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LETTER

Rainfall intensification in tropical semi-arid regions: the Sahelian case

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Abstract

An anticipated consequence of ongoing global warming is the intensification of the rainfall regimes meaning longer dry spells and heavier precipitation when it rains, with potentially high hydrological and socio-economic impacts. The semi-arid regions of the intertropical band, such as the Sahel, are facing particularly serious challenges in this respect since their population is strongly vulnerable to extreme climatic events. Detecting long term trends in the Sahelian rainfall regime is thus of great societal importance, while being scientifically challenging because datasets allowing for such detection studies are rare in this region. This study addresses this challenge by making use of a large set of daily rain gauge data covering the Sahel (defined in this study as extending from 20°W–10°E and from 11°N–18°N) since 1950, combined with an unparalleled 5 minute rainfall observations available since 1990 over the AMMA-CATCH Niger observatory.

The analysis of the daily data leads to the assertion that a hydro-climatic intensification is actually taking place in the Sahel, with an increasing mean intensity of rainy days associated with a higher frequency of heavy rainfall. This leads in turn to highlight that the return to wetter annual rainfall conditions since the beginning of the 2000s—succeeding the 1970–2000 drought—is by no mean a recovery towards the much smoother regime that prevailed during the 1950s and 1960s. It also provides a vision of the contrasts existing between the West Sahel and the East Sahel, the East Sahel experiencing a stronger increase of extreme rainfall.

This regional vision is complemented by a local study at sub-daily timescales carried out thanks to the 5 minute rainfall series of the AMMA-CATCH Niger observatory (12000 km^2). The increasing intensity of extreme rainfall is also visible at sub-daily timescales, the annual maximum intensities have increased at an average rate of 2%–6% per decade since 1990 for timescales ranging from 5 min to 1 hour. Both visions—regional/long term/daily on the one hand, and local/27/years/sub-daily, on the other—converge to the conclusion that, rather than a rainfall recovery, the Sahel is experiencing a new era of climate extremes that roughly started at the beginning of this century.

1. Introduction

It is now widely accepted that global warming of the atmosphere will significantly impact rainfall regimes. In fact, several authors have documented that rainfall intensification has already occurred in several regions of the world (Alpert *et al* 2002, Alexander *et al* 2006, Westra *et al* 2013, Fischer and Knutti 2014, Donat *et al* 2016, Fischer and Knutti 2016), even though the link with anthropogenic greenhouse gas emissions is difficult to establish with total certainty (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 hydrological climate, that

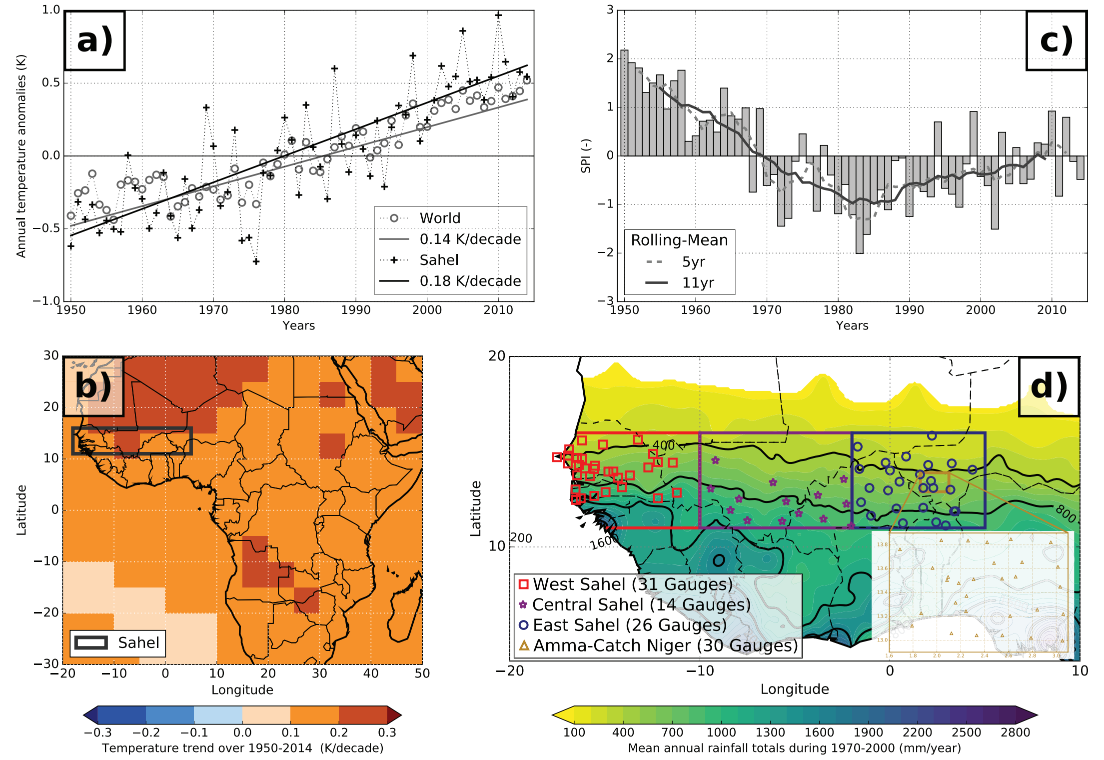

Figure 1. (*a*) Comparison of temperature anomalies and trends (Theil–Sen estimator) for the entire world and the Sahelian region from the mlost dataset (Vose *et al* 2012). (*b*) Temperature trends for Tropical Africa, computed over the 1950–2014 period from the mlost dataset (Theil–Sen estimator). (*c*) Standardized annual precipitation index computed over the whole Sahelian region represented by the black rectangle in (*b*). (*d*) Long term rainfall series used to quantify rainfall intensification over three boxes at daily scale and over the AMMA-CATCH Niger area at sub-daily timescales; mean annual rainfall totals are also represented for the period 1970–2000.

