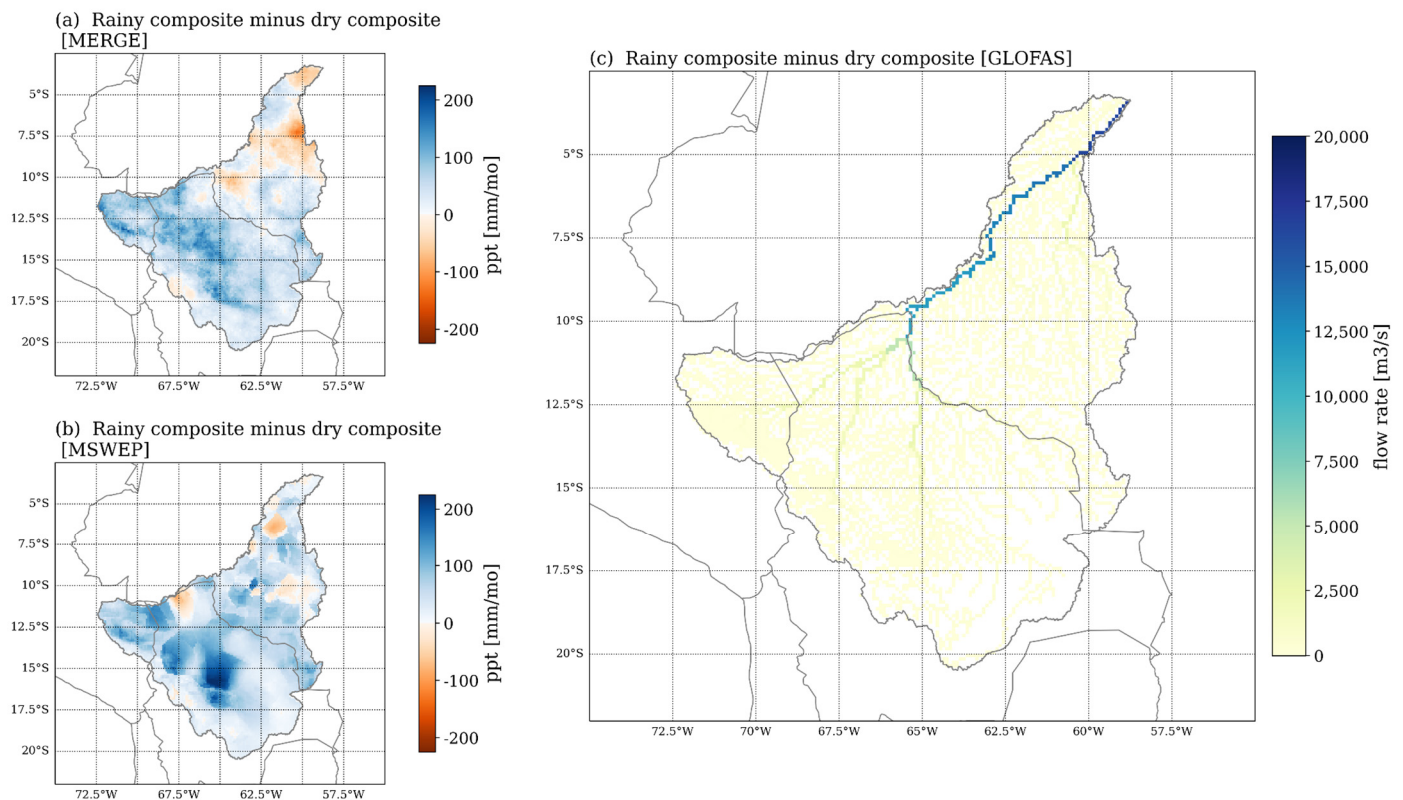


Figure 9. Precipitation and flow rate difference between the mean rainy (2009, 2014) and the mean drought (2005, 2016, 2020, 2022) years, using (a) MERGE, (b) MSWEP, and (c) GloFAS datasets.

