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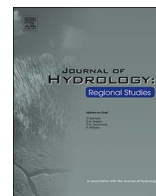
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Bayesian trend analysis in annual rainfall total, duration and maximum in the Kara River basin (West Africa)



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ABSTRACT

Study region: The Kara River basin, northern Togo and Benin, West Africa.

Study focus: This study investigated long-term trends in annual rainfall (annRAIN), annual rainfall duration (DURATION) and annual maximum rainfall (MAXAN) for seven stations between 1950 and 2010. A Bayesian trend analysis was performed by fitting the Lognormal, Normal and Generalized Extreme Value (GEV) distributions to annRAIN, DURATION and MAXAN, respectively, with a time covariate for both the location and scale parameters. Spatio-temporal variation of the mean decadal rainfall and the seasonality of the mean monthly rainfall were also analyzed.

New hydrological insights for the region: The results indicate that the interannual variability of annRAIN is decreasing over time at all stations, and the average annRAIN is also markedly decreasing at several stations. However, DURATION is increasing at most stations suggesting that in those parts of the basin where annRAIN is decreasing, rainfall occurs more frequently but with less intensity. For MAXAN, evidence for decreasing trend is found in two stations, and for increasing trend in one station. It is also shown that the peak of the rainy season shifted from September to August since the 1980s. Furthermore, changes in the spatio-temporal distribution of the mean decadal rainfall are also observed. This study provides valuable new insights into trends affecting rainfall variables in the Kara River basin.

1. Introduction

1.1. The importance of rainfall trends

Historical trends in climatic variables are of interest in a variety of academic disciplines, such as ecology, agriculture and water

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resources management, but also from an economic perspective (MacKellar et al., 2014). In fact climate change is expected to have significant impacts on rainfall variables such as rainfall extremes, annual rainfall, rainy events and rainy days etc. (Trenberth et al., 2007). For instance climate-induced modifications of the frequency and intensity of extreme rainfall as well as periods with low rainfall totals can potentially enhance floods and droughts (Boukhris, 2008) and result in significant impacts on human livelihood and socio-economic development. Furthermore, these changes also affect water availability, the vegetative period, crop productivity and rainfall-runoff dynamics. Within this context, Miranda et al. (2011) showed that changes in rainfall quantity, frequency and seasonality affect the productivity and physiology of plant communities in the semi-arid southeast region of the Iberian Peninsula. The authors could also assess the resilience of the community to high variability in rainfall regime. Pielke and Downton (2000) found that the trend in flood damage in United States between 1932 and 1997 was related not only to societal factors (increasing population and wealth) but also to trends in climate variables as shown for increasing precipitation. Further studies indicated that the observed increase in precipitation has masked a tendency for increasing drought related to increasing temperature (Easterling et al., 2007).

1.2. Rainfall trends in West Africa

Several studies attempted to understand rainfall variability and trends in West Africa (Collins, 2011; Fink et al., 2010; Le Barbé et al., 2002; Le Lay and Galle, 2005; Riede et al., 2016; Sylla et al., 2015, 2013). While there is a strong evidence of increasing temperature, there are still higher uncertainties in precipitation trends which exhibit higher spatial and seasonal variabilities (Collins, 2011; Riede et al., 2016). Nevertheless, it is very likely that precipitation has decreased between 1950 and 2010 with a recovery over the last 20 years (Riede et al., 2016). Le Barbé et al. (2002) analyzed rainfall variability in West Africa during 1950–90, and showed that a severe drought occurred during the period 1970–90 due to decreasing frequency of rainy events in July–August, leading to decreasing totals. Le Lay and Galle (2005) investigated the oceanic and continental West African monsoon regimes which control rainfall variability in the region, and showed that the majority of rainfall changes occur in the continental regime. The rainfall peak associated with this regime has occurred increasingly earlier in the season (July–August) between 1950 and 2002. Also the annual rainfall deficit is mainly linked to the decrease in the number of large events during the continental part of the season (Le Lay and Galle, 2005). Mouhamed et al. (2013) analyzed climate extremes in the West African Sahel between 1960 and 2010 and concluded that trends in rainfall indices are not uniform in time. There is a general decreasing tendency in annual total rainfall and maximum number of consecutive wet days while an increasing trend is observed in the cumulated rainfall of extremely wet days. The authors also found that while the maximum number of consecutive wet days is decreasing in general, there has been an upward recovery from the late 1980s to 2010 after an important decrease from 1960 to mid 1980s.

1.3. Probabilistic assessment of trends

The use of statistical and probabilistic methods has been widely recognized to play an important role in characterizing hydrologic and meteorological phenomena (Gamage et al., 2013; Markovic, 1965; Yue and Hashino, 2007). In particular, the estimation of probability distributions, and hence of quantiles, is a key component of such characterization, with many engineering applications (design and planning of hydraulic and water resources systems, hazard mapping, etc.) (Ouarda and El-Adlouni, 2011).

Many studies used an assumption of independence and identical distribution of the target variable. However, the latter assumption is questionable in the contexts of climate change or low-frequency climate variability which imply long-term fluctuations of the distribution of the target variable, and hence of its parameters. According to Milly et al. (2008), “stationarity is dead” and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Some authors argued the contrary (e.g. Montanari and Koutsoyiannis, 2014) and suggested that the word “stationarity” is sometimes misused. In any case, there is a need to derive probabilistic models that go beyond the independence and identical distribution assumptions and to use those models to manage water systems (Milly et al., 2008).

Non-stationary (or at least non-identically-distributed) analysis of hydro-meteorological phenomena has gained particular interest during recent decades. The most common approach is to introduce covariate(s) through the parameters of a target distribution and to assess whether the parameters are changing with the covariate(s). For instance, covariate-based extreme value analysis has been widely used (Cheng et al., 2014; Katz et al., 2002; Ouarda and El-Adlouni, 2011; Renard et al., 2006; Renard et al., 2013; Strupczewski and Kaczmarek, 2001; Strupczewski et al., 2001a,b; Sugahara et al., 2009).

Fitting probability distributions with covariates in the parameters requires good estimation methods that are in general computationally intensive and complex. Bayesian inference in combination with Markov Chain Monte Carlo methods offer a consistent framework to estimate complex statistical models and, importantly, to quantify estimation and predictive uncertainties (Renard et al., 2013).

1.4. Objectives and outline

The primary objective of this paper is to estimate time-varying distributions for the annual rainfall, the annual rainfall duration and the annual maximum daily rainfall within the Kara River basin. Located in West Africa, the Kara River basin is a semi-arid hydrology catchment of the Volta basin covering Togo and Benin which is poorly investigated in terms of climate research. The majority of studies on climate trends were carried out at larger scales such as the great Volta basin, at country level or in West Africa in general (Le Barbé and Lebel, 1997; Le Barbé et al., 2002; Le Lay and Galle, 2005; Mouhamed et al., 2013; Panthou, 2013). In addition, the methods applied for the statistical trend analyses varied among the studies. Although some of these studies provide

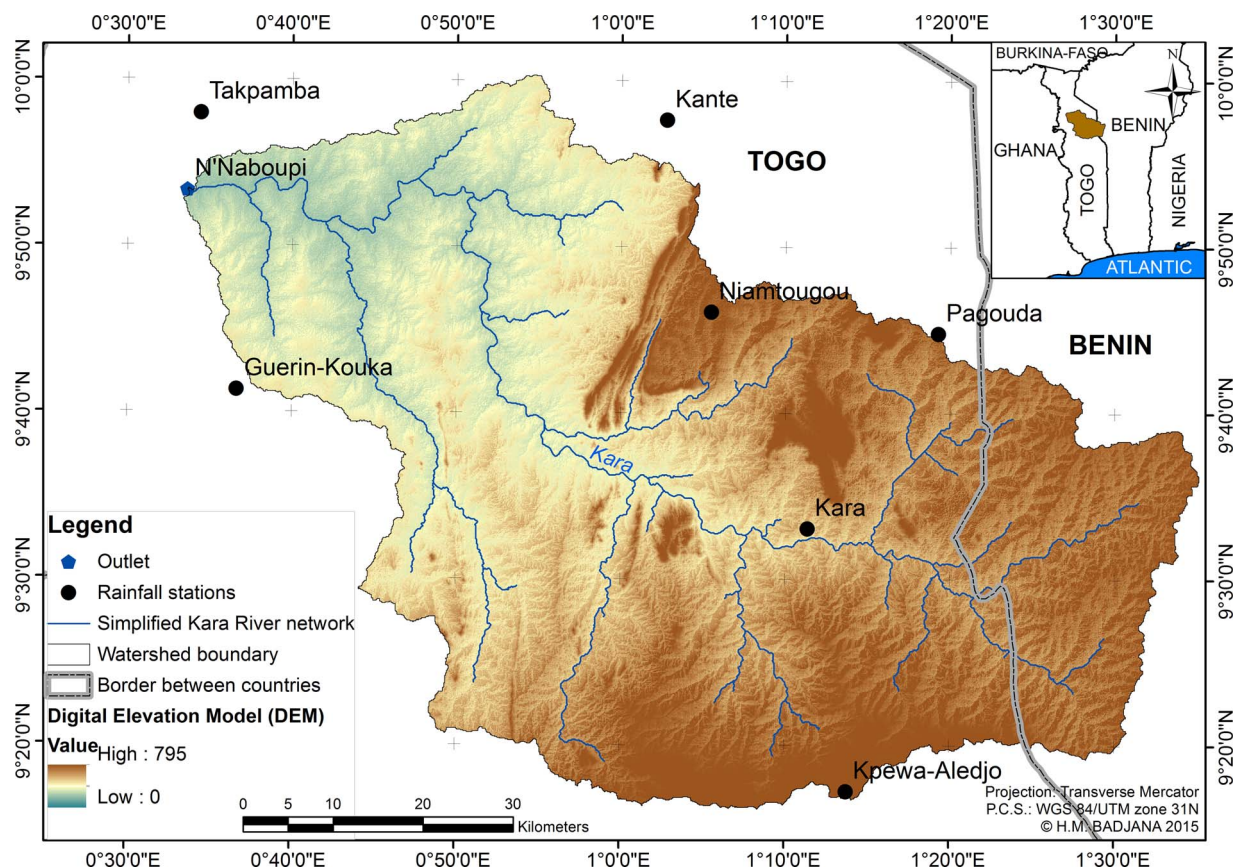


Fig. 1. Map of the Kara River basin at N'Naboupi with the rainfall stations used for the study (DEM Data Source: Jarvis et al., 2008).

insights into the spatio-temporal climate variability of West African regions, the information on the relationship between precipitation extremes, annual precipitation and rainfall duration at regional level remains incomplete.

