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Drying climate in Ghana over the period 1960-2005: evidence from the resampling-based Mann-Kendall test at local and regional levels

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Drying climate in Ghana over the period 1960–2005: evidence from the resampling-based Mann-Kendall test at local and regional levels

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Abstract Trends in rainfall series were investigated at 16 stations in Ghana over the period 1960–2005. Time series were first de-correlated using an effective pre-whitening methodology and then submitted to the resampling-based Mann-Kendall test. Field significances were assessed using the regional average Kendall statistic. Although no significant changes were observed in annual rainfall, the analysis reveals: (a) a reduction in the number of wet season days totalling less than 20 mm of rainfall, between latitudes 6° and 9.5°N; (b) a delay (about 0.5 d year^{-1}) in the wet season onset at several locations throughout the country; and (c) a lengthening (about 0.1 d year^{-1}) of rainless periods during the wet season in the south and centre of Ghana. All these changes, which remained insignificant at more than half of the individual stations, were found to be regionally significant at the 95% confidence level. The results highlight the importance of evaluating regional significance when investigating climate trends.

Key words rainfall; trend; Mann-Kendall; pre-whitening; regional significance; Ghana

Assèchement du Ghana de 1960 à 2005: preuve par le test de Mann-Kendall basé sur une technique de rééchantillonnage, aux niveaux local et régional

Résumé Des tendances dans des chroniques de pluies sont recherchées au niveau de 16 stations pluviométriques sur la période 1960–2005. Les chroniques sont d'abord décorrélées à l'aide d'une technique préliminaire de décorrélation ajustée puis soumises au test de Mann-Kendall basé sur une technique de rééchantillonnage. Les significativités statistiques des tendances régionales sont estimées par la statistique régionale moyenne de Kendall. Bien qu'aucune tendance significative ne soit observée pour les cumuls annuels de pluie, l'analyse révèle: (a) une réduction du nombre de jours totalisant moins de 20 mm de pluie pendant la saison des pluies, entre les latitudes 6° et 9,5°N; (b) un retard (environ 0,5 jour an^{-1}) du début de la saison des pluies en plusieurs endroits du pays; et (c) un allongement (environ 0,1 jour an^{-1}) des périodes sèches pendant la saison des pluies dans le sud et le centre du Ghana. Tous ces changements, qui restent non significatifs pour plus de la moitié des stations pluviométriques, sont régionalement significatifs au seuil de confiance de 95%. Ces résultats soulignent l'importance des tests de significativité régionale pour la recherche de tendances climatiques.

Mots clefs pluie; tendance; Mann-Kendall; décorrélation préliminaire; significativité régionale; Ghana

INTRODUCTION

In Ghana, climate seasonality and variability, and insufficient capacity to cope with that variability, lies behind much of the prevailing poverty and food insecurity. At least 60% of the economically active population depends on agriculture for their livelihoods, but less than 1% of farmed land is irrigated (Aquastat 2005). As a result, the majority of the country's food production is highly susceptible to rainfall variability. River flows are also extremely sensitive to precipitation and, in dry years, electricity production

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at the Akosombo hydropower plant has to be curtailed (Andreini *et al*. 2000). Consequently, the vagaries of rainfall influence not only livelihoods and food security but also economic development.

The climate in Ghana is dominated by the rain-bearing southwesterly tropical maritime air mass and the dry, northeasterly tropical continental air mass (Dickson and Benneh 1988). The two air masses meet at the Inter-Tropical Convergence Zone (ITCZ) forming a quasi-frontal zone of low pressure which migrates across West Africa (Anyadike 1993). At any location, the rainy season begins when the ITCZ has passed overhead northward bound and ends with its southward retreat. Consequently, there is a general tendency for rainfall to decrease from the south to the north, though this general effect is disrupted in a few places, largely as a consequence of local relief. Between May and August (i.e. the West African Monsoon), the ITCZ moves to the north and the whole country lies under the influence of the tropical maritime air mass. These months yield approximately 75% of the total annual rainfall for the country. In the vicinity of the coast, rainfall is bimodal, falling between May and October, with a short dry season, July/August, separating two peaks in rainfall (Dickson and Benneh 1988). The two rainfall peaks tend to disappear northward and, in the northern part of the country, the rainfall distribution is uni-modal (Figs 1 and 2). In addition to seasonality, inter-annual variability is considerable. This was previously thought to be associated with anomalous displacements of the ITCZ, but more recent work has indicated that the causes are in the structure of the complicated zonal winds that form over West Africa in the summer (Nicholson 2005).

It is anticipated that climate change, in conjunction with increasing population, may aggravate the imbalance between water demand and supply in Ghana. However, as yet there is no clear picture of how climate may have already changed, or how it

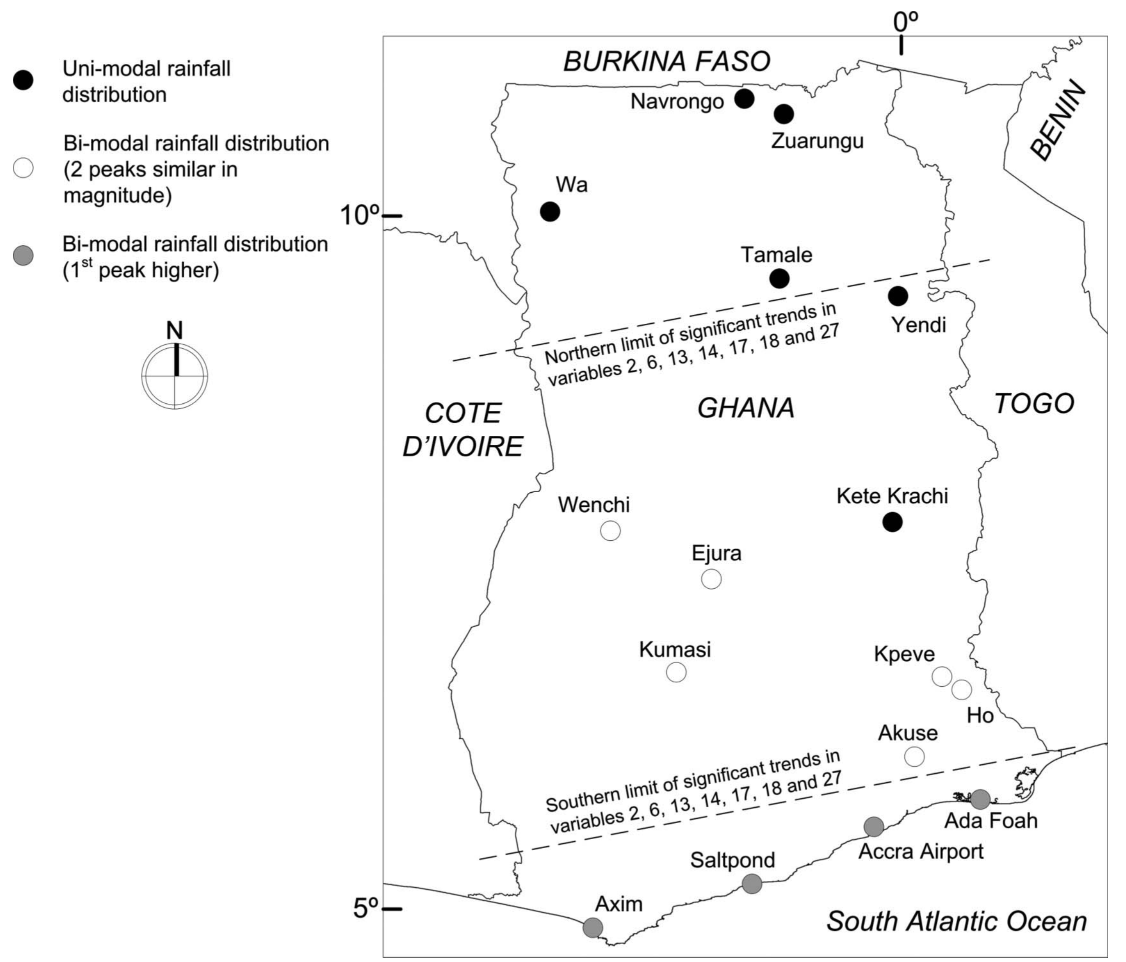

Fig. 1 Location of rainfall stations, types of rainfall pattern and areas exhibiting negative trends in rainfall depths and number of rainy days as presented in Table 2 and Fig. 2.

