# Non-stationary analysis of spatial patterns of extreme rainfall events in West Africa

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**Abstract** Heavy storm events frequently cause extensive damage, and often result in loss of life and property. The objective of this work is to build maps of Annual Maximum Daily Rainfall (AMDR) for various return periods for the Senegal River Basin. However, traditional stationary analyses are not suitable, since meaningful trends have been detected in historical hydrometeorological time series. Therefore, the GAMLSS (Generalized Additive Models for Location, Scale and Shape) tool is applied to fit the parameters of the probability density functions (pdfs). AMDR time series were estimated using observed daily rainfall grids and regional climate models (RCMs). The wide divergence in predicted trends from RCMs imposes the use of ensemble pdfs, which can be built using bootstrapping techniques. The plausible AMDR maps associated with various quantiles, interpolated from these ensemble pdfs, could be used by stakeholders to develop strategies of mitigation and adaptation to climate change impacts on floods events.

**Key words** non-stationarity; GAMLSS; regional climate models; bootstrapping; ensemble probability density function; maximum daily rainfall

## INTRODUCTION

The increase in rainfall and evaporation rates, caused by global warming in some areas of the Earth, has theoretically become a threat to the population, given the increased frequency of extreme events (Kundzewicz *et al.*, 2007). Moreover, these threats affect the developing countries unequally, where resources for adaptation measures and mitigation are limited (Huntington, 2006).

In particular, the Senegal River Valley (West Africa) is an area where land degradation and loss of vegetation cover is a persistent problem, due to terrain aridity and poor agricultural practices and grazing (Lebel *et al.*, 2009). In the future, these environmental problems will be exacerbated by severe floods associated with higher maximum rainfall. The hydrological systems in this region are affected by different drivers (climate change, land-use changes, demographic growth, among others), which do not allow one to assert that stationary conditions can be valid. Therefore, a non-stationary probabilistic model capable of reproducing the existing hydroclimatic variability should be used (Milly *et al.*, 2008).

Currently, regional climate models (RCM) constitute a tool for simulation of plausible climate scenarios, with a spatial resolution suitable for studies addressing the impact of climate change at the basin scale. In conjunction with Generalized Additive Models for Location, Scale and Shape (GAMLSS), it is possible to simulate the non-stationarity of the probability density functions (pdfs) of maximum rainfall and to obtain a measure of the uncertainty of change. However, due to the divergence in the results obtained from different RCMs, the use of ensemble techniques is needed to simulate the variability in precipitation.

The aim of the present study is the assessment of change in the pdfs of the annual maximum daily rainfall (AMDR) on the Senegal River Basin (West Africa), and the spatial pattern associated with the change. The first section describes the database used and the study area. Then, the procedure to be followed to identify the skill score of each RCM in ensemble building pdf for the sites is described. The results and discussion section presents a brief analysis of the maps constructed, and finally the findings of the work.

## STUDY AREA AND DATA

The study area consists of the Senegal River Basin (Fig. 1), which presents a strong decreasing gradient of precipitation in a south–north direction. This corresponds to the eco-regions Guinean

Forest Savanna (GFS), West Sudanian Savanna (WSS) and Sahelian Acacia Savanna (SAS), according to Olson *et al.* (2001). The main resources of the basin lie in the mountains of Fouta Djalon within GFS, where rainfall can exceed 2000 mm/year, while in the Sahel arid region there are areas with precipitation of less than 200 mm/year (Andersen *et al.*, 2001).

