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Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL096754

Key Points:

- Flood peaks tend to occur at the same time of year as annual soil moisture peaks and lag behind annual rainfall peaks by 3 weeks
- Flood seasonality is linked mainly with soil moisture peaks in Amazonia and central Brazil, where soil storage capacity is high
- Flood timing is highly correlated with rainfall and soil moisture peaks in the south and southeast, where soil storage capacity is low

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Chagas, V. B. P., Chaffe, P. L. B., & Blöschl, G. (2022). Process controls on flood seasonality in Brazil. *Geophysical Research Letters*, *49*, e2021GL096754. https://doi.org/10.1029/2021GL096754

Received 23 OCT 2021
Accepted 17 FEB 2022

Process Controls on Flood Seasonality in Brazil

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Abstract A coincidence in the timing of floods and their drivers can be used as a proxy for the causality of flood generation. Here, we investigate the relationship between the seasonality of floods, maximum annual rainfall, and maximum annual soil moisture data of 886 basins in Brazil for 1980–2015 to shed light on process controls of flood generation. Floods tend to occur at the same time of year as soil moisture peaks and lag behind rainfall peaks by 3 weeks. In Amazonia, central and northern Brazil, flood timing is more correlated with the timing of soil moisture peaks than with that of rainfall peaks, which is interpreted as resulting from high subsurface water storage capacities. In southern and southeastern Brazil, on the other hand, flood timing is highly correlated with both soil moisture and rainfall because of low subsurface water storage capacities. These findings can support flood forecasting and climate impact studies.

Plain Language Summary In warm regions, floods are usually generated by a combination of intense rainfall and wet soils. In this paper, we analyze the average timing within the year of floods, extreme rainfall, and soil moisture to elucidate how floods come about in the main Brazilian rivers. We find that in some regions, such as Amazonia and central Brazil, floods tend to occur when soils are wet. In other regions, such as southern Brazil, floods tend to occur when rainfall is most extreme. We believe that these differences are related to differences in the soil water storage capacity. The understanding of the regional importance of each of these components helps increase the efficiency of flood prevention measures and climate change adaptation.

1. Introduction

River floods are usually generated by the interplay of event precipitation, antecedent soil wetness, and snowmelt (Merz & Blöschl, 2003; Rosbjerg et al., 2013; Tarasova et al., 2019). One way of exploring the relative importance of these drivers is by analyzing flood seasonality, defined as the day of the year that floods occur. A coincidence in the timing of floods and their drivers can be used as a proxy for the causality of flood generation (Parajka et al., 2010; Sivapalan et al., 2005; Tramblay et al., 2021).

The relative importance of the drivers of flood seasonality depends on climate, landscape properties, and has a large regional variability (Berghuijs et al., 2016, 2019; Parajka et al., 2010; Tramblay et al., 2021; Wasko et al., 2020). In northeastern Europe, for example, floods are aligned with the onset of the warm season that leads to snowmelt (Blöschl et al., 2017; Kemter et al., 2020). In much of Western Europe, floods are associated with soil moisture peaks in the winter because, even though rainfall peaks in the summer or autumn, it gets stored in the soil which slowly becomes wet over several months (Berghuijs et al., 2019; Blöschl et al., 2017). On the other hand, in central Europe's mountain ranges, flood timing frequently coincides with annual rainfall peaks (Berghuijs et al., 2019; Kemter et al., 2020). A similar pattern is found in the USA, where floods are linked with snowmelt in the coldest regions in the north, soil moisture peaks in the central-east, and extreme rainfall in the mountain ranges in the west (Berghuijs et al., 2016; Brunner et al., 2020; Stein et al., 2020).

In South America, more specifically Brazil, few studies have analyzed flood seasonality (Bartiko et al., 2019; Cassalho et al., 2019; Do et al., 2020). So far, no study has explored the process controls of flood seasonality by considering the interplay of rainfall and soil moisture. Even though soil moisture is crucial in determining if rain infiltrates or runs off (Bonell, 2004; Elsenbeer, 2001), floods in Brazil have usually been explained in terms of extreme rainfall and meteorological phenomena such as the South American monsoon, mesoscale convective systems, and the El-Niño-Southern Oscillation (Cavalcanti, 2012; Fleischmann et al., 2020; Lima et al., 2017; Marengo & Espinoza, 2016; Schöngart & Junk, 2007; Sena et al., 2012; Towner et al., 2021).

The objective of this paper is to explore the main process controls on flood generation in Brazil. We investigate whether annual floods are linked mainly with maximum annual rainfall or soil moisture considering the similarity of their seasonalities. We use circular statistics to analyze the mean dates of occurrence and interannual variabilities of hydrometeorological data of 886 basins in Brazil, from 1980 to 2015.

