Characterizing fine-scale extreme rainfalls over West Africa.
Past&future changes, and operational implications.

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I. Context

It is now widely accepted that global warming will significantly impact rainfall regimes globally but also locally. Such rainfall intensification has already been detected in several regions of the world (Alpert *et al.*, 2002; Alexander *et al.*, 2006; Westra *et al.*, 2013; Fischer and Knutti, 2014; Fischer and Knutti, 2016), even though their attribution to the climate warming is not straightforward (see Min *et al.*, 2011; Zhang *et al.*, 2013, for such attribution studies). Rainfall intensification is part of what Giorgi *et al.* (2011) have defined as a more extreme climate, that is longer dry spells and more intense rainfall when it does rain (Trenberth *et al.*, 2003; Trenberth, 2011).

In West Africa (see map of FIGURE 1a), a region particulary known for the great drought in the 70th-80th (FIGURE 1b), a rainfall intensification has been detected since the beginning of the XX^e century by Panthou *et al.* (2014b). In the central Sahel daily rainfalls have been shown to be more intense than it was during the preceding wet period in the 50s and the 60s . In fact, the Sahel is experiencing a new climate era (FIGURE 1c). Indeed, the risk of dry periods during the rainy season remains at a similar level to those observed during the great drought but it is accompanied by an intensification of the rainy events when they occur. This increase of heavy rainfall events seems to be related to the warming of the Sahara (itself a consequence of global warming) and is expected to continue in the coming decades (Taylor *et al.*, 2017). A recent study shows that the increase in cumulative rainfall events is accompanied by an increase in sub-daily intensities (Panthou *et al.*, submitted).

A better characterization of the distribution of hydrological extremes (tail, evolution over time, ...) may induce changes for many operational services from hazard forecasts and annoucement to the definition of rules for any hydraulic studies. This PhD will help to better detect changes in extreme precipitation regime, to better characterize these changes and finally help to redefine operational rules. Such changes in hydrological extremes are particularly pressing for decision makers in West Africa, as the statistical tools used for infrastructure design have not been updated since the 1970s (Amani and Paturel, 2017). To cope with ongoing increasing of hydro-climatic hazards and risks (Wilcox *et al.*, in prep. Di-Baldassarre *et al.*, 2010), there is an urgent need to update these procedures in order to design and manage structures such as dams and dikes and, as a result, aid in risk mitigation, as well as the development of hydroelectric energy and irrigation systems. This adjustment will have to be articulated around three pillars:

1. A quantitative **detection** of how extreme hydro-meteorological variables evolve over time.
2. An improved **understanding** of physical processes involved in this evolution: this will allow to **attribute** the past changes, and then **project** the future changes.
3. Formatting the information about the non-stationarity of hydro-meteorological extremes to facilitate: its interpretation and put it in the form of operational tools so that it can be used by the end users.

Depending on the hydro-meteorological variable and the spatio-temporal scale studied, these three pillars bring out different scientific barriers that have been more or less tackled.

These changes are well documented concerning the daily rainfall distribution over the the Sahel, but less have been done concerning sub-daily rainfall intensities. To our knowledge, the only exception is Panthou *et al.* (submitted), but a lot of works remain concerning the quantification of the detected increase of sub-daily intensities. Yet, quantify such changes is very valuable for both atmospherician and hydrologists:

- a better detection of trends in sub-daily intensities would help to better understand the underlying factors and processes that have driven such changes, and thus is a prerequisite for attribution studies;
- such changes would have large hydrological consequences increasing the runoff and the number of flood events through both pedological transformations and the enhancement of the primary hydrological processes (hortonian runoff).

Moreover, this intensification may have dramatic consequences for the environment and populations because they favor: (i) the degradation of the surface (soil crusting), (ii) socio-economic damages (e.g. crops, house, infrastructure, ...), (iii) the production of large runoff, themselves at the origin of endoreism burst and floods, (iv) displacement of population from flooded area (hazards and ponds/river enlargement), and (v) societal habits changes associated with a change in the hydrological season. All these associated with poorly prepared infrastructures make this region one of the most vulnerable to face climate changes.