The AMDR series were obtained from the observed daily rainfall grids and from RCMs provided by the European ENSEMBLES Project (Christensen *et al.*, 2009). The observed series compiled by the IRD (Institut de Recherche pour le Developpement; previously ORSTOM, France) have been widely used in other studies of high-frequency cycles of rainfall in West Africa (Diedhiou *et al.*, 1999; Janicot & Sultan, 2001; Messager *et al.*, 2004; Paeth *et al.*, 2005; García & Giraldo, 2010). The IRD database has spatial resolution of 1°, and constitutes the baseline data for the bias analysis based on empirical cumulative distribution functions (cdfs), in spite of lacks of spatial continuity, which imposes restriction on the analyses (Fig. 1(a)). Because the RCMs have spatial continuity, for the analysis 120 sites on a regular grid of 1° × 1° (Fig. 1(a)) were selected. However, the spatial discontinuity of IRD data constrains the bias analysis to only 43 of these sites (Fig. 1(b)). The main features of the RCMs used in conjunction with IRD data, are presented in Table 1. The selection of RCMs was based on their temporal coincidence with the IRD data (period 1970–1990), which enables the bias analysis. A detailed description of the RCMs used in this study is presented by Christensen *et al.* (2009).

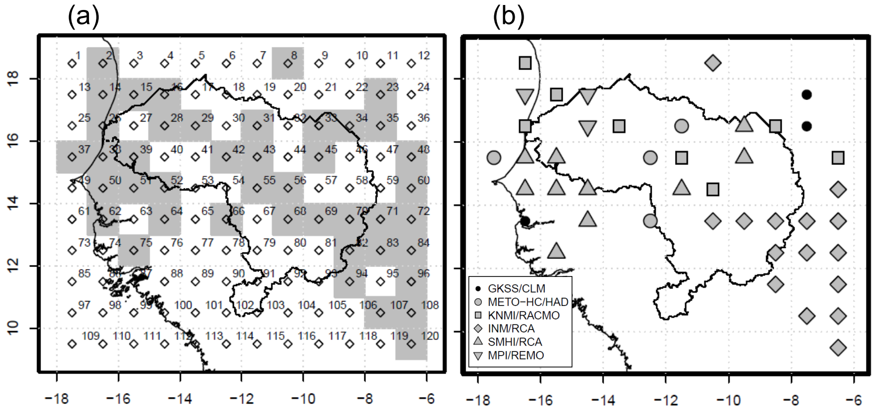


**Fig. 1** Senegal River Basin and the results of the bias analysis: (a) sites selected for analyses. The IRD sites are highlighted with gray squares; and (b) results of AMDR bias analysis. Markers indicate the RCMs which best fit the actual AMDR cdf in each site with IRD time series.

**Table 1** Summary of characteristics of the IRD data and selected RCMs.

| Name | Institute | GCM | RCM | Temporal coverage |
|---|---|---|---|---|
| IRD | | | | 1970–1990 |
| GKSS/CLM | GKSS(1) | ECHAM5 | CLM | 1961–2050 |
| METO-HC/HAD | HC(2) | HadCM3Q0 | HadRM3P | 1951–2099 |
| KNMI/RACMO | KNMI(3) | ECHAM5-r3 | RACMO | 1970–2050 |
| INM/RCA | INM(4) | HadCM3Q0 | RCA | 1951–2099 |
| SMHI/RCA | SMHI(5) | HadCM3Q0 | RCA | 1951–2100 |
| MPI/REMO | MPI(6) | ECHAM5-r3 | RACMO | 1950–2050 |

(1)Institute for Coastal Research, Germany; (2)Hadley Centre, UK; (3)Royal Netherlands Meteorological Institute; (4)National Institute of Meteorology, Spain; (5)Swedish Meteorological and Hydrological Institute; (6)Max Planck Institute, Germany.

## METHOD

### Bias analysis

Due to the spatial discontinuity of IRD data, the bias analysis was restricted to 43 sites as shown in Fig 1(a). For each of these sites, cdfs were constructed using AMDR series obtained from daily

IRD data and RCM databases, for the period 1970–1990. The bias analysis was carried out through computing the p-value of the two-sample Kolmogorov-Smirnov goodness-of-fit test between the AMDR cdf from IRD and the selected RCMs (Sheskin, 2000; Marques de Sa, 2003).