2. Materials and Methods

2.1. Hydrometeorological Data

We use daily streamflow data of 886 hydrometric stations from the Brazilian National Water Agency (http://www.snirh.gov.br/hidroweb) as made available by the CAMELS-BR data set (Chagas et al., 2020). The analysis period is from 1980 to 2015 because of its large data availability. The criteria for selecting the 886 hydrometric stations are: (a) at least 25 years of data from 1980 to 2015 with less than 5% missing; (b) approved by a quality control similar to that of CAMELS-BR, on which stations with typographical errors or unrealistic high flows are discarded; (c) basins with a ratio between total water storage in artificial reservoirs and annual flow lower than 25% (using a ratio of 5% we arrive at similar results—not shown); and (d) basins with urban land cover lower than 10%, as we are interested in large-scale hydrological patterns and minimizing local impacts. The basin sizes range from 11 km^2 to 4.7 million km^2.

The daily rainfall data are from CHIRPS v2.0 (Funk et al., 2015), from 1981 to 2015. CHIRPS has a spatial resolution of 0.05° and uses data from meteorological stations and satellite sensors. We chose CHIRPS because it shows a good accuracy compared with other precipitation products (Beck et al., 2017; Wongchuig-Correa et al., 2017). Furthermore, we use surface soil moisture data from GLEAM v3.5a (Martens et al., 2017; Miralles et al., 2011), from 1980 to 2015, with a spatial resolution of 0.05°. GLEAM is based on satellite data and presents good performance compared with other soil moisture products (Beck et al., 2021). We use surface soil moisture data instead of moisture data from deeper layers because it has better accuracy (Beck et al., 2021; Brocca et al., 2017) and is more relevant for runoff processes (Bonell, 2004). We conducted alternative analyses using root zone soil moisture data from GLEAM and rainfall data from ERA5-Land (Hersbach et al., 2020; Muñoz-Sabater et al., 2021) and obtained similar conclusions (not shown). The rainfall and soil moisture time series are computed as basin averages. Snow data is not included because it is not a dominant hydrological variable in the analyzed basins (Chagas et al., 2020).

2.2. Seasonality Analysis

We investigate links between floods and their drivers by comparing the seasonalities of maximum annual streamflow (floods), maximum annual rainfall of a 7-day moving average series (maximum rainfall), and maximum annual surface soil moisture of a 7-day moving average series (maximum soil moisture). The 7-day time scale is relevant to both small and large basins and is widely used in flood studies (e.g., Berghuijs et al., 2016; Blöschl et al., 2017; Stein et al., 2020; Tramblay et al., 2021; Wasko et al., 2020). We conducted an alternative analysis with time scales of 1, 3, and 14 days. For the latter two we obtained similar conclusions and for the 1-day time scale neither driver is strongly linked to floods (Figure S4 in Supporting Information S1).

We analyze the seasonality of floods and their drivers using circular statistics (Bayliss & Jones, 1993; Mardia & Jupp, 2009) because, unlike traditional statistics, it treats the first and last day of the year as temporally adjacent. We first calculate the mean dates of floods, maximum rainfall and soil moisture. The water year starts in September and the ordinal day D_i is transformed into an angular value θ_i with

$$\theta_i = \frac{D_i}{m_i} \cdot 2\pi \quad (1)$$

where m_i corresponds to the number of days in the year t_i and $i = 1, \ldots, n$, where n is the number of years of record. The mean date of occurrence $\bar{\theta}$ (in radians) is defined by (Bayliss & Jones, 1993; Mardia & Jupp, 2009)

$$\bar{\theta} = \begin{cases} \tan^{-1}\left(\frac{s}{c}\right) & c > 0,\ \ s \geq 0 \\ \tan^{-1}\left(\frac{s}{c}\right) + \pi & c \leq 0 \\ \tan^{-1}\left(\frac{s}{c}\right) + 2\pi & c > 0,\ \ s < 0 \end{cases} \tag{2}$$

with

$$s = \sum_{i=1}^{n} \sin(\theta_i) \tag{3}$$

$$c = \sum_{i=1}^{n} \cos(\theta_i) \tag{4}$$

where s and c are the sine and cosine components of the mean dates; n is the number of observations, in this case the number of years. Then, we calculate the seasonality strength with the mean resultant length R, defined by

$$R = \frac{1}{n}\sqrt{c^2 + s^2} \tag{5}$$

which ranges from 0 (no seasonality, flood peaks are evenly distributed throughout the year) to 1 (higher seasonality, flood peaks always occur on the same day of the year). We verify if the seasonality of each basin is statistically significant and unimodal with the Rayleigh test (Mardia & Jupp, 2009; Rayleigh, 1880). Out of the 886 basins analyzed, 750 have significant unimodal flood seasonalities ($p < 0.05$). Even though multimodal seasonalities might be present in Brazil, we do not analyze their strength and mean dates of occurrence as these metrics are only reliable for unimodal regimes. The circular histograms of the annual maxima for the basins analyzed are available in Chagas et al. (2022) so that their flood regimes can be checked visually.

