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Evolution of some observed climate extremes in the West African Sahel

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ABSTRACT

Climate variability and change affect most socioeconomic sectors in West Africa. It is now admitted that the variability of climate has increased since the 1950s mainly because of the increased concentration of anthropogenic greenhouse gases in the atmosphere. In this study, we analyze the evolution of some extreme temperature and precipitation indices over a large area of West Africa spanning from latitudes 10–25°N and longitudes 17°W–15°E. The results show a general warming trend throughout the region during the period from 1960 to 2010, namely through a negative trend in the number of cool nights, and more frequent warm days and warm spells. This was the case not only for locations inside the continent, but also for those in coastal areas. Trends in rainfall related indices are not as uniform as the ones in temperatures. Nevertheless, a general tendency of decreased annual total rainfall and maximum number of consecutive wet days characterizes the study period. The cumulated rainfall of extremely wet days shows a positive trend in most locations. As for the maximum number of consecutive wet days, it shows an overall decreasing trend from 1960 to the mid 1980s, but starting from the late 1980s, an increasing trend is observed in several locations, indicating that extreme rainfall events have become more frequent in the West African Sahel during the last decade, compared to the 1961–1990 period. Policy implications of these observed trends may include investment and promotion of low cost and environmentally friendly energy production systems, the redesign of infrastructure and production systems to account for higher risks of losses due to floods and/or droughts, and the promotion of research for more heat tolerant crop/animal species and cultivars/breeds.

1. Background

Climates in different parts of the world are characterized by their variability that affects several sectors. This variability has increased since the 1950s, and particularly during the latest decade, mainly because of the increased concentration of anthropogenic greenhouse gases in the atmosphere as argued by some authors (Hegerl et al., 2007; Stott et al., 2011; Trenberth et al., 2007a, 2012; Min et al., 2011; Solomon et al., 2007, 2009, 2010). In this context, it is argued that surface temperature has increased by 0.7 °C over the last century with a significant warming in many regions; and with the land areas warming faster than the oceans (Trenberth et al., 2007a). In the West African Sahel, an increasing trend was observed in both maximum and minimum temperatures for all the three main ecological zones (Sudanian, Sahelian and Sahelo-Saharan) with minimum temperatures increasing at a faster rate (CEDEAO-ClubSahel/OCDE/CILSS, 2008).

It is also argued that increased temperatures will lead to greater evaporation according to the Clausius–Clapeyron relationship, whereby saturation vapor pressure increases exponentially with temperature. In its turn, the increase of water vapor in the atmosphere affects precipitation events and the risk of flooding. The changing climate is thus perceived through extreme events which tend to modify the magnitude of the predicted climate. This can be supported by the number of flood events having increased on average from less than 2 per year before 1990 to more than 8 or 12 on average per year during the 2000s (Sarr, 2011). Also, the evolution of total annual rainfall has been characterized by a succession of wet years from 1950 to 1969, followed by a period with the persistence of dry years from 1970 to 1993 (L'Hote et al., 2002; Ali, 2011). This has resulted in a southward movement of isohyets by about 200 km (Diouf et al., 2000). After 1993, another mode of variability, characterized by an alternation between very wet years and very dry years, seems to have started in the region (Ali, 2011). Moreover, the same author indicates that while there is a tendency of persisting drought in the Western Sahel, the East is experiencing gradual return to wetter conditions.

The occurrence of extremes is usually the result of different factors at different time scales. A large amount of the available

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scientific literature on climate extremes is based on the use of the so-called 'extreme indices', which can either be based on the probability of occurrence of given quantities or on threshold exceedance. In the recent years, the number of publications related to those extremes emerged in some specific countries, in particular in the developing world where, most of the time, data are not available and not always distributed by meteorological services. Especially in Africa, very few studies document such changing climate because of several difficulties in accessing to daily meteorological data (Lamptey, 2009). However the World Meteorological Organization, through the Climate Variability and Predictability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring Indices (ETCCDMI), coordinated a series of workshops in different regions of the world to help scientists and national experts discuss and quality control climate data. Some regional analyses were thus undertaken for the understanding of climate extreme and trends (Easterling et al., 2003; Aguilar, 2005; Vincent et al., 2005; Haylock, 2006; Peterson, 2008). Recent studies in Africa, when analyzing daily climate in terms of trends and extreme indices revealed some significant increases and decreases in annual precipitation, increases in longest wet spells, increases in high daily precipitation amounts and average rainfall intensity (New et al., 2006; Alexander et al., 2006; Collins 2011). Minimum temperature was found to have increased faster than maximum temperature, thus contributing to narrow the diurnal temperature range (Easterling, 1997; Caesar et al., 2006). Numerous indicators in the extreme indices can be analyzed to further investigate the perception of changed climate in a widespread area in the West African Sahel, where very few studies have documented the changes that occurred in those extremes. The objective of this study is to analyze the evolution of some extreme temperature and precipitation indices over a large area in this region.

Table 1
List of meteorological stations in West Africa used in the study.

