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Space-time representation of Lee et Heghinian approach: case of the Congo watershed

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Key Points:

- The Lee et Heghinian approach applied to 9021 rainfall series at the scale of the Congo watershed leads to the spatiotemporal representation

- A delimitation not predefined in advance of the climatic rupture regions
- The regions not yet studied were not affected by the climatic change over the period 1968-1971

Abstract

The local or regional approach is often used in studies to detect the point of change of the mean in the hydro-climatic time series. These approaches have been applied by previous studies on a limited part of the Congo basin, in particular on the right bank of the Congo river. This study is a comprehensive spatio-temporal analysis over the Congo Basin that deals with the detection of the point of change of the mean in the precipitation time series using the Lee et Heghinian approach. The latter has been applied on 9021 precipitation time series over the Congo watershed which resulted in a spatio-temporal representation of the probabilities of the point of change of the mean. A clear cut of the study area unto distinctive zones with high or low probabilities has been obtained. The point of change of the mean in the precipitation time series occurred in 1969 or 1970 with high probabilities over two areas of the basin which correspond to the sub-basins of Oubangi and Kasai. These sub-basins are seemingly more vulnerable to climate change than other sub-basins such as the Batéké Plateau sub-basin as well as regions not yet studied.

Keywords: Lee et Heghinian approach; Congo watershed; Rainfall; Climatic discontinuities

1 Introduction

The past severe drought in the subsaharan Africa has been extensively studied as well as its consequences on water resources and the environment. Indeed, during 1970s and 1980s the African continent, particularly the north and west Africa has experienced a significant hydrological deficit (Bricquet et al., 1997; Houndenou et

49 Hernandez, 1998; Laraque et al., 2001; Mahé et Olivry, 1995; Morel, 1998; Nguimal
 50 et Orange, 2013, 2019; Servat et al., 1998) that has been characterized by a high
 51 frequency of low water level occurrence (Bricquet et al., 1997; Kisangala, 2009;
 52 Pandi et al., 2009) A memory effect on base flows that leads to the depletion of water
 53 resources has also been reported (Bricquet et al., 1997; Laraque et al., 1998,2001;
 54 Nguimalet et Orange, 2013,2019; Olivry et al., 1998; Orange et al., 1997; Wesselink
 55 et al., 1996). The cause of this drought is attributed to a significant rainfall deficit
 56 observed in Subsaharan Africa (Hubert et al., 1989; Laraque et al., 2001; Mahé et
 57 Olivry, 1995; Nguimalet et Orange, 2013, 2019) during 1968s years with an early
 58 start in Senegal (Morel, 1998). Morel (1998) has analyzed occurrence of the drought
 59 and its progression over the West Africa, including the Sahelian and the Gulf of
 60 Guinea zones. He found that the start of the drought has a space-time gradient. In
 61 fact, the drought has progressed from the northeast to the southeast (Morel, 1998).
 62 Thus, the equatorial zone, including the Gulf of Guinea (Houndenou et Hernandez,
 63 1998) and the Congo Basin (Asani, 1999, 2000; Demarée et al., 1998) has also been
 64 affected. The causes of this rainfall deficit are multiples. We can mention the
 65 anomalies (space-time variation) of the ITCZ position, especially the reduction its
 66 northward migration over the Atlantic Ocean (Citeau et al., 1989; Lamb, 1978) and
 67 physical processes related to the atmospheric and oceanic modes of variability,
 68 including the Atlantic Multi-decadal Oscillation (AMO) (Shanahan et al., 2009) and La
 69 Nina events (Druyan, 2010). According to Nicholson et al (2018), the Western
 70 equatorial Africa (i.e. the North of Angola, the Congo-Brazzaville/Gabon and the
 71 Cameroon regions), which represents the western side of the Congo Basin,
 72 describes two opposites precipitation trends since the three last decades of the 20th
 73 century. Trends in Cameroon region mimics those in Sahel and the dryness

conditions prevail since 1968, year during which an abrupt change or discontinuity in precipitation series has been detected over this region. In contrast to the Cameroon region, the Congo/Gabon and Angola are characterized by an increase of precipitation since 1980. The shift in precipitation time series over Africa has been found to be related to the natural variability in a changing climate and have been used to detect the onset of the rainfall deficit (Demarée et Nicolis, 1990). The natural discontinuity of precipitation time series on the western side of the Congo Basin has been addressed in other studies such as those by Mahé et Olivry (1995) and Laraque et al (2001). These studies use different approaches including the Hubert approach (Hubert et al., 1989) and the Lee et Heghinian approach (Lee et Heghinian, 1977). The variability of the river discharge over the Western and the Northern side of the Congo Basin (i.e. the the right bank of the Congo River) has been also examined by Laraque et al (2001). Only Two studies (Kisangala, 2009; Tshitenge et al., 2016) analyzed the temporal variability of the river discharge in the left bank of the Congo river. They particularly focused on the catchment of the Kasai River. Approaches for detecting the point of change of the mean in the time series have not been applied to analyze the spatiotemporal variability in large-scale river discharge of the entire Congo Basin.

The Congo Basin is the most significant wet zone of Africa, which is covered by the biggest bloc of the tropical rainforest of the continent. This forest is the most important sink of carbon in the world and the most important biodiversity hotspot. Congo Basin is also an important hydrological region in the World that covers more than 4.1 million km² and its drainage represents 40% of the continent's total discharge (Crawley et al., 2006). Understanding the space-time variation in precipitation in the changing climate over the Congo Basin is an important task. It will

lead, for instance, to understand the variation of the balance between precipitation and runoff, the evapotranspiration that explain the recent decrease in the river flow. Unfortunately, less attention has been deserved on this issue over the entire Congo Basin given to a lack of precipitation gauge data. As noted by Shem et Dickinson (2006), despite the resources the basin has, it has not yet received sufficient attention in the area of climate and hydrological research. Therefore, it seems important (1) to extend the study of shift in rainfall series over the central and eastern part of the Congo Basin and to consider the whole Basin given to its significant ecological importance, in order to detect the shift but to find out the space-time variation of this shift and the intensity of change in precipitation over this region, i.e. to determine the spatial range of the years of ruptures; (2) to verify whether the results are consistent to the previous findings over the northern and western side of the Congo Basin.

Moreover, several approaches have been developed and successfully used with to detect the point of change of the mean (rupture) in a time series in many studies, such as : Hubert et al (1989), Lanzante (1996), Lee et Heghinian (1977), Pettitt(1979), Bruneau et Rassam(1983), Ruggieri (2012). A lot of them have been applied to detect points of change of the mean in the time series of precipitation and runoff over various parts of sub-Saharan Africa that have experienced drought (Hubert et al., 1989; Laraque et al., 2001; Nguimalet et Orange, 2013, 2019). Some of them have been focused on detecting trends in precipitation over the 20th and early 21st centuries (Biasutti, 2019), while many others have addressed the issue of shift in precipitation time series in order to determine the onset of precipitation deficit.

2 Study area

The Congo Basin is located in the heart of the African continent (Figure 1). It has an area of approximately 3665916.7 km² (Tshimanga, 2012) expanded from 09°20'N to 13°35'S and 12°05'E to 34°00'E. The Congo Basin is basically located in the Democratic Republic of Congo that accounts at least 63% of the total area. The rest of the area is distributed between Cameroon (2.2%), CAR (10.9%), Angola (7.6%), Burundi (0.4%), Congo (6.7%), Tanzania (4.3%), Zambia (4.8%) and Rwanda (0.11%)