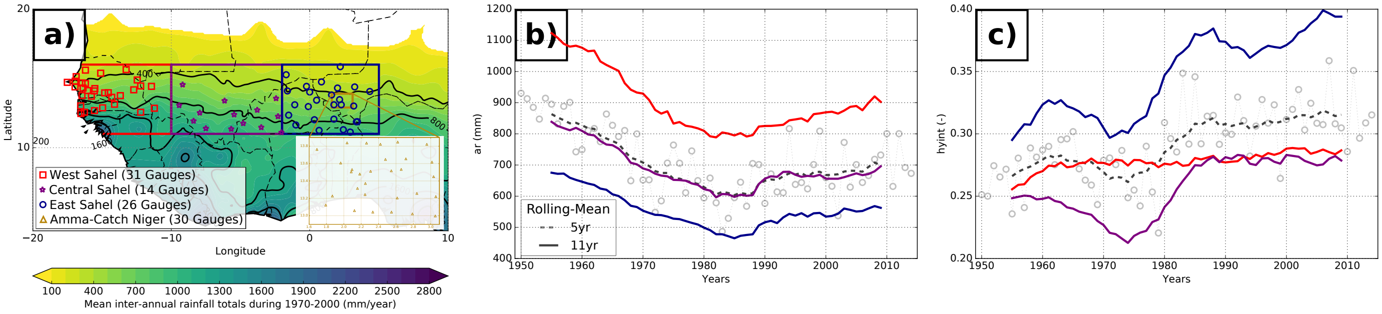

Figure 1: a) Map of West-Africa: boxes represents sub-Sahelian regions where daily rain-gauges are represented by points; the AMMA-CATCH Niger network is also displayed. b) Evolution of annual totals over the three sub-sahelian boxes. c) Evolution of hydro-climatic intensity over the three sub-sahelian boxes.

II. Issues and objectives

Rainfall intensities changes at daily timescale can be different than the rainfall intensities changes at sub-daily timescales (hourly, sub-hourly). Hydrological and ecological processes (runoff, soil crusting, ...) in this region are particularly sensitive to high fine-scale intensities (spatio-temporal scale of convective cells – ≤ 1 h in time, and ≤ 20 km^2 in space). The declination of the three pillars described below is given in the following.

1. As compared to temperature, for which detection of warming all over the world is undisputable, detecting rainfall regime changes is much more challenging, for two main reasons. One is that the rainfall interannual variability is much larger than that of temperatures, meaning that longer time series are needed to obtain a signal to noise ratio allowing a statistically significant detection of any trend or break point Hawkins and Sutton, 2012. Secondly, rainfall is also much more variable in space, even when considering annual totals, meaning that a larger number of point series have to be used in diagnostic studies so as to diminish bias linked to sampling effects. In the semi-arid tropics these two sampling effects are especially pronounced because rainfall variability is remarkably strong and because it is not properly captured by the low density of the national meteorological networks.
2. Recently, extreme rainfall in West Africa has received increasing attention from scientists. Some deal with the atmospheric environment associated with case studies of extreme events (Engel *et al.*, 2017; Lafore *et al.*, 2017), others have more global approaches (Taylor *et al.*, 2017). However, they are still few in number, and there is still much to be discovered concerning the quantification of past changes, and projections of future changes for which there is no studies that have already addressed this issue.
3. To describe how the extreme distribution of rainfall intensity change with the time-scale, operational organizations uses the so-called Intensity-Duration-Frequency – IDF – curves (see black curves in Figure 2).

Such charts are based on stationary hypothesis. Taking into account the non-stationarity of extreme rainfall distributions will requires to modify such charts and their interpretation.

This thesis subject propose to address these three scientific issues. It is based on recent statistical developments used to derive IDF curves using a framework that combine Extreme Value Theory (Coles, 2001) and fractal theory (Menabde *et al.*, 1999). Such framework will permit to tackle the different issues presented before and will allow to: detect changes in fine-scale extreme rainfalls during the recent past, project future changes, and propose new metrics usable by operational organizations and taking into account the non-stationarity of extreme rainfalls.