2.3. Importance of the Flood Seasonality Drivers

We analyze links between the seasonality of floods, maximum rainfall and soil moisture with two methods. In the first, we examine differences between their mean dates as described in Section 2.2. This method may be affected by the differences in flood travel times in the basins (that is, the time an intense rainfall event takes to propagate through a basin), so we complement it with the second method.

In the second method, we analyze the interannual variability by correlating the time series of flood timing with maximum rainfall and soil moisture timing. For each basin, we compute the circular correlation (Jammalamadaka & Sengupta, 2001) with

$$\rho = \frac{\sum_{i=1}^{n} \sin(\alpha_i - \bar{\alpha}) \sin\left(\beta_i - \bar{\beta}\right)}{\sqrt{\sum_{i=1}^{n} \sin^2(\alpha_i - \bar{\alpha}) \sin^2\left(\beta_i - \bar{\beta}\right)}} \tag{6}$$

where α_i and β_i are the dates of occurrence (in angular values) of the correlated variables for the year t_i and $i = 1, \ldots, n$, where n is the number of observations; $\bar{\alpha}$ and $\bar{\beta}$ are mean dates of occurrence computed with Equation 2. For each basin, we analyze the correlation between the timing of floods and maximum rainfall and the correlation between the timing of floods and maximum soil moisture. The circular correlation is not affected by different mean dates in the variables, since it considers annual dates of occurrence as anomalies from their respective average by subtracting one from the other. The correlation is less affected by contrasting flood travel times in the basins as, for each basin, it removes the time gap between the mean dates of floods, maximum annual rainfall and soil moisture.

Furthermore, we explore the regional importance of each flood seasonality driver by spatially interpolating the circular correlations. We interpolate the correlations with ordinary block kriging sized 2° by 2° (approximately 222 by 222 km at the equator) using the best fit variogram model with the gstat R package (Gräler et al., 2016; Pebesma, 2004).