The summary of the results of bias analysis is presented in Fig. 1(b). The INM/RCA was the RCM with a better skill in 15 of the 43 bias analysis sites (grouped in the southeast part of the study area); followed by SMHI/RCA (10 sites, mostly in the west part of the study area); and the KNMI/RACMO (eight sites, distributed in the Senegal River Valley). The METO-HC/HAD (four sites), along with the GKSS/CLM and MPI/REMO (with three sites each), were the RCMs with less skill. The results of the bias analysis will be considered in the construction of the ensemble pdf for each site in the study area, giving greater weight to the RCMs with less bias.

### GAMLSS applied to non-stationary analysis

To analyse the trend of the pdf associated with the AMDR series for each site, the Generalized Additive Models for Location Scale and Shape (GAMLSS) were used. In the analysis, four theoretical probability distributions of two parameters were considered: Gumbel (GU), gamma (GA), Lognormal (LN) and Weibull (WEI). According to Rigby & Stasinopoulos (2005), and Stasinopoulos & Rigby (2007), GAMLSS are semi-parametric regression models for adjusting the parameters of the pdf of the response variable (AMDR) as a function of an explanatory variable (time) using nonparametric smoothing functions. GAMLSS has proved useful in modelling the evolution of pdf parameters of nonstationary hydrological time series of peak flows (Villarini *et al.*, 2009), temperatures (Villarini *et al.*, 2010), and dry spells of rainfall (Karambiri *et al.*, 2011). As an example, the results of the GAMLSS adjustment to the six RCMs considered are shown in Fig. 2 for site 28. Figure 2 shows the temporal variation of the pdf of AMDR represented with curves for different percentiles (5, 10, 25, 50, 75, 90 and 95%). The goodness of fit to the statistical model was assessed by evaluating the normality of the residuals and visual inspections of the qq-plots and the worm plot (not shown), according to the methodology presented by van Buuren & Fredriks (2001).

### Definition of skill scores for ensemble pdf

As seen from Fig. 2, the GAMLSS adjustment to various series of AMDR in each site predicts trends that differ in magnitude and sign, depending on the RCM considered. Therefore, for the building of the ensemble pdf for each site, greater weight was given to the RCMs that showed a better performance in the bias analysis, using bootstrapping techniques (Efron & Tibshirani, 1993). Random subsamples of size $N$ = 1000 of each RCM were built as they have had good performance in the bias analysis (e.g. 15 random samples of INM/RCA, for only three samples of GKSS/CLM or MPI/REMO). To obtain the evolution of the probability distribution of AMDR in each site, ensemble pdfs were constructed for each ten years in the period 1970–2050, and basic statistics (mean $\mu$ and standard deviation $\sigma$) and the quantiles for 5, 10, 25, 50, 75, 90 and 95% with their respective confidence intervals (95% CI) were estimated. The ensemble pdf built by applying this methodology for site 28 is shown in Fig. 3.

## RESULTS AND DISCUSSION

Once the statistics for the ensemble pdf at each site have been obtained for the period 1970–2050, these values were interpolated to generate maps depicting the spatio-temporal evolution of the AMDR distribution. In Fig. 4, the maps constructed for the mean, standard deviation and for the 90% quantile (or $Tr$ = 10 years) for 1990 and 2050, and the percentage difference between them, are presented.

The maps constructed for $\mu$ (Fig. 4(a)) have a spatial structure that matches the latitudinal gradient of mean annual precipitation in the region, yet the difference between them does not preserve this structure. Significant increase in $\mu$ is expected in the Senegal River Valley and the