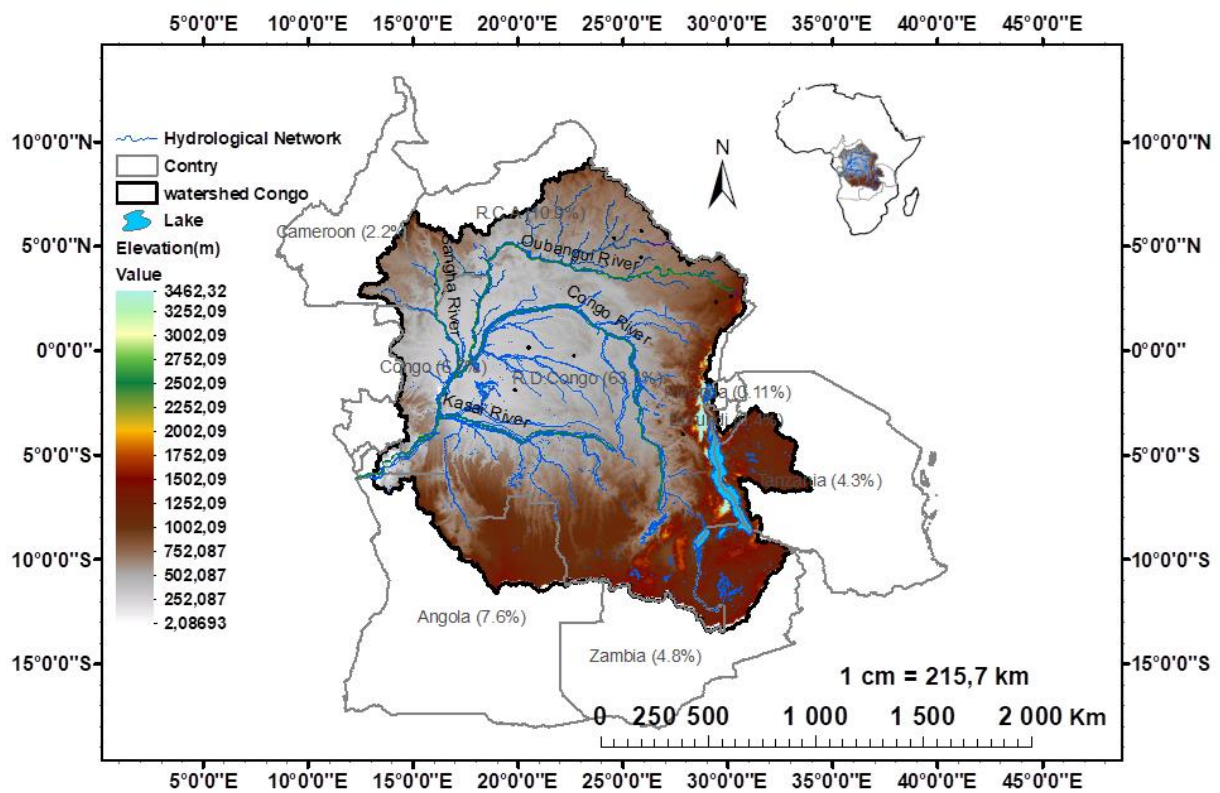


Figure 1 : Location of the Congo watershed in the African Continent. (D.R.C:

Democratic Republic of Congo, C.A.R: Central African Republic, TZA Tanzania:

United Republic of Tanzania).

In the present study, the Congo Basin is subdivided into 18 sub-watersheds. . Figure 2 shows this subdivision. The rivers of sub-basins of Bangi (06), sangha (15) and Kasai (10) belong to the main tributaries of the Congo River.



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A depression that does not exceed 400 meters of altitude dominates the center of the basin. It consists mainly of sandy sandstone formations and Mesozoic argillites topped with ferrallitic soils. This depression is covered by a dense rainforest so that 35% of the basin area is partially flooded during floods (Laraque et Olivry, 1995).

The Congo Basin is subdivided into the following climatic zones: (1) the equatorial zone located on the center and astride the equator is characterized by an absence of a true dry season; (2) the tropical zone on the north and the south of equatorial zone; (3) the temperate zone over the mountains in the east (Bultot, 1971). In the equatorial zone of the Congo Basin the annual precipitation amount varies between 1500 and 2000 mm and the temperature average temperature is estimated at 26 ° C (Tshimanga, 2012).

However, its different characteristics give it enormous potential for the development of its water resources on a regional scale, such as hydropower, irrigation, navigation, etc.

3 Data

In this study, we used the CRU TS 3.1 gridded dataset provided by CRU (Climate Research Unit) of the University of East Anglia. The CRU uses an iterative homogenization procedure to obtain homogenized data. Based on this procedure, the reference series is used to correct any heterogeneity in the station records. The corrected data are then merged with the existing database and converted to anomalies (Mitchell et Jones 2005). The resulted anomalies were then interpolated to produce gridded data of 0.5x0.5 spatial resolution using the function Spline Technique and the Inverse Weighted Distance. Both techniques are adapted for data irregularly distributed in space. The CRU TS 3.1 dataset is described with details in Harris et al (2013).

The CRU climate data consist of concatenated global grids, in which the first line represents cells with centres on 89.75°S and the first column represents cells with centres on 179.75°W. Thus, the first cell in the file - and of every subsequent global grid is centered on (89.75°S, 179.75°W). For the purpose of this study, the CRU gridded data that cover the Congo Basin (with about 9021 grids) for the period 1940 to 2009 have been downloaded and then transformed to create monthly and annual time series. Thus, the dataset used in this study consists of the CRU T.S. 3.1 gridded monthly precipitation with spatial resolution of 0.5x0.5 for the period 1940-2009 and covering the entire area of the Congo Basin that accounts 9021 node points.

The CRU grid has already been proven globally and regionally (Döll et Fiedler, 2008; Tshimanga, 2012). In addition, this gridded dataset allows large scale studies and spatial analysis and is appropriate for large scale regions. Therefore, it may be more useful than a set of individual stations (Mitchell et Jones, 2005).

4 Methods

In this study, two different approaches are used to detect the point of change of the mean in the time series of precipitation. The first is a Bayesian-based approach developed by Lee et Heghinian (Lee et Heghinian, 1977) and the second is a statistical segmentation approach of Hubert (Hubert et al., 1989). The Lee et Heghinian approach is used to study the space-time variation of the change in mean rainfall over the Congo basin. It was selected given to its ability to associate a point change's in the mean of a time series with its corresponding probability. The Hubert's approach is used to perform a comparative analyze, on the one hand with the Lee et Heghinian approach and, on the other hand, with previous studies.

4.1 Lee et Heghinian's approach

The Bayesian approach supposes the "a-priori" existence of a change of the mean or rupture somewhere in the series and yields at each time step an "a-posteriori" probability of rupture (Bruneau et Rassam, 1983). Lee et Heghinian (1977) use the Bayesian approach to obtain the marginal and joint posteriori distributions of the time point and the amount of the shift. Unlike other tests or approaches for detecting changes in the mean (rupture) of a time series such as Pettitt (1979) or of Hubert (Hubert et al., 1989), the Lee et Heghinian approach has the advantage of associating the posteriori probability with the date of changing average (date of rupture). The Lee et Heghinian approach is particularly accurate because it uses a Bayesian approach. However, its disadvantage lies in detecting a single change in the mean in a time series (Bruneau et Rassam, 1983).

The Lee et Heghinian's approach has been used as described in Lee et Heghinian (1977). It has been applied on 9021 annual precipitation time series, which are distributed on regular grid of 0.5x0.5 resolution covering the Congo Basin as described in the previous section, to detect change of mean (rupture), to estimate the probability of change of mean (probability of rupture) and to calculate the amount of shift in each time series. It is also applied to 18 yearly precipitation time series of different sub-basins selected in this study.

4.2 Hubert's approach

Hubert's approach consists in splitting the series into m segments ($m > 1$) so that the average calculated on any segment is significantly different from the average of the segment (s) neighbors. According to Hubert et al (1989), the segmentation approach can be viewed as a stationary test, where "the analyzed time series is stationary " constitutes the null hypothesis. Stationary is related to the duration of observations. If

the approach does not produce acceptable segmentation greater than or equal to 2, then the null hypothesis is accepted. No significance level was assigned to this test. This approach is suitable for looking for multiple changes of mean. It has been used in several studies focused on precipitation changes over Africa (Ardoin, 2003; Laraque et al., 2001; Ouedraogo, 2001; Paturel et al., 1997; Servat et al., 1998). Using this approach, it was possible to highlight and detect the climatic rupture on almost the entire African continent between 1969 and 1971 (Mahé et Citeau, 1993). In this study the Hubert's approach has been applied as described in Hubert et al (1989) on the annual areal precipitation time series of the selected sub-basins. The areal time series were calculated as described in the following section. Moreover, it is important to mention that the Hubert's approach was not applied on the 9021 time-series of precipitation due to its ability to detect multiple dates of rupture in a time series. It has been used only for comparison purposes which takes into account all segments.

4.3 Estimation of areal averaged precipitation

Studies of change in the mean over time series of rainfall often use the areal precipitation series of a given area. In general, average rainfall over a surface is estimated using interpolation techniques. Nevertheless, since we used the CRU gridded precipitation data, it was no longer useful to apply the interpolation approach. Instead, we used an approach that consists of superimposing the outline of a sub-watershed on the grids of the CRU database. The superposition allowed performing several calculations of a parameter of a grid for each mesh independently. Therefore, we calculated the average rainfall at a monthly time step on a hydrological sub-watershed by summing the values of the elementary meshes located on its contour.

4.4 Comparison with alternative approaches

As mentioned above, several previous studies (Kisangala, 2009; Laraque et al., 2001; Nguimalet et Orange, 2013, 2019) have already carried out climatic rupture analyze over smaller parts of the Congo Basin displayed in the Figures (06, 10, 15, 17 et 18) using different approaches. The present study has extended the analyze of climatic rupture in precipitation series over the whole Basin, given to fact that this zone deserves much attention in its entirety. It seems important to compare both the results of this study with those of previous studies on the scale of the Congo Basin. For the purpose of comparison, the Congo Basin has been subdivided onto 18 “sub-watersheds” (figure 2). The subdivision relied on the confluences of the main tributaries of the Congo River and took into account the sub-basins already defined in the previous studies, such as Kisangala (2009), Laraque et al (2001) and Nguimalet et Orange (2013, 2019).

