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Spatial and seasonal patterns of flood change across Brazil

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ABSTRACT

Brazil has some of the largest rivers in the world and has the second greatest flood loss potential among the emergent countries. Despite that, flood studies in this area are still scarce. In this paper, we used flood seasonality and trend analysis at the annual and seasonal scales in order to describe flood regimes and changes across the whole of Brazil in the period 1976–2015. We identified a strong seasonality of floods and a well-defined spatio-temporal pattern for flood occurrence. There are positive trends in the frequency and magnitude of floods in the North, South and parts of Southeast Brazil; and negative trends in the North-east and the remainder of Southeast Brazil. Trends in the magnitude (frequency) were predominant in the winter (summer). Overall, floods are becoming more frequent and intense in Brazilian regions characterized by wet conditions, and less frequent and intense in drier regions.

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Introduction

Floods are one of the main causes of socio-economic and environmental damage all over the world (Petrow and Merz 2009, Villarini *et al.* 2011a, Hall *et al.* 2014, Mallakpour and Villarini 2016, Slater and Villarini 2016). Traditional methods developed for flood design and estimation are generally based on the assumption of stationarity, which might be invalid in the face of hydroclimatic changes (Milly *et al.* 2008). Information about floods (and flood changes) is crucial in order to optimize our response to them (Hirsch and Archfield 2015) and should be incorporated in design and safety guidelines (Madsen *et al.* 2014, Hodgkins *et al.* 2017). However, past changes and future projections in flood behaviour are still limited by our knowledge of the processes that control the magnitude, timing and frequency of flood events (Merz *et al.* 2012, Hall *et al.* 2014, Mallakpour and Villarini 2015).

Recently, several analyses of trends in flood frequency and magnitude have been reported (Espinoza Villar *et al.* 2009, Petrow and Merz 2009, Villarini *et al.* 2011b, Mallakpour and Villarini 2015, Mediero *et al.* 2015, Hodgkins *et al.* 2017). It is possible that for the same region the frequency and magnitude trend signals are not the same (Petrow and Merz 2009), or that a significant trend exists in only one of them (Mallakpour and Villarini 2015). While a relatively large effort has been made in the detection of changes in flood peak records, there is less information related to flood seasonality around the world. Seasonality provides information about the time of year in which flood events tend to occur (Villarini 2016) and can also be applied for the identification of regional differences in flood-generating mechanisms (such as synoptic systems, convective precipitation or snowmelt) (Hall *et al.* 2014), or the identification and attribution of the causes for observed changes in flood discharge.

The understanding of regional differences in flood-generating mechanisms is essential for historical flood analysis and in order to reduce uncertainty in future flood estimation (Berghuijs *et al.* 2016). That is also crucial for the evaluation of anthropogenic and natural effects on flow regimes. Even though climate factors are a primary driver for this type of analysis (Madsen *et al.* 2014), stream dynamics and watershed characteristics are also identified as drivers of flood behaviour (Merz *et al.* 2012, Blöschl *et al.* 2015, Slater and Villarini 2016). In some circumstances, trends can be mainly associated with anthropogenic activities, such as the construction of dams and land-use /land-cover change due to urbanization and agricultural activities (Villarini *et al.* 2011c, 2012, Slater and Villarini 2017).

A recent analysis of "hidden hotspots", based on growth in GDP (gross domestic product) and flood risk indices, has shown that Brazil has the second greatest flood loss potential of all the emergent countries (Swiss Re 2012, UNISDR 2015). Extreme hydrological events in the country were responsible for 36% of the total of US$60 billion in damages and injuries due to natural disasters in the period 1995–2014 (CEPED/UFSC 2016). In 2013 alone, floods affected 4 356 550 people and were responsible for 108 fatalities (CENAD 2014). In addition to the existing loss potential, some studies indicate that floods have become more frequent or intense in Brazil. Berghuijs *et al.* (2017) evaluated the largest floods observed in the 1980–2009 period in 244 Brazilian catchments and identified an increase in the number of extreme flood occurrence and in their magnitude. Alves *et al.* (2013) found trends in the magnitude of floods in South, Midwest and South-East Brazil when evaluating 143 fluviometric series corresponding to the inflows of hydro-electric power plants. Recently, Gudmundsson *et al.* (2019) described positive trends in extreme streamflow indices from southeastern South America

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Supplemental data for this article can be accessed here.

and the Amazon basin, while there were negative trends in North-East Brazil.