The paper is organized as follows: Section 2 describes the materials and methods used including the description of the study area, the datasets and the models. Bayesian inference of these models is also explained. Section 3 presents the results for the three variables at all sites, in terms of parameter estimates, trends and time-varying quantiles. In addition, results related to the decadal variability of rainfall are also presented in order to better understand the estimated trends. In Section 4, we discuss the meanings of the results at various spatial and temporal scales and their link to previous regional studies before summarizing our findings in the conclusion and outlook Section 5.

2. Materials and methods

2.1. Study area

The study is carried out in the Kara River basin (5287 km²), a sub-catchment of the Oti River basin (75,859 km²) which itself is a sub-catchment of Volta basin (398,390 km²) situated in West Africa. The Kara basin is located between Longitudes 0° 30' and 1° 38'E and Latitudes 9°15' and 10° 01'N (Fig. 1) and covers Togo and Benin. The climate is tropical with two seasons: one rainy season from June to October with high rainfall variations and one dry season on the remaining period of the year. Rainfall generation is governed by the West African monsoon dynamics. The mean annual rainfall in the basin varies between 1100 mm and 1400 mm. It is drained by the Kara River and its tributaries, which belong to the interior savannah ecological zone. The geology comprises Neoproterozoic to Paleozoic formations, Buem, Atakora and gneiss-migmatite units, and the basic and ultrabasic massifs (Tairou et al., 2012). Topography and soils are much diversified, due to the great diversity of geological, petrographic, tectonic and geomorphologic factors (Faure, 1985). The terrain includes hills with the maximum altitude reaching 782 m at Lama-Koumea, depressions, flat plains, plains and plateaus. The soils are mainly ferralsols, leptosols, fluvisols and lixisols (UNEP-GEF Volta Project, 2013).

According to the results of the last population censuses in Togo and Benin, the population within the Kara basin is about 460,000 inhabitants (Direction Générale de la Statistique et de la Comptabilité Nationale (DGSCN) - Gouvernement du Togo, 2010; Institut National de la Statistique et de l'Analyse Economique (INSAE) - République du Bénin, 2015). The main socio-economic activities in the basin are agriculture and livestock husbandry: the majority of the population is relying on subsistence agriculture and is thus

strongly dependent on natural resources.

2.2. Datasets

The data used in this study are observed daily rainfall from seven stations collected by the National Meteorological service of Togo “Direction Générale de la Météorologie Nationale (DGMN)”. The seven stations selected based on the availability of data over a relatively long period are Guerin-Kouka, Kante, Kara, Kpewa-Aledjo, Niamtougou, Pagouda and Takpamba. A time period common to all stations was chosen between 1951 and 2010 with a 46 years minimum record to achieve maximum temporal coverage. Moreover, some rainfall data from other stations in and around the basin, available for 10–20 years and at a monthly scale, were also collected.

After their collection, all data were quality-controlled in terms of consistency and outliers. To this end, visual plot assessment and boxplots were used to detect outliers in data. The detected outliers have been historically checked from archives and local populations. After the quality control, the target analysis time series, namely annual maximum rainfall (MAXAN), cumulative annual rainfall (annRAIN) and annual rainfall duration (DURATION) for the seven stations were derived.

MAXAN time series were extracted using the Block maxima method (Coles, 2001). For each station, if a month in the rainy season (June–October) contains more than 10 missing values, the year is excluded from the MAXAN time series.

For the annRAIN time series, years with missing values were cancelled from the analysis since the gaps are in most cases present for the whole year. For few specific years in which there are less than ten missing values in one rainy month, the latter is considered as missing and rainfall amount for that month is generated by Kriging before computing the annual sum. This avoids cancelling a whole year from the analysis because of a few missing values.

DURATION time series correspond to the annual number of rainy days and contain almost no internal missing values. In fact these time series are not affected by missing values because even if the precipitation amount is not measured on a specific day, the information that it rained or not is still collected.

In addition to MAXAN, annRAIN and DURATION, mean decadal rainfall and mean monthly rainfall are computed and analyzed in order to better understand the variability of rainfall variables.

2.3. Methods of analysis

The methodological approach used for trend analysis in this study is a typical Bayesian analysis that consists in combining available prior knowledge with the information contained in the data (through the likelihood function) into the posterior distribution. Markov Chain Monte Carlo (MCMC) sampling is then used to summarize the important features of the posterior distribution (Glickman and van Dyk, 2007).

2.3.1. Models

Based on previous studies in the region (Edwards et al., 1983; Ghosh and Desai, 2006; L'Hôte et al., 1975; Panthou, 2013), expert knowledge and preliminary analyses, three probability distributions were chosen: the Generalized Extreme Value (GEV) distribution for MAXAN, the Log-normal distribution for annRAIN and the Normal distribution for DURATION. For each distribution, a time covariate is introduced into the location and scale parameters in order to investigate the trend over time (Renard et al., 2013).

2.3.1.1. The generalized extreme value or GEV distribution for MAXAN. The choice of the GEV distribution is based on extreme value theory (Coles, 2001) which indicates that the GEV distribution is appropriate for the block maxima when blocks are sufficiently large (Klein Tank et al., 2009). Also, it has been shown to fit well annual maximum rainfall in the region (Panthou, 2013).

Under a no-trend assumption, the model M_0 can be formalized as follow:

$$M_0: X_t \sim GEV(\mu, \sigma, \xi) \quad (1)$$

$\mu \in \mathbb{R}$, $\sigma > 0$ and $\xi \in \mathbb{R}$ are respectively the location, scale and shape parameters.

A trend model can then be derived by assuming that the location and scale parameters are functions of time while the shape parameter remains constant (Ouarda and El-Adlouni, 2011; Renard et al., 2013):

$$\mu_t = \mu_0(1 + \mu_1 t) \quad (2)$$

$$\sigma_t = \exp(\sigma_0(1 + \sigma_1 t)) \quad (3)$$

$$\xi_t = \xi_0 \quad (4)$$

Note that an exponential function is used in Eq. (3) to ensure that the scale parameter always remains positive. The corresponding non-stationary GEV model is:

$$M_1: X_t \sim GEV(\mu_0(1 + \mu_1 t), \exp(\sigma_0(1 + \sigma_1 t)), \xi_0) \quad (5)$$

The inference will therefore be made for the five parameters, μ_0 , μ_1 , σ_0 , σ_1 , ξ_0 through their posterior distribution. Parameters μ_1 and σ_1 control the strength of the trend on the location and scale parameters, respectively.

2.3.1.2. The lognormal distribution for annRAIN. The selection of the model for annual rainfall is based on Edwards et al. (1983) and

Ghosh and Desai (2006) who indicated the suitability of Log-normal distribution in semi-arid areas. In addition, L'Hôte et al. (1975) demonstrated that the Log-normal distribution fits well the annual rainfall of two stations in the basin. Moreover, preliminary analyses (not described here) indicated that the Log-normal distribution provides a better fit than alternative choices such as the Normal distribution.

The M_0 model for a Log-normal distribution can be written as follow:

$$M_0: X_t \sim \ln N(\mu, \sigma^2) \quad (6)$$

Where $\mu \in \mathbb{R}$ and $\sigma > 0$ are respectively the location and scale parameters. We use the parameterization where μ and σ represent the mean and standard deviation of $\ln(X_t)$, respectively.

Using a similar parameterization as with the GEV model, the assumption of time-varying location and scale parameters leads to the following model M_1 :

$$M_1: X_t \sim \ln N(\mu_0(1 + \mu_1 t), (\exp(\sigma_0(1 + \sigma_1 t)))^2) \quad (7)$$

2.3.1.3. The normal distribution for DURATION. The annual rainfall duration (DURATION) is computed as a number of rainy days, and is therefore discrete. At first sight, a discrete distribution might therefore be considered as preferable. However, we consider that the discrete nature of DURATION is only due to a resolution issue: the annual rainfall duration is actually a continuous variable, but we can only approximate it as an integer number of days due to the availability of daily data only. In principle, non-integer rainfall duration would make perfect sense (and would even be preferable if data were available at a subdaily resolution). Furthermore, preliminary analyses using the discrete Poisson distribution showed that it provided a poor fit to the DURATION data, mostly due to its constraining property that the variance is equal to the mean. The continuous Normal distribution was therefore favored, and provides an acceptable fit as will be shown subsequently.

The no-trend model for the Normal distribution can be written as:

$$M_0: X_t \sim N(\mu, \sigma^2) \quad (8)$$

Where $\mu \in \mathbb{R}$ and $\sigma > 0$ are respectively the location and scale parameters.

As previously, the assumption of time-varying location and scale parameters leads to the model

$$M_1: X_t \sim N(\mu_0(1 + \mu_1 t), (\exp(\sigma_0(1 + \sigma_1 t)))^2) \quad (9)$$

2.3.2. Inference functions

2.3.2.1. Likelihood. For all three studied variables, observed values (x_1, \dots, x_n) are assumed to be mutually independent, which leads to the following likelihood:

$$p(x_1, \dots, x_n | \theta) = \prod_{t=1}^n f_t(x_t | \theta) \quad (10)$$

where f_t is the probability density function (pdf) of the assumed distribution (GEV, Lognormal or Normal) at time t , and θ is the vector of inferred parameters ($\mu_0, \mu_1, \sigma_0, \sigma_1$ for the Normal and Lognormal distributions, augmented with ξ_0 for the GEV distribution). The independence assumption is deemed reasonable since we are using annual values (total, maximum or duration), and is a standard assumption made in this type of analysis (see e.g. Perreault et al., 2000a; Panthou et al., 2012, amongst many others).

2.3.2.2. Prior and posterior distributions. Little prior knowledge on parameters was available for all three studied variables. Consequently, 'flat' non-informative prior distributions were specified ($p(\theta) \propto 1$). The only exception is the shape parameter of the GEV distribution for the MAXAN variable, which is constrained to physically reasonable values by using a Gaussian prior distribution with mean zero and standard deviation 0.25. This is similar to "geophysical" priors frequently used in the hydrologic literature (e.g. Martins and Stedinger, 2000; Renard, 2011, amongst many others)

The posterior distribution can then be evaluated up to a constant of proportionality using Bayes' formula:

$$p(\theta | x_1, \dots, x_n) \propto p(x_1, \dots, x_n | \theta) p(\theta) \quad (11)$$

2.3.3. Posterior MCMC sampling and use of MCMC simulations

The Metropolis-Hasting algorithm, a Markov-chain Monte Carlo (MCMC) method was used for posterior sampling. For all variables, 100,000 iterations of the algorithm were run, and the first 10% of MCMC samples were discarded as a burn-in period. The convergence was visually assessed by using traceplots of the MCMC-simulated parameters.