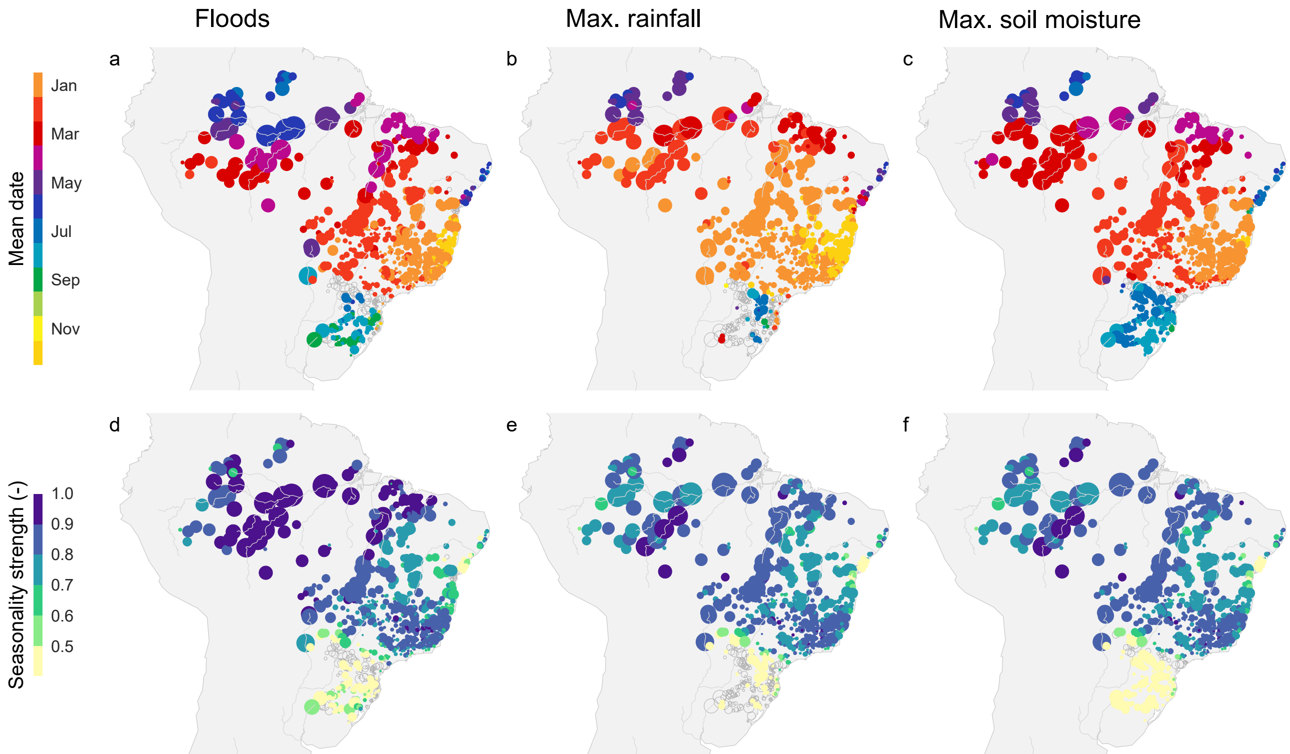

Figure 1. Mean dates and seasonality strength of (a, d) floods, (b, e) maximum annual rainfall, and (c, f) maximum annual soil moisture. Seasonality strength ranges from 0 (no seasonality) to 1 (floods always occur on the same day of the year). Gray open circles are non-significant or non-unimodal seasonalities ($\alpha = 0.05$). Circle size is proportional to the logarithm of the basin area.

3. Results

3.1. Flood, Rainfall, and Soil Moisture Seasonality

Floods are remarkably seasonal in Brazil (Figure 1). Flood seasonality is most pronounced in Amazonia (Figure 1d, strength greater than 0.9, $p < 0.001$), where streamflow peaks in March on the southern tributaries and June on the northern tributaries (Figure 1a). Floods are highly seasonal in central-eastern Brazil (strength between 0.7 and 0.9, $p < 0.001$) and occur in the summer (December–February). On the other hand, flood seasonality is less pronounced in the south (strength below 0.5, $p < 0.05$), with mean dates in the winter (July–September) but with frequent floods also in spring and autumn.

Similar to floods, rainfall and soil moisture peak in the summer in central Brazil (Figures 1b and 1c), May-June in northern Amazonia, and are less seasonal in southern Brazil (Figures 1e and 1f). However, in Amazonia, rainfall and soil moisture peaks are notably less seasonal than floods. In southern Brazil, rainfall seasonality is not statistically significant (significance level $\alpha = 0.05$) even though soil moisture and floods are. In addition, a visual comparison of the panels in Figure 1 suggests that maximum rainfall tends to occur a few months before the floods, but this does not seem to be the case for maximum soil moisture.

A more detailed inspection shows that the mean dates of floods are closer to those of soil moisture than to those of rainfall (i.e., closer to the 1:1 line in Figure 2). Floods occur on average 20 days after maximum rainfall and 5 days before maximum soil moisture. Floods usually lag behind maximum rainfall by 14 days or more in 60% of the basins (Figure 2a). Floods and maximum rainfall are within 14 days of each other in 38% of the basins. On the other hand, floods and soil moisture occur within 14 days of each other in 65% of the basins, with the remaining 35% distributed similarly between before and after the 14 days difference (Figure 2b).

We explore the regional seasonality patterns with six hotspots with distinct flood regimes, climates, and located in the upstream areas of major rivers (i.e., Amazon, Araguaia, Uruguay, Parnaíba, Doce) (Figure 2c). In the Southern Amazonia hotspot, flood and maximum soil moisture timings coincide but floods and maximum