Despite the great flood-loss potential in Brazil and South America, its continental dimension, and the presence of some of the largest and most important rivers in the world, flood changes have still been only explored to a limited extent. To our knowledge, combined flood seasonality and trend analysis have never been investigated from a large-scale perspective in this region of the world. With the exception of Alves *et al.* (2013), Berghuijs *et al.* (2017) and Gudmundsson *et al.* (2019), we could not find magnitude and frequency trend studies in this area. By analysing a large region and a large dataset, it is possible to reduce local noise and identify spatial patterns in the observed changes with greater confidence (Petrow and Merz 2009, Hall *et al.* 2014).

In this paper, we took into account a regional perspective and an extensive-unexplored dataset in order to analyse floods across the whole of Brazil. The objective of this work was to evaluate seasonality and recent changes in the magnitude and frequency of floods in Brazil. Some of the open questions we attempted to answer are:

(1) Is there significant seasonality in the flood time series of Brazilian rivers?
(2) Are there significant trends in flood frequency or magnitude?
(3) What are the seasons with significant trends in flood magnitude or frequency?
(4) What are the spatial patterns of flood trend and seasonality in Brazil?

Materials and methods

Study area

Brazil has a total area of 8 515 759 km^2 (IBGE 2017) and is divided into five large regions: South, South-East, Midwest, North and North-East (Fig. 1). Due to the continental dimensions of Brazil, the climate in the regions is diverse, influenced by geographical location, significant coastal extent and the different air masses that act on a territory (Zandonadi *et al.* 2016) Added to these complex interactions, there are influences by other systems and atmospheric phenomena, such as the South Atlantic Convergence Zone (SACZ), the Intertropical Convergence Zone (ITCZ) and the El Niño-Southern Oscillation (ENSO). The different circulation patterns influence the seasonality of precipitation in all regions of Brazil. Overall, the maximum precipitation occurs in the austral summer months in most regions of Brazil (South–East, Midwest and part of the North, South and North-East regions) (Rao *et al.* 2016).

Fluviometric data selection

We obtained a total of 3254 streamflow time series from the Hidroweb portal of the Brazilian National Water Agency, ANA,[1] corresponding to all types of catchments. We limited our analysis to catchments with a length of at least 30 years in the 1976–2015 period and considered only the data between those dates. In addition to the minimum record length, we evaluated the time series in terms of missing values. Similar to Papalexiou and Koutsoyiannis (2013), we identified the 40% lower maximum annual daily discharge values and evaluated the percentage of missing data in the corresponding years. If in any identified year the percentage of missing data was equal to or greater than 30%, the time series was discarded.

Most of the gauges are located in the South, South-East and North-East regions. The location of the 738 fluviometric gauges whose time series matched the filtering criteria are presented in Fig. 1. Figure 2(a) shows the length of record (in years) for all 738-time series used in this study while Fig. 2(b) shows the number of available time series in a given year.

Similar to Mallakpour and Villarini (2015), we used a block maximum approach to detect changes in the magnitude and frequency of flood peaks. We selected the maximum daily discharge for each block – year or season (summer: January-February-March, JFM; autumn: April-May-June, AMJ; winter: July-August-September, JAS; and spring: October-November-December, OND) – in order to deal with the analysis of annual maxima series (AMS) and seasonal maxima series (SMS). For the flood frequency trend analysis, we used the peak-over-threshold (POT) approach based on the 95th percentile of the daily discharge values to identify flood peaks. We counted the number of daily discharge values that exceeded the threshold in every annual or seasonal block with no more than one flood peak in a two-week time window in order to guarantee that the events were independent. This methodology is similar to that adopted by Mallakpour and Villarini (2015, 2016) and resulted in an average of 3.3 events per year.

Trend and abrupt change analyses

Magnitude

We used the Pettitt test (Pettitt 1979) to identify abrupt changes in flood magnitude at the annual scale and the probable date of those occurrences. We assumed that there is no more than one change point in the time series for abrupt change evaluation, as in Villarini *et al.* (2011a), Villarini *et al.* (2011b). Similar to Mallakpour and Villarini (2015) and Villarini *et al.* (2012), we used the Mann-Kendall test (M-K) (Kendall 1975) for annual and seasonal blocks to identify monotonic trends in the magnitude of maximum discharge. A significance level of 5% (α = 0.05) was adopted for both the Pettitt and Mann Kendall tests.

Before applying the M-K test we checked for autocorrelation in the time series (Petrow and Merz 2009, Petrow *et al.* 2009), since it changes the variance of the M-K statistic (Yue *et al.* 2002). We corrected the data for serial correlation using the procedure of trend-free pre-whitening (TFPW) described by Yue *et al.* (2002). If no significant autocorrelation is found, the M-K test is applied to the original series. Otherwise, the lag-1 autocorrelation is removed from the series.