To compare climatic rupture approach described above, i.e. Lee et Heghinian’s approach and Hubert’s approach have been applied on the same areal precipitation time series of the same selected sub-catchments (figure 2). The outputs have been considered with regard to the previous studies, particularly Kisangala (2009), Laraque et al (2001) and Nguimalet et Orange (2013, 2019), over the sub-catchment identified in Figure 2 as 06, 10, 15, 17 and 18. Although these authors do not use exactly the same area of the sub-basins and the same length of the time series of the sub-basins precipitation, however, the comparison of their results on the climatic rupture in a time series with those obtained in this study gives a very good indication of the relevance of the results of the approaches used in this study.

4.5 Selection of time window

The application of the Lee et Heghinian approach on 9021 time series located on 9021 geographic points on the scale of the Congo Basin leads to a space-time representation on the scale of the basin. In fact, this approach not only detects the date of climatic rupture (time variable) but also its posteriori probability, its amplitude of change in the mean (amplitude of rupture) as well as the posteriori probability of the amplitude of rupture (Bruneau et Rassam, 1983; Lee et Heghinian, 1977). The latter therefore constitute the spatial variables of the space-time representation of the approach.

The analyses of spatial structure of the values of these variables lead to assess the area covered by these values at the basin scale. The ratio expressed as a percentage of the area of extension of a value of one of the spatial variables over the total area of the basin is called "area ratio"(figure 3a) or "spatial range".

However, a top-down classification of the surface ratio values allows the selection of the dominant values of one of the spatial variables over basin. The selection of n first dominant values of the classification of the surface ratio of years rupture leads to the selection of n time windows over the basin.

5 Results

The results of analysis are displayed in Figures 3-5 and Table 1. They are relative to (1) the occurrence, the probability and the amplitude of years of rupture in 9021 grid points as displayed in Figure 3 (the area ratio of: (a) years of rupture, (b) posteriori probabilities of ruptures, (c) amplitudes of ruptures, (d) posteriori probabilities amplitudes of rupture over the Congo Basin); (2) the probability of rupture during years that have higher spatial ratio, i.e. 1968 -1971 (Figure 4) and (3) the comparison of the Hubert segmentation procedure and the Lee et Heghinian approach by

superposition the probability maps of one selected year 1969 over selected sub catchment (Table 1 and Figure 5).

The Figure 3a shows the spatial representativeness of years of rupture. It shows the occurrence of years of rupture over 9021 points regularly distributed over the whole Congo Basin.. According to this Figure 3a, the rupture in the years 1969 and 1970 have higher area ratio over the Congo Basin than other years, and they are followed by 1943. However, the selection of the 1943 time window is rejected because of the number of values used to estimate the probabilities in this year (Ouarda et al., 1999).

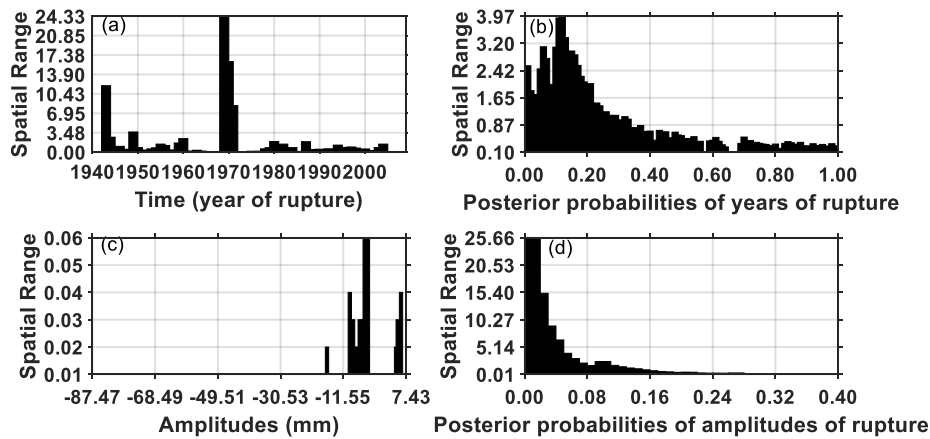


Figure 3 : (a) Years of rupture, (b) Posteriori probabilities of ruptures, (c) amplitudes of ruptures, (d) Posteriori probabilities of amplitudes of rupture, as a function of spatial range at the scale of the Congo catchment.

The spatial distribution of the probabilities of ruptures is shown in Figure 3b. The probabilities of ruptures varying from 0.00 to 0.20 have a very high spatial scope over the Congo. In fact, about 53.33% of the Basin area is dominated by probabilities of ruptures under 0.50.

Negative amplitudes between -11.95 mm to -2.51 mm are the most dominant in the basin (Figure 3c). Negative amplitudes represent a decrease in the average precipitation when the rupture occurred in the time series. The probabilities of ruptures amplitudes under 0.20 characterize 55.20% of the basin area (Figure 3d).

Figure 4 presents the spatial representation of the Lee et Heghinian approach for the years: (a) 1968, (b) 1969, (c) 1970 and (d) 1971. In fact, during these years the rupture was spatially extended over a larger area in the Congo Basin than during remaining years (figure 3a).

At first glance, the probabilities are all generally close to 0.10, except in the extreme north and center of the basin that have probabilities around 0.50 (Figure 4). Some points in these areas have probability values as high as 0.94.

The year 1970 shows the highest probability of rupture. It is followed by the year 1969. Compared to the probability of rupture of the year 1968 and the year 1971, there is a high probability of rupture in the year 1971. During this year, the highest values are characterized the center of the Basin.

The applications of the Hubert approach and the Lee et Heghinian approach on the selected sub-basins at the Congo catchment scale (Figure 2) are summarized in Table 1. In this table, the first column represented by the ID field represents the identifiers of the sub-basins selected at the scale of the Congo watershed. The second column gives the area of these sub-basins. The third presents the Hubert segmentations associated respectively with their averaged annual rainfall values. The fourth, when it is, gives in percentage the variation of the average of the segmentations. The fifth column shows the year's values of rupture obtained using the approach of Lee et Heghinian. The last column gives the values of the probabilities of ruptures associated with years of rupture of the fifth column.

As it can be seen, the Hubert's approach does not detect any change in mean (rupture) in the time series of sub-basins 02 and 18 (Table 1). Nevertheless, it detects three segmentations in sub-basins 05, 06, 07, 08, 10, 11, 12, 13, 15, 16, 19.

The maximum number of segmentations detected by Hubert's approach is four. This

number has been detected in the series of sub-basins 03, 14, 17 (Table1). The other sub-watersheds are characterized by two Hubert segmentations in their time series (Table 1). Moreover, an important variation in change of mean, which exceeds 13% is observed in the time series representing the sub-basins 14 and 16 respectively during the periods 1985 to 2009 and 1944 to 1963 (table 1).

The rupture or change in the mean of the time series in Hubert approach is frequently observed during the periods: 1943-1944, 1947-1948, 1958-1959, 1964-1965, 1969-1970 and 1996-1997 (Table 1). The highest frequency is observed during the period 1969-1970 or 1996-1997 (five times for all sub-basins); it is followed by the periods 1943-1944 or 1964-1965 (three times for all sub-basins) and 1947-1948 or 1958-1959 (two times for all sub-basins).

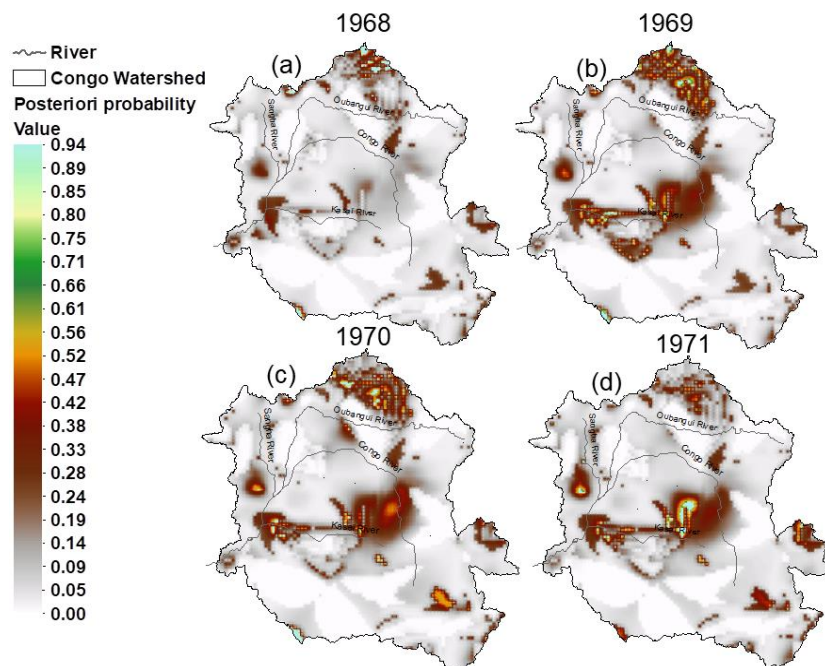


Figure 4 : A posteriori probabilities of rupture at the scale of the Congo Watershed to the year: (a) 1968, (b) 1969, (c) 1970, (d)1971.