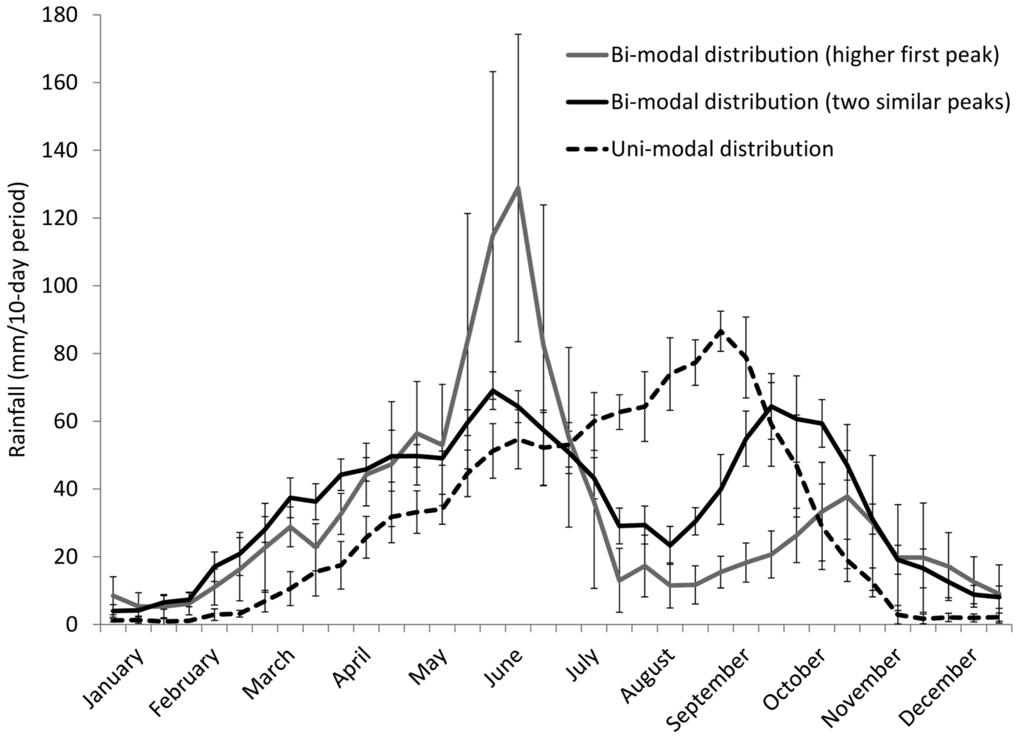

Fig. 2 Seasonal rainfall patterns in Ghana, derived from 16 studied rainfall stations, averaged over the period 1960–2005. Grey solid curves: average from stations Axim, Ada Foah, Accra Airport, Saltpond. Black solid curve: average from stations Akuse, Ho, Kumasi, Wenchi, Ejura, Kpeve. Dotted curve: average from stations Kete Krachi, Navrongo, Tamale, Wa, Yendi, Zuarungu. Vertical error bars: standard deviation between stations.

will in future. Currently, there is little understanding of how spatial and temporal patterns of rainfall have changed or are changing across the country (Jung 2006).

Against this background, insights into historical rainfall trends are necessary for both agricultural and water development planning. However, detection of changes in time series of highly variable meteorological data is not straightforward, particularly in areas like Ghana, where rainfall generating mechanisms are complex and uncertain, and historic records are scarce.

A number of recent studies have investigated trends in the West African Sahel region (Nicholson and Palao 1993, Tarhule and Woo 1998, Nicholson *et al*. 2000). Using gridded monthly precipitation data available at 0.5° intervals over the period 1951–2000, one study showed that West Africa has undergone a period of diminished rainfall with an apparent shift in the rainfall regime towards a longer dry season (Owusu *et al*. 2008). Other studies have shown an abrupt decline in annual rainfall in areas north of latitude 11°N (i.e. in the vicinity of the northern border of Ghana) since the 1970s, with uncertainty as to whether or not rainfall has recovered in more recent years (L'Hôte *et al*. 2002, Ozer *et al*. 2003, Nicholson 2005). However, to the south of this, the picture is less clear. Analysis of 40 years of rainfall and runoff from the southwestern part of Ghana and from the White Volta has shown a significant reduction in rainfall and runoff (Opoku-Ankomak and Amisigio 1998). A more recent study of the whole Volta basin (including the portion located in the Sahel), using 0.5° gridded climate data from the Climate Research Unit at the University of East Anglia, UK, found a decline in basin average precipitation of about 10% after 1970 (Oguntunde *et al*. 2006). Mahé *et al*. (2001) investigated discontinuities in standardized annual rainfall time series over the period 1951–1989 using a data set of 891 rainfall stations covering 23 countries in West and Central Africa. On the northern coast of the Gulf of Guinea, the authors found that annual rainfall followed a decreasing trend which became weaker southward. A study using the standardized precipitation index has shown that the frequency, intensity and areal extent of droughts have increased for the Volta basin since the 1970s (Kasei *et al*. 2010). Gyau-Boakye and Tumbulto (2006) compared annual rainfall and stream flows from northern and southern parts of Ghana between the periods 1950–1970 and

1971–1991. They found that, between the first and second periods, rainfall decreased by about 20% in the southern region, while it reduced by between 1.5 and 11.3% in the northern region. Yengoh (2010) investigated the presence of trends in agriculturally-relevant rainfall characteristics, using daily rainfall data from the Tamale station, in northern Ghana, over the period 1960–2007. The author identified an increase in daily rainfall intensity, while no changes were observed in the onset of rains, the annual rainfall total or days with maximum rainfall. However, a decrease was observed in the number of rainy days.

This review indicates that most of the previous trend studies were undertaken at the sub-continental level and mainly focused on annual rainfall. The few studies looking at spatial variations within Ghana did not assess trend significance, and changes in agriculturally-relevant rainfall indicators were assessed locally only, without any assessment of spatial variations of trends.