[1]http://www.snirh.gov.br/hidroweb/publico/apresentacao.jsf [downloaded December 2018].

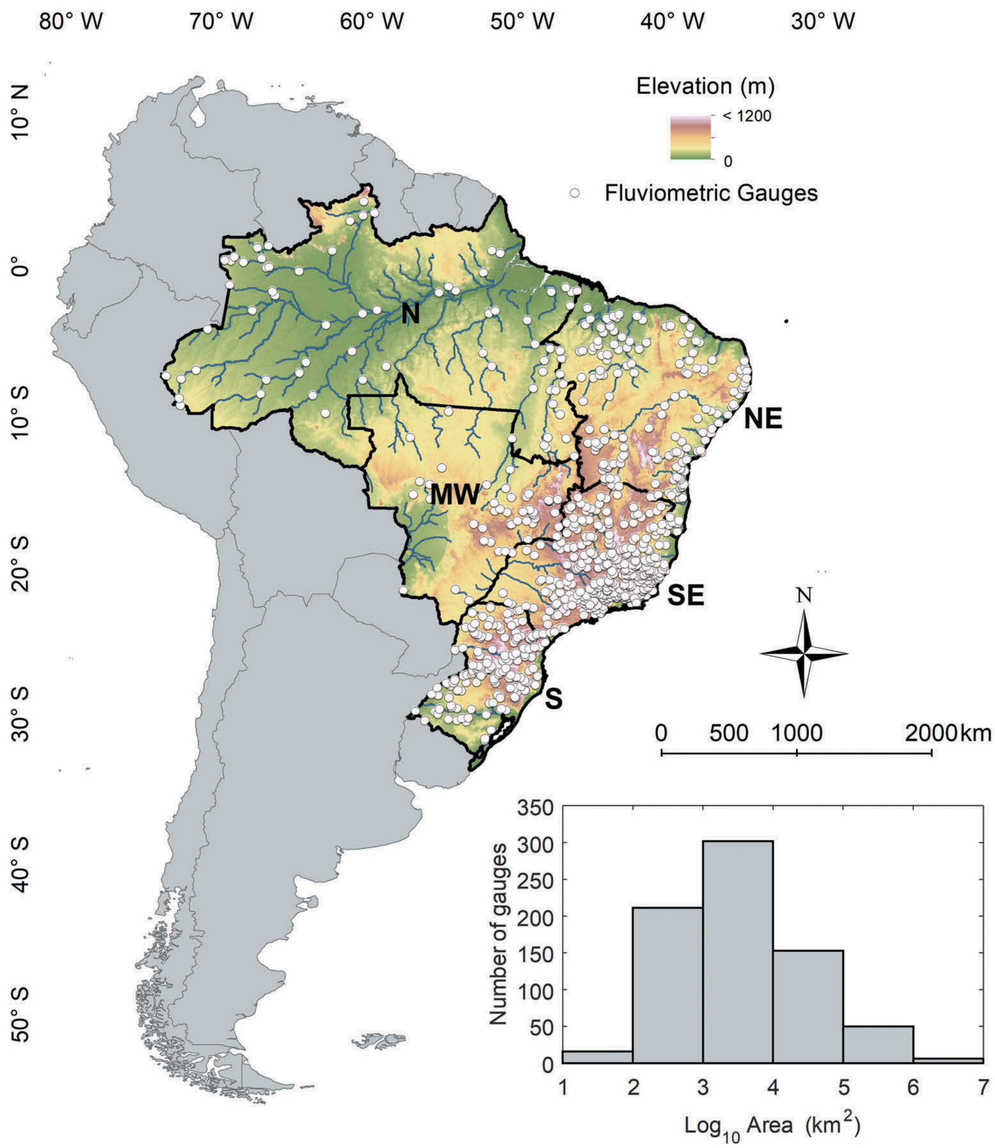

Figure 1. Location of the 738 fluviometric gauges whose time series matched the quality criteria. S, SE, NE, MW and N represent the South, South-East, North-East, Midwest and North regions, respectively. The histogram shows the distribution of the basin area of each of the gauges.