72% of rainfall ruptures detected using the Lee et Heghinian approach are also observed in Hubert's approach (Table 1). However, only 44% of these ruptures have probabilities greater than 0.50. The frequency (number of ruptures detected over the

total number of sub-basins) of the years of ruptures detected by the approach of Lee et Heghinian is estimated at 5% or at 11% with the exception of the year 1969 where a detection frequency of 22% is estimated with probabilities greater than 0.50 except that of sub-basin 14 (Table 1).

Table 1: Hubert's precipitation segmentation, the years and the a posteriori probabilities of rupture in precipitation from Lee et Heghinian over the selected sub-basins

ID [Sub-basin]	Sub-basin area [Km ²]	Segmentation : precipitation (mm) and variation (%) [Hubert]	Year and posteriori probability of rupture in the precipitation (mm) [Lee et Heghinian]	
01	123 866	1940-1958 : 1407 1959-2009 : 1452 +3.1%	1958	0.01
02	976 568	1940-2009 : 1190	1996	0.20
03	755 589	1940-1959: 1712 1960-1988 : 1748 +2.1% 1989-1996 : 1596 -8.7% 1997-2009 : 1711 +6.7%	1988	0.12
04	133 518	1940-1981 : 1590 1982-2009 : 1522 -4.3%	1981	0.86
05	35 152	1940-1947 : 1796 1948-1975 : 1691 -5.8% 1976-2009 : 1620 -4.2%	1947	0.50
06	495 213	1940-1969 : 1567 1970-1996: 1461 -6.8% 1997-2009 : 1526 +4.3%	1970	0.55
07	28 603	1940-1964 : 1761 1965-1980 : 1592 -9.6% 1981-2009 : 1687 +5.6%	1966	0.34
08	178 572	1940-1969 : 1475 1970-1990: 1312 -11.0% 1991-2009: 1411 +7.0%	1969	0.77
09	70 086	1940-1947 : 1673 1948-2009 : 1539 -8.0%	1947	0.12
10	888 463	1940-1977 : 1502 1978-1996 : 1422 -5.3% 1997-2009: 1501 +5.3%	1977	0.26
11	51 955	1940-1978 : 1389 1979-1995: 1296 -6.7% 1996-2009 : 1393 +7.0%	1949	0.06

363 **Table 1** continued

ID [Sub-basin]	Sub-basin area [Km ²]	Segmentation : precipitation (mm) and variation (%) [Hubert]		Year and posteriori probability of rupture in the precipitation (mm) [Lee et Heghinian]	
12	338 742	1940-1969 : 1661		1969	0.88
		1970-1996 : 1562	-6.0%		
		1997-2009 : 1620	+3.6%		
13	57 848	1940-1969 : 1754		1969	0.59
		1970-1996: 1649	-6.0%		
		1997-2009 : 1720	+4.1%		
14	21 494	1940-1969 : 1695		1969	0.46
		1970-1979: 1590	-6.2%		
		1980-1984 : 1385	-12.9%		
		1985-2009: 1598	+13.3%		
15	274 463	1940-1943 : 1509		1964	0.66
		1944-1964 : 1680	+10.2%		
		1965-2009 : 1589	-5.5%		
16	64 018	1940-1943 : 1460		1963	0.89
		1944-1963 : 1693	+13.8%		
		1964-2009 : 1557	-8.0%		
17	54 069	1940-1943 : 1582		1970	0.19
		1944-1958: 1758	+10.0%		
		1959-1964 : 1925	+8.7%		
		1965-2009 : 1709	-11.2%		
18	18 667	1940-2009 : 1682		1958	0.07

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365 Figure 5 shows the superposition of probabilities in 1969 with the selected sub-
366 basins. It shows strong variability probabilities of rupture in Kasaï and Bangi sub-
367 basins in 1969. The highest probabilities were located in two areas highlighted by the
368 rectangles (Figure 5). For example, in sub-basin 08, the high probabilities vary
369 between 0.40 and 0.94.

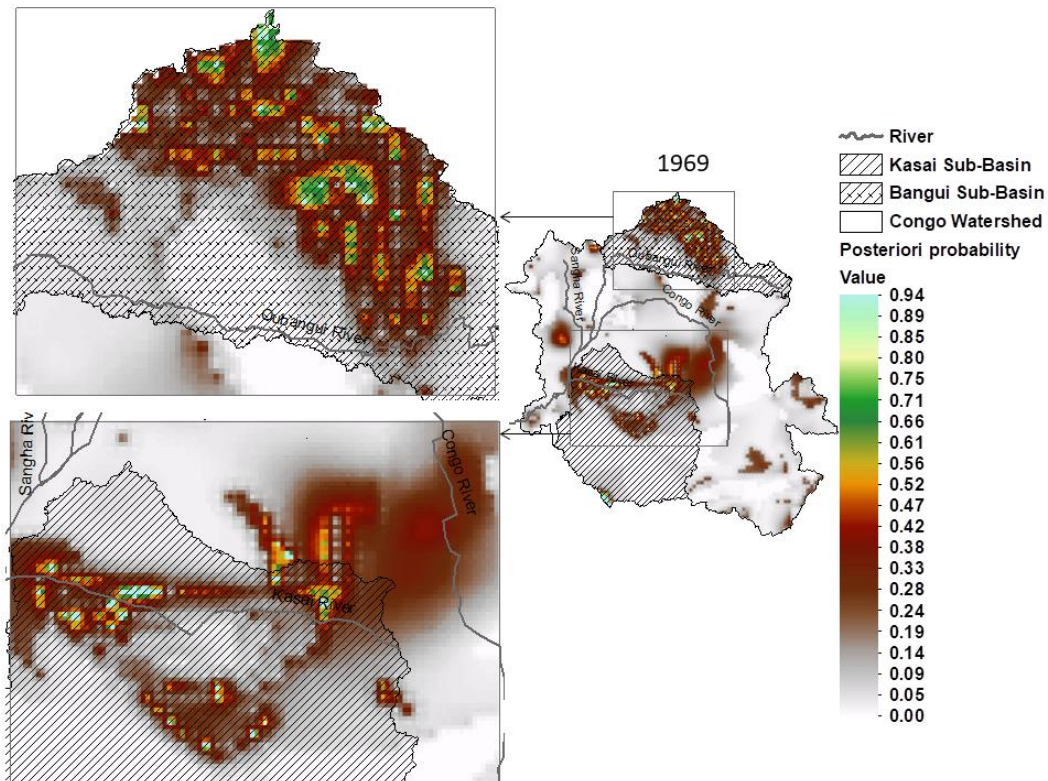


Figure 5: Superposition of posteriori probability of rupture in 1969 with of Kasai and Bangi sub-basins at the scale of the Congo catchment showing regions with high and low probabilities of ruptures.

6 Discussion

The approach of Lee et Heghinian has been widely used in numerous studies mainly as time-based approach that aims at detecting change in mean values and probability of change. However, its space-time representation also confirmed the exceptional climatic rupture of 1969 or 1970 over the Congo Basin reported by several authors such as Laraque et al (2001) and Nguimalet et Orange (2013, 2019). Indeed, Figure 4 shows the high and low probability zones of rupture in the year 1969 or 1970. The areas with high probability of rupture are located particularly in the sub-basins Bangi and Kasai (Figure 5). Both basins have experienced on their rivers the problem of the decrease of the number of navigable days towards the decades 1970 and 1980 (Kisangala, 2009; Pandi et al., 2009). This problem thus testifies to the extent of the phenomenon of climatic rupture in this year. Seen in this light, the

space-time representation approach of Lee et Heghinian provides additional and precise information on the vulnerability of climate in a region. Therefore, it allows completing the information of the climatic rupture on the right and left banks of the Congo river.

On the right bank of the Congo River, the first rupture occurred in the Bangi sub-basin (ID = 06) in 1960 (Laraque et al., 2001). However, this rupture was not detected by Nguimalet et Orange (2019). On the other hand, they detect a single rupture in 1970. The source of used data and the length of the time series can be at the origin of this difference. Despite the data source, the length and the period of observation different from those used by Nguimalet et Orange (2019), we were able to detect the rupture of the year 1970, with a probability of rupture of 0.55 (Table 1). However, Nguimalet et Orange (2019) estimate a rainfall deficit of 5% contrary to the present study, which overestimates it by 2% more (Table 1).

The result of the application of Hubert's approach to sub-basin 18 (Figure 2) or the Léfini sub-basin gives no rupture detection (Table 1). This result is in agreement with Laraque et al (2001). Nevertheless, the Batéké plateau (the Léfini sub-basin is included in the Batéké plateau) represented here by the sub-basin 01 (Figure 2) shows a rupture in 1958 (Table 1). The latter was also detected in the Nkeni sub-basin (included in the Batéké Plateau) by Laraque et al (2001). Although these authors (Laraque et al., 2001) demonstrated an appearance of climatic rupture in 1969 in the Batéké plateau, Figure 5 clearly shows a very low probability of rupture in this year in the plateau. Although the presence of the strong sandy-sandstone aquifer in the Batéké plateau plays a role in mitigating the flood peak and helping to minimize drought (Laraque et al., 2001; Olivry, 1967), this area (Sub-Basin 01) has not yet experienced a significant rainfall deficit (Table 1 and Figure 5).