The Mann-Kendall test (Mann 1945, Kendall 1975) is one of the most frequently used trend detection tests applied to hydro-meteorological time series since its first use in climatology by Sneyers (1955). This non-parametric test is robust, as it does not require the data to follow any particular statistical distribution, and it has low sensitivity to outliers. However, like most trend detection tests, the Mann-Kendall test requires the data to be independent, since positive and negative auto-correlations induce over-estimated and under-estimated significances of trend, respectively (Cox and Stuart 1955). In most cases, as indicated by the presence of multi-year wet and dry periods, climate time series are auto-correlated (Hurst 1951). In order to address this issue, two main techniques have been used in the past to remove serial correlation in hydro-meteorological time series prior to trend testing: (a) the "pre-whitening" method, which consists of removing serial correlation (e.g. by using a lag-one autoregressive AR(1) process) (von Storch 1995); and (b) the "trend-free pre-whitening" method, which consists of calculating the lag-one autoregressive parameter (ρ) on pre-detrended time series (Yue *et al*. 2002). There are constraints on both these methods: on the first, because de-correlation alters trends, and on the second, because the initial removal of an apparent trend before estimating ρ tends to result in loss of significance and underestimation of ρ. Consequently, these two techniques result in either over- or under-estimated values of the correlation coefficient and of the trend. In an attempt to avoid these problems, a more effective way of pre-whitening time series has been proposed (Hamed 2009). This consists of simultaneously estimating the slope trend and the autocorrelation coefficient using the ordinary least-square method and then correcting the bias in the correlation coefficient.

A trend detection test applied to a point rainfall time series determines whether a trend exists locally. However, such a test does not confirm if a trend is evident throughout an entire region of interest where spatially heterogeneous trend patterns may occur. The field significance introduced by Vogel and Kroll (1989) indicates whether a significant trend emerges from a group of stations in the same region. Similar to the existence of auto-correlation, the presence of cross-correlation in a network inflates the significance of a regional trend and impedes the analytical evaluation of field significance. Cross-correlations duplicate the information contained at each site (e.g. if two stations are highly correlated then the second station merely duplicates the first and does not provide much new information). Consequently, resampling techniques, which account for spatial dependencies while preserving the spatial structure of cross-correlated data, are generally performed to assess the significance of regional trends (Douglas *et al*. 2000, Kundzewicz and Robson 2004).

The objectives of the current study were two-fold: (1) to assess the statistical significance of point and regional trends in 28 annual variables derived from daily rainfall measured from 1960 to 2005 at 16 stations located throughout Ghana, and (2) to determine whether there was any particular pattern in the spatial distribution of significant trends within the country. The non-parametric resampling-based Mann-Kendall trend test (Mann 1945, Kendall 1975) was applied to time series subjected to the pre-whitening process proposed by Hamed (2009). For each of the 28 annual variables, the local trend significances were compared to the regional significance calculated as suggested by Douglas *et al*. (2000).

DATA AND METHODOLOGY

Among more than 50 raingauges available in Ghana, 16 were selected as providing nearly continuous daily rainfall records from January 1960 to December 2005. There was only 0.6% missing data in the selected time series. Data gaps were filled through multiple linear regressions with, in each case, the best correlated stations ($R^2 > 0.6$) selected among the 50 available raingauges. Regression analyses were performed at the monthly time step with time series including, at least, 15 years of common period of record with the time series to be filled. Each regression analysis involved between two and five stations. As errors in measurements (as a result of instrument malfunction, change in measurement techniques, in instrumentation, or in instrument location) could induce artificial trends, the homogeneity of the data set was assessed using the method of the regional vector to identify spurious data (Hiez and Pouyaud 1987). The regional vector is a series of annual indices derived from the whole rainfall data set and capturing the inter-annual variation of rainfall over the region. An error in measurement, likely to occur at one station only at a given time, should result in a break in the time series of deviations between the annual indices of the station and the annual indices of the regional vector. The non-parametric breakpoint detection test introduced by Pettitt (1979) was successively applied to the 16 time series of annual deviations between each station and the regional vector. As none of the deviation time series exhibited significant break points at the 95% confidence level, it was concluded that the data set was exempt from any artefact likely to result in artificial trends in the rainfall time series. In addition, the quality of daily rainfall data was controlled by calculating the number of rainy days and the maximum daily rainfall depth per year at each station. Outliers were detected using the non-parametric median absolute deviation methodology suggested by Hampel (1974). Maximum deviation values in the number of rainy days were found to be six times higher than the respective median deviations. As these extreme values, observed at eight stations, all occurred in 1968, they most likely reflect a natural cause rather than an artefact expected to disrupt data at individual stations. Among the 10 greatest values of daily rainfall in the data set, nine values, ranging from 200 to 300 mm d^{-1}, are associated with return periods of 7 to 120 years by the Gumbel (1954) distribution model, indicating that these values remain realistic. Conversely, the highest value, 510 mm d^{-1}, corresponds to a return period of about 17 000 years, and so most likely results from an error. However this outlier was found to have a negligible effect on the study results because of the low sensitivity of the Mann-Kendall test to outliers.

Twenty-eight (28) annual variables were computed from the daily rainfall to capture the seasonality, intensity and frequency of rainfall. These variables are presented in Table 1. Two points are worth mentioning: (a) the computation of rainfall depths and of the number of rainy days per season for different ranges of daily rainfall (variables 1 to 24) enables contrasting changes that may occur in different weather extremes (light/heavy rainfall) to be observed: trends in small variables are not offset by the presence or absence of trends in the variables involving larger values; and (b) when the rainfall distribution is bimodal, i.e. in the southern part of the country (Fig. 1), variable 25 corresponds to the beginning of the first rainfall peak and variable 26 generally corresponds to the recession of the last rainfall peak (Table 1). Because of the high variability in the seasonal rainfall pattern, it was not possible to clearly distinguish two rainfall peaks in every year, thus preventing the systematic determination of rainfall minimum between the two peaks. Consequently, the wet season defined in the present study may include a varying number of rainfall peaks, depending on their respective magnitude (cf. Fig. 3).

Each of the 448 annual time series (16 stations × 28 annual variables) was first de-correlated using an effective pre-whitening approach (Hamed 2009). Each of these time series was assumed to follow a first-order auto-correlated process including a linear trend, and was modelled as follows:

$$X_t = \rho X_{t-1} + \alpha + \beta t + \varepsilon_t \tag{1}$$

where X_t and X_{t-1} are the observations of the time series at times t and $t-1$, respectively; ρ is the auto-correlation coefficient; α is a constant intercept term; β is the slope of the trend with respect to time; and ε_t is an uncorrelated noise term. Estimated values of ρ, α and β were given by the matrix calculation:

$$[\rho \quad \alpha \quad \beta]^{\mathrm{T}} = (Z^{\mathrm{T}}\boldsymbol{Z})^{-1}Z^{\mathrm{T}}\boldsymbol{y} \tag{2}$$

where $\boldsymbol{Z}$ is the matrix of size $(n-1) \times 3$ whose first column contains the observations x_1 to x_{n-1}, the second column contains $(n-1)$ values equal to 1, and the third column contains the numbers 2 to n; and $\boldsymbol{y}$ is a vector of size $(n-1) \times 1$ containing the observations x_2 to x_n (Hamed 2009). The correlation coefficient ρ is then corrected for bias using the Van Giersbergen (2005) first-order bias:

$$\rho^* = \frac{n\rho + 2}{n-4} \tag{3}$$

where ρ^* is the unbiased autocorrelation coefficient and n is the total number of observations in the time series. Given a time series X_i ($i = 1, \ldots, n$), the test statistic S of the Mann-Kendall test is given by:

Table 1 Description and computation methods of the 28 rainfall variables.