is longer dry spells and more intense rainfall when it rains (see also, Trenberth *et al* 2003, Trenberth 2011). Tropical semi-arid regions are extremely vulnerable to such long term modifications of the rainfall regimes, for two major reasons. One is that rainfall is below potential evapotranspiration most of the year, meaning that vegetation is generally stressed and that any decrease of rainfall occurrence will jeopardize the delicate process that allows trees, bushes, and grass to adapt to such unfavorable conditions. Secondly, more intense rainfall negatively affects the soil cohesion and produces intense runoff threatening infrastructures in an environment where Hortonian runoff is predominant (overland flow is generated when rainfall intensity exceeds the infiltration capacity of the soil—Horton 1933).

No other tropical semi-arid region is more at risk facing climate change than the region extending from the Atlantic Ocean to the Indian Ocean south to the Sahara desert, forming the largest continuous area of this kind on Earth. The West African part of this vast semi-arid band is commonly referred to as the Sahel, extending from 20° W to 10° E. It is particularly vulnerable given its fast growing population (Niger has the largest natural increase of population in the world with a total fertility rate of 7.6 births per woman), that could reach 240 million by 2050 and 540 million by 2100, from 90 million in 2015 (Population Reference Bureau 2016). The economy relies heavily on rainfed agriculture and regular watering is essential for the survival of crops due to extremely high temperatures recorded in this region. The Sahel is experiencing an increase of temperatures (average rate of 0.18 K decade^{-1} over the past 60 years, see figures 1(*a*) and (*b*)) which is expected to increase the potential evapotranspiration. This region is also known for the intense and long-lasting drought of the 1970–2000 period (figure 1(*c*)), raising the issue of how this drought and the so-called recovery of the recent years (Dong and Sutton 2015, Sanogo *et al* 2015) translated in terms of rainfall intensities at daily and sub-daily timescales.

Compared to temperature, for which detection of warming in most regions of 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.

Another key issue regarding the hydrological implications of rainfall intensification relates to timescale effects. The most common rainfall series available worldwide are daily, which is often not appropriate for hydrological studies. This timescale issue is of particular concern in semi-arid regions such as the Sahel, because rainfall is highly intermittent there (lasting for a few hours), and rainfall series at sub-daily timescales are extremely rare if not inexistent. In a very fragmented hydrological landscape (Desconnets *et al* 1997) where ephemeral streams are dominant, Vischel and Lebel (2007) showed that the annual runoff estimation over small catchments may be underestimated by 65% when using daily rainfall totals instead of the observed 5 minute values as input to a Hortonian model. Thus, assessing how rainfall intensification may translate into hydrological intensification—i.e. more extreme runoff and floods, and more extreme water scarcity—requires working at timescales that allow a proper representation of sub-daily rainfall intensities.

This paper addresses this timescale issue by combining the information provided by West African national weather services at daily scale since 1950 with the 5 minute data of the AMMA-CATCH observatory (Lebel *et al* 2009) in operation since 1990.

Two recent studies have dealt with rainfall intensification in the Sahel. Panthou *et al* (2014) showed that, over the last two decades, extreme rainfall accounted for an increasing share of the annual totals for a 6° × 12° Sahelian sub-region. Taylor *et al* (2017), on the other hand, found that the number of extreme storms has increased during the last thirty years over the whole region. This paper refines the above results in two ways. First (in the next section), it updates the daily rainfall analysis at the scale of the entire Sahel and also identifies differences between sub-regions. Secondly (section 3), attention is paid to changing extreme rainfall characteristics at sub-daily timescales, using a specific research dataset.

2. Sub-regional changes in the rainfall regime at daily timescale

2.1. Whole Sahel

In their seminal paper, Giorgi *et al* (2011) have coined the concept of hydro-climatic intensification, a climatic transient state combining a rarefaction of rainfall occurrence (commonly quantified through a yearly or monthly decrease of the number of rainfall events) and a reinforcement of the rainfall intensities when it rains (a notion that may refer to various timescales of rainfall accumulation, typically ranging from sub-hourly to daily). In the first such study regarding Africa, Panthou *et al* (2014) have shown that rainfall intensification is indeed taking place in a region roughly corresponding to the East Sahel box of the present study (see figure 1). Using 71 stations available over the Sahel (20°W–5°E; 11°N–16°N; figure 1), the Sahelian regional mean hydro-climatic intensity is computed at the daily scale for each year y of the period 1950–2014 as:

$$\overline{\mathrm{HCI}_S(y)} = \frac{\overline{R_S(y)}}{\overline{N_S(y)}} \qquad (1)$$

where $\overline{R_S(y)}$ stands for the regional mean intensity of rainy days for year y and $\overline{N_S(y)}$ stands for the regional mean number of rainy days. A threshold of 1 mm was used to differentiate dry and rainy days (as recommended by Zhang *et al* 2011) in order to eliminate under-reporting of very small rainfall values at some stations. The term 'regional' refers here to a mean point value, not to an areal-averaged value—computed over the Sahel box (or over one of the sub-Sahelian boxes, see figure 1(*d*)). The regional mean values were computed using a kriging approach, see details of computation in the supplementary materials available at stacks.iop.org/ERL/13/064013/mmedia.