Country	Station name	Longitude	Latitude
Burkina Faso	Bobo-Dioulasso	−4.30	11.17
Burkina Faso	Boromo	−2.92	11.73
Burkina Faso	Dedougou	−3.48	12.47
Burkina Faso	Dori	−0.03	14.03
Burkina Faso	Fada N'Gourma	0.35	12.07
Burkina Faso	Gaoua	−3.18	10.33
Burkina Faso	Ouagadougou	−1.52	12.35
Burkina Faso	Ouahigouya	− 2.43	13.58
Mali	Bamako	−7.95	12.53
Mali	Bougouni	−7.50	11.42
Mali	Kayes	−11.43	14.43
Mali	Kenieba	−11.35	12.80
Mali	Kita	−9.45	13.07
Mali	Segou	− 6.15	13.40
Mali	Sikasso	−5.68	11.35
Mauritania	Aioun	−9.60	16.70
Mauritania	Akjoujt	−14.37	19.75
Mauritania	Atar	−13.07	20.52
Mauritania	Bir Moghrein	−11.62	25.23
Mauritania	BoutilimitT	−14.68	17.53
Mauritania	Kaedi	−13.52	16.13
Mauritania	Kiffa	−11.40	16.63
Mauritania	Nema	−7.27	16.60
Mauritania	Nouadhibou	−17.03	20.93
Mauritania	Nouakchott	−15.95	18.10
Mauritania	Rosso	−15.82	16.50
Mauritania	Tidjikja	−11.43	18.57
Mauritania	Zouerate	−12.70	22.68
Niger	Birni N'Konni	5.28	13.80
Niger	Maine Soroa	11.98	13.23
Niger	Maradi	7.08	13.47
Niger	Niamey	2.17	13.48
Niger	Tahoua	5.30	14.90
Niger	Tillabery	1.45	14.20
Senegal	Bambey	−16.47	14.70
Senegal	Kaolack	−16.07	14.13
Senegal	Matam	−13.25	15.63
Chad	N'Djamena	15.03	12.13

2. Methods

2.1. Study region

The study was conducted in West Africa over 6 countries, namely Senegal, Mauritania, Mali, Burkina Faso, Niger and Chad, covering three major agro ecological zones: arid, semi arid and sub humid (FAO, 1978). Average annual rainfall varies from 30 to 1000 mm per year (Nicholson, 1993). Mean annual minimum and maximum temperatures are comprised between 16 and 20 °C for the minimum and 27 and 35 °C for the maximum depending on the proximity of the ocean. The rainfall season is unimodal, with the onset of the rains occurring in agricultural areas from May to July and ending in September–October (Sivakumar, 1988; Camberlin and Diop, 2003). The temporal distribution of temperature is typically bimodal with one maximum in April-May and another one in October, except for coastal zones, particularly in Mauritania and the North of Senegal, where it is unimodal with a maximum occurring in September. The list of the meteorological stations used in this study is given in Table 1.

2.2. Rainfall and temperature data

The data used in this study consist of daily observations of rainfall and temperature available at the AGRHYMET Regional Center for the 1960–2010 period. All the station data were quality controlled using the Rclimdex package (Zhang and Yang, 2004) which is freely downloadable from the ETCCDMI website (http://cccma.seos.uvic.ca/ETCCDMI/index.shtml). The quality control consisted in detecting negative precipitations and minimum temperatures greater than maximum temperatures. To verify the quality of the datasets, simple box plot techniques were also used in order to detect some probable erroneous information in the time series. The result showed some few outliers in the datasets. Stations with high potential of erroneous data and missing data more than 20% were removed from the study

2.3. Climate indices

One of the ways to characterize the frequency, intensity and duration of climate extremes is to calculate climates indices based on daily time series of temperature and rainfall (Karl et al., 1999; Peterson et al., 2002). International research groups such as the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) have undertaken a set a regional analyses for understanding climate extremes and trends (Peterson et al., 2002; Easterling, 2003; Vincent, 2006; New et al., 2006). Among the 27 core indices computed on the daily basis by Rclimdex, we selected 9 that we consider most relevant for our study region (Table 2).

2.4. Trend analysis

To estimate the trend in the set of extreme indices time series, an estimator of the slope based on Kendall rank correlation was used (Vincent et al., 2005). In the study, statistical analyses were done over the last 50 years since 1960 including the climatological normal period of 1961–1990. Maps and tables of trends for the period 1961–2010 for some selected indices were constructed by developing scripts with the R open source software (Core Team, 2012).

Table 2
Definitions of the temperature and rainfall indices used in the study. Tn and Tx are daily minimum and maximum temperature respectively.