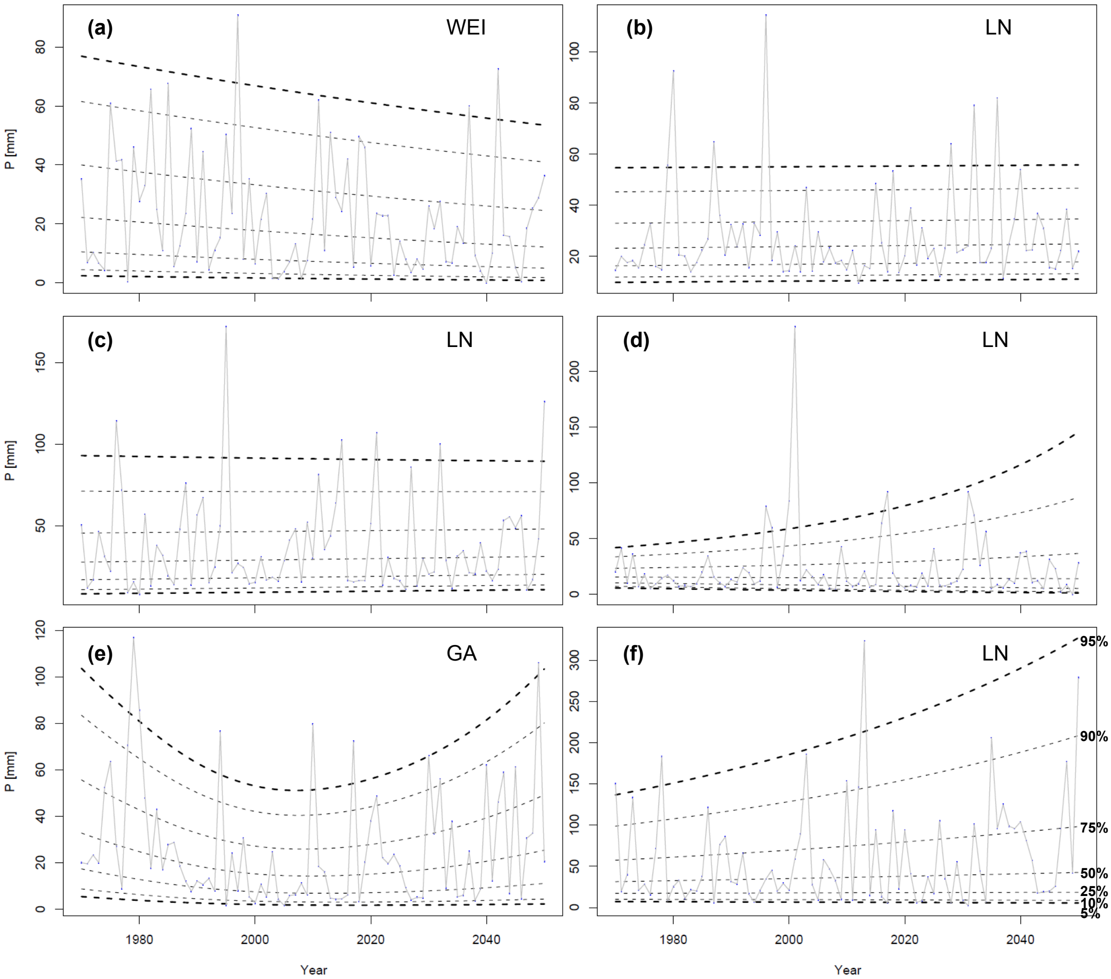


**Fig. 2** GAMLSS analysis of AMDR for site 28 for several RCMs: (a) GKSS/CLM, (b) METO-HC/HAD, (c) KNMI-RACMO, (d) INM-RCA, (e) SMHI/RCA, and (f) MPI-M-REMO. The centile curves (5 to 95 %) are represented by dashed lines. It should be noted that the ordinate scale is automatically fixed. The pdf used are gamma (GA), lognormal (LN) and Weibull (WEI).