The Sahelian regional mean annual rainfall total – $\overline{\mathrm{AR}_S(y)}$—is also computed for y ranging from 1950–2014, and reported with the interannual evolutions of $\overline{N_S(y)}$, $\overline{R_S(y)}$, and $\overline{\mathrm{HCI}_S(y)}$ in figure 2.

$\overline{\mathrm{AR}_S(y)}$ and $\overline{N_S(y)}$ display a similar monomodal evolution characterized by a decrease between 1950 and 1985 (drought signal) followed at the end of the 1980s by a slight recovery. Since then, $\overline{N_S(y)}$ stays at a mean level (43 events per year) that remains clearly below the 1950–1970 average (52) as well as below the 1950–1990 average (47), while $\overline{\mathrm{AR}_S(y)}$ has continuously increased and is reaching the 1950–2014 average (≈700 mm yr^{-1}).

$\overline{R_S(y)}$ has an overall similar shape with a decrease between 1960 and 1975, followed by a stabilization, and then an increase from the mid-1980s. Two important differences are however noticeable: in relative values, the overall 1950–1980 decrease is smaller for $\overline{R_S(y)}$ than for $\overline{N_S(y)}$ (10% against 25%) and the overall increase over 1985–2014 is larger for $\overline{R_S(y)}$ than for $\overline{N_S(y)}$ (10% against 5%). As a result, the mean intensity of rainy days is now roughly at the same level as it was in the 1950s, while the mean number of rainy days still displays a deficit of 20%.

$\overline{\mathrm{HCI}_S(y)}$ displays an evolution that stems directly from that of the two previous parameters, with four stages: an increase from 1950–1960 linked to the decrease of the rainfall occurrence while the mean intensity of rainy days remains roughly stable; a stabilization from 1960 to 1975, as a result of both $\overline{N_S(y)}$ and $\overline{R_S(y)}$ decreasing simultaneously over this period; a sharp increase from 1975–1990 as $\overline{N_S(y)}$ was still decreasing while $\overline{R_S(y)}$ was increasing; and finally the last 20 years displaying a slower but continuous increase due to the intensity increasing at a greater rate than the occurrence.