Element	Index	Descriptive name	Definition	Units
Tn	Tn10p	Cool night frequency	Percentage of days with TN < 10th percentile of 1961–1990	%
Tn	Tn90p	Warm night frequency	Percentage of days with TN > 90th percentile of 1961–1990	%
Tx	Tx10p	Cool day frequency	Percentage of days with TX < 10th percentile of 1961–1990	%
Tx	Tx90p	Warm day frequency	Percentage of days with TX > 90th percentile of 1961–1990	%
Tx	WSDI	Warm spells	Annual count of days with at least 6 consecutive days with TX > 90th percentile of 1961–1990	days
Rainfall	RX5day	Maximum 5-day precipitation	Maximum 5-day precipitation	mm
Rainfall	CWD	Consecutive wet days	Maximum number of consecutive wet days	days
Rainfall	R99p	Extremely Wet days	Annual total PRCP when RR > 99th percentile	mm
Rainfall	PRCPTOT	Annual Total Rainfall	Annual total PRCP in wet days (RR ≥ 1mm)	mm

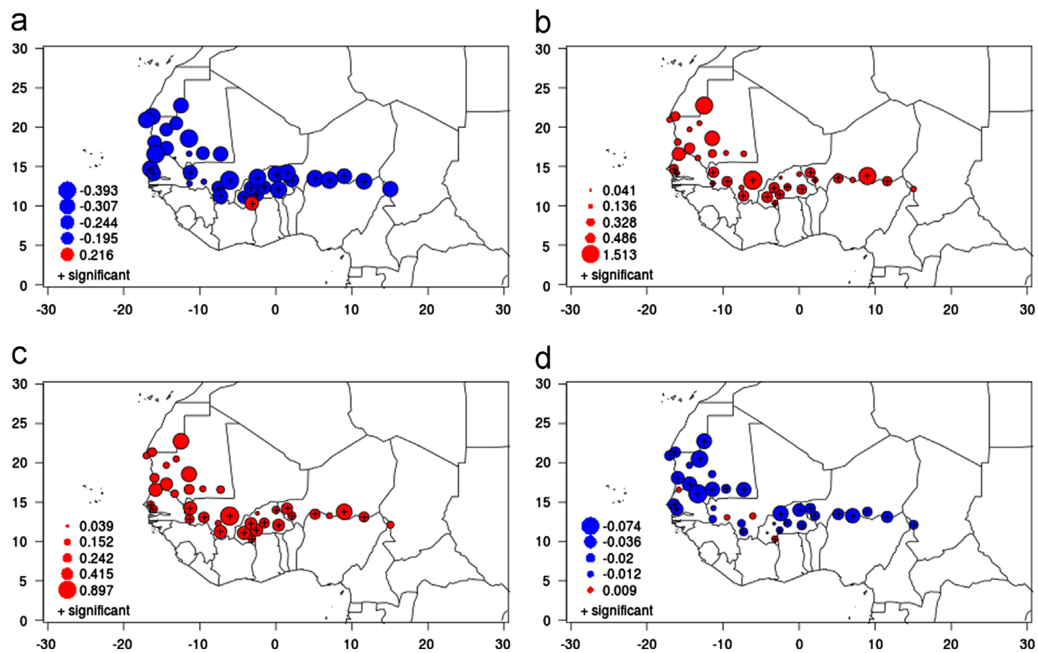

Fig. 1. Observed trends in some temperature indices in West Africa from 1960 to 2010. (a) Cool nights (Tn10p), (b), Warm days (Tx90p), (c) Warm Spells (WSDI), and (d) Diurnal temperature range (DTR).

3. Results

3.1. Temperature indices

Temperature indices show a general warming trend throughout the West African Sahel during the period from 1960 to 2010 (Fig. 1). Indeed, if one examines the frequency of cools nights (Fig. 1a), it appears that all the stations show a negative slope varying from −0.2 to −0.4, meaning that the nights have become warmer. Warm days and warm spells have also become more frequent (Fig. 1b and c). Except for some few locations, the diurnal temperature range shows a negative trend (Fig. 1d). Given that both maximum and minimum temperatures have increased during the period, this means that the warming has been faster with minimum temperature. Figs. 2 and 3 illustrate, through some selected locations, that a steady warming took place during the study period. Indeed, while the frequency of cool nights and of cool days decreased, that of warm nights and warm days, and also of warm spells increased. This was the case not only for locations inside the continent, but also for those in coastal areas where temperature regime is different because of the influence of the ocean. In Table 3, one can notice that for the last two decades, the frequency of cool nights decreased about twofold, going from 10.1 to 2.9, 10.3 to 7.4, 10.1 to 4.2, and 10.2 to 04.8, respectively for Nouakchott, Bamako, Ouagadougou and Niamey.

3.2. Rainfall indices

Trends in rainfall related indices are not as uniform as the ones in temperatures. While a general tendency of decreased annual total rainfall and maximum number of consecutive wet days is observed in the region (Fig. 4b and d), the cumulated rainfall of extremely wet days shows a positive trend in most locations (Fig. 4c, Table 4). However, those observed trends are significant only for a few locations. Moreover, regarding the maximum number of consecutive wet days, if an overall decreasing trend is observed since 1960, one can notice a reversal of this from the late 1980 s in some locations, where an increasing trend can now be observed, except for Nouakchott in Mauritania (Fig. 5). One can also notice from Table 4 that, in some selected locations across the subcontinent, maximum 5-day rainfall amount, total annual rainfall, and the amount of rainfall during extremely wet days have all increased. The maximum number of consecutive wet days, on the other hand, has decreased.