Variables	Name	Description	Computation method for each station
1 to 12	Rainfall depths per season and per range of daily rainfall	Cumulative depths of daily rainfall for three periods (whole year, wet season and dry season) and four ranges of daily rainfall depths (whole range, low, medium and high rainfall).	Two thresholds defining the low, medium and high ranges of daily rainfall depths were determined as follows: for each of the three periods (whole year, wet season and dry season), the sorted cumulative distribution of daily rainfall from 1960–2005 was split into three identical depths. The two daily rainfall thresholds were defined as the antecedents of one-third and two-thirds of the total depth of this distribution, using the sorted cumulative distribution function. These thresholds are displayed in Table 3.
13 to 24	Number of rainy days per season and per range of daily rainfall	Number of rainy days (rainfall >1 mm d^{-1}) for the similar pairwise combinations of periods and ranges of daily rainfall depths as described for the group of variables 1 to 12.	
25 and 26	Occurrence of the wet season (start and end)	Julian date (number of days since the beginning of the calendar year) of the start of the wet season (variable 25), and of the end of the wet season (variable 26).	The start of the wet season was defined as the first day of the first 10-day period that meets two conditions: (i) the 10-day rainfall depth is higher than the mean 10-day rainfall depth averaged over the period 1960–2005; and (ii) at least two of the next three 10-day periods satisfy the first condition. Because of the high rainfall variability, the variations between consecutive 10-day rainfall depths were first smoothed by a three time-step moving average. The end of the wet season was defined by symmetrical conditions, starting from the end of the calendar year and moving backward through the 10-day periods. Figure 3 illustrates how variables 25 and 26 are defined.
27	Rainfall intensity index	Number of heaviest rainy days that constitute two-thirds of the total annual rainfall (Sun *et al*. 2006).	
28	Length of the longest rainless period during the wet season	Largest number of consecutive dry days (rainfall <1 mm d^{-1}) occurring between the start and the end of the rainy season.	

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i) \tag{4a}$$

where:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 0 \\ 0 & \text{if} \quad \theta = 0 \\ -1 & \text{if} \quad \theta < 0 \end{cases} \tag{4b}$$

Pre-whitened time series were submitted to a resampling-based version of the Mann-Kendall test (Kundzewicz and Robson 2004). This version of the Mann-Kendall test differs from the original one in the sense that the test statistic S calculated with equation (4) is not compared, after standardization, to the standard normal variate. Instead, it is compared to an empirical cumulative distribution function of S generated by resampling years (by permutations) 10 000 times in the original data set and by calculating the new statistic value for each re-sampled data set. The reason for opting for this alternative methodology is that such a test allows accurate comparison of local and regional trend significances, as the regional Mann-Kendall test (described below) is necessarily resampling-based. Yue and Pilon (2004) demonstrated that the power of the original and

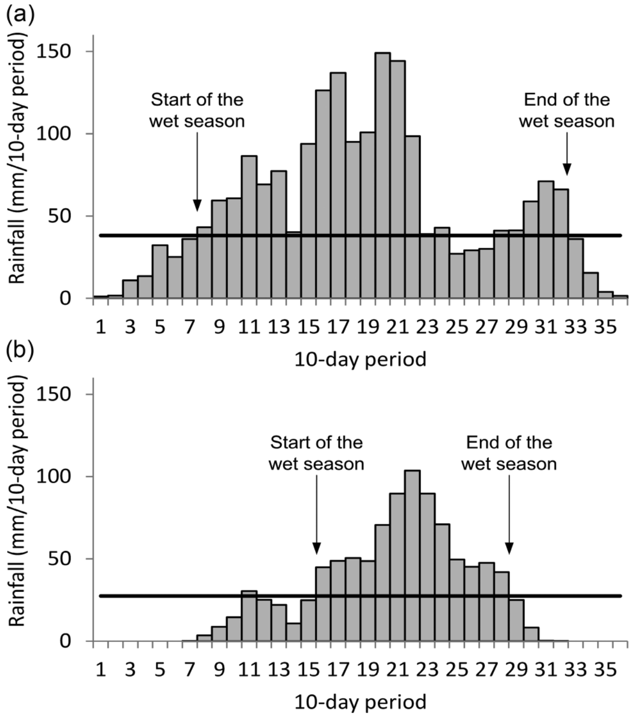

Fig. 3 Graphical illustration of method used to determine the start (variable 25) and end (variable 26) of the wet season at (a) Kumasi and (b) Navrongo for example year 1966. Horizontal line: mean 10-day rainfall depth averaged over the period 1960–2005.

resampling-based Mann-Kendall tests is similar. For each of the 28 rainfall variables, a regional average Kendall statistic, S_m, was calculated, as proposed by Douglas *et al*. (2000):

$$S_m = \frac{1}{m} \sum_{k=1}^{m} S_k \tag{5}$$

where S_k is the statistic S of the Mann-Kendall test for the kth station among the m stations of the region ($m = 16$ in our study). For each of the 28 variables, S_k ($k = 1, \ldots, m$) and S_m were compared to their empirical cumulative distribution functions, which preserve the spatial correlation structure of the original data set. The location of the original S_k and S_m statistics on the empirical cumulative distribution curves enables the existence of a possible trend in the time series to be determined for a given confidence interval. If the test concludes that a significant trend exists, its slope is calculated using the Sen slope estimator, E_o (Sen 1968):

$$E_o = \text{median}\left(\frac{X_j - X_i}{j - i}\right) \quad \forall i < j \tag{6}$$

RESULTS

Table 2 presents the results of the Mann-Kendall tests for each of the 28 rainfall variables and for two levels of confidence (90% and 95%). Figures 4 and 5 display the time series and significant trends for the 28 variables at Kumasi where the greatest number of significant trends were observed. No significant trends were found in annual rainfall depth, except at Akuse where a decreasing trend was detected at the 90% confidence level. Declining trends (95% confidence level) in low annual rainfall depth were observed at seven stations and at the regional level. Trends in the "medium" and "high" ranges of annual rainfall (variables 3 and 4) are minor with only one significant rising trend for each variable, at the stations Navrongo and Tamale, respectively. Wet-season trends in rainfall depths were similar to those observed in annual rainfall amounts: they predominantly affect the "low" range of rainfall depths, as reflected by the presence of a 95%-significant declining trend at four stations and at the regional level. Similar to the changes observed in annual rainfall amounts, trends in wet-season rainfall were virtually non-existent in the "medium" and "high" ranges (variables 7 and 8). Table 3 presents the rainfall thresholds used to compute the "low", "medium" and "high" ranges of rainfall depths at each station. The inter-station variability of the low thresholds (i.e. defining the "low" range of rainfall depth) is moderate: coefficients of variation vary from 9% for the dry season to 17% for the wet season. Therefore, their averaged values were used to characterize the long-term changes over the region: for annual and wet-season rainfall amounts, the "low" range, where most of significant declining trends were observed, corresponds, on average, to the accumulation of daily rainfall lower than 18.9 and 21.0 mm d^{-1}, respectively. Significant trends observed during the dry season were minor, as they affect only one station (Kumasi), at the 90% confidence level, for the "whole" range, and two stations (Akuse and Kumasi), at the 95% confidence level, for the "low" range. No significant trends were observed for the "medium" and "high" ranges during the dry season.

Trends in the number of rainy days (variables 13 to 24) were similar to those observed in rainfall depths (variables 1 to 12): 90%- and 95%-significant trends in the annual and wet-season numbers of rainy days were negative and predominantly affected the "all" and "low" ranges of daily rainfall. Significant regional trends were observed for four variables (i.e. 13, 14, 17 and 18) at the 95%, 95%, 90% and 95%

Table 2 Trends in rainfall variables 1 to 28 over the period 1960–2005. **Bold** values: Sen slope of trends significant at the 95% confidence level. *Italic* values: Sen slope of trends significant at the 90% confidence level. Zero values: absence of significant trend. “>0” and “<0” correspond to significant positive and negative regional trends, respectively.