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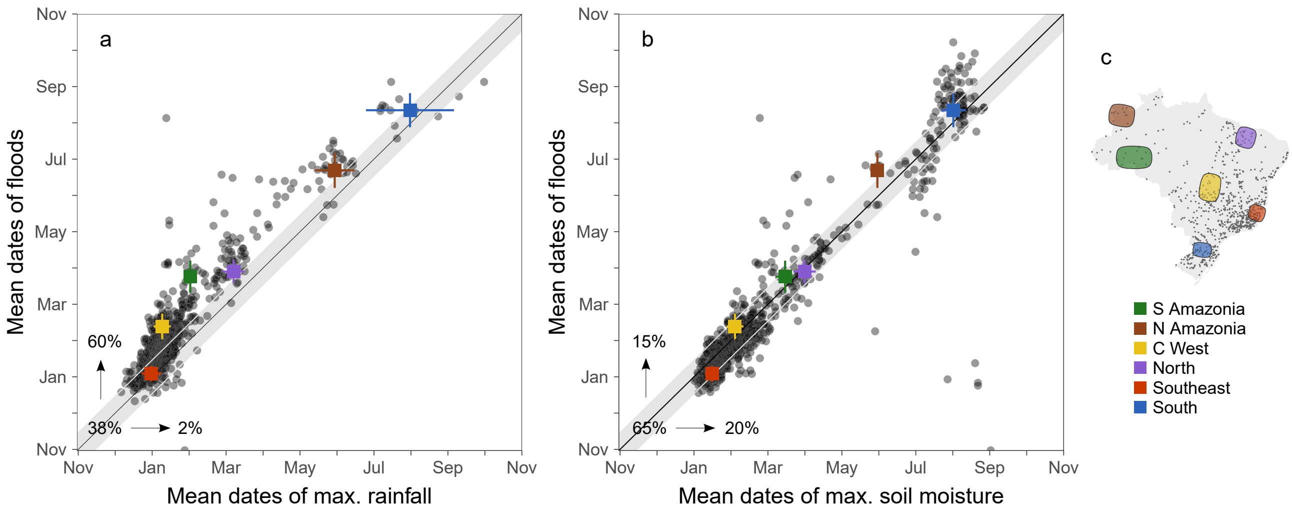

Figure 2. Mean dates of floods as a function of mean dates of (a) maximum annual rainfall and (b) maximum annual soil moisture. Points represent basins, squares indicate the median value of each hotspot shown in (c), and error bars show ± one standard deviation. The black line is a 1:1 function and the gray band and lines indicate ± 14 days. Points above the 1:1 line represent basins where floods generally occur after the mean dates of maximum annual rainfall in (a) and after the mean dates of maximum annual soil moisture in (b). The numbers indicate the percentage of basins within, above, or below the gray band. Basins with non-significant ($\alpha = 0.05$) or non-unimodal seasonalities are not included.

rainfall tend to occur more than 6 weeks apart. Such large differences are likely affected by flood travel times, as Southern Amazonia has the largest basins among the hotspots. A similar pattern is observed in the Central-West and North hotspots, where floods and maximum soil moisture coincide but lag behind maximum rainfall by 3–5 weeks. These findings are independent of basin size (Figure S1 in Supporting Information S1). In the South and Southeast hotspots, mean dates of floods, maximum rainfall and soil moisture are within 14 days of each other, suggesting that both drivers have similar importance for the process controls of flood seasonality.

3.2. Interannual Variability of Flood Seasonality

The interannual variability analysis shows how between-year deviations from the mean dates of floods, maximum rainfall and soil moisture are correlated. As opposed to the method used in Section 3.1, the interannual variability is not affected by different mean dates in the variables. The interannual variability is less influenced by contrasting flood travel times in the basins as, for each basin, it removes the time gap between the mean dates of floods, maximum annual rainfall and soil moisture.

The interannual variability of flood timing is more correlated with that of maximum soil moisture timing than with that of maximum rainfall timing in 87% of the study area (Figures 3a and 3b). The mean correlation with soil moisture is higher than 0.4 in 36% of the study area and, with rainfall, in 15% of the study area (Figures 3a and 3b). Floods and soil moisture correlations are high particularly in central, northern, southern, and eastern Brazil. Floods and rainfall correlations, on the other hand, are high in part of southern and eastern Brazil. The correlations of individual basins and their associated statistical significance are presented in Figure S2 in Supporting Information S1.

Most hotspots present either greater importance of soil moisture or similar importance of both drivers of flood seasonality (Figure 3c). Greater importance of soil moisture is noticeable in the North (median correlations with soil moisture and rainfall of 0.67 and 0.45, respectively), Central-West (median correlations of 0.46 and 0.25, respectively), and Northern Amazonia hotspots (correlations of 0.38 and 0.20, respectively). On the other hand, similar importance of soil moisture and rainfall is observed in the South and Southeast hotspots. Median correlations in both hotspots are around 0.50, approximately 70% of which are significant ($\alpha = 0.05$). Once again, as with the analysis of mean dates, Southern Amazonia is the hotspot with the weakest links between flood timing and its drivers, with correlations generally below 0.25 and mostly non-significant ($\alpha = 0.05$).