4. Discussion

Previous studies in other regions of the world showed the same tendencies in temperature indices we found in the West African Sahel. For example, New et al. (2006) found statistically significant warming trends for most of southern Africa and some few

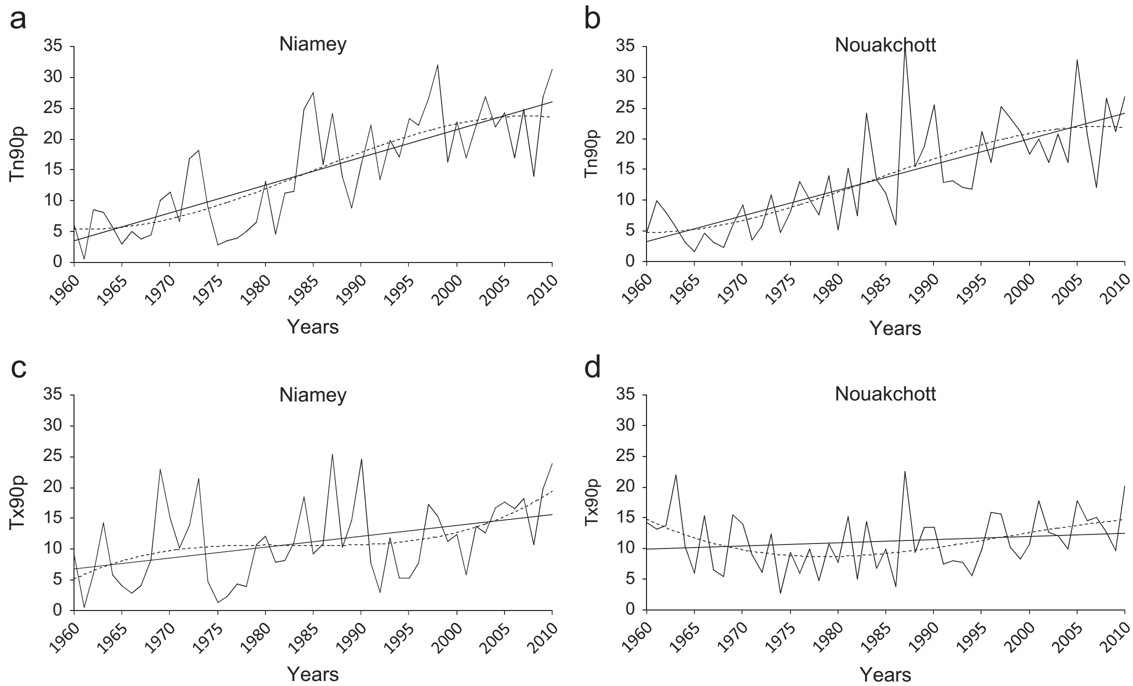

Fig. 2. Evolution of the percentage of warm nights (Tn90p) and that of warm days (Tx90p) in Niamey, Niger (a and c) and Nouakchott, Mauritania (b and d) from 1960 to 2010.