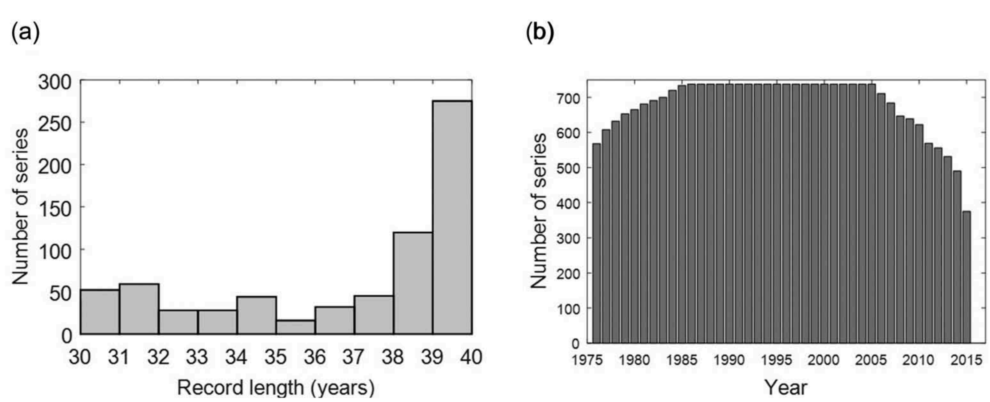

Figure 2. (a) Histogram of the record length (in years) for all 738 gauges used in this study, and (b) number of gauges with available data in a given year.

In addition to the verification of autocorrelation, we also evaluated the presence of long-term persistence in the time series, which might lead to an underestimation of the serial correlation of the data and an over-estimation of the significance of the M-K test (Sagarika *et al.* 2014). We used the method proposed by Hamed (2008) to identify the long-term persistence in the time series.

Similar to Sagarika *et al.* (2014), we evaluated field significance to assess if the trend results for each Brazilian region are significant overall using the Walker test (Wilks 2006) at a significance level of 5% (α = 0.05). A brief description of the Mann-Kendall, Pettitt and Walker tests and TFPW procedure is provided in the Supplementary material (Supplemental I, with a spreadsheet of the analysis in Supplemental II).

Frequency

A similar methodology was applied to the POT time series to detect abrupt and monotonic changes in magnitude, for annual and seasonal blocks. However, the Pettitt and M-K tests are not recommended to detect abrupt and monotonic changes in POT time series, as these are composed of discrete values (number of days that exceed a threshold in a certain year). As in Villarini *et al.* (2013) and Mallakpour and Villarini (2015), we used segmented regression (Muggeo 2003) for detecting abrupt changes in the POT time series at the annual scale, considering no more than one change-point in the time series. Poisson regression was used to detect monotonic trends in POT time series (Villarini *et al.* 2012) of annual and seasonal blocks. We adopted a significance level of 5% (α = 0.05) for both segmented and Poisson regressions. The Walker test (Wilks 2006) was applied to assess if the trend results for each Brazilian region are significant overall, at the 5% significance level. (For a brief description of the segmented regression and Poisson regression methods, see the Supplementary material, Supplemental I).

Seasonality

We used a directional statistic method (Mardia and Jupp 1999) to evaluate the presence of seasonality in the AMS series, similar to Black and Werritty (1997), Koutroulis *et al.* (2010), Parajka *et al.* (2010) and Villarini (2016). The Rayleigh test (Mardia and Jupp 1999) was used to verify the data uniformity at a significance level of 5% (α = 0.05). (Brief descriptions of the directional statistic method and the Rayleigh test are presented in the Supplementary material, Supplemental I).

Results and discussion

Abrupt changes

We identified 128 annual time series with significant abrupt changes in the magnitude of floods (Fig. 3(a)). All Brazilian regions showed field significance (Fig. 3(a)). On the other hand, only 30 annual time series presented significant abrupt changes in the frequency of floods (Fig. 3(b)). The Midwest region was the only one to present field significance (Fig. 3(b)). Abrupt changes in the magnitude of floods occurred mainly in the 1985–-1995 period in the North-East and part of the South-East and North regions of Brazil. The more recent changes, in the 1995–2005 and 2005–2015 periods, are concentrated in the North and the eastern part of the South-East regions. There is no clear temporal or spatial pattern for abrupt changes in flood frequency. Our results are summarized in Fig. 4 in terms of percentage of time series that presented abrupt changes and monotonic trends for each Brazilian region.

Even though abrupt changes are usually suggested as a result of anthropogenic effects, such as the construction of dams and reservoirs (Villarini *et al.* 2011b, 2011c, 2012), previous works attributed the occurrence of hydrologic changes to climatic factors in exactly the same period that we identified abrupt changes, especially in the North region. The years of abrupt change occurrence in the North are consistent with the results reported by Espinoza Villar *et al.* (2009), Marengo *et al.* (2012) and Barichivich *et al.* (2018). These studies indicate that extreme floods are becoming more frequent or intense in the Amazon Basin (which covers almost all of northern Brazil) in recent decades, which might be related to the abrupt changes identified in our analysis.