411 Hubert's approach applied in sub-basin 17 does not detect during 1965 - 2009 rupture
 412 (Table 1). But the application of the approach of Lee et Heghinian (Table 1) and the
 413 results found by Laraque et al (2001) (in the Kouyou and Alima sub-basins included
 414 in region 17) show a rupture in 1970. However, its probability of rupture is very low
 415 (Table 1 and Figure 4c). The low probability of rupture simply means no rupture.
 416 Therefore, the two approaches used in this study fail to detect the rupture in sub-
 417 basin 17 unlike Laraque et al (2001). This discrepancy can come from: the estimation
 418 of the delineated area of the sub-basins, the length of the time series as well as the
 419 data sources used. According to Figure 4, the rupture did not occur over the sub-
 420 basin 16 (figure 2) during 1968-1971. This result is consistent with that obtained
 421 using the Hubert's approach (Table 1).

422 A significant divergence of results is observed with those found by Laraque et al
 423 (2001) in the Sangha sub-basin. Indeed, the Sangha time series used by Laraque et
 424 al (2001) shows an appearance of a single climatic rupture in 1973 while in the same
 425 sub-basin represented here by the identifier 15 (Figure 2), we count three
 426 segmentations whose rupture occur in 1943 and 1964 (Table 1). However, the 1943
 427 rupture must be taken with caution as it uses only the first four values in the series for
 428 its estimation. The cause of this discrepancy can be attributed to the delimitation of
 429 the area of the Sangha sub-basin. In fact, Laraque et al (2001) estimate an area of
 430 158000 km² in Ouessou in contrast in the present study, it is estimated at 274463 km²
 431 (Figure 2). Therefore, the area of the Sangha sub-basin is 1.7 times larger than that
 432 estimated by Laraque et al (2001).

433 On the left bank of the Congo River, high probabilities of rupture during the period
 434 1968-1971 are located on the one hand in the Kasai sub-basin (sub-basin 10) and on
 435 the other hand in the drainage sub-basin of the Congolese cuvette (sub-basin 03)

(figures 2 and 4). It should be noted that the left bank of the river is an under researched area. Only the Kasai watershed benefited from several studies (Devroey, 1939; Kisangala, 2009) that however, did not apply the techniques for detecting ruptures. The most recent study (Thsitenge et al., 2016) in the sub-basin combines the statistical techniques of detection of ruptures and those of wavelet to characterize the temporal variation of the hydrological regime of the Kasai river. However, the basin falls under the category of catchment or area with very sparse spatial coverage in meteorological stations or observational data. The Kasai basin, large with 901,000 km², accounts only four operational climatological stations and two gauging stations (Kisangala, 2009).

During the 1968-1971 period, the two climate rupture approaches used in this study failed to detect rupture in precipitation time series of sub-basins 02, 03 (Table 1). Indeed, a large part of the area of these two sub-basins contains probabilities of ruptures close to zero between 1968 and 1971 (Figure 4). Therefore, by estimating the average rainfall in these sub-basins, both approaches fail to detect the rupture during this period.

7 Conclusion

The approaches of detection of rupture hydro-climatic have been applied by several authors in different regions of the world. In this study, an attempted spatio-temporal approach was exploited. This approach does not estimate a regional average, but it does use all the observations from different hydrological or meteorological stations located in a region. It can be considered as a generalization of local approach. The new approach has distinctly allowed highlighting the clear delimitation of regions with a low or high probability of rupture, unlike previous studies based on regional approach where the delimitation of the regions of rupture is predefined in advance.

To validate the new approach, a comparison of the results found in the present study with previous studies was necessary. Thus, a subdivision of the Congo Basin into different sub-basins contributed to this comparative analysis.

Whatever the source of different data, the results of this study converge fairly well to validate the results found by authors. This convergence illustrates well the validation of the climatic vulnerability map or the space-time representation of Lee et Heghinian at the scale of the right bank of the Congo River. Nevertheless, despite the powerful aquifer located in the Bakété plateau to minimize drought in this region, the latter has not yet experienced a significant rainfall deficit. A fairly good convergence of the results of the applications of two approaches of the ruptures on the sub-basins located along the Kasai river illustrates well the validation of the maps of the climatic vulnerability on the left bank of the Congo river. Thus, the space-time representation of Lee et Heghinian clearly demonstrates that the effects of drought are visibly more pronounced in the north than in the south on the right bank of the Congo river. On the scale of the left bank, it shows that the Kasai sub-basin experienced a remarkable drought around the 70s.

For the unexplored regions of the Congo basin such as sub-basins 02 and 03, this study provides useful results regarding the climatic rupture: these regions were not affected by climatic rupture in the period from 1968 to 1971 except the south-east and the extreme east-south.

This study used the approach of Hubert and Lee et Heghinian for the validation of the vulnerability maps or the space-time representation of Lee et Heghinian at the scale of the Congo watershed. However, several other techniques can also be used for this validation. In addition, the use of different sources of climate data can be an excellent tool for validating these maps. An exact delineation of the sub-basins used by others

studies of rupture climatic can lead to an excellent comparative study and validation of these vulnerability maps. It should be noted that despite the use of two different data sources, the comparison of our results with those in the literature shows a fairly good convergence with a few differences often due to the estimate of the sub-basin. However, the vulnerability maps or the space-time representation of Lee et Heghinian necessitates the selection of the temporal window. Although the analysis of surface percentages of detection of rupture years has made it possible to select the windows of 1969, 1970 and 1943, any new techniques that may help in the selection of time windows will be relevant.

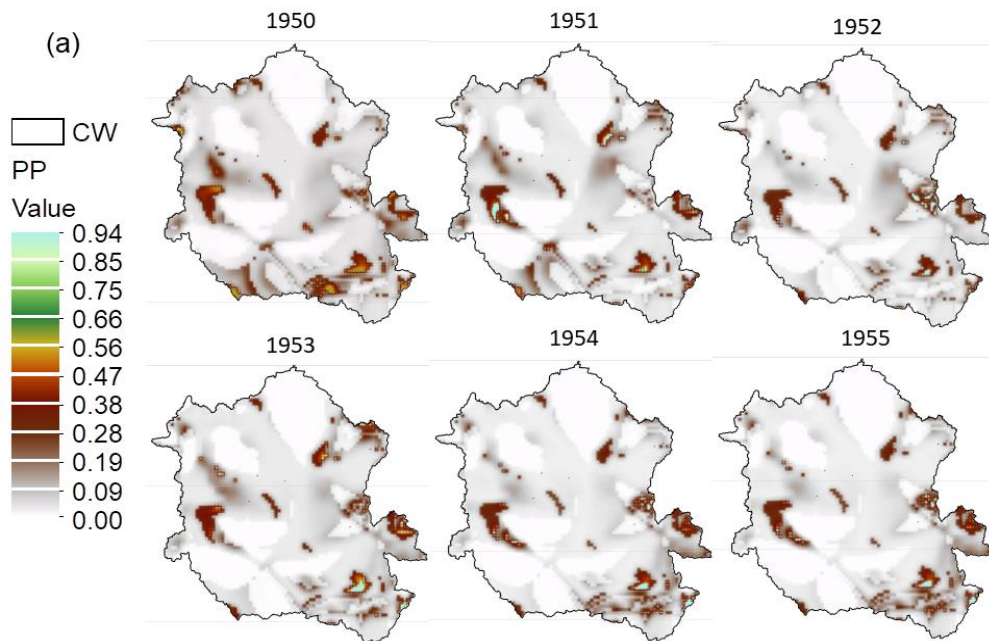
In the present study, the time variable (date of the climatic rupture) was invariant in space. However, we can also consider it to be spatially variable while taking turns fixing the other three variables. For example, a specialized representation of the distribution of years of climatic rupture as a function of the probability of rupture can be obtained. In general, we can consider a function $\psi = \varphi(x_1, x_2, x_3, x_4)$ with x_1 = dates of rupture, x_2 = probabilities of rupture, x_3 = amplitudes of rupture and x_4 = probabilities of rupture amplitudes. It can be defined in the field of study of a given region such that these variables obey the assumptions and relationships of the Lee et Heghinian approach.