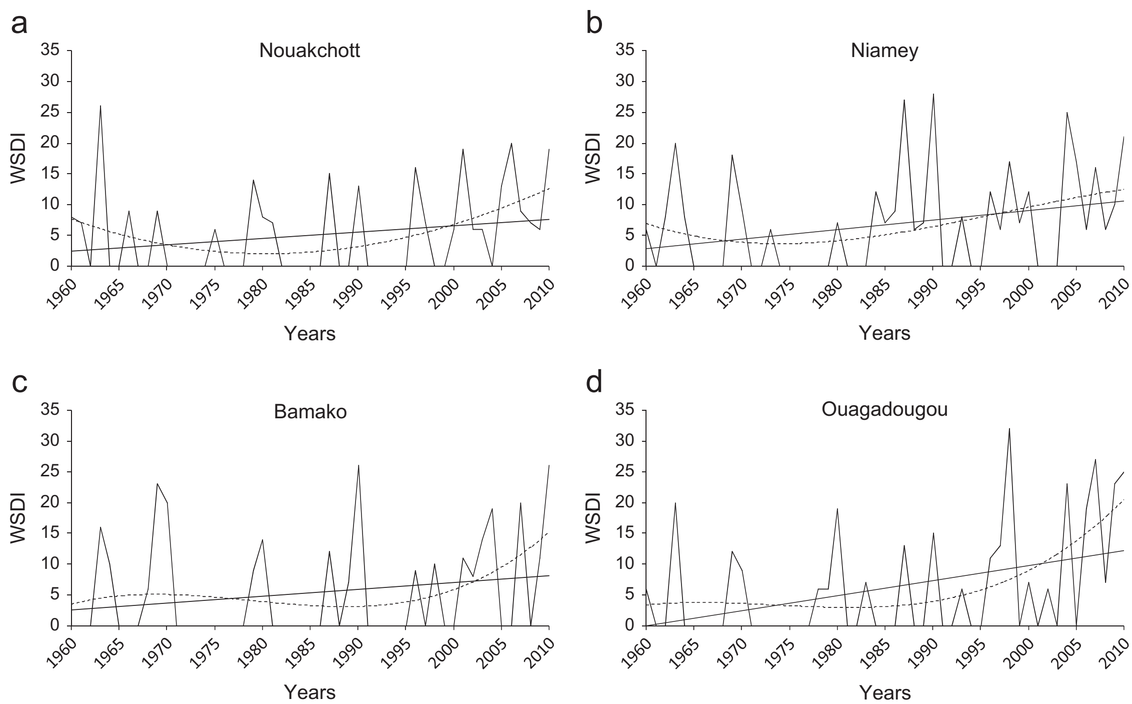

Fig. 3. Evolution of Warm spells (WSDI) in some selected locations in West Africa from 1960 to 2010. (a) Nouakchott (Mauritania), (b) Niamey, Niger (c) Bamako, Mali, and (d) Ouagadougou, Burkina Faso.

locations in Nigeria and The Gambia during the period from 1961 to 2000. Kruger and Sekele (2013) also found that in South Africa, warm extremes increased and cold extremes decreased for all of the weather stations during the 1962-2009 period. For South America, although Vincent et al. (2005) did not find consistent changes in the indices based on daily maximum temperature, they noticed some significant increasing trends in the percentage of warm nights and decreasing trends in the percentage of cool nights at many stations. Our results in the West African Sahel are consistent with this later finding. The same authors also noticed that stations located in coastal areas have the most significant warming trends. We did not observe this difference among coastal and inland locations in the West African Sahel, probably because of the reduced ocean-land temperature gradient that is characteristic of the monsoon regions as pointed out by Trenberth et al. (2007b) and Giannini et al. (2008).

Table 3
Evolution of the annual temperature indices between the 1961–1990 and 1991–2010 periods in some selected stations in West Africa.

Indices	Nouakchott		Bamako		Ouagadougou		Niamey		Units
Periods	1961–1990	1991–2010	1961–1990	1991–2010	1961–1990	1991–2010	1961–1990	1991–2010	s
Cool nights	10.1	2.9	10.3	7.4	10.1	.2	10.2	4.8	%
Warm nights	10.3	19.4	9.9	10.8	10.3	24.3	10.2	22.1	%
Cool days	10.3	7.2	10.2	9.7	10.4	8.0	10.3	8.3	%
Warm days	10.4	12.1	10.1	12.2	10.2	17.4	10.3	12.6	%
Warm spells	3.8	6.7	04.8	6.4	3.6	10.0	05.0	8.5	Days

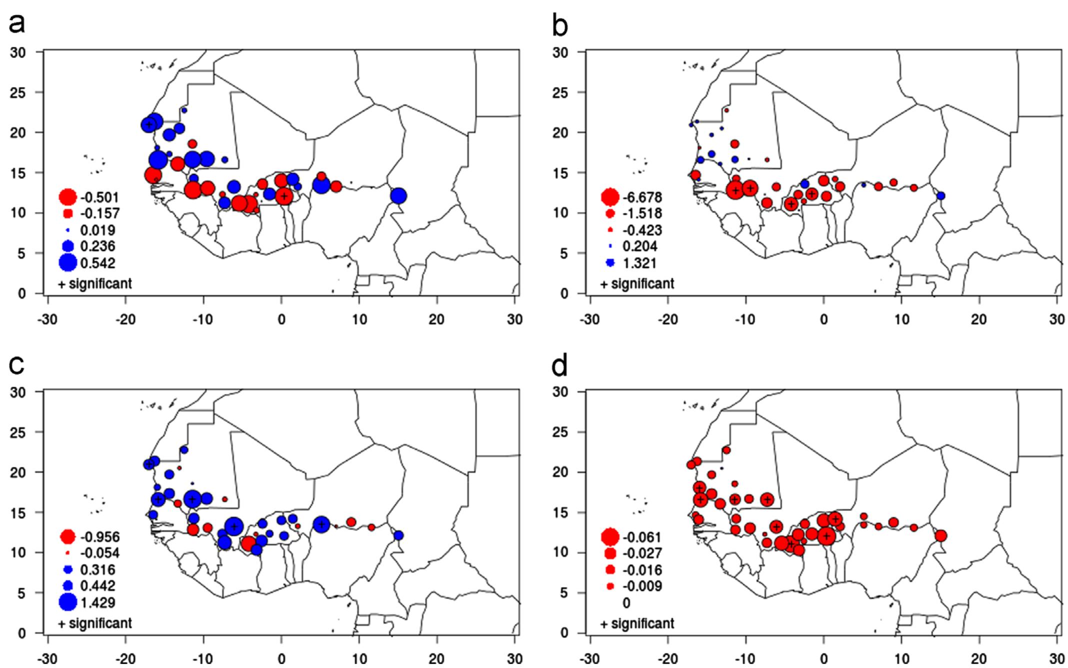

Fig. 4. Observed trends in some rainfall indices in West Africa from 1960 to 2010. (a) 5-day cumulative rainfall, (b) Total annual precipitation, (c) Cumulated rainfall of extremely wet days, and (d) Maximum Consecutive Wet days.