III. Thesis subject

III.1. Methods

The thesis topic proposes to use the methodological developments realized in Panthou *et al.* (2014a) and Sane *et al.* (2017) concerning the statistical modeling of extreme rainfall at fine scale. These studies are based both (i) on the methodological framework of Extreme Values Theory (modeling the distribution of extreme rainfall intensity) and (ii) on fractal theory to characterize scale relationships (link between distributions of different time scales). These studies are based on the famous "stationary hypothesis" of extremes[1] that will be challenged in this thesis work. This framework model the random extreme samples I for different duration D as:

$$I(D) \sim \text{EVD}\left\{\theta(D)\right\} \qquad (1)$$

in which: EVD is an Extreme Value Distribution (either GEV or GPD, depending on how I are defined, see Coles, 2001, for explanation on Extreme Value Theory); and θ is a vector of parameters that describe the distribution over a range of durations.

III.2. Detect past changes in extreme fine-scale rainfalls

It is proposed here to adapt this methodological framework by making the parameters of the model dependent on time in order to model the evolution of extreme rainfall (**detection**). In this case, EQUATION 1 becomes EQUATION 2:

$$I(D, t) \sim \text{EVD}\left\{\theta(D, t)\right\} \qquad (2)$$

where t denotes the time. FIGURE 2 illustrates possible changes between in stationary model (in black) and a non stationary model (in this case return levels goes from black to coloured lines following the obtained time-dependence). The model is expected to minimize sampling effects by aggregating the extreme rainfall of different scales in the same sample.

Such analysis will be done using the unique network AMMA-CATCH Niger (Lebel *et al.*, 2009). This network is composed by 30 tipping-bucket rain gauges located around Niamey FIGURE 1, that have recorded the rainfalls intensities at 5-minute timesteps since 1990 to now, giving thus a unique dataset of 30 long-term (27 years) 5-minute rainfall series.

III.3. Project future changes in extreme fine-scale rainfalls

Using the methodological developments and results of the previous section (III.2), the thesis will focus on the projection of future changes in fine-scale rainfalls using different projections of rainfalls over West-Africa. This will be done by applying the non-stationary IDF models on different datasets:

- CORDEX Africa: This is an ensemble of Regional Climate Model (RCM) simulations that have been realized over different period (past, and future using different Greenhouse Gaz emissions scenario). In such simulations, the grid size is around dozen of km and the convection is parametrized.
- CP-4: This is a Convective Permitting regional simulation of African climate. This simulation is representative of a present-day period and a end of century period (using the highest GHG emission scenario – RCP8.5). In this simulation, the grid size is 4.5 km and the convection is explicitly resolved.

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[1] Extreme sample are i.i.d: independent and identically distributed

- StochaStorm: This is a stochastic rainfall simulator that simulate Mesoscale Convective Systems (MCS) at a very high resolution (1 km^2). Present day simulations are already available and ongoing work is realized to produce future scenarios.

The present-day period of these different datasets will be used to evaluate the realism of the different simulations. Future period will be used to estimate non-stationary IDF evolution.

III.4. Develop non-stationary metrics for risk assessment

In a stationary framework, the IDF curves can be used directly by operational organizations (via charts called intensity-duration-frequency. The impact of non-stationarity on the expected operational tools is consequent and will require a big effort of adaptation of the current tools: it requires to correctly interpret the evolution of return levels presented in FIGURE 2, which is a tricky point. New concepts, terms, and metrics have been recently developed, such as the Design Lile Level, or the reliability. The implementation of such metric will be the heart of the third part of the thesis.