Goodness of fit of the model was evaluated using a probability–probability plot (pp-plot) obtained by plotting the empirical non-exceedance frequencies against the non-exceedance probabilities computed from the model. More precisely, model probabilities refer to the sorted probabilities of non-exceedance computed from the estimated cumulative distribution function ($\hat{F}_1(x_1), \dots, \hat{F}_n(x_n)$) while empirical probabilities denote the cumulative frequencies ($(1 - 0.5)/n, (2 - 0.5)/n, \dots, (n - 0.5)/n$). Note that an alternative quantile–quantile plot (qq-plot) representation is often favored, especially for extremes: it is based on plotting the sorted values (x_1, \dots, x_n) against the model quantiles ($\hat{F}^{-1}((1 - 0.5)/n), \dots, \hat{F}^{-1}((n - 0.5)/n)$). However, the qq-plot representation cannot be applied with non-

identically-distributed models such as those used in this paper. Indeed, it requires that the same quantile function F^{-1} applies to all data, which does not hold when the distribution changes through time. By contrast, the pp-plot representation can be applied with non-identically-distributed models because the probability-transformed values $F_i(x_i)$ all follow the same uniform distribution between 0 and 1.

The evidence for a trend is investigated through the posterior distributions of the trend parameters μ_1 and σ_1 : for instance, a posterior pdf concentrated on strictly positive values would correspond to a strong evidence for a positive trend. As a quantitative summary for all variables and all stations, we compute the probability of the trend parameters μ_1 and σ_1 being strictly positive, $\Pr(\mu_1 > 0)$ and $\Pr(\sigma_1 > 0)$. The probability is estimated by the fraction of positive MCMC-generated values for trend parameters μ_1 and σ_1 . A value close to one suggests a strong evidence for a positive trend, while a value close to zero suggests a strong evidence for a negative trend. Conversely, if the posterior pdf of μ_1 for instance is concentrated on both positive and negative values, this indicates that the evidence for a trend is weak. In terms of MCMC sampling, this would materialize by both positive and negative values being simulated – and the fraction of positive values would therefore be far from zero or one. We stress that we only use these posterior probabilities as a way to numerically summarize the posterior distribution of trend parameters. This is a fairly standard approach that has already been used in several papers (in the context of hydro-climatic trends, see e.g. [Ortego et al., 2012](#); [Sun et al., 2015](#); [Sun et al., 2014](#)). However, these posterior probabilities should not be mistaken for the p -values used in frequentist hypothesis testing: while both correspond to exceedance probabilities, they are computed from fundamentally distinct distributions (the posterior distribution of parameters in the Bayesian case, the sampling distribution of the test statistics under the H_0 hypothesis in the frequentist case). For more details on these interpretations, the interested reader may refer to e.g. [Pereira et al. \(2008\)](#), or in a more applied hydrological context, [Perreault et al. \(2000b\)](#).

2.3.4. Additional methods

After investigating trends in time series, additional methods have been used to better understand how the trends occurs in space and time. The analysis was performed by using Bayesian Kriging of the mean decadal rainfall by means of the R package [geoR \(Ribeiro and Diggle, 2001\)](#). For Kriging of the mean decadal rainfall, monthly data from additional stations were used to improve the accuracy of the results. The seasonality of mean monthly rainfall and mean monthly rainfall duration was also investigated for the seven stations.

3. Results

3.1. Trend analysis in time series

3.1.1. Rainfall extremes (MAXAN)

The application of the Bayesian inference is first illustrated for a particular station (Pagouda). The left panels of [Fig. 2](#) show the MCMC-simulated values for the five parameters of the GEV model. A density plot of these values allows visualizing the marginal posterior density of each parameter. For this particular station, the evidence for a trend is weak for both location and scale parameters, since the value zero is located in the center of the posterior densities for both parameters μ_1 and σ_1 . This is further confirmed by [Table 1](#), which shows that the probability of being positive is far from zero and one for both parameters.

[Fig. 3](#) displays the pairwise scatterplots of MCMC-simulated values and allows visualizing the dependencies between each pair of the five parameters of the non-stationary GEV model. Parameters μ_0 and μ_1 on the one hand, and σ_0 and σ_1 on the other hand are strongly negatively correlated, while correlation between any other parameter pair is weak.

The left panel of [Fig. 4](#) shows the P–P plots obtained with the estimated non-stationary GEV distribution for all sites. All pp-plots are close to the diagonal, which indicates that the non-stationarity GEV distribution fits well the observed MAXAN at all sites and therefore can be used to assess MAXAN changes.

[Fig. 5](#) shows the posterior distributions for all parameters of the non-stationary GEV distribution for all sites as boxplots. In general, the median location parameter over the basin ranges from 59 at Takpamba to 74 at Kara with the stations of Kara and Pagouda recording the highest intensities of annual maximum rainfall while Takpamba records the lowest amount. The interannual variability of MAXAN is maximal at Kara and minimal at Niamtougou with median scale values of 3.1 and 2.3 respectively (in log-space). The interannual variability of MAXAN does not change importantly between the remaining stations. A strong evidence for a decreasing trend in the location parameters is detected for the stations of Kara and Niamtougou while a strong evidence for an increasing trend appears at Takpamba ([Table 1](#)). There is strong evidence that the interannual variability is decreasing at Kara (negative trend parameter for scale) but a moderate evidence of increasing variability at Kpewa-Aledjo and Niamtougou. For the remaining stations, there is no consistent trend in the location and scale parameters. The shape parameter is always positive corresponding to a heavy-tail behavior and ranges from 0.01 at Pagouda to 0.20 at Kara ([Fig. 5](#)).

Trends detected with strong evidence are also discernible in the estimated quantiles ([Fig. 6](#)). At Kara for instance where both the location and scale parameters are decreasing, 0.5 and 0.9-quantiles decreased from about 82 mm to 57 mm and 138 mm to 85 mm respectively. Conversely, the two quantiles are increasing at Takpamba and Kpewa-Aledjo. The station of Niamtougou shows a different situation: the 0.5-quantile is decreasing while 0.9-quantile does not change importantly. Actually the 0.5-quantile is mostly influenced by the location parameter which is decreasing, while the 0.9-quantile is also influenced by the scale parameter which increases moderately. The decrease of the location parameter and the increase of the scale have opposite effects on the 0.9-quantile which hence doesn't show any trend.

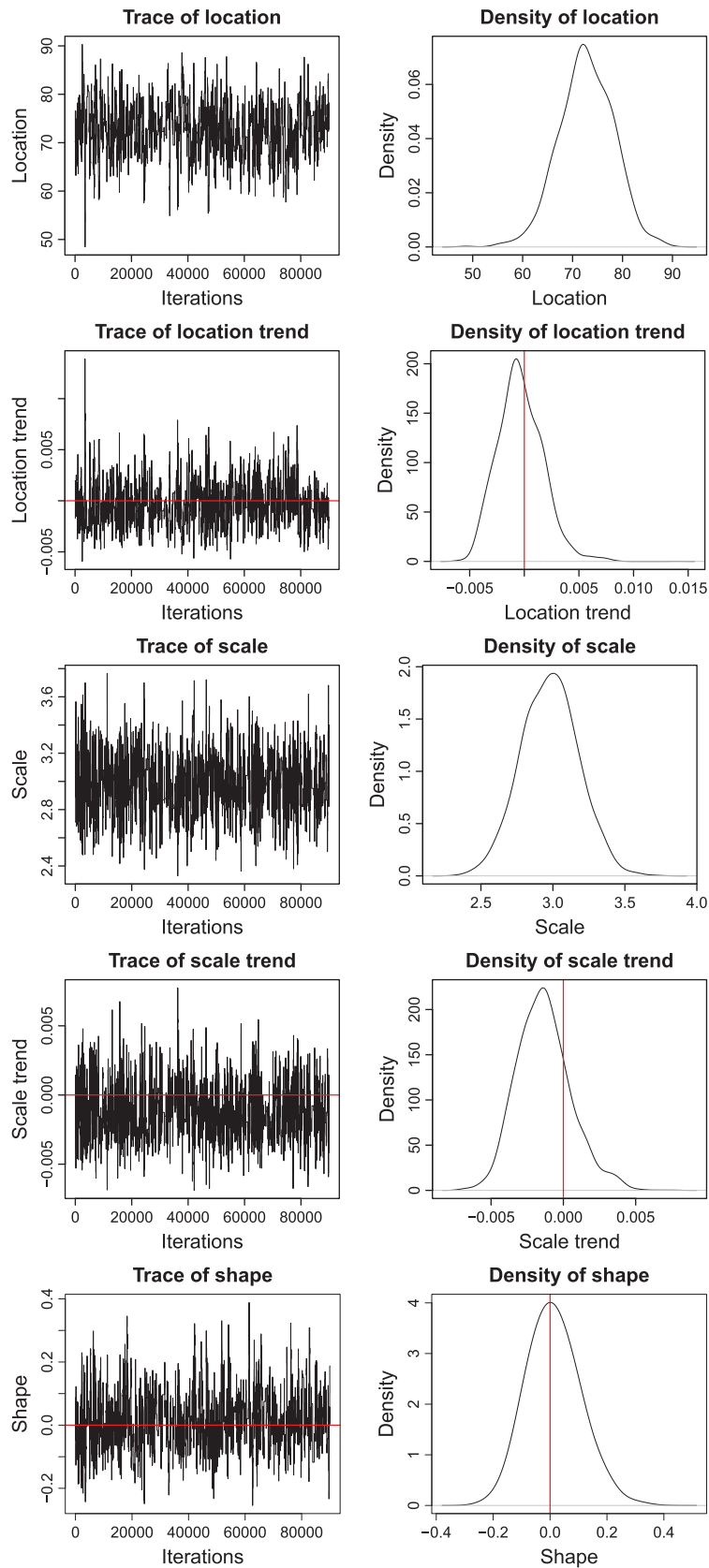


Fig. 2. MAXAN: trace and posterior density plots of non-stationary GEV parameters for Pagouda station.

Table 1

Trend assessment in location and scale parameters for variables MAXAN, annRAIN and DURATION. A probability higher than 0.9 (resp. smaller than 0.1) is interpreted as a strong evidence for a positive (resp. negative) trend; a probability between 0.8 and 0.9 (resp. between 0.1 and 0.2) is interpreted as a moderate evidence for a positive (resp. negative) trend; for other probabilities, the evidence for a trend is weak. (For interpretation of the references to colour in this Table, the reader is referred to the web version of this article.)