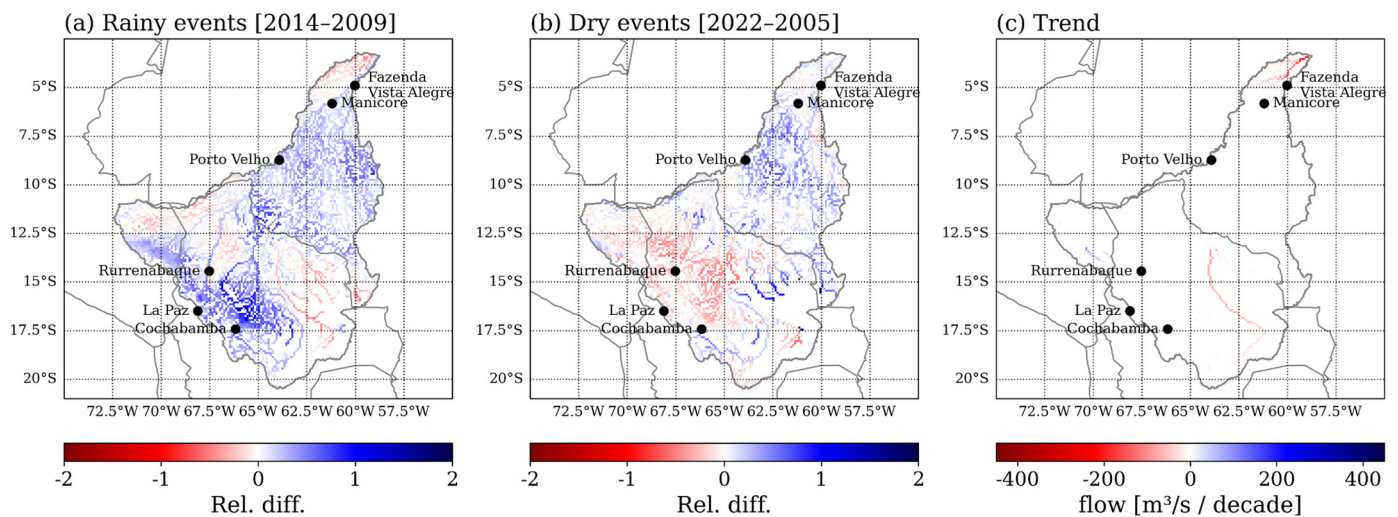


Figure 10. Relative difference in river discharge between the most recent and previous rainy (a) and dry (b) year events in the Madeira River basin, and (c) river flow trend (m³/s/decade) for the period from 2001 until 2023. The trend is indicated for regions with a significance level $\alpha = 0.05$, according to the Mann–Kendall test. The GloFAS dataset disregards reservoir operations in the modeling of river discharge. The dots represent the densely populated cities in the basin.

The differences in river discharge between the drought events of 2022 and 2005 result in an interesting pattern. Although some regions had reduced discharge in 2022 compared to 2005, most areas in the central–north part of the basin had increased discharge, as revealed by the positive differences in Figure 10b. Accordingly, the 2022 drought was worse than the 2005 drought in most Peruvian and Bolivian territories, whereas higher

river discharge occurred in the Brazilian portion of the basin. Other water availability, management, and monitoring aspects can be related to these differences. Regardless, the pronounced response in terms of the lower Madeira River discharge differs from that of the upper Madeira River during extreme dry events, which leads to different impacts in the tributary rivers. In addition, the river discharge observed during drought events is even lower, and, more concerning, it occurs just before the onset of the rainy season and for prolonged periods.

The relative differences in river discharge (Figure 10a,b) indicate reduced river flow in the northernmost part of the basin during both rainy and dry events. This pattern indicates tendencies confirmed by the trend evaluation in Figure 10c. Negative coefficients reveal a reduction in river flow in recent years in the eastern part of the basin. In the Peruvian part of the basin, positive coefficients indicate an increase in the river flow in recent decades. The most significant trends are found in the Brazilian part of the basin, namely a reduction trend of more than $400 \text{ m}^3/\text{s}$ per decade, which reflects the decrease in river flow in recent years. Manicoré and Fazenda Vista Alegre exhibit a reduction in river flow of 578 and $126 \text{ m}^3/\text{s}$ per decade, respectively. The uncertainty in the observational dataset in the region is obvious. Additional observational studies should increase the confidence of the results.