Barichivich *et al.* (2018) state that there is mounting evidence that the hydrological cycle of the Amazon Basin has intensified since the late 1990s. Eight of the 14 largest floods that occurred in the 1903–2015 period at Manaus gauge (northern Brazil) were in the recent years 2015, 2014, 2013, 2012, 2009, 1999, 1994 and 1989. Barichivich *et al.* (2018) estimated that there has been a significant fivefold increase in

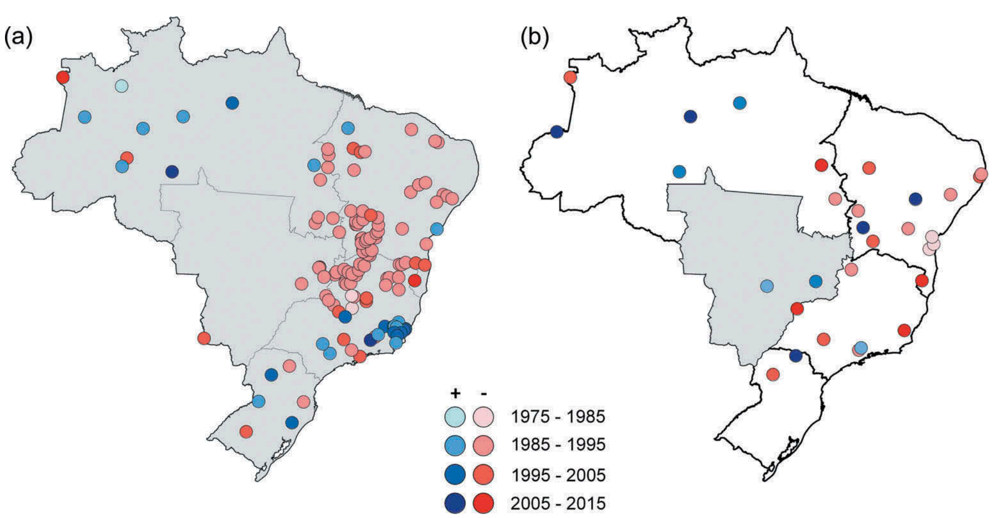

Figure 3. Abrupt changes in (a) the magnitude of floods and (b) the frequency of floods. Stations with a positive trend are shown in blue, while negative ones are in red. The regions in grey show field significance. (Colour is shown in the online version.).

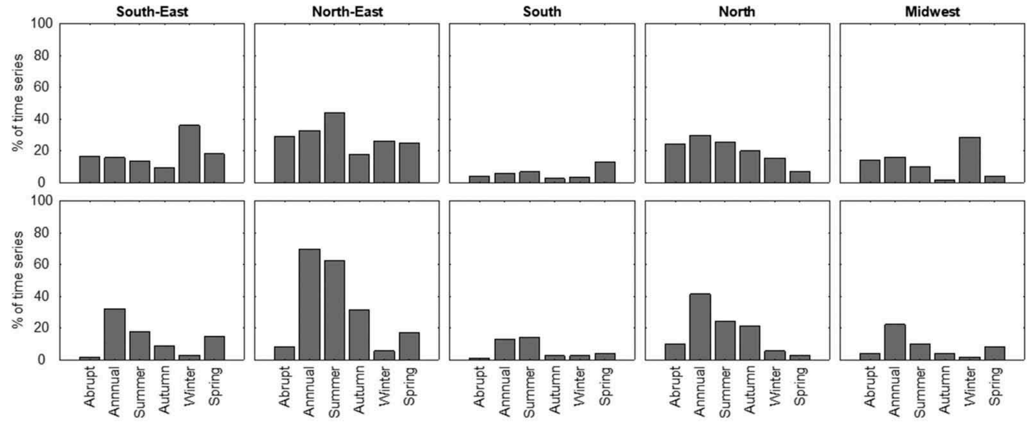

Figure 4. Percentage of gauges with significant changes in the magnitude (top) and frequency (bottom) of floods for each Brazilian region, at annual and seasonal scales.

flood frequency, from roughly one flood every 20 years during the first half of the 20century to one about every 4 years from the 2000s onward. Similarly, Marengo *et al.* (2012) reported that, of the six largest floods recorded in the Amazon Basin in more than 100 years, three were recorded in 1989, 1999 and 2009. Espinoza Villar *et al.* (2009) reported an increasing trend in the mean and maximum daily streamflow in the northwestern Amazon basin, with an abrupt change in the maximum daily streamflow in 1992, characterized by a 16% run-off increase after that year.