	MAXAN		annRAIN		DURATION	
	Pr($\mu_t > 0$)	Pr($\sigma_t > 0$)	Pr($\mu_t > 0$)	Pr($\sigma_t > 0$)	Pr($\mu_t > 0$)	Pr($\sigma_t > 0$)
Guerin-Kouka	0.59	0.57	0.12	1.00	0.26	0.02
Kante	0.35	0.48	0.40	0.49	0.85	1.00
Kara	0.01	0.07	0.48	1.00	1.00	0.31
Kpewa-Aledjo	0.66	0.83	0.06	0.93	0.40	0.03
Niamtougou	0.06	0.87	0.09	0.86	0.98	0.39
Pagouda	0.44	0.23	0.26	1.00	1.00	0.1
Takpamba	0.95	0.65	0.75	0.75	0.05	1.00

3.1.2. Annual rainfall (annRAIN)

The annual rainfall greatly varies from one station to another, with the estimated median location parameters varying from 6.94 (in log-space) at Takpamba to 7.34 at Kpewa-Aledjo (Fig. 7). Similarly, the median scale varies from one station to another. The greatest interannual variability of annual rainfall is observed at Pagouda station with the highest scale parameter (-1.00 in log-space) and the lowest variability is observed at Niamtougou with a median scale parameter of -1.70 .

There is a positive trend in the scale parameter at all stations, with moderate or strong evidence for 5 out of the 7 stations. This positive trend of the scale parameter corresponds to a decrease in the inter-annual variability: indeed, parameter σ_0 is negative for all stations, and with the parameterization of Eq. (3), a positive value of σ_1 therefore corresponds to more negative scale values in log-space, i.e. to a scale closer to zero. In addition, three stations show a negative trend in the location parameter.

These trends are also observed in the estimated quantiles (Fig. 8). Indeed for most stations, 0.1 and 0.9-quantiles tend to be closer as time advances, which corresponds to the decrease in the interannual variability as shown previously from Table 1. In general, the 0.5-quantile has a decreasing tendency at most stations except at Takpamba where it tends to increase together with the 0.1-quantile. An important decrease in the 0.5-quantile occurred at Kpewa-Aledjo and Niamtougou.

3.1.3. Annual rainfall duration (DURATION)

Estimated location parameters are highest at stations of Niamtougou and Kpewa-Aledjo (102 and 99 respectively), corresponding to larger annual rainfall duration (DURATION) compared to other stations (Fig. 9). The smallest DURATION is observed at Pagouda where the estimated median location parameter is 77. The greatest variability of DURATION is observed at Pagouda and Kpewa-Aledjo where the median scale parameter is 3.2 and 3.1 (in log-space) respectively while being less than 3 at all the remaining stations. The station of Kante records the lowest variability with a scale parameter of 2.10. In general, trend in the location and scale parameters of DURATION is heterogeneous across stations. A positive trend in the location parameter is found at Kante, Kara, Niamtougou and Pagouda with strong evidence, while at Takpamba strong evidence is found for a negative trend (Table 1). Moreover, there is evidence for a negative trend in the scale parameter at Kpewa-Aledjo and Pagouda and a positive trend at Kante and Takpamba.

Like MAXAN and annRAIN, the detected trends are clearly observed in the estimated quantiles (Fig. 10). For Kante, Kara, Niamtougou and Pagouda stations where consistent evidence of positive trend in the location parameter is found, quantiles are increasing. At Takpamba where a negative trend is found, there is a decline in 0.1 and 0.5 quantiles while 0.9 quantile does not change importantly. In general, 0.1 and 0.9 quantiles tend to get closer for the stations where a negative trend in the scale parameter is found (Guerin-Kouka, Kpewa-Aledjo, Pagouda), materializing a decrease in the interannual variability. The opposite phenomenon occurs at Kante and Takpamba where the two quantiles tend to move apart, therefore confirming the increase in the interannual variability of DURATION.

3.1.4. Simultaneous analysis of the variability of MAXAN, annRAIN and DURATION at different sites

The analysis of the three rainfall variables at different sites shows that the annual maximum rainfall (MAXAN), the cumulative annual rainfall (annRAIN) and the annual rainfall duration (DURATION) don't have the same trends over the basin. At Guerin-Kouka, there is moderate evidence of decreasing annRAIN while there is strong evidence that interannual variability of annRAIN is decreasing. At Kante, only DURATION and its interannual variability are increasing. At Kara, a decreasing trend is detected in MAXAN and its interannual variability as well as in the interannual variability of annRAIN; DURATION is increasing with no marked trend in its interannual variability. At Niamtougou and Kpewa-Aledjo, a same phenomenon of moderate increasing tendency in the interannual variability of MAXAN and decreasing annRAIN and its interannual variability is observed. In addition to this, MAXAN is

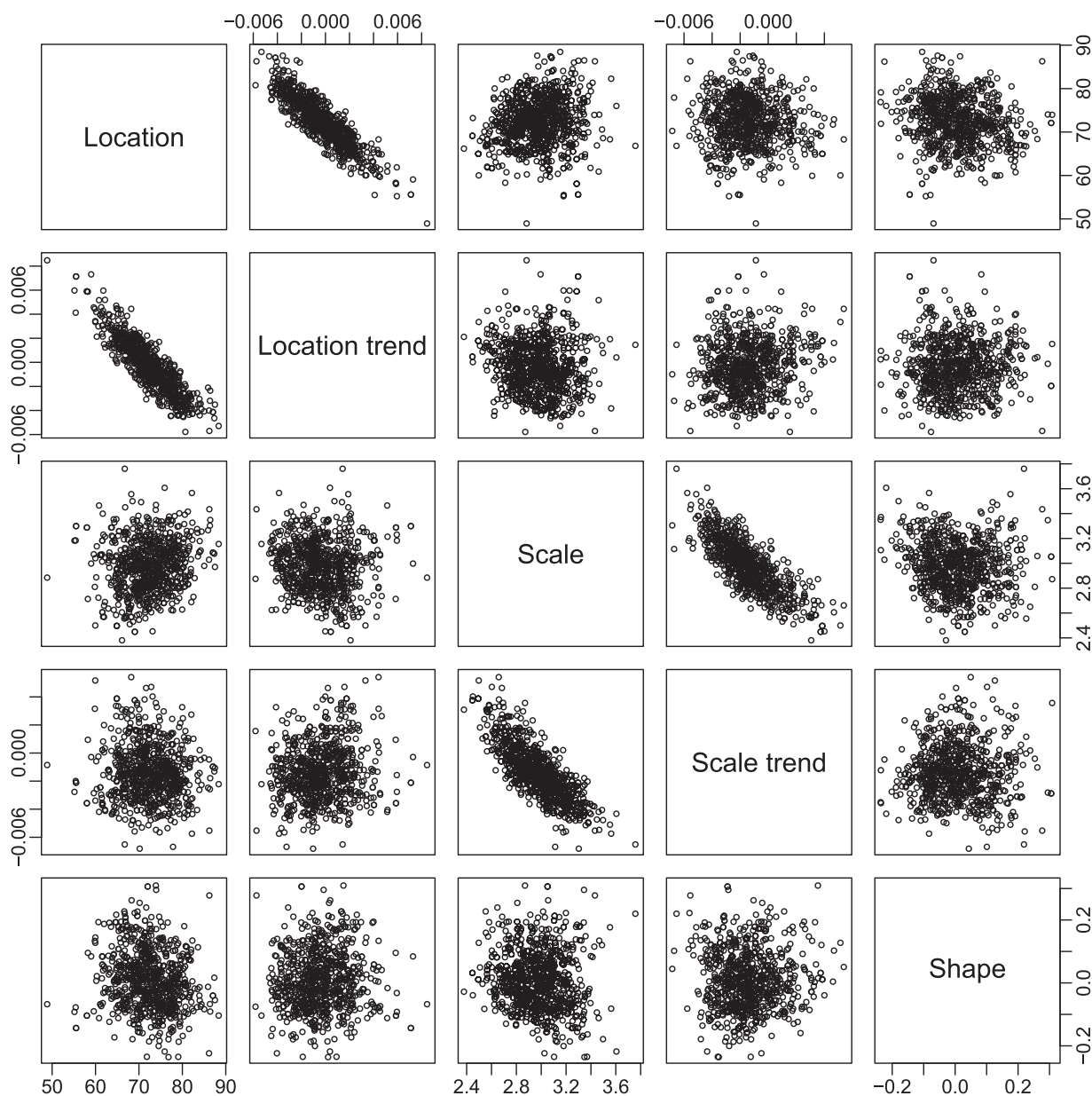


Fig. 3. MAXAN: pairwise scatterplot of MCMC-simulated parameters for the non-stationary GEV model (Pagouda station).

decreasing and DURATION is increasing at Niamtougou while at Kpewa-Aledjo, the interannual variability of DURATION is decreasing. Changes in rainfall variables that occurred at Pagouda are the increasing trend in DURATION and a decreasing trend in the interannual variability of both annRAIN and DURATION. At Takpamba, there is a strong evidence of decreasing trend in DURATION and increasing trend in MAXAN, while the interannual variability of DURATION increases.

In general, all the stations tend to show a similar decreasing tendency in the interannual variability of annRAIN. Moreover, the stations of Takpamba and Kante on the one hand and the remaining ones on the other hand seem to have the same trend in the interannual variability of DURATION. It can be observed that the heterogeneity in the trend in MAXAN over the basin is higher than that in annRAIN and DURATION. In most cases, the station of Takpamba shows a particular situation when compared to other stations.

3.2. Analysis of mean decadal and mean monthly rainfall

The Kriging of the mean decadal rainfall helps to understand the spatio-temporal variations of rainfall over the basin (Fig. 11). Spatially, isohyets are generally oriented North-East to South-West and rainfall intensities varies according to the direction North-

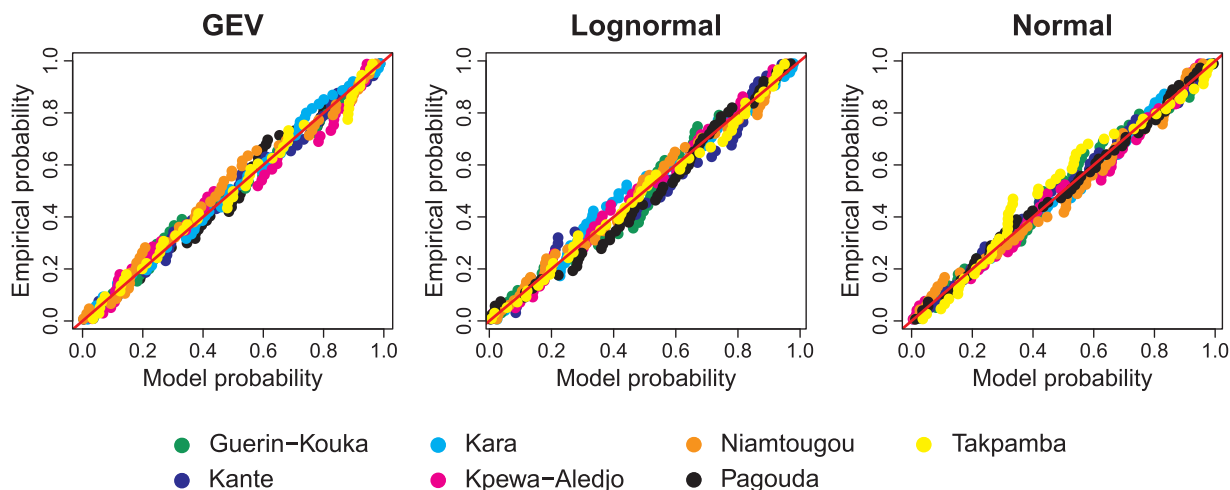


Fig. 4. PP-plots obtained with the non-stationary GEV, Log-normal and Normal distributions (respectively for MAXAN, annRAIN and DURATION) for all sites.