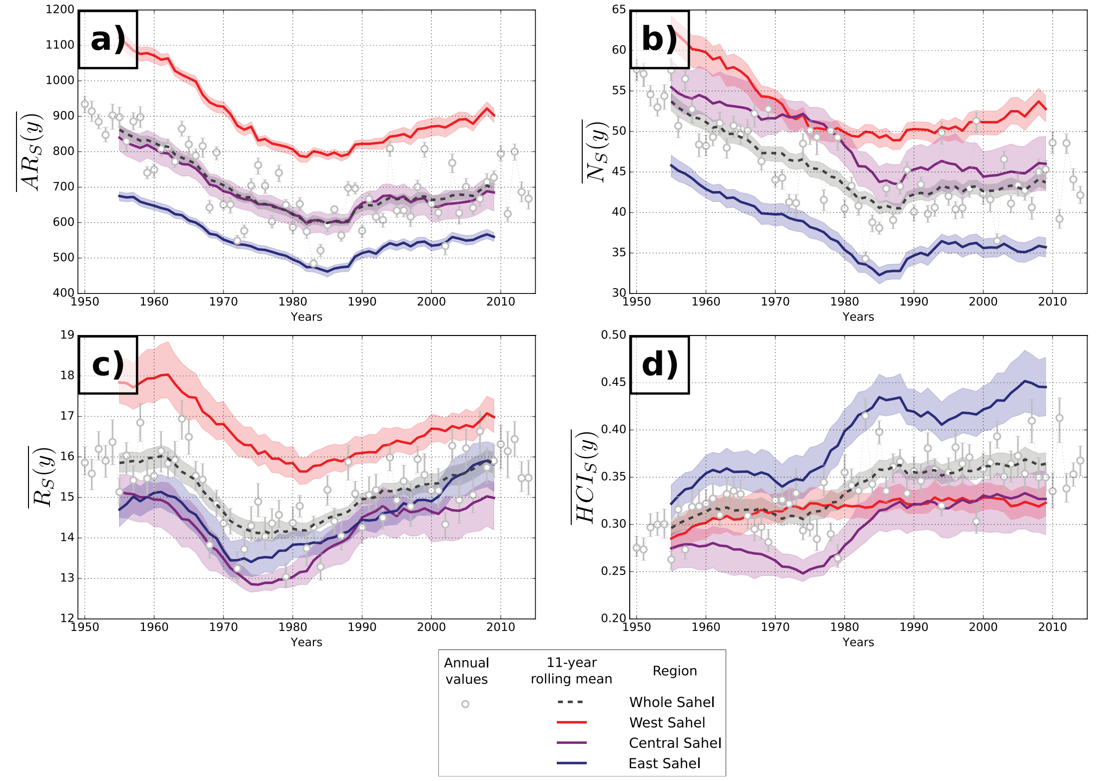

Figure 2. Evolution of (*a*) the mean annual rainfall totals (mm yr^{-1}), (*b*) the mean number of rainy days (*d*), (*c*) the mean intensity of rainy days (mm d^{-1}), and (*d*) the mean hydro-climatic intensity (mm d^{-2}); over the whole Sahel and sub-domains (West, Central and East Sahel). Error bars (resp. shaded area) delineate 80% confidence intervals for annual values (resp. 11 year rolling mean).

There is thus clear evidence of hydro-climatic intensification in the Sahel since the mid-1970s. It is also worth noting that, as is shown below when discussing the West–East contrast, the increase of the mean intensity of rainy days over the last 2–3 decades is largely due to an increasing occurrence of the highest daily intensities (see table 1), as already evidenced by Panthou *et al* (2014) and Taylor *et al* (2017).

2.2. East–West Contrast

Early on, Ali and Lebel (2009) have pointed to a weaker coherency of the rainfall regime at decadal scale between the West and the East Sahel, starting approximately at the end of the 1990s. This trend is also seen in model simulations in a context of global warming (Biasutti 2013, Seth *et al* 2013). This pattern has persisted over the past decade (figure 2(*a*), table 1), West Sahel remaining drier (15% less rainfall over 2005–2014 than over 1955–1964) than East Sahel (12% less rainfall over 2005–2014 than over 1955–1964). The different behavior between West Sahel and East Sahel also holds when considering the evolution of $\overline{\mathrm{HCI}_S(y)}$ over the last 60 years (figure 2(*d*)). In the West, the index increased by 15% between 1950 and 1970 and then remained fairly stable. In the East, following an initial increase during the 1950s, the index reached a plateau in the 1960s, such that in the mid-1970s the value of the index is 10% higher than it was at the beginning of the 1950s. The index then sharply increased by almost 20% between 1975 and 1985; a new period of increasing hydro-climatic intensity is observed since 1995, the index reaching the unprecedented value of 0.45 in 2006. This is the result of a different evolution of $\overline{N_S(y)}$ and $\overline{R_S(y)}$, as may be seen from figures 2(*b*) and (*c*). $\overline{N_S(y)}$ reached its lowest values in the middle of the 1980s; it slightly increased afterwards but the average over the last ten years remains around 15% below the average of the 1955–1964 period for both regions, see table 1. On the opposite, $\overline{R_S(y)}$ is now 6% larger than it was in the mid-1950s in the East, while it remains 5% smaller in the West. Consequently, while $\overline{\mathrm{HCI}_S(y)}$ was roughly 15% larger for the East Sahel as compared to the West Sahel in the mid-1950s, it is now 35% larger. This discrepancy is also visible when considering the share of the annual total produced by extreme rainfall (as defined in Panthou *et al* 2014)—which increased by 13% in the East and by 4% in the West (table 1).

For the sake of clarity and conciseness, the results for the Central Sahel are not discussed in detail here. Due to the slight meridional tilting of the annual isohyets (figure 1(*c*)), this box has a larger annual rainfall total (700 against 560 mm yr^{-1}) and a larger number of rainy days (49 against 38) than the East Sahel; however it displays similar patterns of evolution for the different statistics—$\overline{\mathrm{AR}_S(y)}$, $\overline{N_S(y)}$, $\overline{R_S(y)}$, and $\overline{\mathrm{HCI}_S(y)}$—in clear contrast with the West Sahel.