Monotonic trends

There are significant trends in the magnitude and frequency of floods in Brazil at both annual and seasonal scales, and there is a well-defined spatial pattern in their signals (Fig. 5). The regional signal pattern for monotonic trends in the magnitude of floods are very consistent to that observed in the abrupt change analysis. Since the spatial pattern for abrupt changes in flood frequency is not clear, it is not possible to compare it with the one found for monotonic trends.

Overall, we found concomitant positive trends in the magnitude and frequency of floods in the South, North and in parts of South-East Brazil. On the other hand, there are negative trends in almost all the North-East and the remainder of the South-East. There is no clear trend pattern in Midwest Brazil. All Brazilian regions had field significance for most of the magnitude and frequency trends at the annual and seasonal scales. Despite these results, it is not possible to reach a solid conclusion about the trends in the North and Midwest regions of Brazil due to the non-homogeneity in the spatial distribution of the selected time series and the limited data availability.

As we found similar trend signals for flood frequency and magnitude in North, South and part of South-East Brazil, we conclude that floods are becoming more intense and frequent in those regions. Similarly, Berghuijs *et al.* (2017) found an increase in the number of extreme flood occurrence and in flood magnitude considering the largest floods observed in the 1980–2009 period in 244 Brazilian catchments, most of which are in the South and South-East regions of Brazil. Positive trends in the mean and maximum streamflow time series corresponding to the South and South-East regions were also identified by Alves *et al.* (2013), who also reported negative trends for time series corresponding to the North-East region. Bartiko *et al.* (2017) reported the impacts of the identified positive trends in southern Brazil for flood

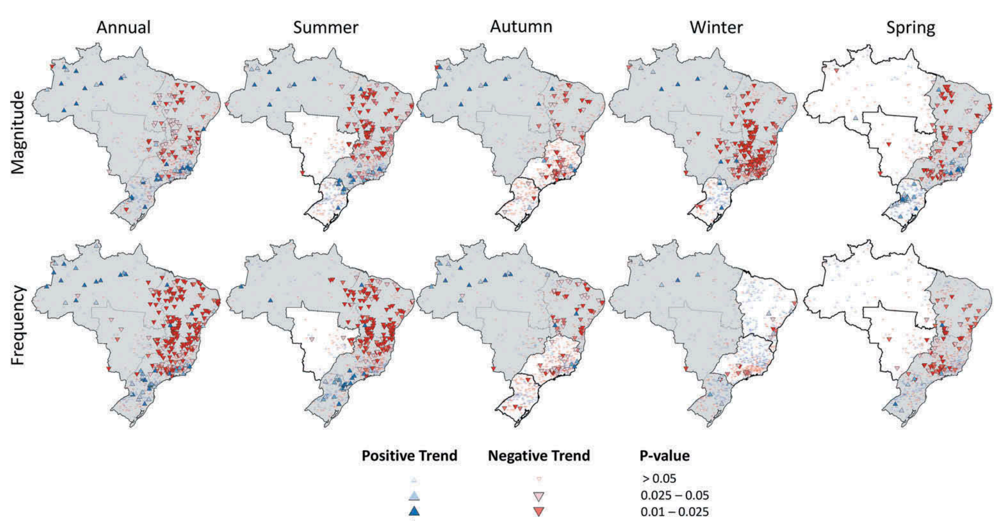

Figure 5. Trends in flood magnitude (top) and frequency (bottom) of floods in Brazil at annual and seasonal scales. The regions in grey show field significance.

frequency analysis, which may significantly reduce the estimated flood return period.

Floods are becoming less intense and frequent in all the North-East and in parts of South-East Brazil. Gudmundsson *et al.* (2019) reported extreme negative trends in the streamflow in North-East Brazil and positive ones in southeastern South America (which includes the South region and parts of the Midwest and South-East regions of Brazil) and the Amazon (which includes the North and part of the Midwest regions of Brazil). It is interesting to note that these studies identified different trends when evaluating three overlapping periods: 1951–1990, 1961–2000 and 1971–2010. Overall, the North-East showed a reverse trend pattern in the last two periods (negative) in relation to the first (positive). Positive trends were identified in southeastern South America in all evaluated periods, which were less significant in the last one. The Amazon exhibited significant increasing trends in the last period. Insufficient data was available for the first two periods.