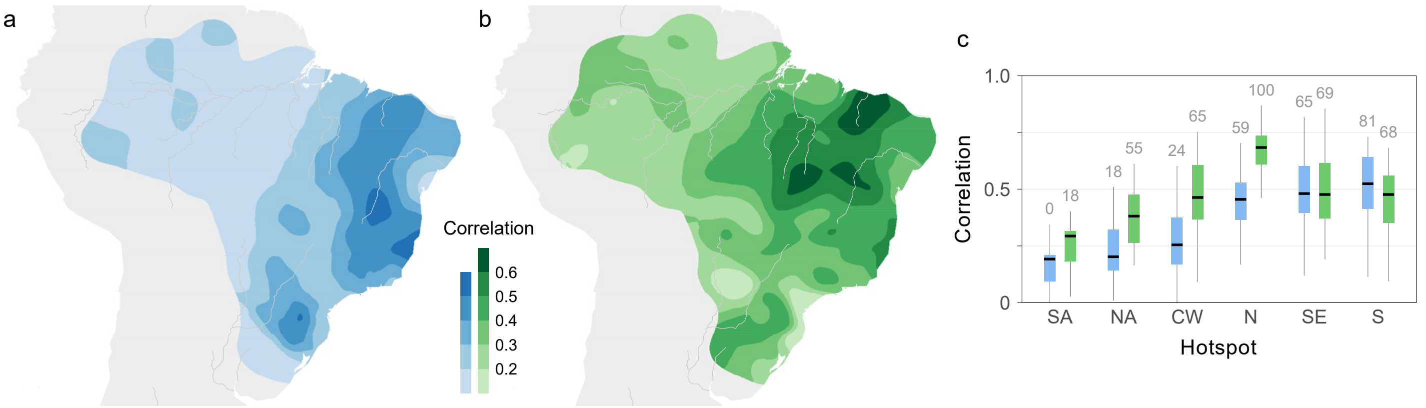

Figure 3. Circular correlation between the interannual variability of the timing of (a) floods and maximum annual rainfall, (b) floods and maximum annual soil moisture. Both (a) and (b) are obtained with interpolation using block kriging. (c) Spatial variability of the correlations with maximum rainfall (blue boxes) and maximum soil moisture (green boxes) over each hotspot. The numbers above the boxplots indicate the percentage of basins with significant correlations ($\alpha = 0.05$). The hotspots are Southern Amazonia (SA, $n = 11$), Northern Amazonia (NA, $n = 11$), Central-West (CW, $n = 34$), North (N, $n = 22$), Southeast (SE, $n = 65$), and South (S, $n = 37$).

We complement the seasonality analysis with an examination of the magnitudes of the variables. For each basin, we analyze the correlations of the timing for two separate groups of events considering the lowest and highest 50% of the floods, respectively. Correlations of the timing of the highest floods to their drivers are substantially higher than those of the lowest floods (Figure S3 and Table S1 in Supporting Information S1). As with the previous analyses, flood seasonality is more closely associated with soil moisture in both groups. However, the correlation uncertainties and their spatial variability are greater. Furthermore, for each basin we correlate the interannual variability of flood magnitudes with maximum annual rainfall and soil moisture magnitudes, again indicating overall greater importance of soil moisture compared with rainfall (Figure S4 and Table S1 in Supporting Information S1).

4. Discussion

4.1. Process Controls on Flood Seasonality

Our results suggest two main patterns of flood generation. In some parts of Brazil, flood timing is aligned mostly with maximum soil moisture timing, suggesting that on average floods are modulated mainly by antecedent soil wetness and less so by variations in event rainfall. In other parts of Brazil, flood seasonality is similar to both maximum rainfall and soil moisture seasonalities, indicating that both are relevant for flood generation.

Figures 4a and 4b illustrates the first pattern of flood generation with the Candeias and Guamá river basins. In the Candeias basin, a tributary of the Madeira river in southern Amazonia, the most intense annual rainfall events usually occur in January before the soil is wet enough to become saturated and generate flood peaks. The soil gets wet during the summer and, when wetness peaks in March, other less intense rainfall events lead to the annual floods. A similar pattern is observed in the Guamá basin, on the northern coast of Brazil. The most intense annual rainfall events can occur at any time in the wet season (January–April), but the flood peaks are only generated when soil moisture peaks at the end of the wet season. This is comparable with those in parts of Western Europe, such as southern England, where flood timing is aligned with annual soil moisture peaks (Berghuijs et al., 2019; Blöschl et al., 2017).

Figures 4c and 4d illustrates the second pattern of flood generation with the Doce and Içana river basins. In the Doce basin, on the southeastern coast, rainfall usually peaks in December and is soon followed by soil moisture peaks in late December or early January. Since peak rainfall and soil moisture are closely aligned, floods also usually occur in December or January. In the Içana basin, a tributary of the Negro river in northern Amazonia, rainfall rates are above 5 mm per day throughout the year without a dry season. Consequently, the soil is always close to saturation and, when intense rainfall events take place in May and April, floods occur.