Acknowledgments

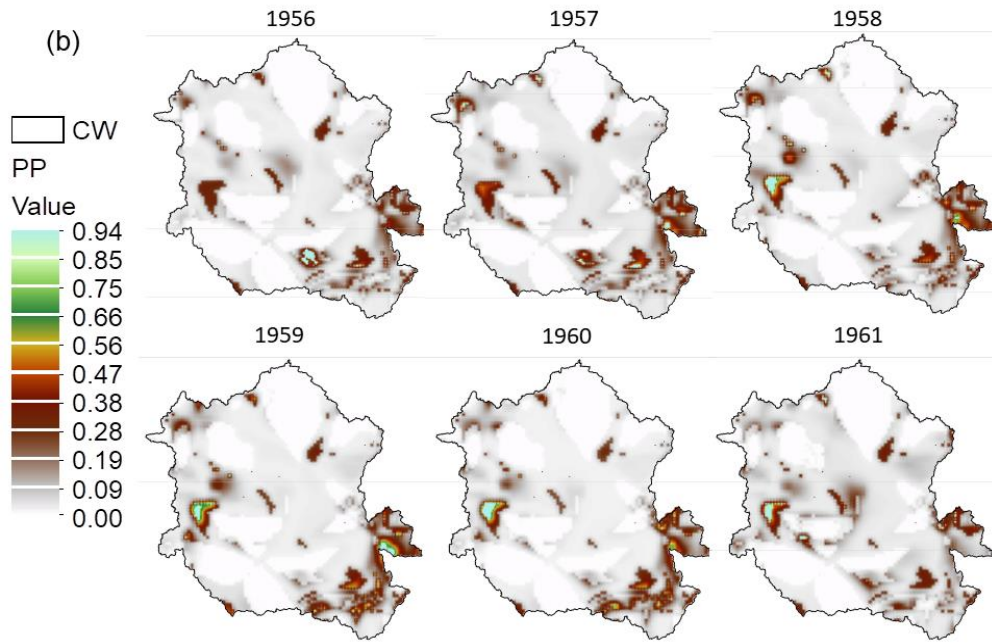
The precipitation data used in this study are available on the CEDA Archive website and can be downloaded via the link http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_3.10/data. The four variables of the Lee et Heghinian approach were estimated using a Matlab script. However, Hubert segmentations is a FORTRAN script available and downloadable via <https://hydrologie.org/MOD/seg/segment.htm>. The different maps presented in this

511 study use the ArcGIS script. However, extracting grid data CRU TS 3.10 in time
 512 series data uses a Python script. This work received no financial support.

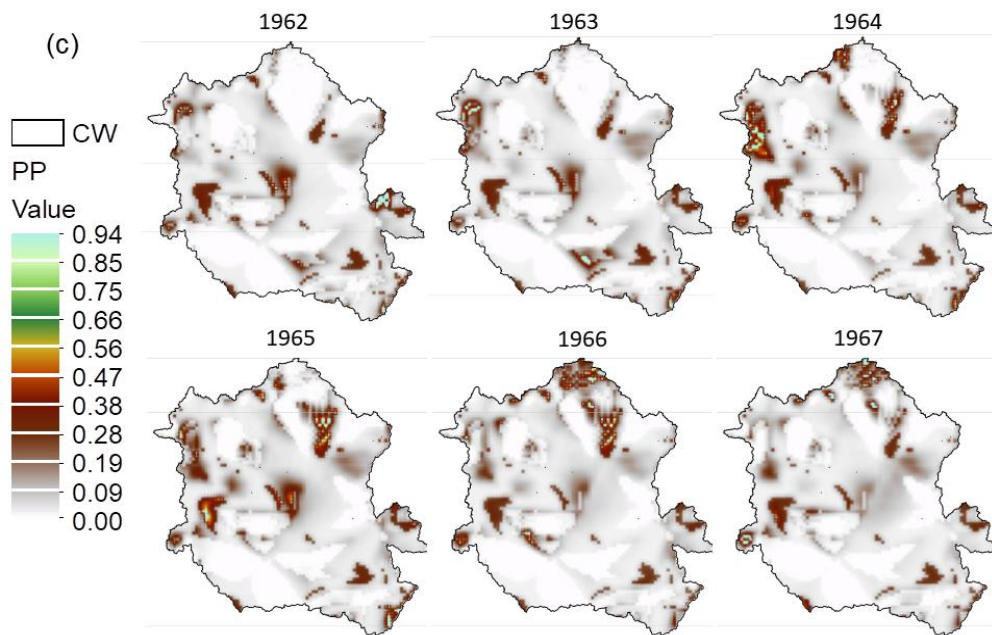
513 **Appendix** spatio-temporal variation of variables of the Lee et Heghinian approach
 514 and the temporal variation of Hubert's approach at the scale of the Congo watershed
 515 and these sub-basins.