The flood trend pattern in the South, South-East, North and North-East regions is similar to that reported for precipitation (Haylock *et al.* 2006; Carvalho *et al.* 2014; Marengo *et al.* 2016, Zandonadi *et al.* 2016) and streamflow (Dai *et al.* 2009, Doyle and Barros 2011, Barichivich *et al.* 2018). Overall, all studies relate the observed trends in flood/precipitation to phenomena like Walker Circulation, ENSO, ITCZ, SACZ and Pacific Decadal Oscillation (PDO).

Carvalho *et al.* (2014) identified a positive trend in the maximum daily rainfall for the Midwest, South-East and South regions of Brazil. Zandonadi *et al.* (2016) and Doyle and Barros (2011) reported an increase in precipitation in the Parana and La Plata catchments (which cover almost all of the South and parts of the South-East and Midwest regions of Brazil). Haylock *et al.* (2006) also identified positive (negative) trends in the precipitation in South and South-East (North-East) Brazil corresponding to the 1960–2000 period. They proposed that conditions of El Niño dominance in that period, with a generally lower Southern Oscillation Index (SOI) value, have contributed to the rainfall changes. According to Dai *et al.* (2009), El Niño tends to increase the streamflow in many rivers around the world, including the Paraná and Uruguay rivers, located in the La Plata catchment. There is also a relationship between the positive phase of the PDO and more intense El Niño events. The last positive phase of the PDO started in the 1970s and remained until at least to the end of the century (Doyle and Barros 2011).

Barichivich *et al.* (2018) attribute to the recent strengthening of the Walker circulation the observed increase in frequency and intensity of severe floods in the Amazon basin. Changes in the Walker circulation were also pointed by Marengo *et al.* (2013) as a cause of precipitation anomalies in this region. There is evidence that the rainfall regime in Amazonia is also controlled by changes in sea-surface temperatures (SST) in the equatorial Pacific Ocean, even though El Niño explains only part of the variability (Marengo *et al.* 2013). An anomalously southward migration of the ITCZ during 2009, due to warmer surface waters in the tropical South Atlantic, was pointed out by Marengo *et al.* (2012) as being responsible for abundant rainfall in large regions of eastern Amazonia, which culminated in flooding with a magnitude and duration observed only a few times in the previous decades. Marengo *et al.* (2016) recalls that changes in SST in the tropical Pacific manifest as extremes of ENSO influence in terms of precipitation anomalies over the North-East region of Brazil via changes in the zonally oriented Walker circulation, but ENSO explains only part of the rainfall variability in this region. The authors also recalls that North-East Brazil rainfall exhibits marked inter-annual variability, part of which has been attributed to ENSO. Significant changes are more pronounced in the flood frequency (Fig. 5, lower panel) than in the magnitude (Fig. 5, upper panel), but the regional pattern for trends in the magnitude and in the frequency are very similar. Although we do not expect that the occurrence of magnitude and frequency trends will be similar, we also emphasize that the tests used for magnitude and frequency trend analysis are different, as was the database used for that (one event per year for magnitude tests, and on average 3.3 events per year for frequency tests). Differences between flood frequency and magnitude trends in Brazil were also found by Berghuijs *et al.* (2017), who reported a larger increase in the number of occurrences of extreme floods compared to the increase in the magnitude of floods. Although our results indicate a predominance of negative trends, in disagreement with Berghuijs *et al.* (2017), we highlight that an expressive number of significant negative trends were identified in the North-East region of Brazil, in which Berghuijs *et al.* (2017) evaluated a smaller number of stations.

We identified significant trends in the magnitude of floods mainly in the winter (25.2%), followed by summer (19.6%), spring (16.7%) and autumn (10.6%). On the other hand, trends in frequency are more evident in summer (26.7%), followed by autumn (13.4%), spring (11.8%) and winter (3.8%). These results show the importance of analysing the presence of trends in the magnitude and frequency of floods at the seasonal scale. The difference between the trends in the magnitude and the frequency for the seasonal analysis are in consonance with those reported by Mallakpour and Villarini (2015).