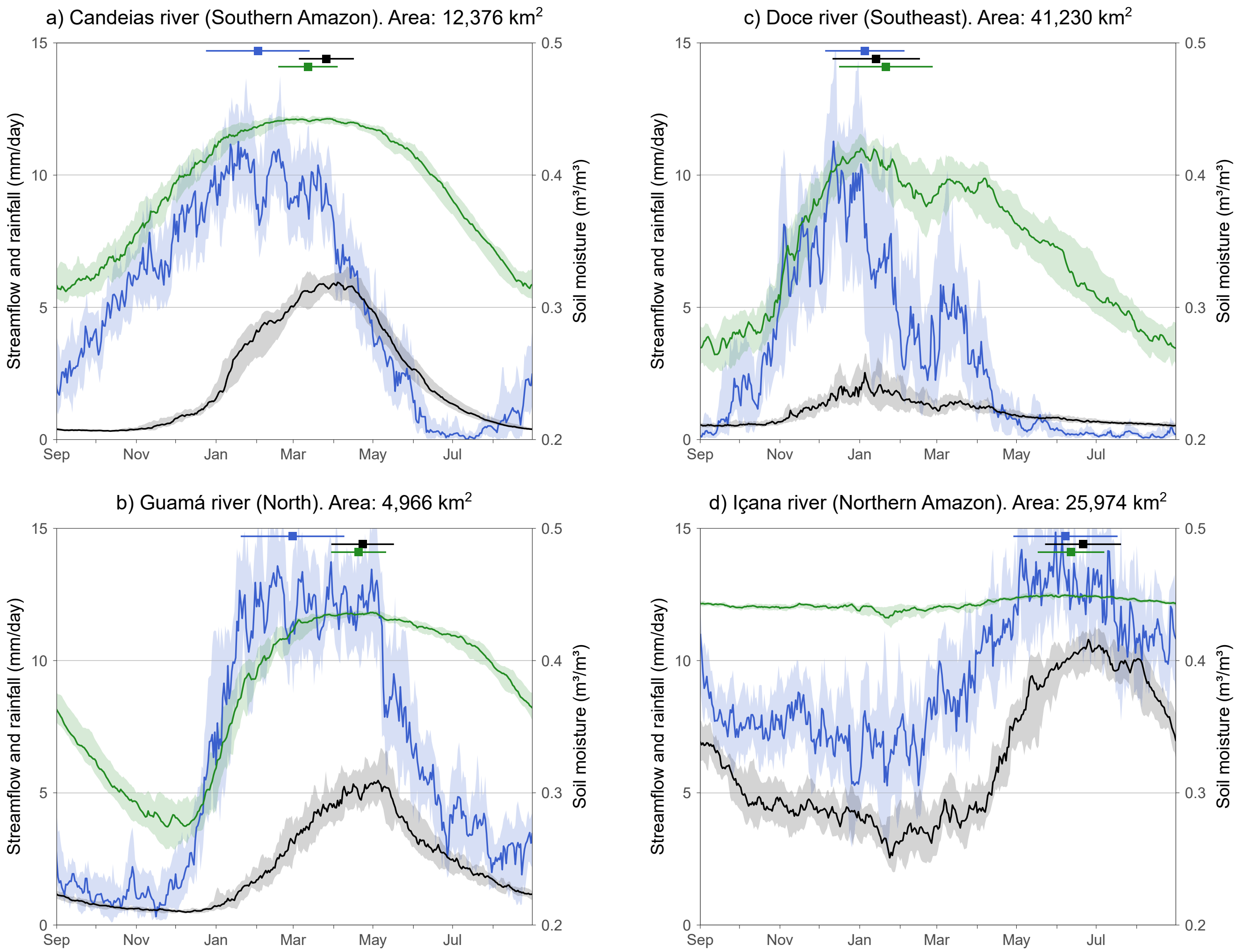

Figure 4. Examples of the two patterns of flood generation. (a, b) Flood seasonality associated mainly with the timing of maximum annual soil moisture. (c, d) Flood seasonality associated with the timing of maximum annual soil moisture and rainfall with similar importance. Lines indicate median daily streamflow (black), 7-day rainfall (blue), and 7-day soil moisture (green) of each day of the year (1980–2015). The bands indicate the percentiles 30 and 70. The squares and error bars on the top indicate mean dates and standard deviations. Streamflow values are normalized by basin area to facilitate inter-basin comparison.