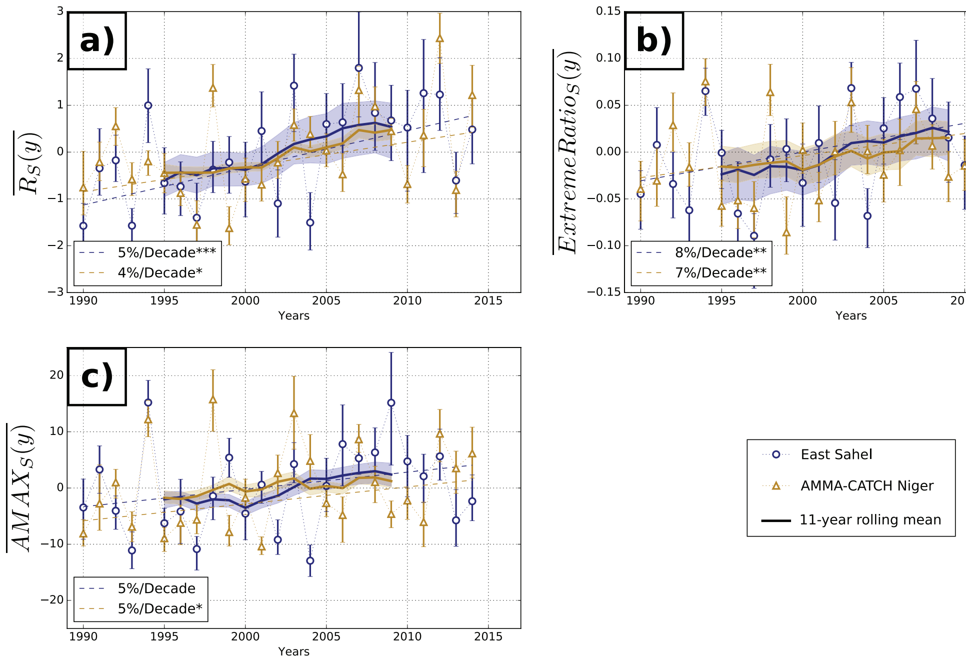

Figure 3. Comparative evolution of the anomalies over the East Sahel box and the AMMA-CATCH box for different statistics: (*a*) mean intensity of rainy days (mm d^{-1}); (*b*) share of annual total produced by extreme rainfall (−) as defined by Panthou *et al* (2014); and (*c*) mean annual maximum daily rainfalls (mm d^{-1}). Trends (Theil–Sen estimator) and significance (Spearman test, 1%***, 5%**, 10%*) are given in the inset legends. Error bars (resp. shaded area) delineate 80% confidence intervals for annual values (resp. 11 year rolling mean).

Table 1. Relative variation of some key statistics of the rainfall regime: (1) over 1975–1984 as compared to 1955–1964, and (2) over 2005–2014 as compared to 1955–1964. These two differences are separated by a semicolon (1; 2). Stars indicate the significance level of the Wilcoxon rank-sum test: 10% (*), 5% (**), and 1% (***).

	Annual totals	Nb of rainy days	Mean intensity of rainy days	Share of annual total produced by extreme rainfall
West Sahel	−25%***; −15%***	−16%***; −12%**	−12%***; −5%*	−14%**; +4%
Central Sahel	−23%***; −15%***	−10%*; −14%***	−13%***; +1%	−25%***; −1%
East Sahel	−23%***; −12%***	−17%***; −17%***	−9%***; +6%**	−11%**; +13%***

3. Rainfall regime changes at sub-daily timescales

The rainfall observations used here to investigate rainfall intensification at sub-daily timescales started in Niger in 1990 (Lebel *et al* 1992) and have since continued as part of the AMMA-CATCH Niger (ACN) observatory (inset in figure 1(*d*)), providing continuous series of 5 m in rainfall at 30 recording sites (Cappelaere *et al* 2009). This constitutes a unique set of *in situ* rainfall data with no other of its kind in tropical Africa, covering the period of rainfall intensification detected on daily series. The ACN box is located right in the center of the East Sahel (ES) box (figure 1(*d*)); despite their large difference in surface area, both boxes display comparable average rainfall climatologies over 1990–2014 (table 2). These similar statistics are all the most significant since there are no station in common between the ACN dataset and the ES dataset. The series of the main annual statistics describing the rainfall regime at daily scale (annual totals, mean intensity of rainy days and number of rainy days) are reasonably well correlated, accounting for the important spatial rainfall variability in this region (table 2). Further investigating whether the climatology of the ACN box may be considered as representative of the climatology of the ES box at daily scale, figure 3 represents the year to year cofluctuation of the parameters describing the intensification of the rainfall regime at daily scale as detected in the previous section over the three sub-regional boxes. The long term trends of these parameters are well captured by the ACN dataset, with comparable values: 4% per decade for ACN against 5% for ES when considering the mean intensity of rainy days; and 7% per decade against 8% when considering the share of the annual total produced by extreme rainfall. The fact that the ACN network is able to capture the regional signature of regional rainfall regime changes is likely due to a combination of three factors: (i) the rainfall regime change is somewhat homogeneous over the East Sahel, (ii) the signal is sufficiently strong compared to the variability and the record length of the series, and (iii) the network density of the ACN network limits the sampling effects

Table 2. Comparison of some key observed statistics of the rainfall regime over the period 1990–2014 between the East Sahel box and the AMMA-CATCH Niger box. The mean regional interannual value is displayed and is accompanied in bracket by the 10th–90th quantile interval. The third column gives the Spearman correlation between AMMA-CATCH and East Sahel rainfall statistics series; stars indicate the significance level of the correlation: 10% (*), 5% (**), and 1% (***).

	East Sahel	AMMA-CATCH Niger	Spearman ρ
Annual totals (mm yr^{-1})	549 [461;641]	511 [430;579]	0.69***
Nb of rainy days (d)	36 [32;40]	35 [31;40]	0.61***
Mean intensity of rainy days (mm d^{-1})	15.3 [13.8;16.5]	14.4 [13.5;15.7]	0.58***
Hydroclimatic intensity (mm d^{-2})	0.43 [0.37;0.46]	0.41 [0.35;0.49]	0.44**

Table 3. Proportion of cases where the annual maximum rainfall amount extracted independently for each timescale occurs within the annual maximum daily rainfall.

	5 m	10 m	15 m	20 m	30 m	45 m	1 h	1 d
Contingency (%)	34%	40%	44%	48%	52%	60%	65%	100%

generated by the small size of the box. The coherency between the trends detected over the two boxes for daily rainfall, provides confidence for inferring that the conclusions of a study at sub-daily timescales using the mesoscale ACN data will be extendable to the sub-regional scale of the ES box.