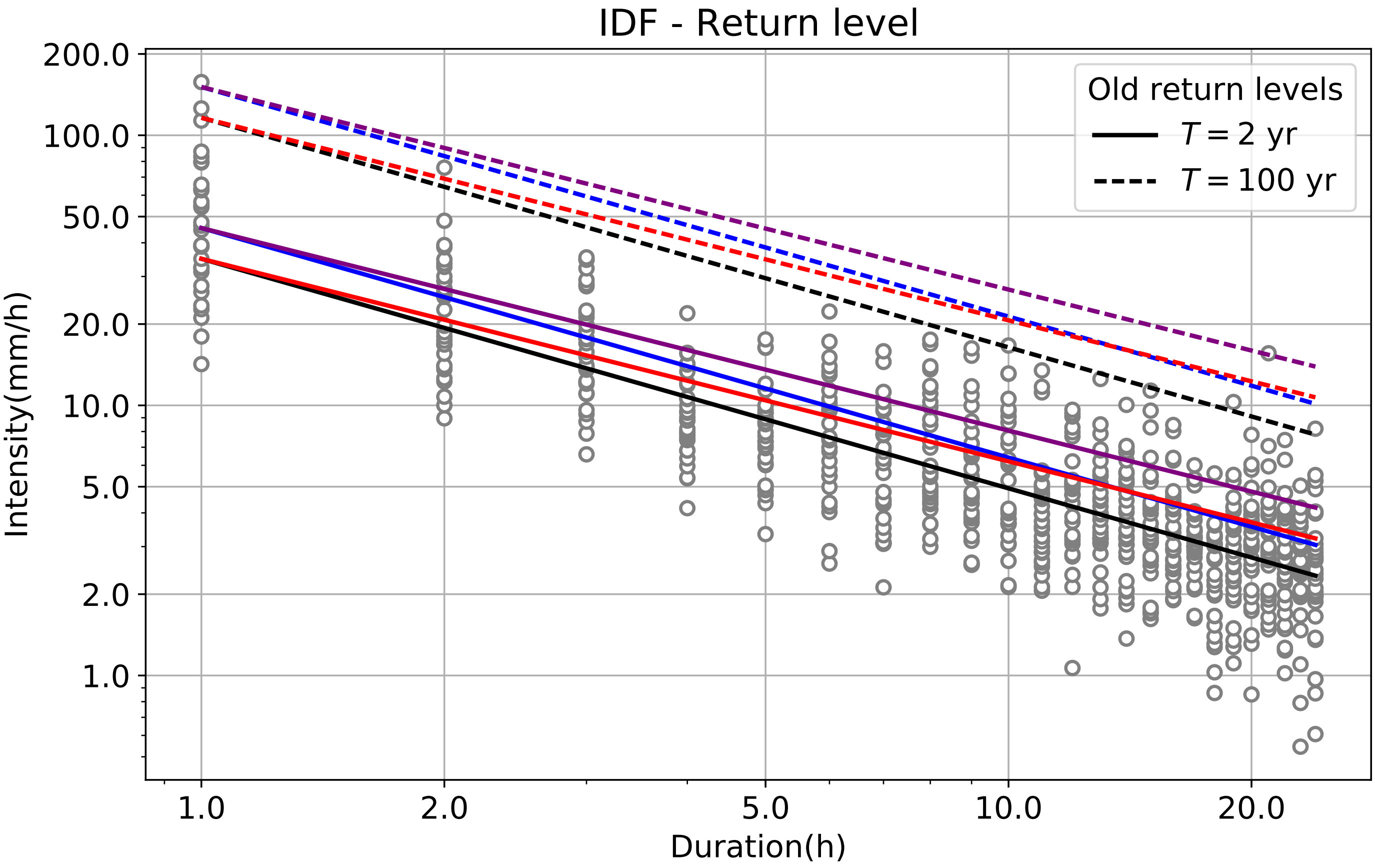

Figure 2: Schematic example of IDF return level. In black: "old" return levels (obtained using a stationary IDF fit, parameter values similar to those observed at Dakar station). Grey circle: randomly generated samples using the stationary IDF. Other colors show possible non-stationary IDF return levels: change in scaling between duration in red; increasing of the intrinsic intensity of rainfall in blue; compound changes in scaling and intensity in purple.

IV. References

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