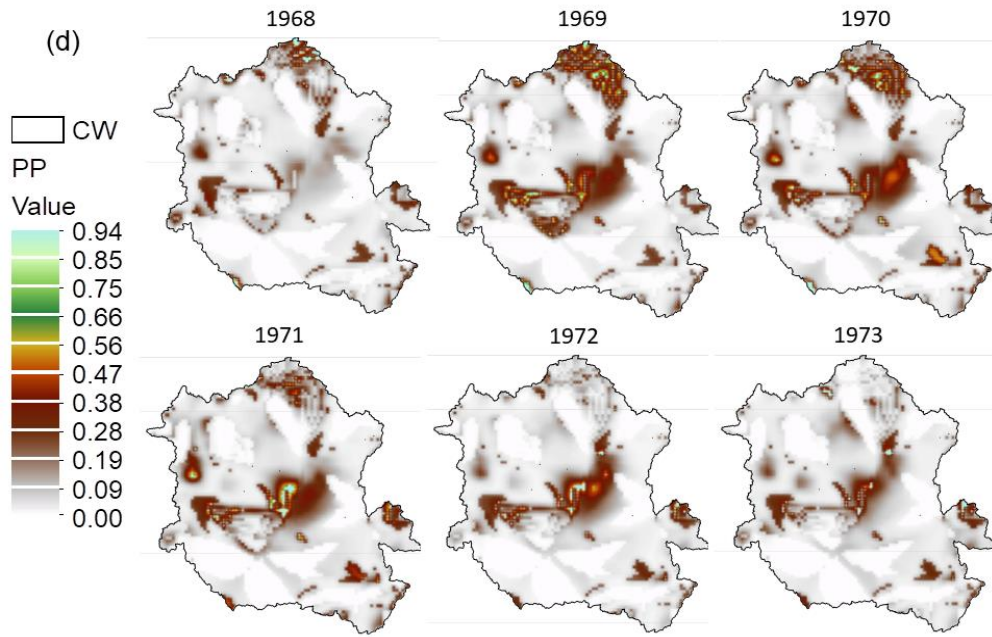
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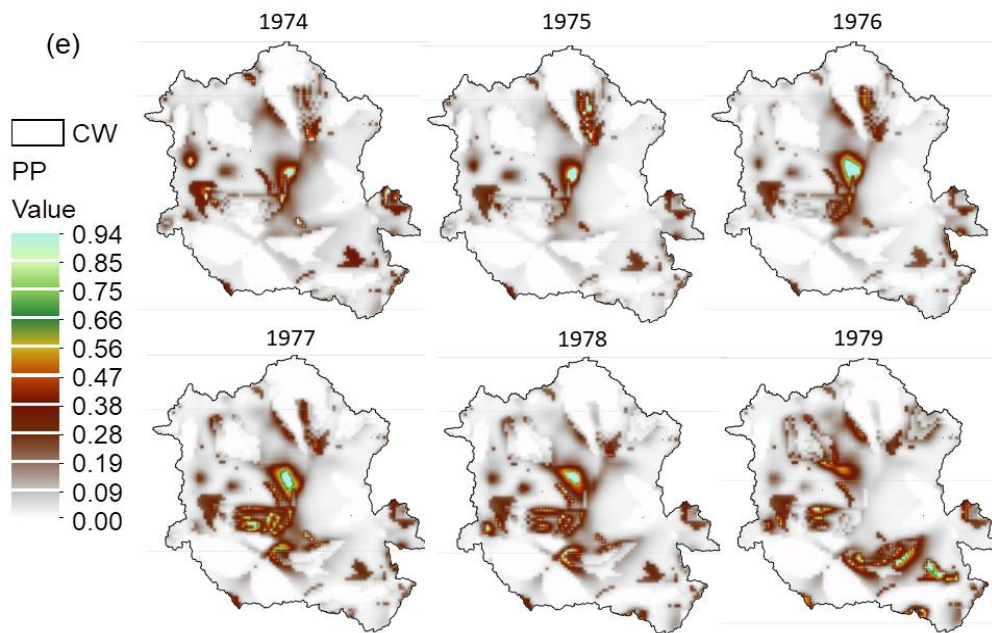
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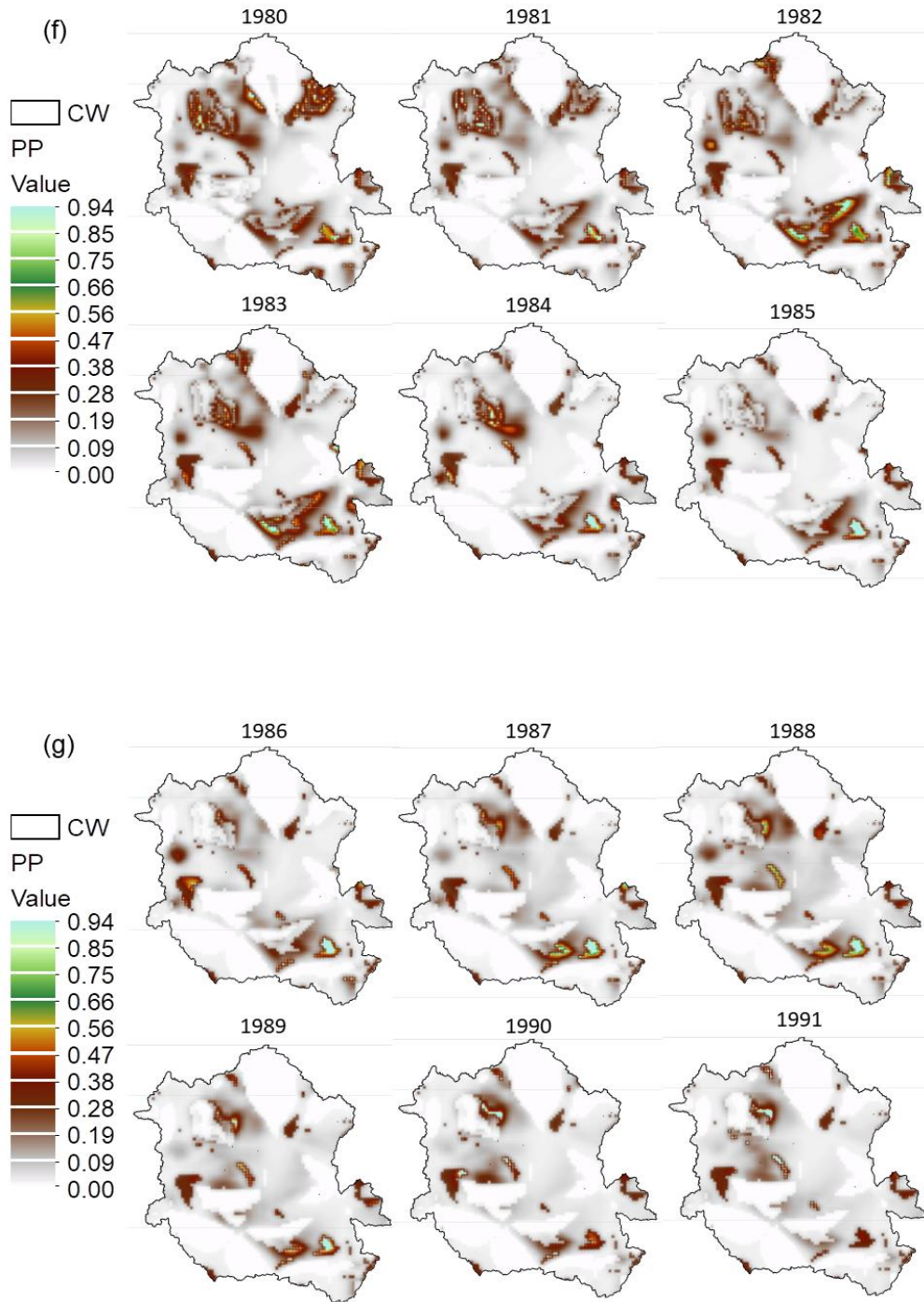
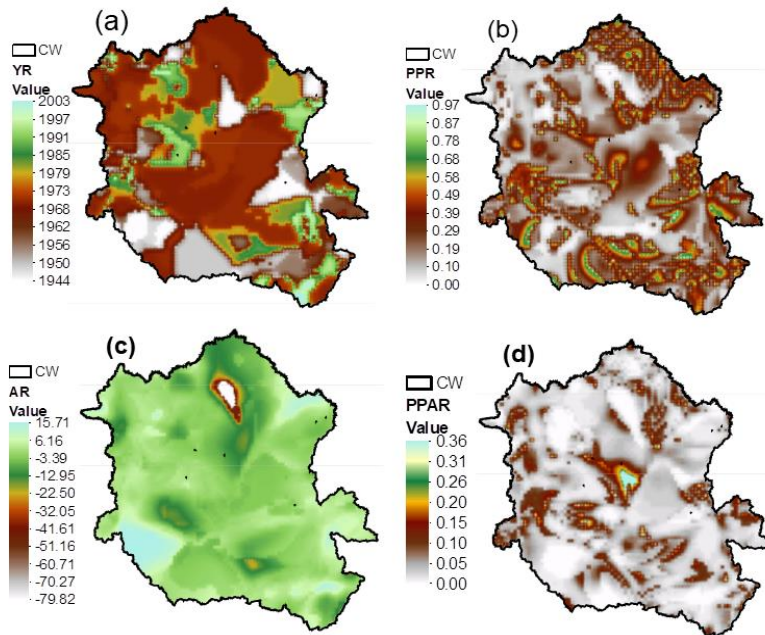


Figure A1: Spatio-temporal evolution of posteriori probability of rupture in the Congo watershed. During (a) : 1950-1955, (b) 1956-1966, (c) 1962-1967, (d) : 1968-1973, (e) 1974-1979, (f) : 1980-1985, (g) 1986-1991. The climatic rupture in the Bangui sub-basin begins around 1966 and ends in 1971. However, the rupture in the Kasai sub-basin begins in 1969 and ends in 1973. It is located in the center of the basin

528 from 1974 until 1978. The period of 1979-1984 is marked by a climatic rupture that is
 529 located towards the northeast and southwest of the basin.



530

531 **Figure A2:** (a) Years of rupture (YR), (b) Posteriori probabilities of ruptures (PPR),
 532 (c) amplitudes of ruptures (AR), (d) Posteriori probabilities of amplitudes of rupture
 533 (PPAR) at the scale of the Congo catchment. CW : Congo watershed. (a) shows that
 534 the basin is dominated by the years of ruptures between 1962-1973, (b) the eastern
 535 part of the basin has a low probability unlike the north, south-east and south-west of
 536 the basin, (c) the basin is dominated by the amplitudes between 6.16 (mm) to -12.95
 537 (mm), (d) the probability of the amplitudes are generally low for the whole basin.