Table 4
Evolution of some rainfall indices between the 1961–1990 and 1991–2010 periods at some selected locations in West Africa.

Indices	Nouakchott		Bamako		Ouagadougou		Niamey		N'Djamena		Units
Periods	1961–1990	1991–2010	1961–1990	1991–2010	1961–1990	1991–2010	1961–1990	1991–2010	1961–1990	1991–2010	
Max 5-day rainfall	33.7	44.7	123	117	104	109	86	97	88	103	mm
Extremely wet day total rainfall	5.7	18.6	48.1	62.7	44.4	45.6	30.9	37.8	29.3	45.7	mm
Annual total rainfall	84.6	95.5	913	943	782	724	535	541	505	583	mm
Max consecutive wet days	2.1	1.5	5.0	5.4	5.1	4.6	3.8	3.8	4.2	3.7	days

Regarding rainfall indices, the decrease in annual total rainfall in the sub-region has been documented extensively (L'Hote et al., 2002; Ali, 2011; Diouf et al., 2000). As for the increasing trend of the cumulated rainfall of extremely wet days and that of the maximum number of consecutive wet days from the late 1980s, this is in accordance with the findings of Sarr (2011), who also noticed that extreme rainfall events became more frequent in the West African Sahel during the last decade, compared to the 1961–1990 period. Studies in other parts of Africa showed in some cases similar trends, but in other cases the trends were different. For example, Kruger (2006) found that some significant increases and decreases occurred in annual precipitation, some increases in the longest annual wet spells, and some increases in high daily precipitation amounts in South Africa over the 1910–2004 period.

5. Conclusion

This study showed that throughout the West African Sahel, all temperature indices point to a general warming trend since 1960. As for rainfall related indices, although there was a general tendency of decreased annual total rainfall, the observed trends are not as uniform as the ones in temperatures, and some indices clearly indicate that extreme rainfall events have become more frequent during the last decade. These observed trends have serious implications on the economies of countries of this region, most of which are not strong enough to cope with adverse climate effects. Indeed, the observed warming trend means a higher demand on domestic energy consumption for cooling, a higher evaporation rate from water bodies and irrigated crops, and a

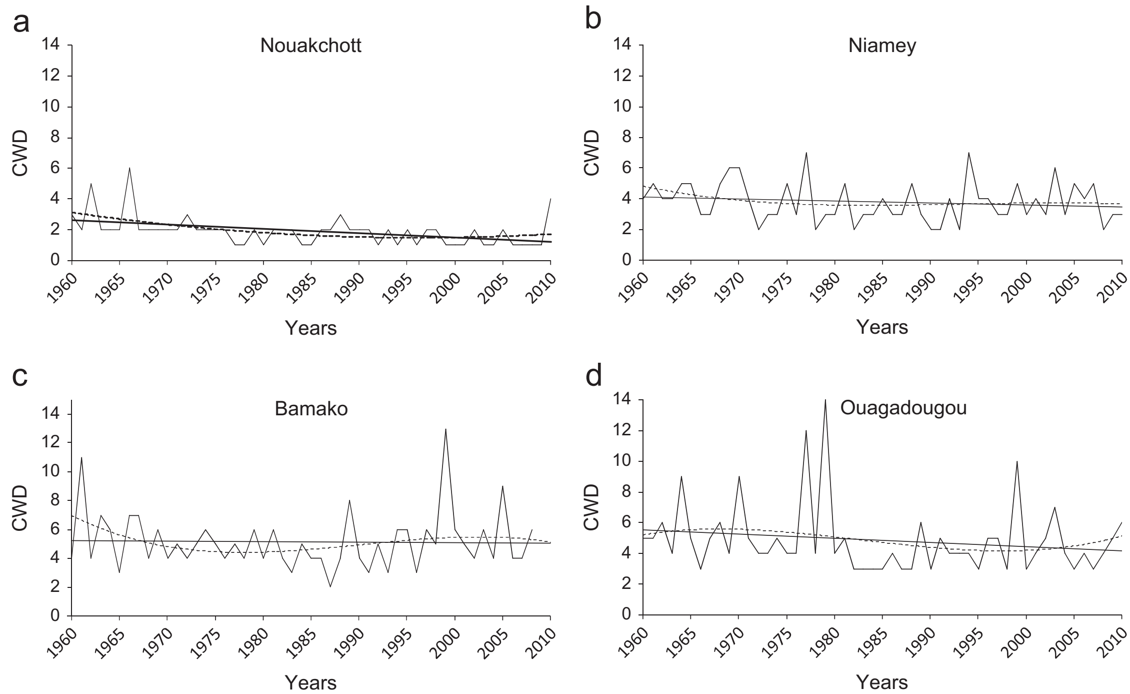

Fig. 5. Evolution of the maximum number of consecutive wet days (CWD) in some selected locations in West Africa from 1960 to 2010. (a) Nouakchott (Mauritania), (b) Niamey (Niger), (c) Bamako (Mali), and(d) Ouagadougou (Burkina Faso).

lower performance of agricultural crops and livestock. On the other hand, an increased frequency of extreme rainfall events such as heavy downpours, long dry or wet spells means more fragile infrastructure and production systems. It is therefore important for policy makers of the region, in order to cope with these changes and avoid additional hardships to their populations, to invest in and promote more energy efficient infrastructure and domestic appliances, including low cost and environmentally friendly energy production systems. For agriculture, research for more heat tolerant crop/animal species and cultivars/breeds should be promoted. The production systems need also be redesigned to account for higher risks of losses due to floods and/or droughts.