There are some methodological issues when it comes to study the intensification at sub-daily timescales, related to the fact that extreme rainfall series at small timescales are well-known for their very low signal to noise ratio (Westra *et al* 2014, Barbero *et al* 2017). One way to improve this ratio is to condition the sampling by extracting the sub-daily rainfall values belonging to the day of the annual maximum daily rainfall. At a timescale of 5 min, 35% of the maximum intensities selected by this procedure correspond to the 'true' (i.e. extracted independently) annual maximum intensities; this ratio grows to 65% for a timescale of 1 hour (table 3). Given this, the trend detection was thus carried out on two samples: the sample of intensities extracted from the daily maxima (denoted SDM) providing the main material of this paper and the sample of the 'absolute' maxima (denoted SAM) provided in the supplementary material.

Figure 4 displays the interannual evolution of the ACN annual maximum intensity for the SDM samples for four timescales from 5 min to 1 hour. This ACN annual maximum intensity is computed as the mean of the 30 annual maxima recorded at each of the ACN stations. For all timescales, there is a general increase of the mean maximal intensity of 3%–4% per decade. Concretely, this comes down to a mean value of the annual 5 minute (resp. hourly) maximum intensity roughly equal to 100 mm h^{-1} (resp. 43 mm h^{-1}) over 1990–1995 as compared to 115 mm h^{-1} (resp. 46 mm h^{-1}) over 2011–2016.

These results are very consistent with those obtained when considering the values of the SAM samples as shown in figure S3, or the values produced by other procedures to extract annual maximum rainfalls (figures S4 and S5), with a positive trend ranging from 2 to 6% per decade, depending on the samples considered. It is nonetheless worth noting that, taken separately, only half of these trends are statistically significant when using a Spearman test. This is not so surprising considering the low signal to noise ratio in maximum series for short timescales.

The strength of the results presented here lies in the coherency of the sign and value of the trend observed whatever the sampling procedures retained (SDM—figure 4, SAM—figure S3, and extractions done for figures S4 and S5) and the sub-daily timescales considered (5 min to 1 hour). The range of trends at sub-hourly timescales is of the same order of magnitude as the values obtained at daily timescale (figure 3(*c*)).

4. Discussion

Based on an updated set of daily observations covering the whole Sahel since 1950, this paper confirms and extends the results obtained by Giannini *et al* (2013), Panthou *et al* (2014) and Sanogo *et al* (2015) suggesting a trend towards more intense rainfall in the Sahel concomitant with a persisting low occurrence of rainfall events. Consequently, the hydro-climatic intensity, as defined by Giorgi *et al* (2011), reaches levels which are unprecedented since 1950. Using the 5 minute measurements of the AMMA-CATCH observatory, it is further shown that this intensification is indeed taking place over a range of timescales from 5 minute to daily rainfall aggregations. This is in line with the recent study of Taylor *et al* (2017) suggesting that the Mesoscale Convective Systems (MCSs) responsible for extreme rainfall in the Sahel have tended to increase their vertical development, favoring the convergence of humidity and producing exceptional cumulative rainfall. The trend for higher rainfall intensities that we identified at small timescales appears quite coherent with these changes in MCS features, likely linked to the warming of the Sahara desert, which accentuates the meridional temperature gradient (Taylor *et al* 2017). Sharper meridional gradients increase wind shear and intrusions of dry air from Sahara at the mid-troposphere level, thus favoring the triggering of more extended (in altitude) and efficient (in term of convergence of humidity) MCSs. Since climate model simulations predict a strengthening of the meridional temperature gradient, Taylor *et al* (2017) assume that this intensification should persist in the coming decades.