4.2. Importance of Water Storage Capacity

According to our interpretation, the patterns of flood generation are related to the root zone water storage capacity, that is, the maximum volume of hydrologically active soil water available for plant transpiration (de Boer-Euser et al., 2016; Wang-Erlandsson et al., 2016). The first pattern (greater importance of soil moisture) may occur particularly in basins with large water storage capacities. In these basins, rainfall in the wet season tends to get stored, increasing soil moisture and groundwater tables continuously until they peak at the end of the wet season when floods are generated. This phenomenon may be particularly noticeable in regions with long rainy seasons, as groundwater tables may rise over a longer period. The second pattern (similar importance of rainfall and soil moisture) may occur mainly in basins with low water storage capacities. Intense rainfall quickly saturates the soil, becoming runoff and generating floods.

The largest estimated water storage capacities are in southern Amazonia (median and standard deviation of 379 ± 83 mm year^{-1}), central-western (328 ± 105 mm year^{-1}) and northern Brazil (472 ± 251 mm year^{-1}) (Wang-Erlandsson et al., 2016) which is also where the first pattern of flood generation is most frequent. This does not come as a surprise, as these regions have several landscape properties associated with high water storage capacities. These include deeply weathered and highly permeable soils, commonly tens of meters deep (Hengl et al., 2017; Pelletier et al., 2016), and low topographic slopes with widespread floodplains and wetlands

(Junk et al., 2014; Nardi et al., 2019). On the other hand, the lowest estimated storage capacities are in southern (108 ± 38 mm year^{-1}) and southeastern (226 ± 92 mm year^{-1}) Brazil (Wang-Erlandsson et al., 2016), where the second pattern of flood generation is most frequent, associated with higher topographic slopes, mountain ranges, and shallower soils (Hengl et al., 2017; Pelletier et al., 2016).

4.3. Links With Meteorological Characteristics

The flood timing found here is consistent with the meteorological characteristics of the region. The South American monsoon carries large amounts of atmospheric moisture to Amazonia, central, and southeastern Brazil particularly in summer (December–February) (Grimm, 2019; Marengo et al., 2012). Cold fronts and transient systems favor convection and lead to frequent intense rainfall events, especially in the wet season. With the dry monsoon phase starting in April, the Intertropical Convergence Zone moves southward producing rainfall in the northeast (Cavalcanti, 2012; Grimm, 2019). In southern Brazil, intense rainfall can occur at any time of year with the wet monsoon phase in summer, mesoscale convective systems in spring or summer, and cold fronts particularly in winter (Cavalcanti, 2012; Durkee et al., 2009). These meteorological drivers play an extremely important role in flood generation through increases in soil moisture, particularly in Amazonia, central-western and northern Brazil.

5. Conclusions

In most of Brazil, flood seasonality is more closely associated with soil moisture seasonality than with rainfall seasonality. We identified two patterns of flood generation. In Amazonia, central and northern Brazil, flood timing coincides with the timing of annual soil moisture peaks. This suggests that, on average, floods are modulated mainly by antecedent soil wetness and less so by variations in event rainfall, which we interpret as occurring mainly in basins with large water storage capacities. On the other hand, in southern and southeastern Brazil, flood timing coincides with the timing of both annual rainfall and soil moisture peaks. This indicates that both antecedent soil wetness and event rainfall are major modulators of flood generation, which we hypothesize as occurring mainly in basins with low water storage capacities. Because of the fast soil saturation, one would expect this pattern to be more sensitive to climate change induced increases in extreme rainfall than the previous one. The understanding of the major controls of flood generation provided here can support flood forecasting, risk management, and climate change and land cover impact studies.

Data Availability Statement

The time series of maximum annual streamflow, precipitation, and soil moisture and their respective mean dates, seasonality strength, Rayleigh's test, and circular histograms are available at https://doi.org/10.5281/zenodo.6050437. Daily streamflow data are available from the CAMELS-BR data set at https://doi.org/10.5281/zenodo.3709337 and from the Brazilian National Water Agency dataset at http://www.snirh.gov.br/hidroweb/. Daily precipitation data from CHIRPS v2.0 are available at https://www.chc.ucsb.edu/data/chirps. Daily surface and root zone soil moisture data from GLEAM v3.5a can be downloaded at https://www.gleam.eu/. Daily precipitation data from ERA5-Land can be downloaded at https://doi.org/10.24381/cds.e2161bac.

Acknowledgments
This work was supported by the Brazilian National Council for Scientific and Technological Development (CNPq). Financial support from the Austrian Science Funds (FWF) (project no. I 4776-N, SPATE) is gratefully acknowledged.

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