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References

Aguilar, E., Peterson, T.C., Obando, P.R., Frutos, R., Retana, J.A., Solera, M., Soley, J., García, I.G., Araujo, R.M., Santos, A.R., Valle, V.E., Brunet, M., Aguilar, L., Álvarez, L., Bautista, M., Castañón, C., Herrera, L., Ruano, E., Sinay, J.J., Sánchez, E., Oviedo, G.I.H., Obed, F., Salgado, J.E., Vázquez, J.L., Baca, M., Gutiérrez, M., Centella, C., Espinosa, J., Martínez, D., Olmedo, B., Espinoza, C.E.O., Núñez, R., Haylock, M., Benavides, H., Mayorga, R., 2005. Changes in precipitation and temperature extremes in Central America and Northern South America, 1961–2003. Journal of Geophysical Research 110, D23107, 10.1029/2005JD006119⟨www.agu.org/pubs/crossref/2005/2005JD006119.shtml⟩.

Alexander, L.V., et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research 111, 10.1029/2005JD006290⟨www.agu.org/pubs/crossref/2006/2005JD006290.shtml⟩.

Ali, A., 2011. Climate variability and change in the Sahel. Understanding the current situation by observing. Climate change in the Sahel. A challenge for sustainable development. AGRHYMET Monthly Bulletin (Special Issue), pp. 17–20. ⟨http://www.agrhymet.ne/PDF/Bulletin%20mensuel/specialChCang.pdf⟩.

CEDEAO-ClubSahel/OCDE/CILSS, 2008. Climate and Climate Change. The Atlas on Regional Integration in West Africa. Environment Series, p.13, ⟨http://www.oecd.org/fr/csao/publications/40121057.pdf⟩.

Caesar, J., Alexander, L., Vose, R., 2006. Large-scale changes in observed daily maximum and minimum temperatures: creation and analysis of a new gridded data set. Journal of Geophysical Research 111, D05101, 10.1029/2005JD006280 (accessed 11.12.12) ⟨www.agu.org/pubs/crossref/2006/2005JD006280.shtml⟩.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), 2007. Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.

Camberlin, P., Diop, M., 2003. Application of daily rainfall principal component analysis to the assessment of the rainy season characteristics in Senegal. Climate Research 23, 159–169.

Collins, J.M., 2011. Temperature Variability over Africa. Journal of Climate 24, 3649–3666, http://dx.doi.org/10.1175/2011JCLI3753.1 ⟨http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI3753.1⟩.

R Core Team, 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN: 3-900051-07-0, ⟨http://www.R-project.org/⟩.

Diouf, M., Nonguierma, A., Amani, A., Royer, A., et al., 2000. Lutte contre la sécheresse au Sahel: résultats, acquis et perspectives au Centre régional AGRHYMET. Sécheresse 11 (4), 57–266.

Easterling, D.R., 1997. Maximum and minimum temperature trends for the Globe. Science 277, 364–367, http://dx.doi.org/10.1126/science.277.5324.364 ⟨www.sciencemag.org/cgi/doi/10.1126/science.277.5324.364⟩.

Easterling, D.R., Alexander, L.V., Mokssit, A., Detemmerman, V., 2003. CCI/CLIVAR Workshop to develop priority climate indices. Bulletin of the American Meteorological Society 8, 1403–1407.

FAO, 1978. Report on the agro-ecological zones project. Vol. 1: Results for Africa. World Soil Resources Report 48/1. FAO, Rome, 158 pp.

Giannini, A., Biasutti, M., Held, I.M., Sobel., A.H., 2008. A global perspective on African climate. Climatic Change 90, 359–383, http://dx.doi.org/10.1007/s10584-008-9396-y.

Haylock, M.R., Peterson, T.C., Alves, L.M., Ambrizzi, T., Anunciação, Y.M.T., Baez, J., Barros, V.R., Berlato, M.A, Bidegain, M., Coronel, G., Corradi, V., Garcia, V.J., Grimm, A.M., Karoly, D., Marengo, J.A., Marino, M.B., Moncunill, D.F., Nechet, D., Quintana, J., Rebello, E., Rusticucci, M., Santos, J.L., Trebejo, I., Vincent, L.A., 2006. Trends in total and extreme South American rainfall in 1960–2000 and links with sea surface temperature. Journal of Climate 19, 1490–1512, http://dx.doi.org/10.1175/JCLI3695.1. (http://journals.ametsoc.org/doi/abs/10.1175/JCLI3695).