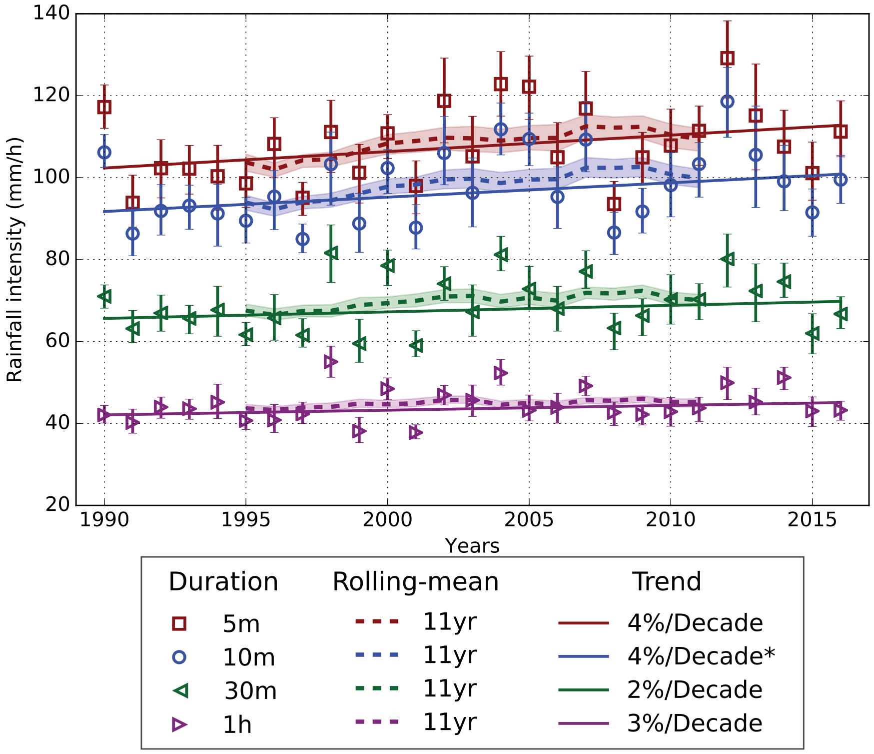

Figure 4. Evolution of the average of the maximum intensities (mm h^{-1}) occurring within the maximum daily rainfall (SDM samples) for different timescales (5 min, 10 min, 30 min, and 1 hour). Trends (Theil–Sen estimator) and significance (Spearman test, 1%***, 5%**, 10%*) are given in the bottom legend. Error bars (resp. shaded area) delineate 80% confidence intervals for annual values (resp. 11 year rolling mean).

A second major result is that there is a clear contrast between the West and East parts of the Sahel with an overall stronger hydro-climatic intensification in the East Sahel. Thus, the early detection by Lebel and Ali (2009) of a contrasting evolution of the Sahelian rainfall at the decadal scale, is compounded by a similar contrasting evolution of the characteristics of the rainfall intensification. Several factors may explain this East–West gradient. For one, Lavaysse *et al* (2016) show that the activity of the Saharan Heat Low has intensified with the warming of the Saharan desert leading to an increase in air subsidence in the West and more intense monsoon circulation in the East, a mechanism also put forward by Monerie *et al* (2017) in a paper underlining the convergence between CMIP5 (Coupled Model Intercomparison Project Phase 5) global climate models in predicting areinforcement of the East–West rainfall gradient. When exploring various assumptions regarding the overall drying or wetting of the Sahel based on idealized modelling experiments, Gaetani *et al* (2017) also conclude that the West Sahel tends to become drier than the East Sahel whatever the dominant forcing factor is (either global sea surface temperature warming producing overall drier conditions or the increase of the global concentration of atmospheric CO_2 producing overall wetter conditions). This does not straightforwardly explain the East–West intensification contrast but it provides food for further investigatation of how modifications of the meridional dynamics of the West African monsoon might be connected to a differential intensification between the East and the West Sahel.

Another important issue indirectly tackled in this paper is the notion of Sahelian rainfall recovery, a terminology widely used in the literature of the past 15 years or so. This has led some medias to report the recent evolution of rainfall in the Sahel as a positive outcome of climate change (see e.g. www.scidev.net 2015). The term 'recovery' is in fact only supported by a moderate increase in mean annual rainfall totals since the end of the 1980s. However annual rainfall totals remain significantly lower than they were before the big drought. Especially important from a water resources point of view is the fact that the number of rain events per year has by far not returned to pre-drought values, meaning that the risk of dry spells within the rainy season remains high, continuing to impact very negatively agricultural yields and food security as well as access to drinking water. In fact, it does not rain much more often than during the drought but when it rains, daily totals and intensities are likely to be stronger. This means that more intense rainfall are more frequent and are likely to produce more intense runoff, producing flood events that are very damaging to a fast growing population (Di-Baldassarre *et al* 2010).

Note also that the reinforced internal contrasts discussed in the previous paragraph is another strong incentive for not characterizing the present Sahelian rainfall trend by a single misleading word overriding the complexity of the rainfall patterns in tropical semi-arid regions and potentially leading to over-simplistic water management strategies.

The detection of long term changes in the rainfall regimes of tropical regions from observations is both challenging and necessary since models often do not agree on this issue—see e.g. figures 11.12 and 12.10 of IPCC (2013), or Pfahl *et al* (2017). Given that over a vast semi-arid region like the Sahel our ability to detect significant changes (significance refers here to both its statistical connotation and the socio-economic consequences involved) depends on the scale and statistics considered, the question is raised of which data are required. While satellite data are increasingly used as a support for analyzing rainfall regimes, they still fall short of providing all the necessary information for detecting the most important changes due to: (i) their quantitative imprecision increasing the noise to signal ratio and rendering statistical detection more difficult; (ii) the difficulty to access the proper scales in terms of human vulnerability; and (iii) the potential inhomogeneity in satellite derived series due to changing sensors and/or algorithms used in satellite products. While daily rain gauge data will therefore remain for long an indispensable source of information, sub-daily timescales are even more critical to consider, when it comes to the hydrological and agricultural impacts. In this respect this study has proved the great asset of a long term hydro-meteorological observatory, such as AMMA-CATCH, dedicated to documenting the evolution of the West African environment in relation with global changes. Since the transient state of the Earth climate is far from being over and since the largest impacts of global warming on the rainfall regimes are still to come, it is especially important to promote a consistent policy for documenting the intensification of the rainfall regime in regions that are both very sensitive (as the tropical semi-arid regions) and deprived of the ground networks required for such a documentation. If the trends revealed in this paper persist, and their connection with global warming is confirmed, then the Sahel is at risk of becoming a very hostile region for mankind.