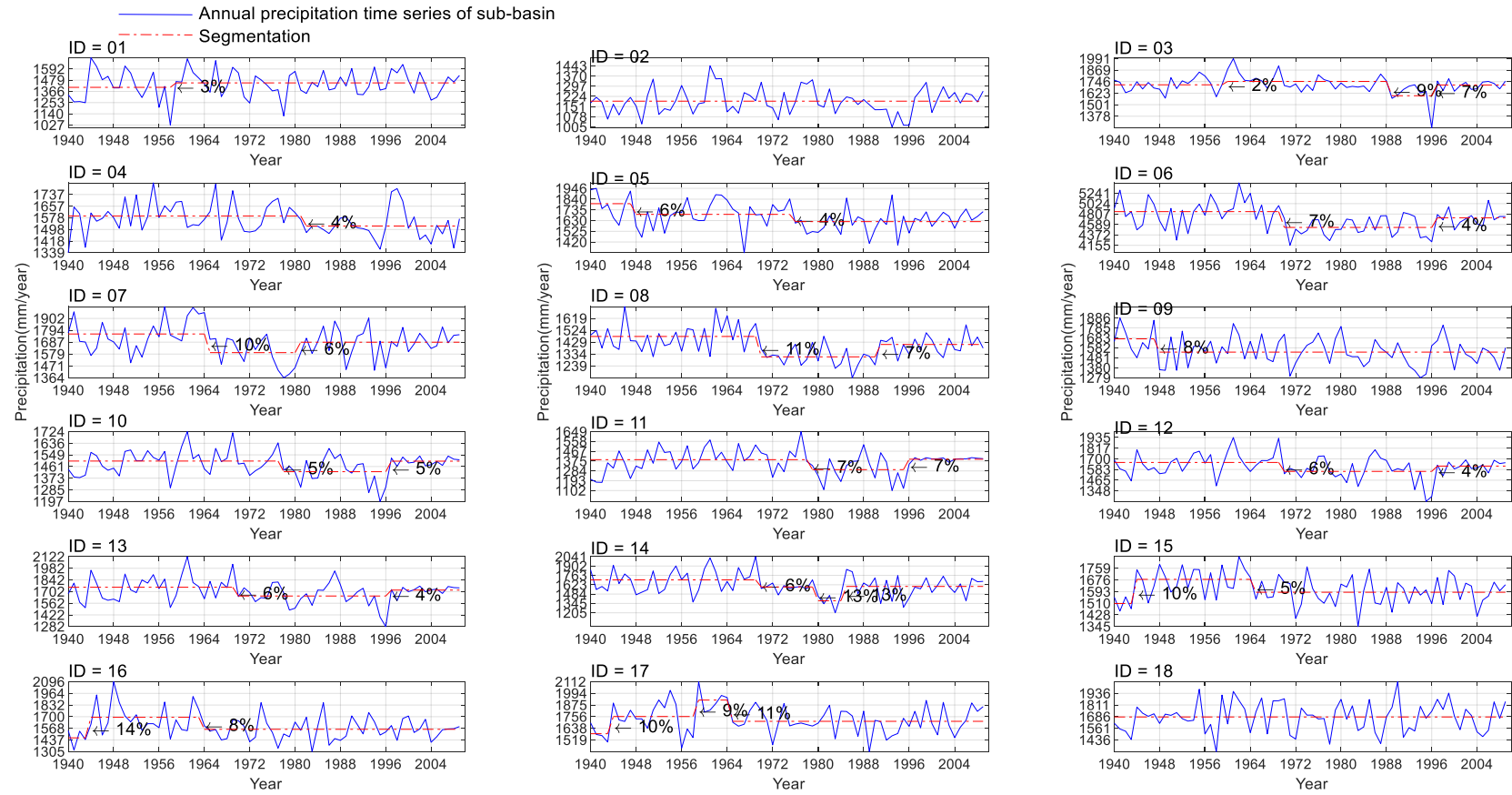
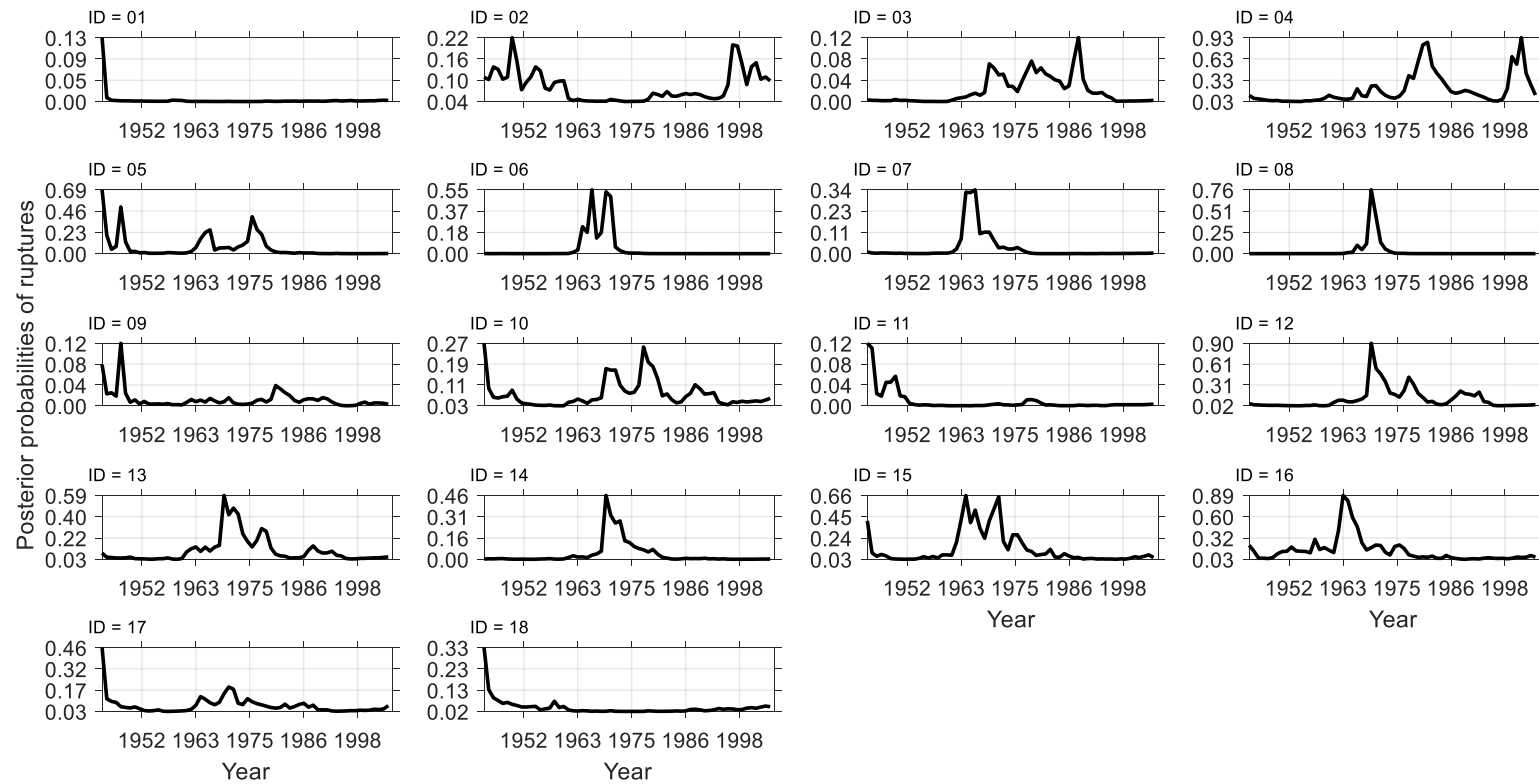


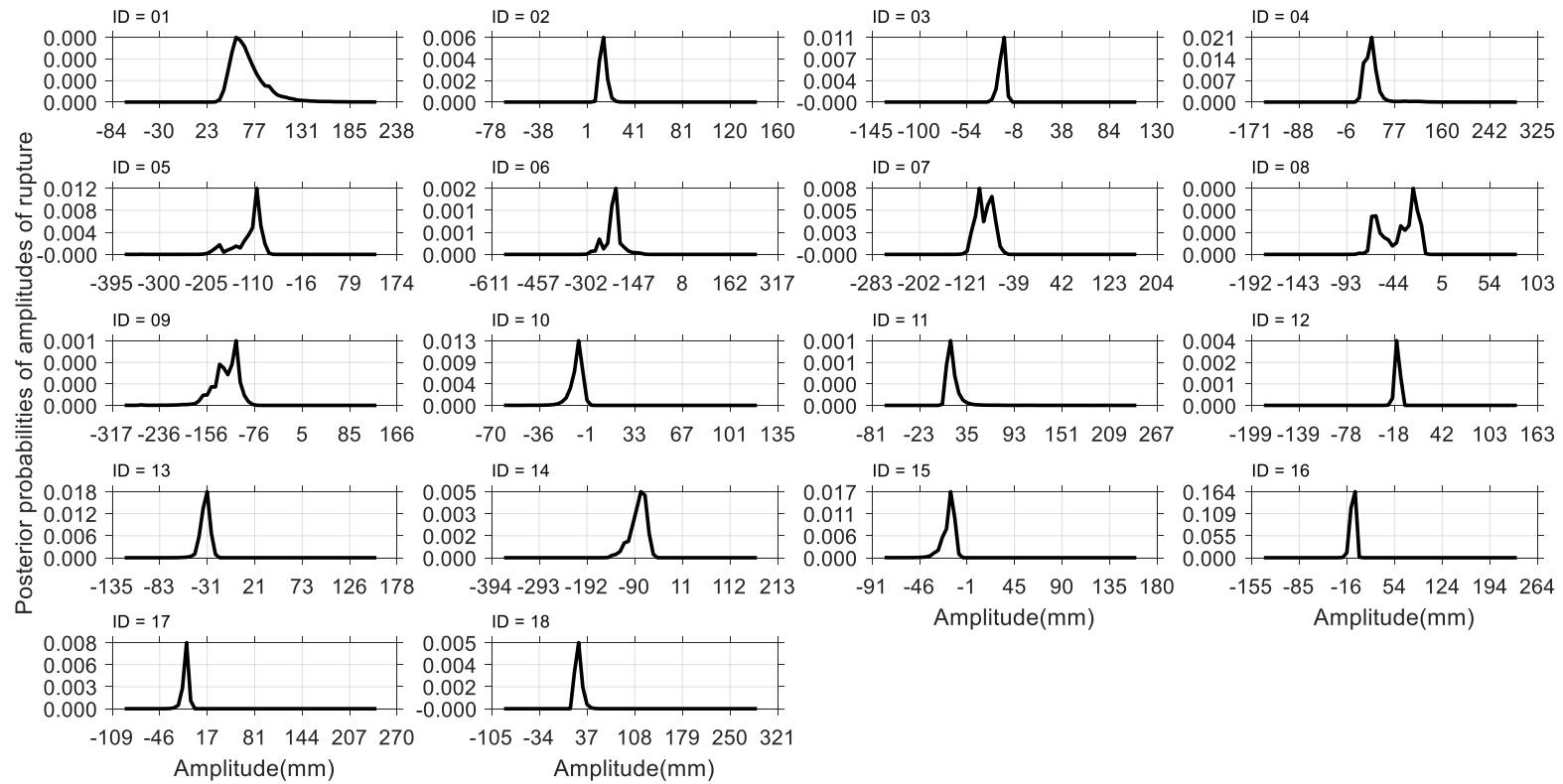
Figure A3: Annual variation in precipitation and Hubert's segmentation of 18 selected sub-basins at the scale of the Congo watershed.



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Figure A4: Posterior probabilities of ruptures in 18 selected sub-basins at the scale of the Congo watershed.



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Figure A5: Posteriori probabilities of amplitudes of rupture of 18 selected sub-basins at the scale of the Congo watershed

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