(a) Variables 1 to 12:

	Coordinates		Altitude (m)	Rainfall depth											
	Lat.	Long.		Year				Wet season				Dry season			
				All (1)	Low (2)	Med (3)	High (4)	All (5)	Low (6)	Med (7)	High (8)	All (9)	Low (10)	Med (11)	High (12)
Axim	4°52′	−2°14′	20	0	**−3.9**	0	0	0	0	0	0	0	0	0	0
Saltpond	5°12′	−1°04′	15	0	0	0	0	0	0	0	0	0	0	0	0
Accra Airport	5°36′	−0°10′	63	0	**−1.8**	0	0	0	0	0	0	0	0	0	0
Ada Foah	5°47′	0°38′	7	0	0	0	0	0	0	0	0	0	0	0	0
Akuse	6°06′	0°07′	12	*−5.4*	0	0	0	*−6.9*	**−3.8**	0	0	0	**0.7**	0	0
Ho	6°36′	0°28′	165	0	0	0	0	0	0	0	0	0	0	0	0
Kpeve	6°41′	0°20′	140	0	**−3.5**	0	0	0	0	0	0	0	0	0	0
Kumasi	6°43′	−1°36′	285	0	**−3.9**	0	0	0	**−4.8**	0	0	*1.2*	**0.6**	0	0
Ejura	7°24′	−1°21′	210	0	**−4.2**	0	0	0	**−4.4**	0	0	0	0	0	0
Wenchi	7°45′	−2°06′	320	0	0	0	0	0	0	0	0	0	0	0	0
Kete Krachi	7°49′	−0°02′	115	0	0	0	0	0	0	0	0	0	0	0	0
Yendi	9°27′	−0°01′	200	0	**−3.3**	0	0	0	**−3.8**	0	0	0	0	0	0
Tamale	9°33′	−0°51′	180	0	0	0	**2.3**	0	0	0	*1.8*	0	0	0	0
Wa	10°03′	−2°30′	310	0	0	0	0	0	0	0	0	0	0	0	0
Zuarungu	10°47′	−0°48′	210	0	0	0	0	0	0	0	0	0	0	0	0
Navrongo	10°54′	−1°06′	192	0	**−2.3**	**2.3**	0	0	0	**1.8**	0	0	0	0	0
Field significance				0	<**0**	0	0	0	<**0**	0	0	0	0	0	0

(*Continued*)

Table 2 (Continued).

(b) Variables 13 to 28:

	Number of rainy days												Occurrence wet season		Intensity index	Drought length
	Year				Wet season				Dry season							
	All (13)	Low (14)	Med (15)	High (16)	All (17)	Low (18)	Med (19)	High (20)	All (21)	Low (22)	Med (23)	High (24)	Start (25)	End (26)	(27)	(28)
Axim	0	0	0	0	0	0	0	0	0	0	0	0	**0.7**	0	0	0
Saltpond	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Accra Airport	*−0.3*	0	0	0	0	0	0	0	0	0	0	0	0	0	**−0.1**	0
Ada Foah	0	0	0	0	0	0	0	0	0	0	0	*0.0*	0	0	0	0
Akuse	**−0.4**	0	**−0.1**	0	**−0.5**	**−0.5**	0	0	*0.1*	**0.1**	0	0	0	0	*−0.1*	0
Ho	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kpeve	**−0.6**	**−0.6**	0	0	0	*−0.4*	0	0	0	*−0.2*	0	0	0	0	**−0.2**	*0.1*
Kumasi	**−0.7**	**−0.6**	0	0	**−0.7**	**−0.7**	0	0	**0.1**	**0.1**	0	0	**0.4**	0	**−0.2**	**0.1**
Ejura	**−0.5**	**−0.5**	0	0	**−0.6**	**−0.5**	0	0	0	0	0	0	**0.4**	0	**−0.2**	**0.1**
Wenchi	0	0	0	0	0	0	0	*0.0*	0	0	0	0	0	0	**−0.2**	0
Kete Krachi	0	0	0	0	0	0	0	0	0	0	0	0	**0.6**	0	0	0
Yendi	0	*−0.2*	0	0	0	*−0.2*	0	0	0	0	0	0	0	0	**−0.1**	0
Tamale	0	0	0	**0.0**	0	0	0	0	0	0	0	0	0	0	0	0
Wa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zuarungu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navrongo	0	0	**0.1**	0	0	0	**0.1**	0	0	0	0	0	0	0	0	0
Field significance	<**0**	<**0**	0	0	*<0*	<**0**	0	0	0	0	0	0	>**0**	0	<**0**	>**0**