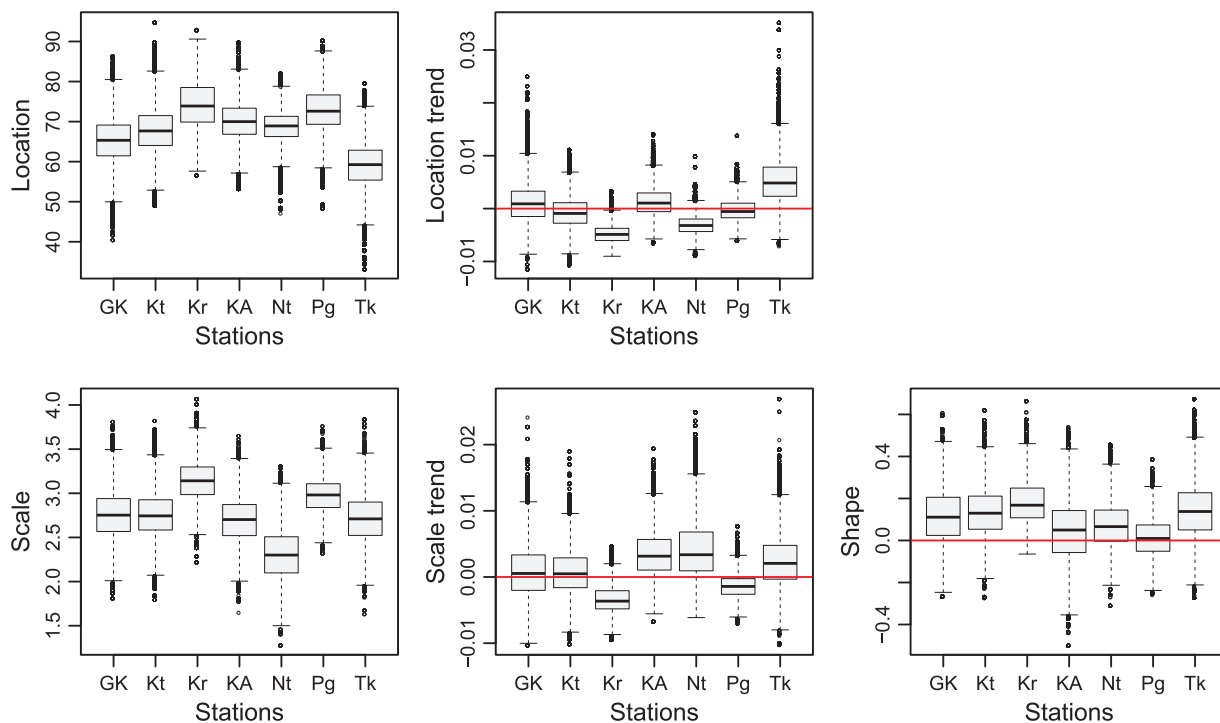


Fig. 5. MAXAN: boxplot of MCMC-simulated parameters of the non-stationary GEV model at different stations, GK = Guerin-Kouka, Kt = Kante, Kr = Kara, KA = Kpewa-Aedjo, Pg = Pagouda, Tk = Takpamba.

West to South-East but with sometimes a concentration over the stations of Kpewa-Aedjo and Niamtougou. The latter stations receive the higher amounts of rainfall in comparison to other stations (Fig. 11). Temporally, the mean decadal rainfall showed important changes from 1950s to 2010s. The 1950s and 1960s were very humid with a maximum of rainfall amount reaching 1680 mm around Kpewa-Aedjo, with the 1960s being more humid than the 1950s. From 1970s, a marked decrease in rainfall occurred over the basin when compared to 1960s. The maximum mean decadal rainfall is 1520 mm around Kpewa-Aedjo and the minimum 1120 mm around Takpamba. The decrease in rainfall spread over 1980s where it was more pronounced. The maximum rainfall is 1400 mm around Kpewa-Aedjo and the minimum 1020 mm around Takpamba. In general, there has been a shift of isohyets south-eastwards and the loss of the great isohyets in the regions that received higher amounts of rainfall during the 1970s and 1980s. The important decrease in rainfall and changes in isohyets have been recorded over the 1980s. When compared to 1980s, an increase has been observed over the 1990s where the minimum increased up to 1200 mm around Takpamba and the maximum was 1520 mm around Kpewa-Aedjo. Over the last decade (2000–2009), rainfall slightly decreased in comparison to 1990s. Here, the minimum was 1120 mm around Takpamba and the maximum 1480 mm around Kpewa-Aedjo. While a general overview of the Kriging maps show that the 1950s,

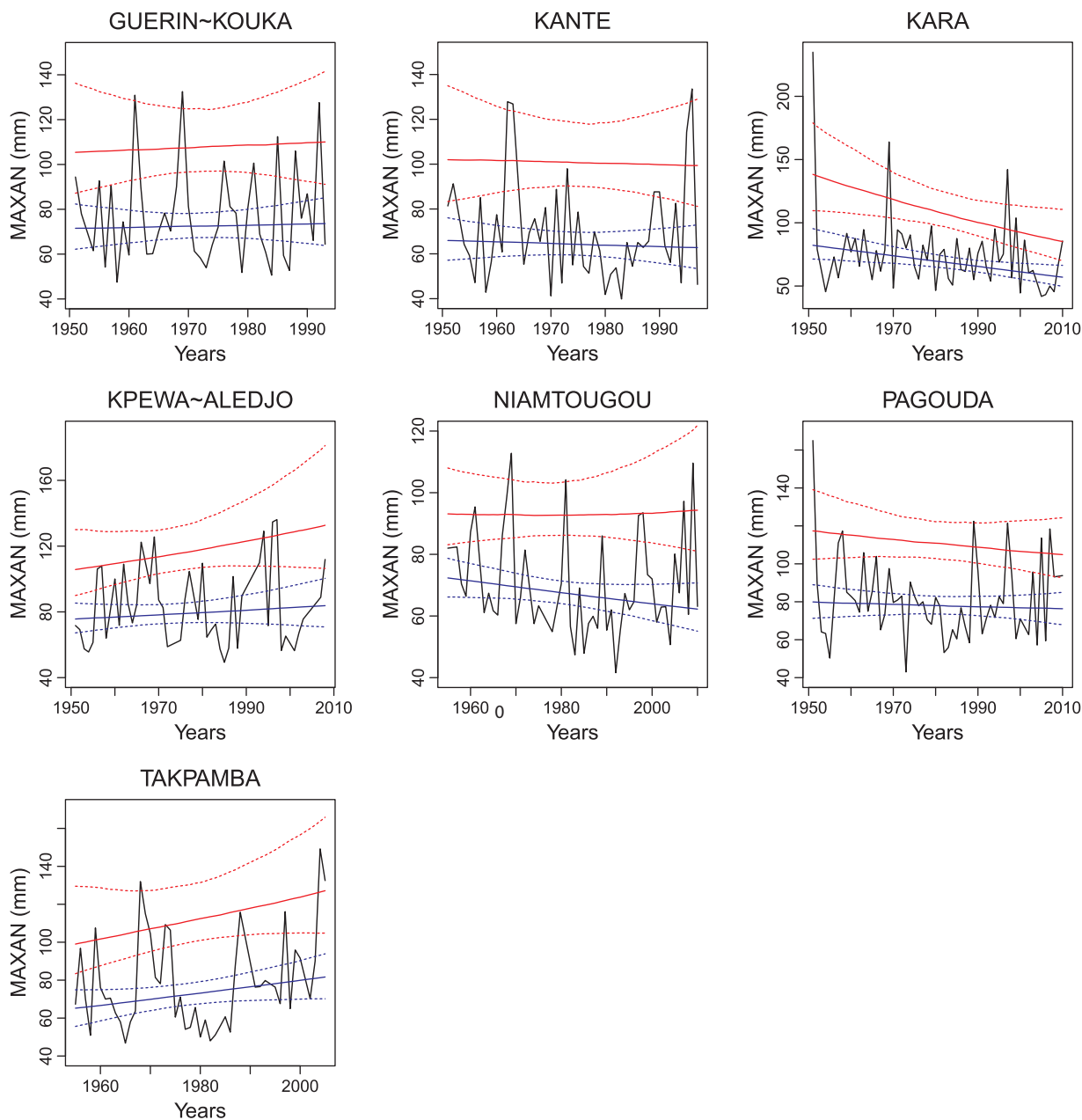


Fig. 6. MAXAN time series and variation of quantiles through time. The blue and red solid lines represent 50% and 90% quantiles respectively. Dotted lines represent 95% posterior intervals for the quantiles.

1960s and 1990s are humid decades, a chronological analysis reveals that rainfall increased from 1950s to 1960s. From 1970s it started decreasing until the end of 1980s, period after which it increased over 1990s before decreasing in 2000s.

In order to better understand the previously detected trends in annual and decadal rainfall, further investigation was carried out on the behavior of the mean monthly rainfall over three periods: before 1970, between 1970 and 1989 and from 1990 to 2009. The three periods were chosen based on the rainfall variability observed in Fig. 11 but also in West Africa in general. Actually the pre-1970 period constitutes a humid period, the 1970s and 1980s are dry and from 1990s to 2000s constitute a period of recovery (Lebel and Ali, 2009; Nicholson, 2005).