Acknowledgments

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References

Alexander L V *et al* 2006 *J. Geophys. Res.* **111** D05109

Ali A and Lebel T 2009 *Int. J. Climatol.* **29** 1705–14

Alpert P *et al* 2002 *Geophys. Res. Lett.* **29** 1–4

Barbero R, Fowler H J, Lenderink G and Blenkinsop S 2017 *Geophys. Res. Lett.* **44** 974–83

Biasutti M 2013 *J. Geophys. Res. Atmos.* **118** 1613–23

Cappelaere B *et al* 2009 *J. Hydrol.* **375** 34–51

Desconnets J C, Taupin J D, Lebel T and Leduc C 1997 *J. Hydrol.* **188** 155–78

Di-Baldassarre G, Montanari A, Lins H, Koutsoyiannis D, Brandimarte L and Blöschl G 2010 *Geophys. Res. Lett.* **37** 1–5

Donat M, Lowry A, Alexander L, O'Gorman P and Maher N 2016 *Nat. Clim. Change* **6** 508–13

Dong B and Sutton R 2015 *Nat. Clim. Change* **5** 757–60

Fischer E M and Knutti R 2014 *Geophys. Res. Lett.* **41** 547–54

Fischer E M and Knutti R 2016 *Nat. Clim. Change* **6** 986–91

Gaetani M, Flamant C, Bastin S, Janicot S, Lavaysse C, Hourdin F, Braconnot P and Bony S 2017 *Clim. Dyn.* **48** 1353–73

Giannini A, Salack S, Lodoun T, Ali A, Gaye A and Ndiaye O 2013 *Environ. Res. Lett.* **8** 024010

Giorgi F, Im E S, Coppola E, Diffenbaugh N S, Gao X J, Mariotti L and Shi Y 2011 *J. Clim.* **24** 5309–24

Hawkins E and Sutton R 2012 *Geophys. Res. Lett.* **39** 1–6

Horton R 1933 *Trans. Am. Geophys. Union* **14** 446–60

IPCC 2013 Climate change 2013: the physical science basis *Contribution of Working Group I to the Fifth Assessment Report of the Intergovern mental Panel on Climate Change* ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press)

Lavaysse C, Flamant C, Evan A, Janicot S and Gaetani M 2016 *Clim. Dyn.* **47** 3479–98

Lebel T and Ali A 2009 *J. Hydrol.* **375** 52–64

Lebel T *et al* 2009 *J. Hydrol.* **375** 3–13

Lebel T, Sauvageot H, Hoepffner M, Desbois M, Guillot B and Hubert P 1992 *Hydrol. Sci.* **37** 201–15

Min S, Zhang X, Zwiers F and Hegerl G 2011 *Nature* **470** 378–81

Monerie P A, Sanchez-Gomez E and Boé J 2017 *Clim. Dyn.* **48** 2751–70

Panthou G, Vischel T and Lebel T 2014 *Int. J. Climatol.* **34** 3998–4006

Pfahl S, O'Gorman P A and Fischer E M 2017 *Nat. Clim. Change* **7** 423–7

Population Reference Bureau 2016 2016 world population data sheet with a special focus on human needs and sustainable resources (www.prb.org/2016-w orld-population-data-sheet)

Sanogo S, Fink A H, Omotosho J A, Ba A, Redl R and Ermert V 2015 *Int. J. Climatol.* **35** 4589–605

Seth A, Rauscher S, Biasutti M, Giannini A, Camargo S and Rojas M 2013 *J. Clim.* **26** 7328–51

Taylor C, Belusic D, Guichard F, Parker D, Vischel T, Bock O, Harris P, Janicot S, Klein C and Panthou G 2017 *Nature* **544** 475–8

Trenberth K 2011 *Clim. Res.* **47** 123–38

Trenberth K, Dai A, Rasmussen R and Parsons D 2003 *Bull. Am. Meteorol. Soc.* **84** 1205–17

Vischel T and Lebel T 2007 *J. Hydrol.* **333** 340–55

Vose R, Arndt D, Banzon V, Easterling D, Gleason B, Huang B, Kearns E, Lawrimore J, Menne M and Peterson T 2012 *Bull. Am. Meteorol. Soc.* **93** 1677–85

Westra S, Alexander L V and Zwiers F W 2013 *J. Clim.* **26** 3904–18

Westra S, Fowler H J, Evans J P, Alexander L V, Berg P, Johnson F, Kendon E J, Lenderink G and Roberts N M 2014 *Rev. Geophys.* **52** 2014RG000464

www.scidev.net 2015 Sahel: Les changements climatiques, une aubaine pour la pluie (www.scidev.net/afrique-sub-saharienne/agriculture/actualites/sahel-les-changements-climatiques-une-aubaine-pour-la-pluie.html)

Zhang X, Alexander L, Hegerl G, Jones P, Tank A K, Peterson T, Trewin B and Zwiers F 2011 *Wiley Interdiscip. Rev. Clim. Change* **2** 851–70

Zhang X, Wan H, Zwiers F W, Hegerl G C and Min S K 2013 *Geophys. Res. Lett.* **40** 5252–7