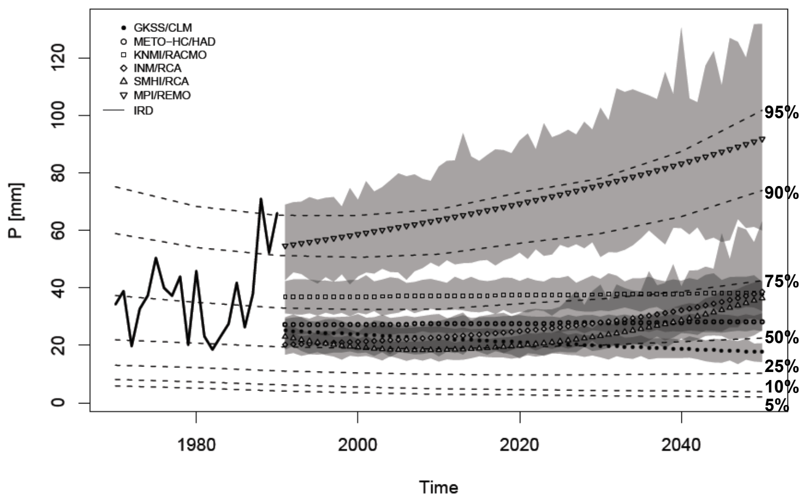


**Fig. 3** Ensemble pdf for site 28. The dashed lines show 5 to 95% quantiles of ensemble pdf, and markers represent RCMs mean values. The grey polygons show the mean variability in the period 1991–2050, using the 95% CI computed with bootstrapping. The IRD AMDR series in 1970–1990 is presented as a solid line.