The results indicate that for all stations, the maximum monthly rainfall which occurs in September at all stations decreased between 1970 and 1989 (Fig. 12). At Pagouda station for instance, there has been a decrease of more than 50 mm. For all the stations, the amount of rainfall received after the peaks till the end of the season decreased on that period. From 1990–2009, there has been an increase in the rainfall when compared to the previous period (1970–1989). Another important change in the distribution of the monthly rainfall is the shift of the peaks from September between 1951 and 1969 to August during the last two decades of the study

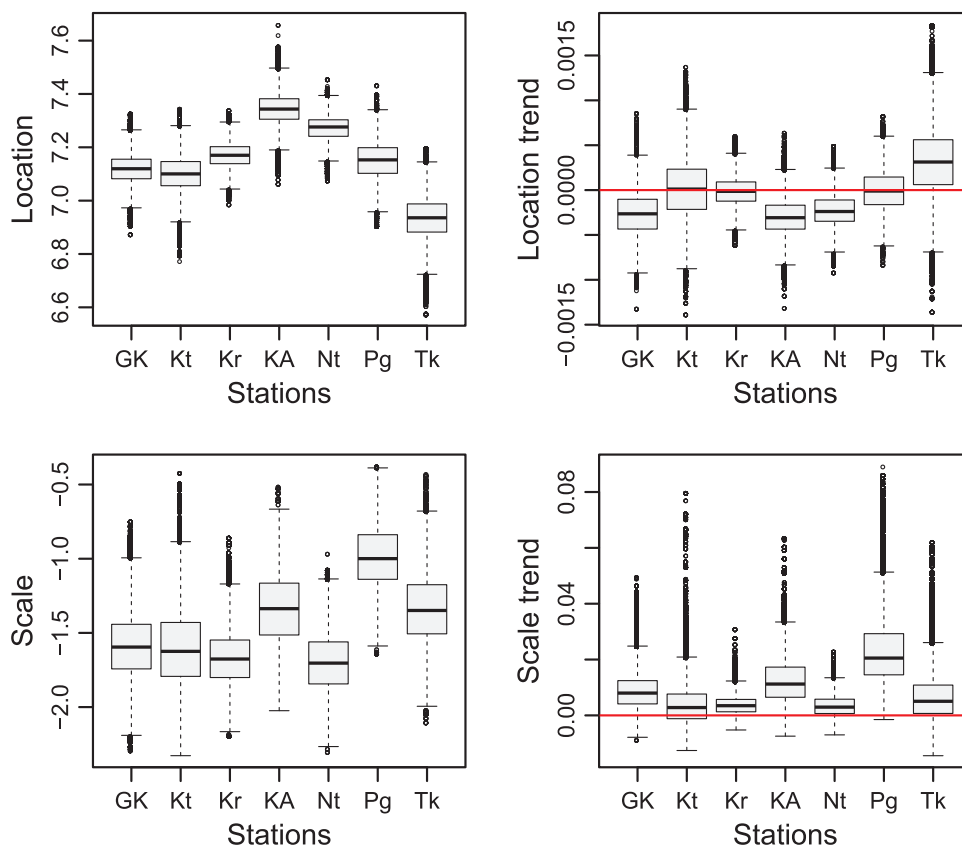


Fig. 7. annRAIN: boxplot of MCMC simulated-parameters of the non-stationary Log-normal distribution at different stations, GK = Guerin-Kouka, Kt = Kante, Kr = Kara, KA = Kpewa-Aedjo, Pg = Pagouda, Tk = Takpamba.

period (1990–2009). During the same period, the rainfall amount in August increased at all stations when compared to the previous one.

Similarly to the annual rainfall, a complementary analysis was carried out in the mean monthly rainfall duration on the three periods: 1951–1969, 1970–1989 and 1990–2009. As a result, the peak of the annual rainfall duration which used to occur in September at all stations between 1951 and 1969, has shifted to August during 1990–2009 (Fig. 12). At Kante, Kpewa-Aedjo, Niamtougou and Pagouda, the monthly rainfall duration increased respectively over the three periods. The increase is especially observed during and around the peak month of the season. At Takpamba, no marked change is observed between 1951 and 1969 and 1970–1989. However, a decrease occurred over 1990–2009. At Guerin-Kouka and Kara, only a slight increase in the monthly rainfall duration during July and August can be observed.

4. Discussion

A number of studies have been carried out previously on trend analysis in rainfall variables in West Africa. However these studies have mostly focused on individual rainfall variables and on regional scales. Also, the results of these studies are not associated with uncertainties while the statistical modeling of trend in rainfall variables still remains rare. In this study, trend in rainfall variables is modeled using probability distributions via a Bayesian framework.

The results show that the GEV and Lognormal distributions fit well respectively the annual maximum rainfall (MAXAN) and cumulative annual rainfall (annRAIN) in the Kara River basin while the Normal distribution can be used to accurately describe the distribution of the annual rainfall duration (DURATION). These results suit well those of Panthou (2013) who found that MAXAN in the region has a GEV distribution. These findings also extend those of L’Hôte et al. (1975) who found that the Lognormal distribution represents well the distribution of annRAIN of two stations within the basin.

The estimated GEV, Lognormal and Normal models’ parameters vary from one station to another but in general, the stations located in mountainous areas have higher location parameters than those in low topographic zone suggesting the influence of local topography and relief on the rainfall variables. Prudhomme and Reed (1998) showed that the spatial distribution of the MAXAN is controlled by complex relationships between relief and position relative to moisture source. They also emphasize that short duration extreme precipitation such as one, two and five days annual maximum rainfalls are greatly impacted by local factors.

It is also established that annRAIN, MAXAN and DURATION between 1951 and 2010 are not identically distributed in the Kara

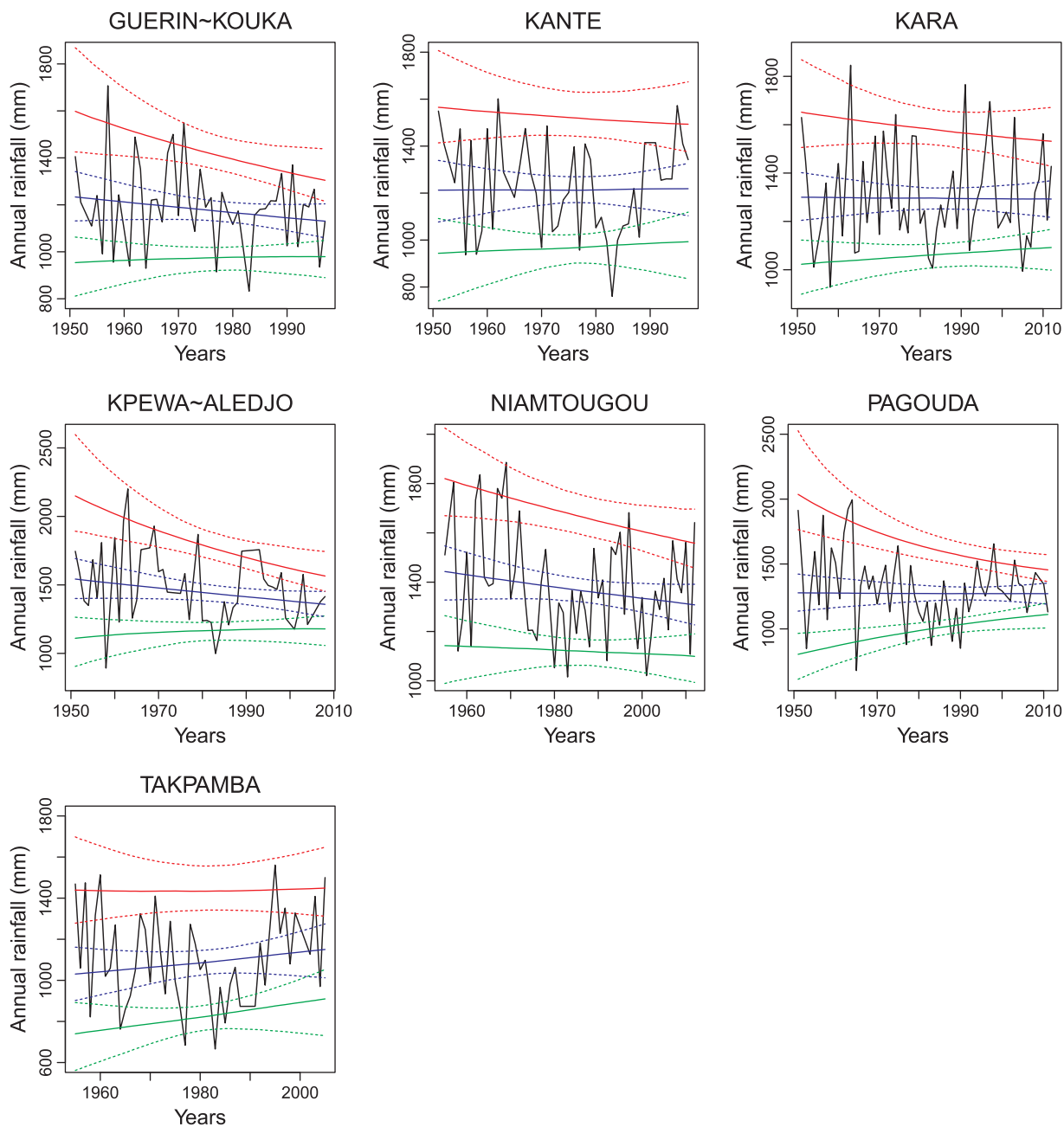


Fig. 8. annRAIN time series and variation of quantiles over time. The green, blue and red solid lines represent 10%, 50% and 90% quantiles respectively. Dotted lines represent 95% posterior intervals for the quantiles.