4. Conclusions

This study seeks to highlight the opposing facets of extreme dry and wet precipitation events in terms of the Madeira River basin. The temporal variability of precipitation reveals the region's susceptibility to extreme climatic events and their impacts on river discharge patterns.

The two precipitation datasets have revealed notable discrepancies, particularly in the Brazilian portion of the Madeira River basin. The MERGE and MSWEP datasets exhibit both spatial and interannual variability discrepancies. The MERGE dataset shows less precipitation in the southern part of the basin, but there are still similarities in the precipitation totals in the major cities. The results could infer a disagreement with the river discharge, which is more closely related to the MSWEP dataset values, due to their alignment with precipitation extremes in the basin. Despite the divergences, both datasets show similar seasonal precipitation cycles, revealing that the rainy season starts in November and ends in March. The variability in the extremes in the rainy season accurately identifies historical floods and drought records in the datasets, as is the case for the 2014 and 2009 enhanced floods [3,10] and the drier events in 2016, 2020, 2022, and 2005, the latter of which relates to a historical drought record [6].

An important result is the significant correlation between the anomalous pattern of the SST in the TNA and the variability of the rainy season in the basin. Composite anomalies confirm this relationship: a cooler TNA is linked with higher levels of precipitation and flooding, while a warmer TNA is linked with drought conditions. The anomalies in the TNA impact the northeasterly trade winds, consequently affecting the winds blowing over the basin and the injection of moisture toward the Amazon basin. The constructed anomalous composites agree with earlier findings [10].

In addition, this study showed that warmer waters appear in the southwestern South Atlantic Ocean during extreme rainy events in the Madeira River basin and cooler waters occur during drought events. This pattern is commonly related to the relationship between precipitation anomalies and the SACZ activity [30,39]. The results displayed anomalous vertical motion and strong wind variations in the LLJs. These results imply that extreme precipitation in the Madeira River basin can cause variations in the moisture content and convective activity in the SACZ climatological pattern [30].

The Madeira River is highly vulnerable to precipitation extremes, and river discharge can vary more than $10,000 \text{ m}^3/\text{s}$ around its mean discharge. However, the relationship between extreme precipitation events and river discharge in the basin is not straightforward. The TNA SST anomalies alone do not fully explain the river response. The comparison

between extreme events driven by the same SST anomaly patterns in different decades revealed that in addition to the precipitation extremes correlated to TNA SST variability, linear trends have reduced river discharge in the Madeira River tributaries in recent years. The negative trends in river discharge are about 100 m³/s per decade in Bolivian and Peruvian territories and more than 400 m³/s per decade in Brazilian cities in the northern portion of the Madeira River.

Climate change has been inducing extreme climate events and affecting hydrological processes. This study illustrates the impacts of extreme precipitation events on river discharge across the Madeira River basin from the point of view of GloFAS, which is a dataset designed to raise awareness of flood occurrence. Future analyses should consider extended periods for climatology, as well as more advanced approaches to confirm the results. To improve the detection of drought periods, we suggest the use of the SPI (Standardized Precipitation Index) obtained with linear moments (L-moments), as in [41,42]. We believe this methodological refinement should add value beyond the studied region, potentially benefiting broader scientific applications. Furthermore, we recommend modeling approaches to river discharge that consider reservoir operations, uncertainties in the precipitation estimates, and the Amazon River discharge at the mouth of the Madeira River. Improving predictability and modeling of river discharge is crucial as extreme events impact the socio-economic activities in the Madeira River basin, such as the sustainable development of conservation units, river navigation, energy production, agriculture, fisheries, and health services.

Although every river has unique characteristics, the methodology applied in this study can be reproduced in other basins. Searching for sources of predictability for extreme events affecting rivers is helpful for properly managing and anticipating disasters. In addition, our research could expose common gaps and challenges in regions with poor scientific interest, such as the Madeira River basin.

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