Seasonality

There is a significant seasonality in 647 of the 738 evaluated time series (Fig. 6). There is a clear regional pattern for the presence and strength of flood seasonality in Brazil (Fig. 6), but the mean date of flood occurrence, and the seasonality strength vary across the study area. Almost all stations in the South-East, North-East, Midwest and North regions exhibit significant seasonality, while seasonality was observed to a lesser extent in only a part of the South region. This spatial difference might reflect differences in flood generating mechanisms, as reported by Villarini (2016) for flood seasonality in the USA and by Blöschl *et al.* (2017) in Europe. Floods mainly occur in the winter in the South, while in the summer and in the end of the spring in the South-East, Midwest and parts of the North-East and North regions of Brazil (Fig. 6(a)). The remainder of the North-East (basically the coastal regions) and North regions of Brazil are characterized by floods in autumn and winter. Seasonality strength is evident for almost all those regions,

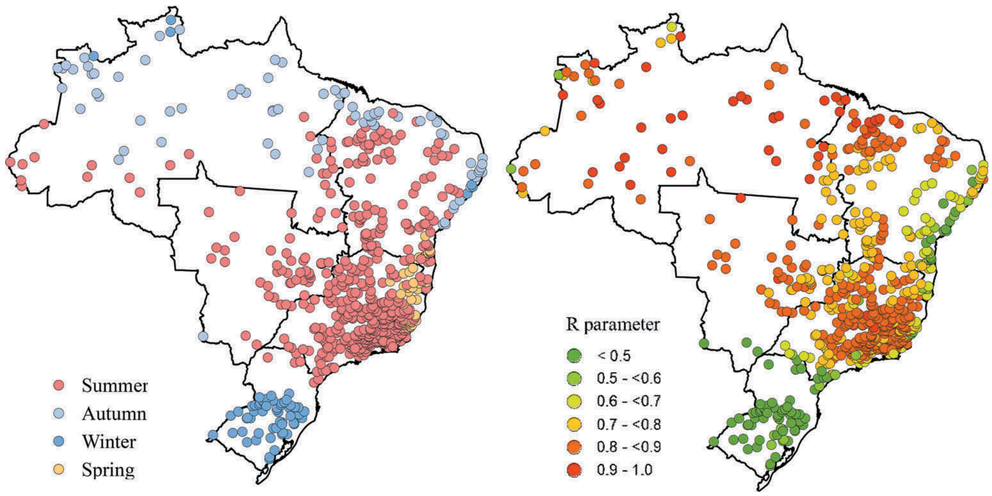

Figure 6. Seasonality of floods. (a) Mean date of flood occurrence and (b) seasonality strength represented by *R*. The *R* parameter can assume values from 0 (no seasonality) to 1 (strong seasonality).

with the exception the South and the coast of North-East of Brazil (Fig. 6(b)).

These results are very consistent with the rainfall regime in Brazil (e.g. Rao *et al.* 2016). Most of the Brazilian climate is characterized by a well-defined rainfall period (Rao *et al.* 2016), with the exception of the South region, which is characterized by no significant seasonality (Grimm 2009). Rao *et al.* (2016) point out that the South-East and Midwest regions are characterized by a rainfall season in the austral summer, and Espinoza Villar *et al.* (2009) emphasize that there is a strong opposition between the rainfall season in the northern and southern Amazon Basin (which covers almost the entire North and part of the Midwest regions of Brazil). The rainfall season occurs in JJA months in the north of the Amazon region and DJF in the south. The reported seasonality in the precipitation of the Amazon Basin is very similar to our results for flood seasonality.

Conclusions

In this paper, we examined flood trends and seasonality across the whole of Brazil using a large dataset. The abrupt changes in flood magnitude occurred mainly in the 1985–1995 period in the North-East and parts of the South-East and North regions of Brazil. The more recent abrupt changes, in the 1995–2005 and 2005–2015 periods, are concentrated in the North and in the east of the South-East. There is no clear temporal or spatial pattern for abrupt changes in flood frequency. We identified both positive and negative trends in the frequency and magnitude of floods, with two well-defined regions. There was a positive trend in the South, North and parts of the South-East regions. When analysing at the annual scale, trends were more evident in the frequency rather than in the magnitude. At the seasonal scale, monotonic trends in the frequency (magnitude) are more evident in the summer (winter) time series, while at the annual scale, trends are more evident in the frequency time series rather than in the magnitude time series.

We identified a strong flood seasonality in almost all of Brazil and a well-defined spatio-temporal pattern in its occurrence, with floods predominating in the austral summer for the South-East, Midwest and North-East regions, and in the winter (autumn) for South (North) Brazil.

Overall, floods are becoming more frequent and intense in Brazilian regions characterized by their wet conditions and less frequent and intense in drier regions. The identification of both seasonality and changes in the magnitude and frequency of floods is a first step towards the characterization of the phenomena responsible for flood changes in this vast area of the Southern Hemisphere.

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Disclosure statement

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