River basin. In general, there is a great interannual variability in MAXAN, annRAIN and DURATION at all sites as well as no important homogeneity of trends over the basin. At Kante, Kara, Niamtougou and Pagouda, even if evidence is weak at certain stations, it can be admitted that MAXAN and annRAIN tend to follow a general decreasing trend while DURATION has an increasing tendency. These results therefore suggest that rainy days are likely becoming more frequent but with less intensity of rainfall. It is important to emphasize that the increase in the duration of annual rainfall occurs most likely during the rainy season especially during the peak and surrounding months in order to rule out any hypothesis of rainy season extension. The observed differences between the stations of Takpamba and to some extent Kante or Guerin-Kouka on the one hand and the remaining stations on the other hand suggest that the studied rainfall variables are likely to follow two homogenous trend regions: a first region covered by Takpamba, Guerin-Kouka and Kante (low-elevation part of the basin, see Fig. 1) and the second one covered by the remaining stations supporting therefore the influence of the topography and relief. Moreover, the decrease in the interannual variability of annual rainfall for all stations suggests that this phenomenon is governed by the same process and is therefore unlikely to result from purely

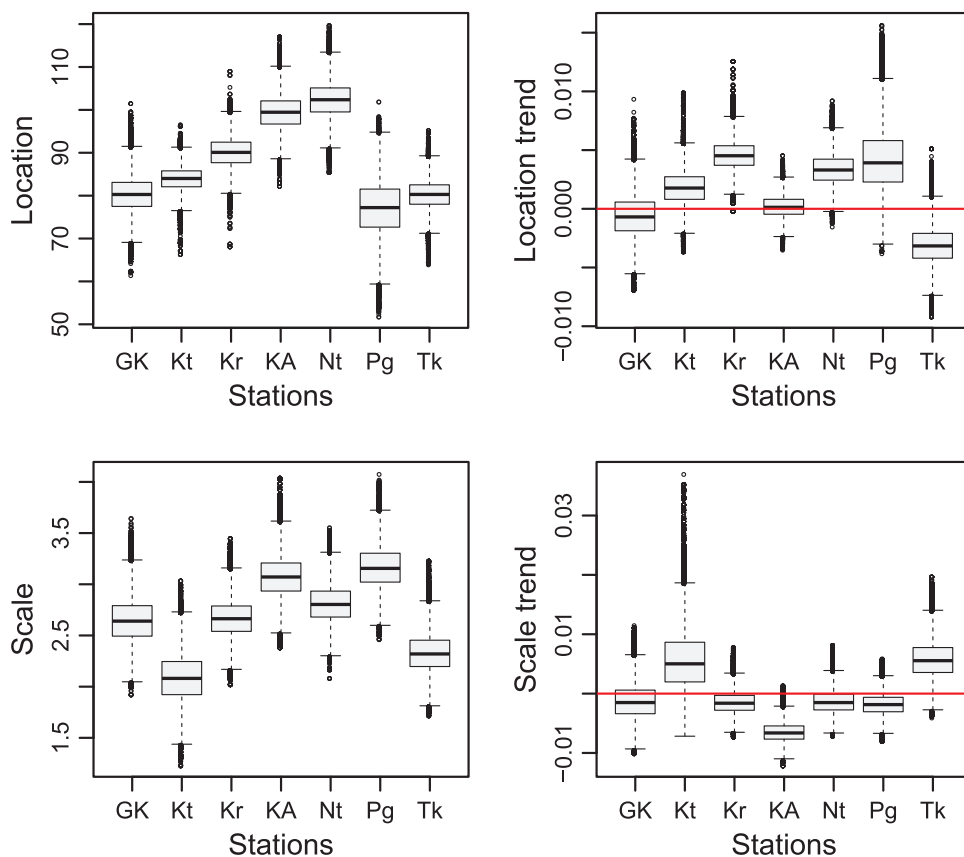


Fig. 9. DURATION: boxplot of MCMC-simulated parameters of the non-stationary Normal model at different stations, GK = Guerin-Kouka, Kt = Kante, Kr = Kara, KA = Kpewa-Aedjo, Pg = Pagouda, Tk = Takpamba.

local factors. The detected trend in the interannual variability also shows the importance of introducing a trend in the scale parameter.

In order to better understand the trends in rainfall variables at the basin scale and provide consistency to the results, a comparison of these results to the trends observed at the West African region scale is necessary. An overall decreasing tendency in annual rainfall has already been observed in West Africa by many authors (IPCC, 2007; Mouhamed et al., 2013; Nicholson, 1993; Paturol et al., 1997; Servat et al., 1997). In addition, Le Barbé et al. (2002) found that between 1951 and 1990, there has been a decrease in the mean annual rainfall which is correlated to the decrease in the average number of rainy events in West Africa. Neumann et al. (2007) indicated that precipitation in the Volta Basin between 1961 and 2001 has both monthly negative and positive trends but only few are significant. They also found that for annual maxima, sums and standard deviations of precipitation, the significant trends which are detected are negative but a conclusion of a general decreasing precipitation in the Volta Basin cannot be established due to a small number of significant cases.

The trend in annRAIN may be related to the tendency in MAXAN since the contribution of MAXAN amount to the annual precipitation in the basin is not negligible (6–7%). The decrease in annRAIN is also probably due to the decrease in the precipitation peaks during the rainy season and the decrease of rainfall amount after the peak, or in other words the earlier offset of rainfall. Le Barbé et al. (2002) have already demonstrated this earlier offset of rainfall in West Africa. The same phenomenon has been assessed by Le Lay and Galle (2005) who showed that the end of the rainy season has shifted of 15 days earlier after 1970 in the upper Oueme River catchment (Benin). Another probable cause of the decrease in annual precipitation might be linked to the changes in rainy events as showed in West Africa in general by Le Barbé et al. (2002). However, this phenomenon has not been explored in this study due to the lack of necessary information and data at hourly time steps. In contrast to the observed changes between annRAIN and DURATION, Frappart et al. (2009) observed a decrease of summer cumulative rainfall in the Sahel band in the Gourma region in Mali which was related to the reduction in the number of rainy days in southern part, and a decrease in both the number of rainy days and the daily rainfall in northern and central parts.

The observed spatio-temporal variability in the mean decadal rainfall indicates that the 1960s was the wettest decade and the 1980s the driest. These results corroborate those of Oguntunde et al. (2006) who found that 1968 and 1983 were respectively the wettest and the driest years in the Volta Basin between 1901 and 2002. Moreover, the spatio-temporal variability in the mean decadal rainfall at the basin scale can also be placed in the context of the drought in West Africa from 1970s and its continuation or ending in 1990s and later. For instance, Ardoin et al. (2003), L'Hôte et al. (2002), Descroix et al. (2009) and Ozer et al. (2003) concluded on the

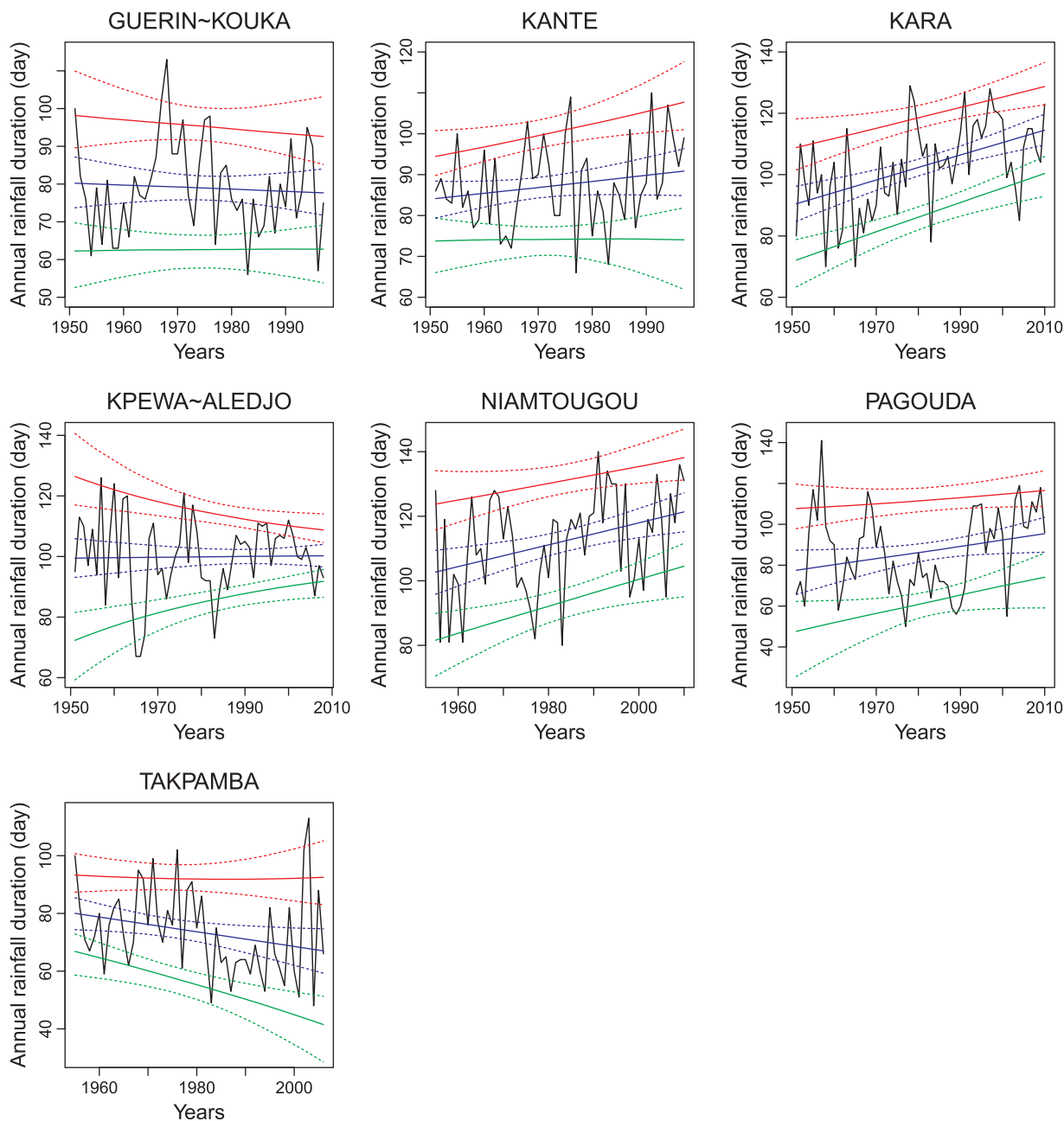


Fig. 10. DURATION time series and variation of quantiles over time. The green, blue and red solid lines represent 10%, 50% and 90% quantiles respectively. Dotted lines represent 95% posterior intervals for the quantiles.

persistence of the drought till the end of 2000. By studying trends in Central and Western Sahel rainfall regime between 1950 and 2007, [Lebel and Ali \(2009\)](#) found that while the rainfall deficit of 1970–1989 remains unabated for the 1990–2007 period in the Western Sahel, the Central Sahel progressively recorded wetter years from the end of 1990s. However the recovery is limited and the average rainfall for 1990–2007 still remains lower than the 1950–1989 average. Comparable results are found for the stations of Niamtougou, Kpewa-Aedjo and Pagouda which have records over 2000s. In fact, the 1951–1989 average rainfall for these stations remains higher than the 1990–2009/2010 average. However no important difference is found for the stations of Kara and Takpamba while this comparison is skipped for Guerin-Kouka and Kante stations since the periods of record end in 1997. Nevertheless for all stations except Kante and Guerin-Kouka which have the record periods ending in 1997, the average rainfall for the current period starting in 1990 remains higher than the average for 1970–1989 but still lower than the 1951–1969 average. Moreover, similar results were also obtained by [Mahé and Paturel \(2009\)](#) who indicated that Sahelian rainfall has increased since the end of the 1990s, but the annual average rainfall is still as low as during the drought of the 1970s.