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., Stott, P.A., 2007. Understanding and attributing climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.
Karl, T.R., Nicholls, N., Ghazi, A., 1999. CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes: workshop summary. Climatic Change 42, 3–7.
Kruger, A.C., 2006. Observed trends in daily precipitation indices in South Africa: 1910–2004. International Journal of Climatology 26, 2275–2285, http://dx.doi.org/10.1002/joc.1368. (http://doi.wiley.com/10.1002/joc.1368).
Kruger, A.C., Sekele, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962–2009. International Journal of Climatology 33, 661–676, http://dx.doi.org/10.1002/joc.3455.
Lamptey, B., 2009. An analytical framework for estimating the urban effect on climate. International Journal of Climatology 30, 72–88.
L'Hote, Y., Mahé, G., Some, B., Triboulet, J.P., 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. Hydrological Sciences —Journal 47 (4), 563–572.
Min, S.-K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470, 378–381, http://dx.doi.org/10.1038/nature09763 http://dx.doi.org/10.1038/nature09763.
New, M., Hewitson, B., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, C.A.S., Masisi, D.N., Kululanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata, L., Mdoka, M.L., Lajoie, R., 2006. Evidence of trends in daily climate extremes over southern and west Africa. Journal of Geophysical Research 111, D14102, 10.1029/2005JD006289 ⟨http://www.agu.org/pubs/crossref/2006/2005JD006289.shtml⟩.
Nicholson, S., 1993. An overview of African rainfall fluctuations of the last decade. Journal of Climate 6, 1463–1466.
Peterson, T.C., Manton, M.J., 2008. Monitoring changes in climate extremes: a tale of international collaboration. Bulletin of the American Meteorological Society 89, 1266–1271.
Peterson, T.C., Taylor, M.A., Demeritte, R., Duncombe, D.L., Burton, S., Thompson, F., Porter, A., Mercedes, M., Villegas, E., Semexant-Fils, R., Klein-Tank, A., Martis, A., Warner, R., Joyette, A., Mills, W., Alexander, L., Gleason, B., 2002. Recent changes in climate extremes in the Caribbean region. Journal of Geophysical Research 107 (D21), 4601, 10.1029/2002JD002251, (16 p.).
Sarr, B., 2011. Return of heavy downpours and floods in a context of changing climate. Climate change in the Sahel. A challenge for sustainable development. AGRHYMET Monthly Bulletin (Special Issue), pp. 9–11. ⟨http://www.agrhymet.ne/PDF/Bulletin%20mensuel/specialChCang.pdf⟩.
Sivakumar, M.V.K., 1988. Predicting rainy season potential from the onset of rains in southern sahelian and sudanian climatic zones of West Africa. Agricultural and Forest Meteorology 42, 295–305.
Solomon, S., Plattner, G.K., Knutti, R., Friedlingstein, P., 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106, 1704–1709.
Solomon, S., Daniel, J.S., Sanford, T.J., Murphy, D.M., Plattner, G.K., Knutti, R., Friedlingstein, P., 2010. Persistence of climate changes due to a range of greenhouse gases. Proceedings of the National Academy of Sciences 107, 18354–18359.
Stott, P.A., Jones, G.S., Christidis, N., Zwiers, F.W., Hegerl, G., Shiogama, H., 2011. Single-step attribution of increasing frequencies of very warm regional temperatures to human influence. Atmospheric Science Letters 12, 220–227.
Trenberth, K., 2011. Changes in precipitation with climate change. Climate Research 47, 123–138, http://dx.doi.org/10.3354/cr00953. (accessed 11.12.12) ⟨http://www.int-res.com/abstracts/cr/v47/n1-2/p123-138/⟩.Trenberth, K.E., 2012. Framing the way to relate climate extremes to climate change. Climatic Change 115, 283–290, http://dx.doi.org/10.1007/s10584-012-0441-5 ⟨http://www.springerlink.com/index/10.1007/s10584-012-0441-5⟩.
Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Tank, A.K., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., 2007a. In: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., Chen, Z. (Eds.), Observations: Surface and Atmospheric Climate Change, Chapter 3 of Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, pp. 235–336.
Trenberth, K.E., Fasullo, J.T., Kiehl, J., 2007b. Earth's global energy budget. Bulletin of the American Meteorological Society , http://dx.doi.org/10.1175/2008BAMS2634.1.
Vincent, L.A., Mekis, E., 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmosphere–Ocean 44, 177–193.
Vincent, L.A., Peterson, T.C., Barros, V.R., Marino, M.B., Rusticucci, M., Carrasco, G., Ramirez, E., Alves, L.M., Ambrizzi, T., Berlato, M.A., 2005. Observed trends in indices of daily temperature extremes in South America 1960–2000. Journal of Climate 18, 5011–5023, http://dx.doi.org/10.1175/JCLI3589.1 ⟨http://journals.ametsoc.org/doi/abs/10.1175/JCLI3589.1⟩.
Zhang, X., Yang, F., 2004. RClimDex (1.0) User Guide. Climate Research Branch Environment Canada. Downsview, Ontario, Canada.