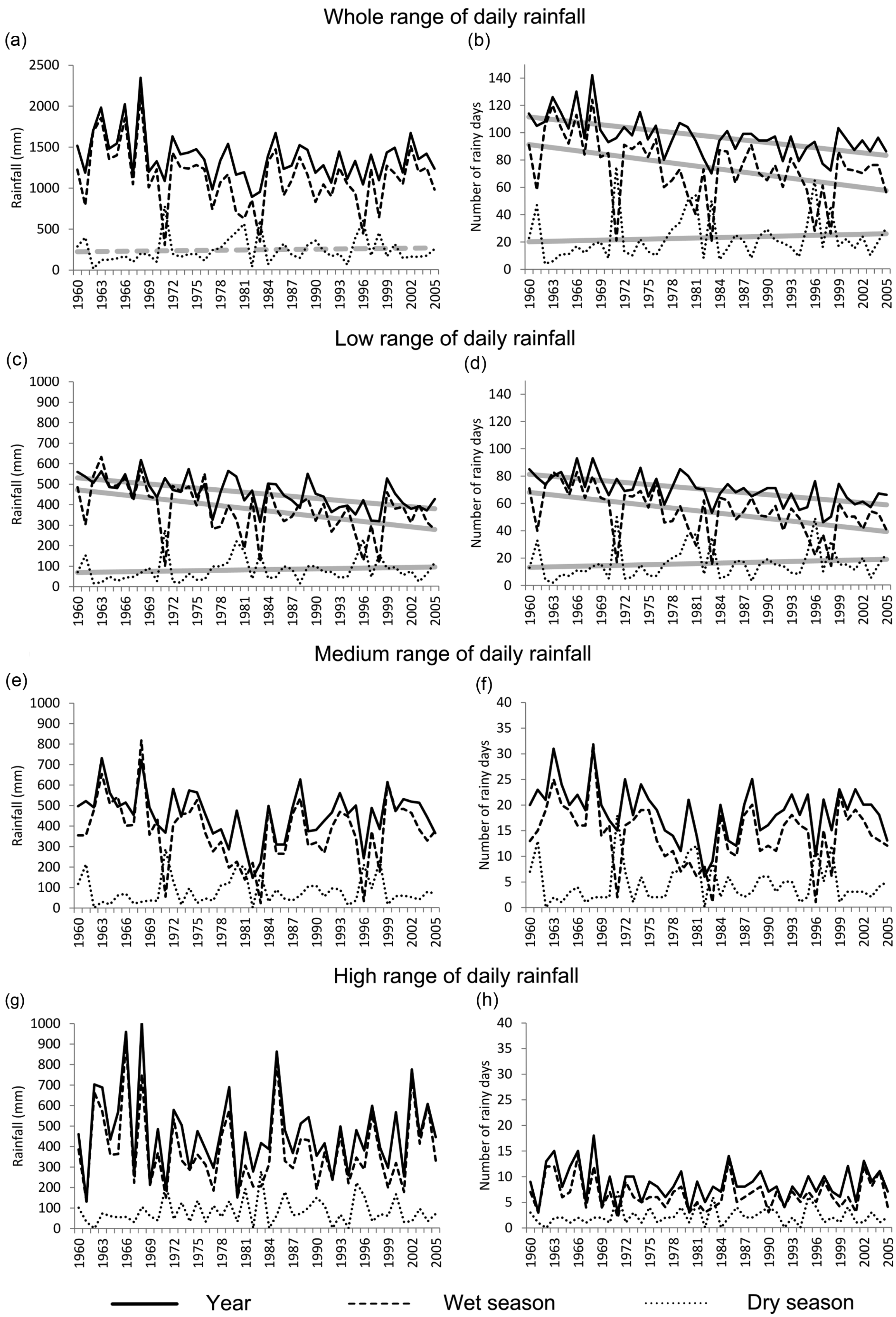

Fig. 4 Time series for: (a), (c), (e), (g) variables 1 to 12 and (b), (d), (f), (h) variables 13 to 24 at Kumasi station. Solid and dotted grey lines: significant trends at the 95% and 90% confidence levels, respectively.

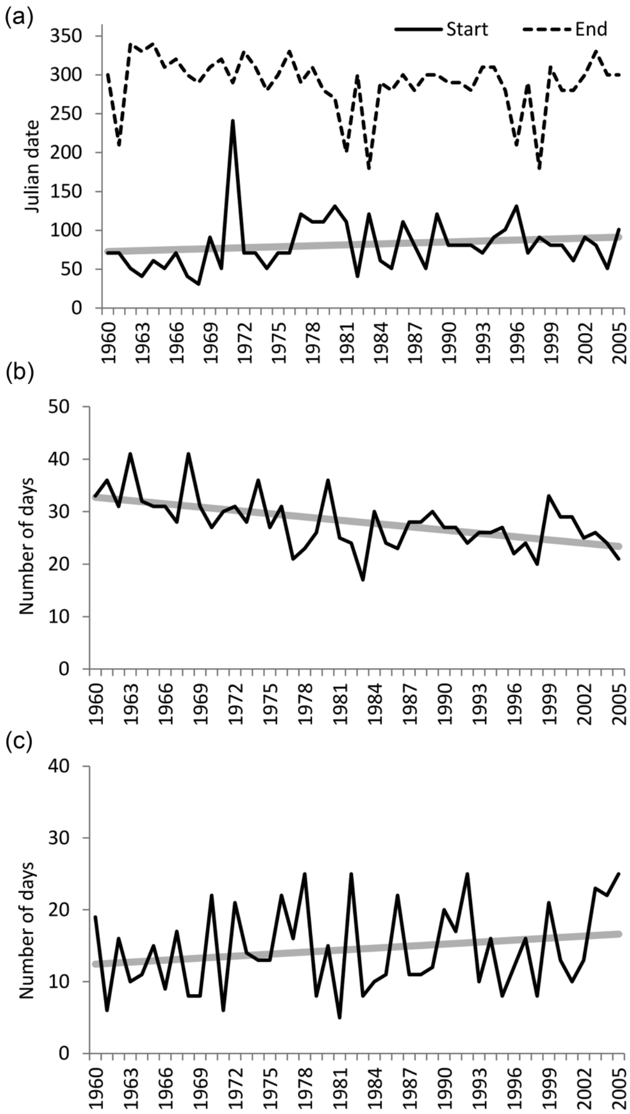

Fig. 5 Time series for (a) variables 25 and 26, (b) variable 27 and (c) variable 28 at Kumasi station. Grey lines: significant trends at the 95% confidence level.

Table 3 Low and high thresholds (mm d^{-1}) defining the low, medium and high ranges of daily rainfall depths.

Station	Year		Wet season		Dry season	
	Low	High	Low	High	Low	High
Axim	24.9	61.0	31.5	70.4	14.0	33.3
Saltpond	20.8	44.2	25.0	51.1	10.9	27.2
Accra Airport	19.1	44.2	22.6	48.8	11.2	22.7
Ada Foah	21.1	46.2	24.4	51.3	12.7	24.9
Akuse	18.8	39.6	20.8	43.2	12.5	27.9
Ho	17.2	35.3	18.5	37.2	13.0	25.7
Kpeve	17.4	35.1	19.1	36.8	11.9	25.1
Kumasi	16.5	36.1	18.0	39.1	11.8	26.9
Ejura	18.5	36.8	19.3	38.1	13.2	27.9
Wenchi	16.3	33.0	17.3	34.8	10.7	22.0
Kete Krachi	20.7	44.5	22.7	47.2	13.4	27.7
Yendi	19.2	37.9	19.8	38.9	13.5	29.3
Tamale	18.8	36.7	19.6	37.1	14.2	31.5
Wa	16.8	32.7	17.5	33.6	11.5	27.7
Zuarungu	17.8	36.6	19.8	38.1	11.4	22.6
Navrongo	18.6	36.6	19.8	38.9	11.3	21.2
Average	18.9	39.8	21.0	42.8	12.3	26.5
Standard deviation	2.1	6.8	3.5	9.0	1.1	3.3
Variation coefficient	11%	17%	17%	21%	9%	12%

confidence levels, respectively. Trends corresponding to the "medium" and "high" ranges of daily rainfall affected no more than two stations per variable during the year and the wet season. Trends observed during the dry season were limited to two stations (Akuse and Kumasi), three stations (Akuse, Kumasi and Kpeve) and one station (Adah Foah) for the "all", "low" and "high" ranges of daily rainfall, respectively. No significant regional trends were observed during the dry season.

Four stations exhibit a 95%-significant rising trend in the occurrence of the start of the wet season (variable 25), meaning that the onset of the monsoon was delayed, resulting in a shorter wet season. A 95%-significant regional rising trend was also observed for this variable. In contrast, no trends were observed in the end of the wet season, either at individual stations or at the regional level.

Six 95%-significant and one 90%-significant declining trends were observed in the intensity index, which captures the combined effect of rainfall and intensity (variable 27), also reflected by a 95%-significant regional declining trend. These trends indicate that annual rainfall amounts at these stations and at the regional level tend to comprise increasingly fewer rainy days. A 95%-significant and a 90%-significant rising trend in the length of longest wet season rainless period (variable 28) were observed at two and one stations, respectively. A 95%-significant regional rising trend was also observed for that variable despite the limited number of significant local trends.