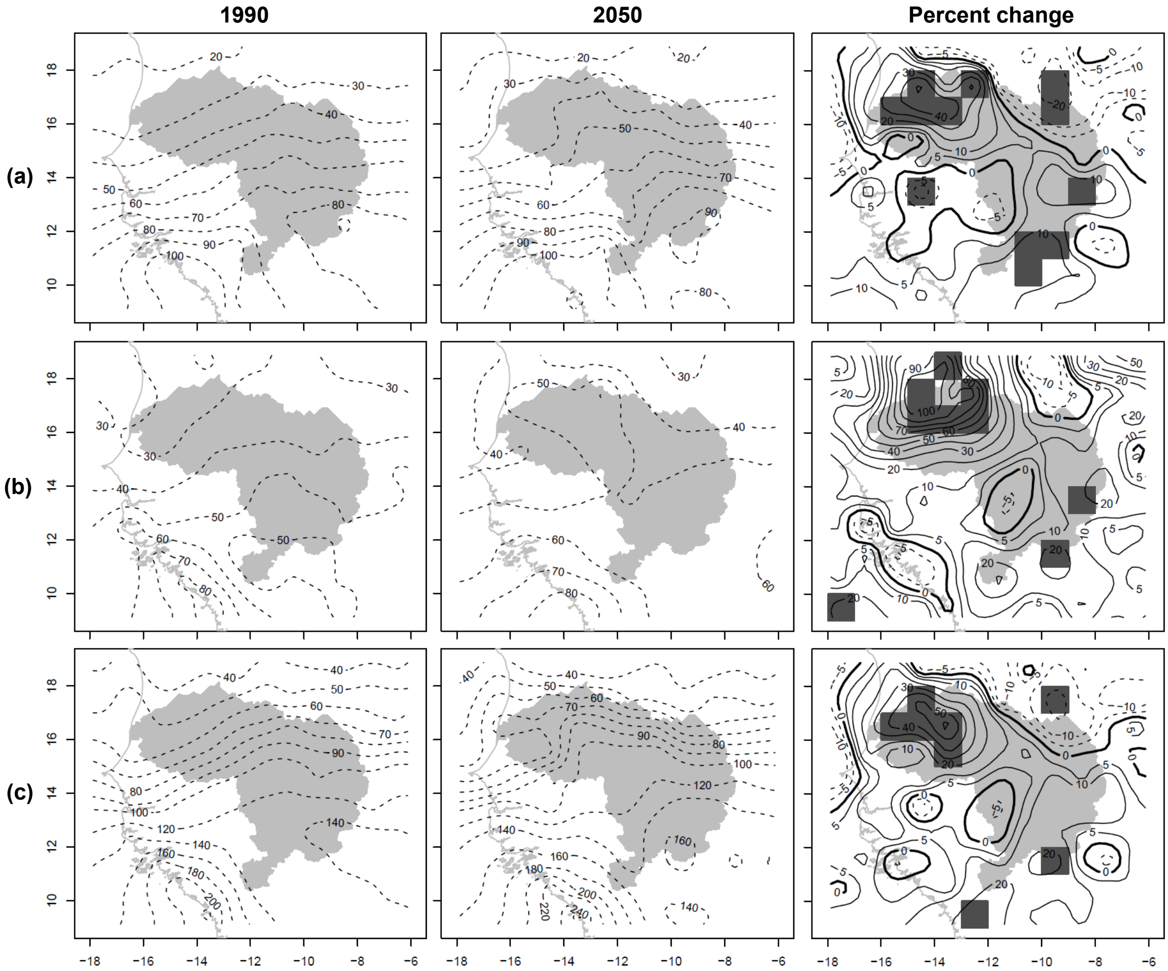


**Fig. 4** Interpolated maps from the GAMLSS analysis for each site: (a) mean $\mu$; (b) standard deviation $\sigma$; and (c) associated with $Tr$ = 10 years. The maps for the years 1990 and 2050, and the percentage difference between them, are presented. In the difference maps, negative values are dashed, while the confidence in projected changes is highlighted with the dark gray square.

upper basin,while in the Sahelian zone a significant decrease is projected. In the Valley area, the expected increase in $\mu$ will be about 10 mm, very similar to the increment for the upper basin, however in the lower basin represents an increase of over 40%. The maps of $\sigma$ (Fig. 4(b)) retain the latitudinal gradient of rainfall maps, although less significant than the $\mu$ maps. The difference between the two maps shows that in the lower basin a significant increase in $\sigma$ is projected, which could reach 100% (30 mm), while in the upper basin the projected increase in this parameter hardly exceeds 20% (10 mm). Finally, the maps for $Tr$ = 10 years (Fig. 4(c)) show a clear latitudinal gradient, with a decrease in maximum annual rainfall northwards. A general increase in the AMDR associated with $Tr$ = 10 years is expected, except at the northern edge of the basin and in some isolated areas of the study area within the Sudanian zone. This significant increase is foreseen in the lower basin, where a difference of more than 20–30 mm was calculated between the reference years (40–60%).

## CONCLUSIONS

In order to distinguish the predicted changes in the severity and frequency of AMDR in the Senegal River Basin, plausible climate scenarios provided by RCMs and observed data were considered. These databases, together with the GAMLSS methodology, allow consideration of the non-stationarity present in hydrometeorology in the Senegal River Basin. However, the good fit of the GAMLSS statistical model to simulated AMDR time series does not imply a proper coupling to the observed series from IRD database. Considering the observed grids of rainfall data, a bias analysis of AMDR time series was obtained from the RCM that allowed evaluation of the ability of climate models. Since an "ideal model" was not identified for the study area, in order to exploit all the information provided by the RCMs, an ensemble pdf was constructed for each site based on the bias analysis. Finally, the ensemble pdf which has been built for each site, allows estimation of the spatio-temporal change of AMDR in the study area. From the interpolated maps, various parameters of the ensemble pdf maintain the latitudinal gradient of rainfall in the area. However, in the difference maps for the reference years considered (1990 and 2050); this spatial pattern is not preserved. The percentage difference shows that in the Valley area, the increase of AMDR will be significantly higher than in the upper watershed area. In the Valley area, the increase in $\mu$ is projected to be more than 40% and the increase in $\sigma$ to be close to 100%. Both increases will be reflected in the maximum precipitation amount for the 90% quantile, which will rise by 40–60% in the lower part of the basin.

Due to the high vulnerability of the population of West Africa to climate variability and change, plausible AMDR maps could be used by stakeholders to develop mitigation and adaptation strategies, and to build "adaptive capacity".

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