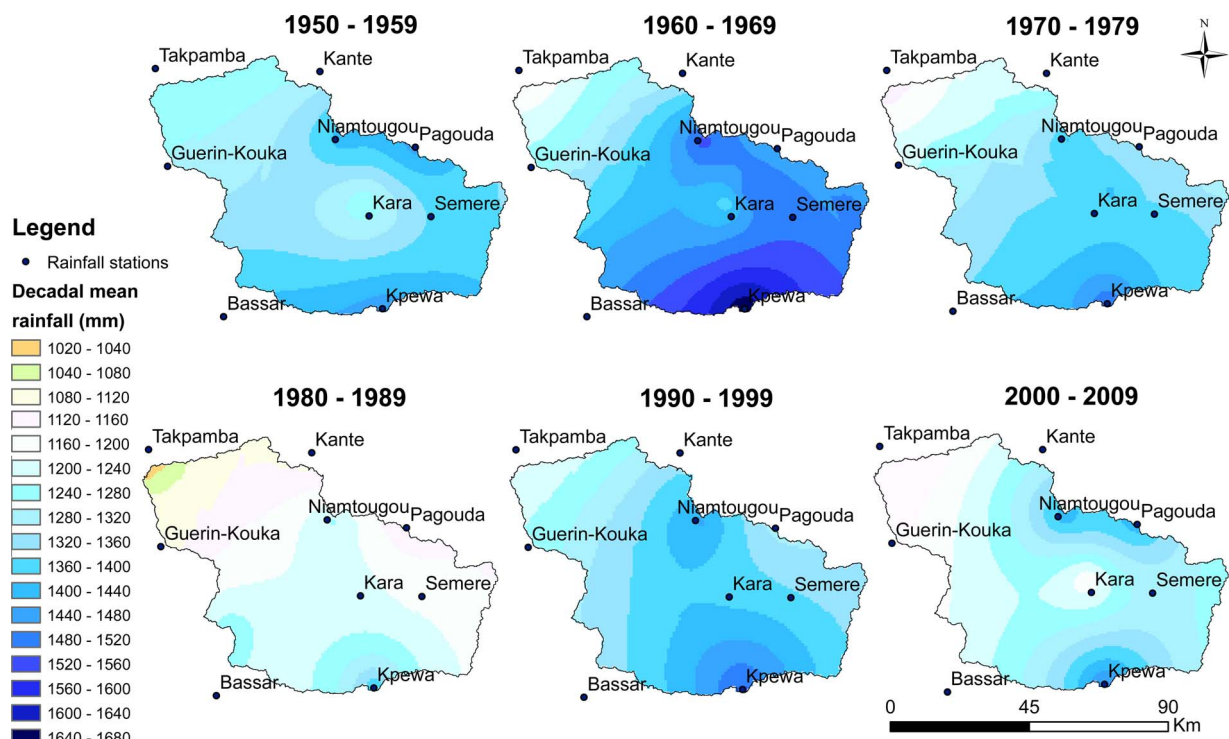


Fig. 11. Spatio-temporal variation of the mean decadal rainfall over the basin.

The existence of great interannual variability in all variables (MAXAN, annRAIN and DURATION) at all stations was raised by most of the studies that have been carried out on climate variability in West Africa (Conway et al., 2009; Dieppois et al., 2013; Le Barbé et al., 2002; Nicholson, 2013; Paeth et al., 2005). Rainfall in West Africa is generally generated by the West African monsoon regime. According to Paeth et al. (2005), interannual monsoon variability is related to coherent changes in Atlantic SSTs and in the large-scale upper-tropospheric circulation, which both induce an enhanced continental-scale moisture advection over West Africa. Nevertheless, there still remains some questions on the interannual fluctuations in rainfall variables due to the limited extent of available data (Le Barbé et al., 2002). Another challenge for a better characterization of rainfall variability from the intra-seasonal to the decadal scales is the lack of accurate and high-resolution data that would allow studying the intensity, spatial extension, and structure of the rain fields at various timescales (Le Barbe et al., 2002).

At all stations and for the three variables chosen in this study, the great interannual variability and differences between stations makes it difficult to map the spatial distribution of estimated parameters. An alternative approach for addressing this challenge would be the use of a regional approach (Gaume et al., 2010; Renard et al., 2008, 2013). This corroborates and extends the conclusion of Panthou (2013) to other rainfall variables in West Africa. Indeed Panthou (2013) underlined that extreme rainfall being highly variable by nature, meaningful conclusions on the spatial distribution of these parameters according to regional or sub-regional atmospheric phenomena can be reached by a regional approach.

Estimated uncertainties are relatively high for the median and very large for 0.1 and 0.9 quantiles whether in MAXAN, annRAIN or DURATION. An estimation of 0.99 quantile values would obviously be associated with considerable uncertainties. Even if the use of non-informative priors may have affected these uncertainties, these are most probably related to the length of the study periods which therefore appears to be insufficient for accurate estimation of more than 50–100 years return levels. In spite of the use of non-informative priors, the use of Bayesian inference provided a convenient framework for estimating uncertainties associated to the results. It has allowed detecting and tracing trend on quantiles which is a great advantage of this methodological approach over non parametric tests such as Mann-Kendall trend test. Estimated uncertainties of current results can be reduced in future work by including appropriate informative priors, increasing the length of records and applying a regional approach.

5. Conclusion and outlook

This study has demonstrated that rainfall variables within the Kara River basin between 1951 and 2010 are not identically distributed. There is strong evidence that the interannual variability of annual precipitation is decreasing over the basin, with the average annual precipitation also decreasing at Guerin-Kouka, Kpewa-Aledjo and Niamtougou. While annual maximum increases at Takpamba, it tends to decrease at Kara and Niamtougou. Moreover, in contrast to the decreasing trend at Takpamba, the rainfall duration is strongly increasing at four other stations, suggesting that it rains more frequently during the season but with less intensity of rainfall. The results also suggest that the decrease in annual rainfall and MAXAN might be also associated to the decrease in rainfall

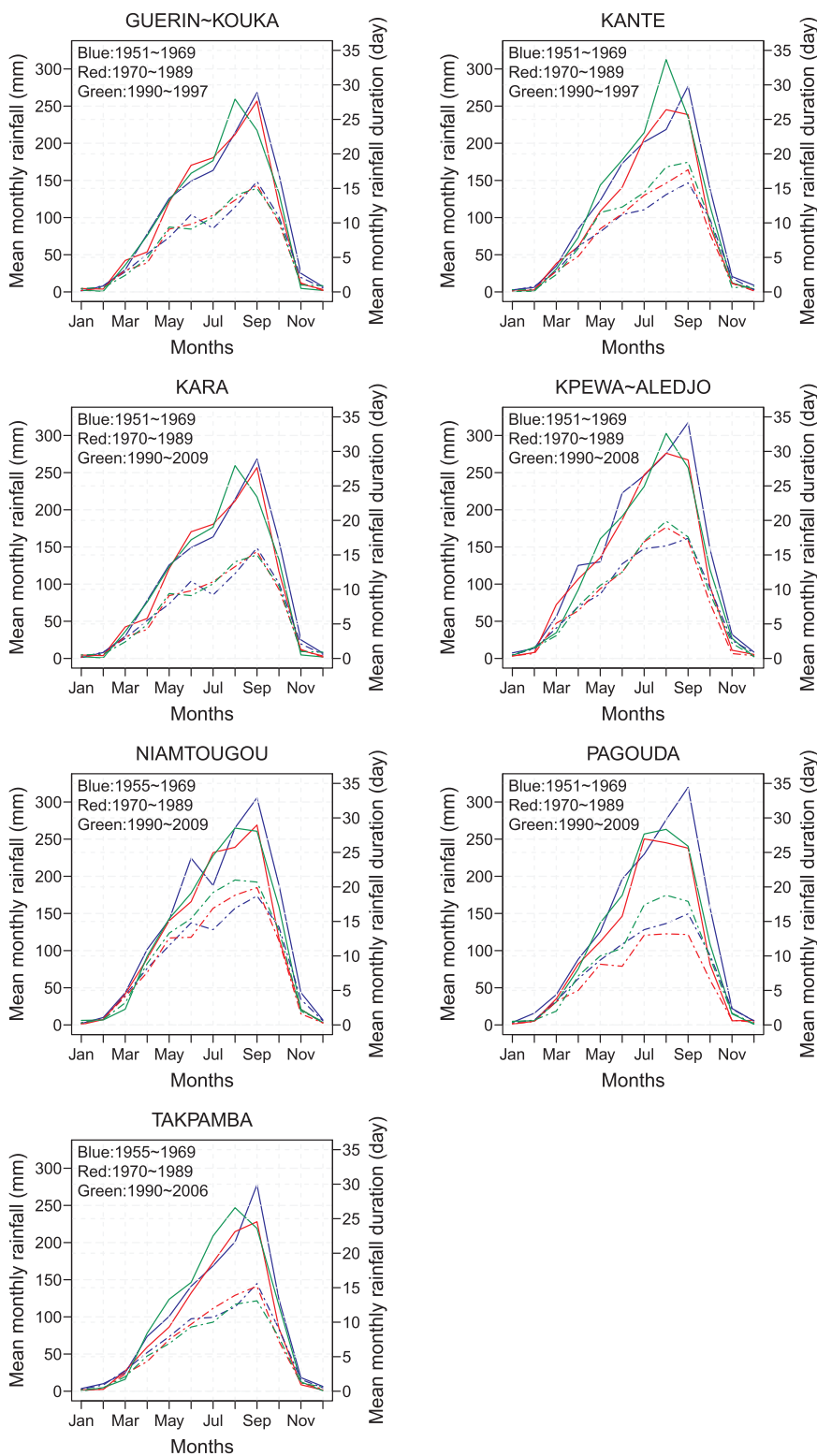


Fig. 12. Inter-annual mean monthly rainfall (solid lines) and mean monthly rainfall duration (dashed lines).

intensity per rainy day. A decrease in seasonal rainfall is also observed in most of the basin with a shift of the peak from September to August.

The results of this study provide a clear description of at-site trends in rainfall variables and constitute good baseline indicators for

the integrated river basin analysis, vulnerability assessment and the sustainable water resources management of the Kara River basin. However further research integrating a regional approach and informative priors is needed in order to better understand the spatial variation of trends, and reduce uncertainties in estimated quantiles. This will lead to the expansion of the analysis to other river basins and the use of the derived models and parameters for extremes or seasonal rainfall prediction for infrastructure design, agricultural practice or in general water resources development in the region.

Acknowledgements

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