The spatial distributions of local trends for those variables that exhibited significant regional trends are illustrated in Fig. 6. At each station, the trend significances for the variables 2, 6, 13, 14, 17, 18 and 27 (related to rainfall cumulative depths and the number of rainy days) have been averaged in a single curve, as the spatial variations of trend significances for these variables are similar (cf. Table 2). Figure 6 indicates that the most significant trends for these variables are observed between latitudes 6° and 9.5°, i.e. for the stations Akuse, Ho, Kpeve, Kumasi, Ejura,

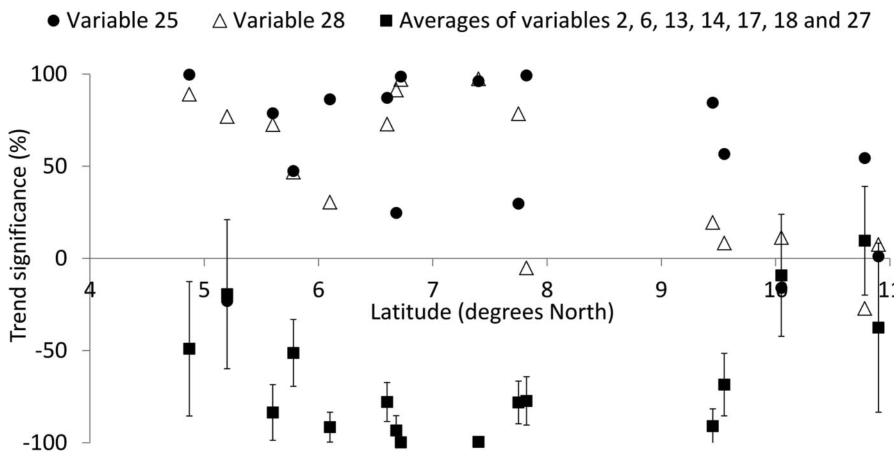

Fig. 6 Local trend significance for variables exhibiting regionally significant trend at the 95% confidence level. The vertical error bars correspond to standard deviations between variables 2, 6, 13, 14, 17, 18 and 27.

Wenchi, Kete Krachi and Yendi (Fig. 1). The spatial pattern of trend significance for variable 25 (start of the rainy season) is more heterogeneous and does not affect any particular region of Ghana. In contrast, the significance of trends for variable 28 (length of longest rainless period during the wet season) is higher in the south and in the centre of Ghana and lower in the north. The possible effect of altitude on trend significance was investigated by calculating the determination coefficients between the stations' elevation and the trend significances for the variables 25, 28 and for the average of variables 2, 6, 13, 14, 17, 18 and 27. The absence of correlation for all variables ($R^2 < 0.02$) suggests that the trend significances are not controlled by the altitude of the rainfall stations.

DISCUSSION

This trend analysis indicates that there was almost no significant change in annual rainfall depths (variable 1) over the period 1960–2005, at either the station level or the regional level. However, several trends are apparent when considering specific periods of the year and/or particular ranges of daily rainfall depths. The main finding of this study is that significant rainfall changes occurred in Ghana from 1960 to 2005, resulting in a reduction in the number of rainy days with totals less than about 20 mm of rainfall, during the wet season, between latitudes 6° and 9.5°N. This reduction was consistently accompanied by a reduction in the cumulative rainfall depths produced by these below-20 mm daily rainfall events. Although these changes were confined to the central part of Ghana, they remain significant at the country level, as attested by the regional Mann-Kendall test. This reduction in the number of "low" rainfall events was consistently accompanied by regionally-significant changes observed in two other variables: a slight delay (about 0.5 d year^{-1}) in the date of the onset of the wet season (variable 25); and a lengthening (about 0.1 d year^{-1}) of the longest rainless period during the wet season (variable 28). The comparative analysis of the trend test results highlights two types of apparent inconsistency:

(a) For all the variables exhibiting regionally significant trends, the number of individual stations with significant trends represents less than half of the total number of stations. This contrast between significance in regional and local trends is particularly marked for the length of the longest wet-season rainless period (variable 28), which exhibits 95%-significant trends at just two stations (Kumasi and Ejura) (i.e. 12% of the stations). This apparent contradiction is explained by the numerous insignificant positive trends hidden by zero values in Table 2. Figure 7 displays the significance level of trends observed at each station and over the whole region for variable 28. Half of the stations display positive trends with a significance level in excess of 70%, and 14 of the 16 stations exhibit positive trends. The 95% significance level of the regional trend can be explained in two ways:
   (i) a similar trend observed at several neighbouring stations is more likely to really exist (and not be the result of a random process) than if it were observed at one station only;

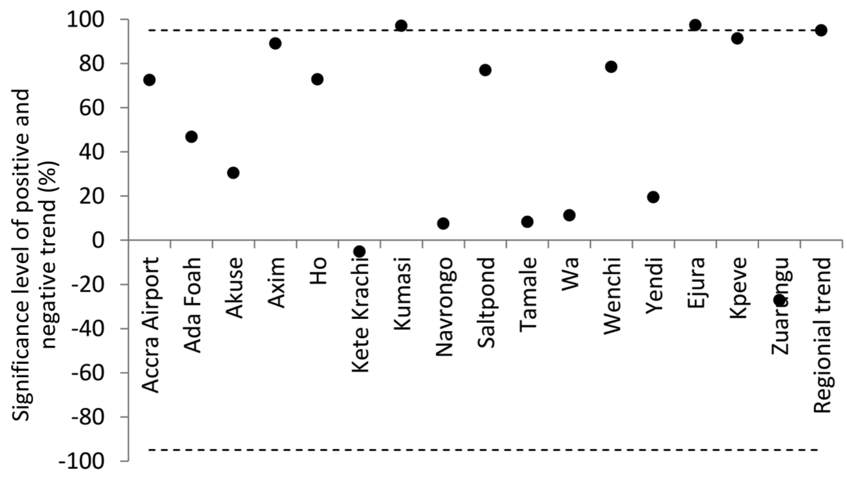

Fig. 7 Significance level of trends observed for variable 28 (length of the longest wet-season rainless period). Positive and negative values correspond to positive and negative trends, respectively. Dotted lines: 95% significance level.

(ii) the significance level of a trend is moderated by the temporal variability of observations, but enhanced by the length of the time series (i.e. number of observations). As a regional trend is derived from a greater number of observations than a local trend, it is expected that the regional trend will have a greater significance when a large majority of local trends have the same sign. Theoretically, the higher significance of the regional trend originates from the fact that the order of years in each re-sampled rainfall data set used to compute S_m (equation (5)) remains the same at each station. Therefore, the non-exceedence frequency associated with the absolute value of S_m may be higher than those associated with each absolute value of S_k.

These considerations highlight the vital importance of evaluating regional trends and not just local trends when characterizing long-term changes in rainfall. As demonstrated, computing regional trends not only indicates the spatial extent of a changing pattern, but also enables the detection of significant changing patterns that remain insignificant at the local level.

(b) Table 2 indicates that despite the presence of significant trends in rainfall depths produced from the low range of rainy days (variables 2, 6 and 10), virtually no significant trends were observed in the rainfall depths produced from the whole range of daily rainfall (variables 1, 5 and 9). Trends in "low" rainfall were hidden by the values of daily rainfall corresponding to the "medium" and "high" ranges (variables 3, 4, 7, 8, 11 and 12), accounting for 66% of annual, wet- and dry-season rainfall. In contrast, significant trends in the number of "low" rainy days (variables 14, 18 and 22) induces, at most locations, a significant reduction in the total number of rainy days (variables 13, 17 and 21) despite the absence of significant trends in the number of "medium" and "high" rainy days (variables 15, 16, 19, 20, 23 and 24). This difference in behaviour is due to the fact that the number of "low" rainy days accounts for about 72% of the total number of rainy days throughout either the year, the wet season or the dry season. Consequently, it has a stronger weighting, and hence influence, on the trend significance of the total number of rainy days.

Comparison with previous results

The comparison of our results with those from previous rainfall trend detection studies is not easy, because of the differences in rainfall variables, periods and geographical areas specific to each analysis. However, some consistencies and discrepancies are noted and tentatively explained:

- Oguntunde *et al*. (2006) observed an insignificant annual rainfall decrease (95% significance level) of 0.2 mm year^{-1} over the period 1970–2002 in the Volta River basin. This result is consistent with the absence of significant trend found for variable 1 in the present study. As Oguntunde *et al*. (2006)

did not investigate changes in seasonal rainfall, nor in any specific ranges of daily rainfall, it was not possible to further compare their study with ours.

- Kasei *et al*. (2010), who investigated temporal characteristics of meteorological droughts in the Volta basin, found that the frequency of droughts has increased from the 1970s onward. Their analysis was based on the standardized precipitation index calculated from annual rainfall depths. Our findings related to the lengthening of longest rainless period during the wet season and the reduction of cumulative rainfall depths produced from light rainy days during the wet season are consistent with the authors' observations made at the annual time step.
- Our results apparently contradict findings from Mahé *et al*. (2001), who observed a significant decreasing trend in standardized annual rainfall over the period 1951–1989 in Ghana. However, although no 95%-significant trends and only one 90%-significant trend were observed in annual rainfall in our study, it should be noted that the test applied to non-pre-whitened time series deduced declining trends, significant at the 90% level at seven stations, and at the 95% level over the whole region. The slight differences in the studied periods may also explain the different results between the two studies.
- The study of Owusu *et al*. (2008) not only confirms the declining trend observed in rainfall but also found that the dry season has become longer over the last half century. These results are consistent with the rising trend that we observed in the date of the wet-season onset.
- Yengoh (2010) focused his rainfall trend analyses on the Tamale station over the period 1960–2007. Applying the *t*-test to time series of several rainfall characteristics at the 95% confidence level, the author found no significant change in annual rainfall and in the onset of rains, while significant negative and positive trends were observed in the annual number of rainy days and in the mean rainfall per rainy day, respectively. A rigorous comparison of the results of Yengoh (2010) with ours is not possible, as the study periods and some of the studied variables differ slightly. However, it is worth questioning why Yengoh observed a negative trend in the number of rainy days, while no significant trend was observed for that variable (i.e. variable 13) at Tamale in our case. A possible explanation for this discrepancy is that Yengoh did not correct the input data for serial correlation. If the Mann-Kendall test is applied to non pre-whitened time series of variable 13, a negative trend significant at the 95% confidence level is observed.

Implications for agriculture

According to the Sen slopes of significant trends displayed in Table 2, the reduction in light rainfall depths ranges from to 2 to 4 mm year^{-1}, equivalent to a total annual reduction of 92 to 184 mm over the entire study period of 46 years. This increased dryness, which translates itself into longer rainless periods during cropping cycles, may have deleterious effects on crop yields, since agriculture in Ghana is predominantly rainfed. The delay in the onset of the wet season (i.e. about 0.5 d year^{-1}, equivalent to a total delay of 23 days over the study period) is also likely to have resulted in a reduction in agricultural yields, since most crop planting commences with the arrival of the first rains and the early stages of the cropping calendar are generally the most sensitive to water shortages.

Implications for water storage/water resource management

It is difficult to predict the impact of the observed changes in rainfall on the water resources of Ghana. However, in arid regions, even small changes in either totals or the temporal distribution of rainfall can have significant impacts on water resources. Small percentage changes in rainfall can result in much greater percentage changes in soil moisture, which in turn can translate into significant impacts on groundwater recharge and river flows (Chiew *et al*. 1995). Using simple water balance models, Andreini *et al*. (2000) found that flow in the Volta basin is very sensitive to rainfall. A 10% decrease in annual rainfall after 1970 has been linked to a 16% decrease in annual flow over the same period (Oguntunde *et al*. 2006). Simple regression of flow measured at Nawuni, the most downstream station in the White Volta basin, showed a decline of 30% between 1961 and 1998, which was linked to a 20% decline in annual rainfall over the same period (Opoku-Ankomah and Amisigo 1998). In the current study, we did not evaluate trends in flow. However, we surmise that, although the declining trend in annual rainfall over Ghana that we found was statistically insignificant, it will nevertheless be associated with increased dryness that may have resulted in runoff and, hence, water storage reductions.

The observed changes in the delay to the onset of the rainy season, the decreased frequency of low rainfall events and the increased length of rainless periods during the rainy season have all most likely increased the periods of soil moisture deficit. As the catchment dries out, more rainfall is required to saturate the soils and, hence, induces both runoff and groundwater recharge. However, the exact impact of the changes in rainfall depends on a number of complex interacting factors, including not only the timing, distribution and intensity of rainfall, but also the nature of vegetation, geology and soils (Aldous *et al*. 2011). Consequently, impacts across Ghana will most certainly have differed, but broadly it can be speculated that:

- in relation to the provision of water for crops, the effectiveness of any soil water conservation measures has been reduced;
- groundwater infiltration may have reduced as a consequence of the delay to the onset of the rainy season, possibly resulting in a decrease in the volume of low flows at the end of the dry season and a delay to the start of the high-flow period;
- although their importance may be greater, the effectiveness of small-scale water storage interventions (e.g. tanks and small reservoirs) may have been diminished as a consequence of reductions in the frequency of filling and increases in the time between periods when they are full.

To date, there have been no studies that have directly tested these hypotheses. However, a recent study of the White Volta basin has shown the link between rainfall and groundwater recharge/baseflow. Using a semi-distributed hydrological model, this study found that, although there was significant spatial and temporal variation across the catchment, groundwater recharge currently equated to approximately 6.5% of mean annual rainfall (i.e. 55 out of 851 mm) and would increase to approximately 7.9% (i.e. 71 out of 904 mm) under a specific climate change scenario (Obuobie 2008). However, more detailed analyses of runoff and flux volumes are needed to quantify the actual impacts of the trends in rainfall regime detected in the current study.

CONCLUSIONS

Patterns of rainfall change in Ghana over the last half century have remained poorly understood as most previous research efforts focused on the West African region north of 10°N latitude. Moreover, past studies predominantly investigated changes only in annual rainfall amount. Previously temporal changes in agriculturally-relevant rainfall characteristics have only been studied at the local level. In several past studies, data were seemingly not corrected for serial correlation prior to trend analyses, thereby reducing confidence in the validity of the trends observed.

In this paper, we investigated the presence of trends over the period 1960–2005 in 28 rainfall characteristics, including indicators of cumulative rainfall depth, rainfall frequency and intensity, and occurrence of the wet season, using daily effectively prewhitened rainfall time series from 16 stations ranging from latitudes 4°52′N to 10°54′N in Ghana. At the country level, the study found an insignificant declining regional trend in annual rainfall. However, several significant regional trends, at the 95% confidence level, were observed: (a) a reduction of light rainfall (<20 mm d^{-1}) during the wet season, (b) a delay in the onset of the wet season (about 0.5 d $year^{-1}$), and (c) a lengthening of rainless periods during the wet season (about 0.1 d $year^{-1}$). Significant (95%) declining trends in light rainfall were observed at individual stations between latitudes 6°N and 9.5°N. These changes may have been deleterious for rainfed crops and, if they continue, may have implications for water resources and storage in the country. However, the cause of the observed trends is unclear and it is not yet possible to conclude that they are a consequence of climate change and will continue.

It is interesting to note that trends in several variables, such as the length of the longest rainless period during the wet season, although insignificant at a majority of rainfall stations, were found to be regionally significant at the country level. This result demonstrates that regionally-significant changes may appear as insignificant when observed at one station only. Hence, the investigation of regional trends should be undertaken using as many stations as possible.

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