METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **19**: 464–472 (2012)
Published online 5 July 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.281

Trends and variability in pan evaporation and other climatic variables at Ibadan, Nigeria, 1973–2008

Philip G. Oguntunde,[a]* Babatunde J. Abiodun,[b] Olawale J. Olukunle[a] and Ayorinde A. Olufayo[a]

[a] *Department of Agricultural Engineering, The Federal University of Technology, Akure, Nigeria*
[b] *Department of Environmental and Geographical Science, University of Cape Town, Rondebosch, South Africa*

ABSTRACT: Understanding changes in evaporation rates is expected to be of great importance for water resource planning and management. This paper examines pan evaporation data as an example of the detection and attribution of trends in climate variables. Records of pan evaporation (E_{pan}), rainfall (R), radiation (S_R), wind speed (W_S), temperature (T_a) and humidity (R_H) for the period 1973–2008 were collected from the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria. Mann–Kendall trend and Sen's slope tests were performed on the respective meteorological variables and a variability index (VI) was also computed for these. The results showed that annually E_{pan}, S_R and W_S significantly decrease ($P < 0.001$) while R, T_a, and R_H showed insignificant increasing trends in the last four decades. E_{pan} and S_R decrease at the rate of 8.3 mm year^{-2} and 37.8 MJ m^{-2} year^{-1}, respectively. Similar to E_{pan}, S_R decreased significantly in all the months ($P < 0.01$) and the reduction ranged from 5.1% *per* decade in March to 9.3% *per* decade in August. The result of VI showed that the decrease in E_{pan} and other explanatory variables is rather recent. Regression between E_{pan} and other variables indicates that about 30, 15 and 6% of its variance can be explained by S_R, W_S and VPD (vapour pressure deficit), respectively. The possible roles of dust-haze known as 'harmattan' winds and monsoon clouds in attenuating S_R and hence reducing E_{pan} are discussed. Copyright © 2011 Royal Meteorological Society

KEY WORDS climate change; evaporation trends; complementary relationship; global dimming

Received 26 December 2010; Revised 21 March 2011; Accepted 23 May 2011

1. Introduction

A change in the rates of evaporation is expected to be of great importance for water resource planning and management, irrigation control and agricultural productivity. It is important to understand causes of changes in pan evaporation in order to make more robust predictions about future changes in the water cycle. Decrease in pan evaporation and/or potential evaporation, has been reported since 1950 in many parts of the world. This trend is contrary to the expectation that global warming will be accompanied by an increase in terrestrial evaporation, known as the pan evaporation paradox (Brutsaert and Parlange, 1998; Cohen *et al*., 2002; Roderick and Farquhar, 2002; Liu *et al*., 2004). Based on physical theory expressed in the Penman Equation (Farquhar and Roderick, 2005), pan evaporation can be directly influenced by net radiation impinging on the pan of water (i.e. heat input which is mostly determined by solar radiation) vapour pressure deficit (VPD) of the air passing over the pan and wind speed. However, average air temperature has no direct effect but can only indirectly affect evaporation by influencing the VPD of the air and the down welling radiation load on the surface.

Evidence that pan evaporation rates have decreased during the past half century was presented by Peterson *et al*. (1995) based on measurements from several hundred evaporation pan stations over the United States and former Soviet Union. Similar trends have been presented for India (Chattopadhyay and Hulme, 1997), Australia and New Zealand (Roderick and Farquhar, 2004, 2005), China (Liu and Zeng, 2004; Liu *et al*., 2004), Japan (Asanuma *et al*., 2004) and Thailand (Tebakari *et al*., 2005). Evidence for a decrease of potential evaporation was also reported from China on the basis of data measured at 60 climate stations using estimates made with the Penman equation (Cohen *et al*., 2002) and more recently at 150 meteorological stations during 1960–2000 in the Changjiang (Yangtze River) catchment (Xu *et al*., 2006). These reductions in pan evaporation are not universal: others have reported an increase at some local stations, for example at Bet Dagan in Israel (Cohen *et al*., 2002), in some parts of United States (Brutsaert, 2006), Kazakhstan (Golubev *et al*., 2001) central China (Liu and Zeng, 2004) and at a few stations in Australia (Roderick and Farquhar, 2004).

Explanation for the observed widespread decreasing trends in pan evaporation continues to generate interesting debate. Some researchers argue that the decrease in pan evaporation is consistent with widespread decreases in solar irradiance received on the Earth's

* Correspondence to: P. G. Oguntunde, Department of Agricultural Engineering, the Federal University of Technology, Akure, Nigeria. E-mail: poguntunde@yahoo.com

surface as a result of increasing cloudiness and aerosol concentrations. The decline in solar irradiance, or global dimming, is seen as the main cause of the decline in pan evaporation, and thus evidence of decreasing landscape evaporation (Peterson *et al.*, 1995; Cohen *et al.*, 2002; Roderick and Farquhar, 2002, 2004; Liu *et al.*, 2004; Xu *et al.*, 2006). Another interpretation, although not necessarily contradictory, is based on a complementary relationship hypothesis between actual evaporation and pan evaporation. From this view, the decrease of pan evaporation is taken as a sign of increasing terrestrial evaporation (increased terrestrial evaporation will increase moist air over the evaporation pan, thus reducing evaporation from the pan): that is, global climate changes have led to increases in actual evaporation (Brutsaert and Parlange, 1998; Lawrimore and Peterson, 2000; Golubev *et al.*, 2001; Brutsaert, 2006).

As this debate continues, the need for additional data and analysis to explain the mechanisms behind the widely observed decline in pan evaporation and its implications for understanding the influence of climate change on the global hydrological cycle was advocated (Cohen *et al.*, 2002; Liu *et al.*, 2004). Whereas most of the contributions to this debate are from many parts of the globe, little or nothing was reported from Africa either at local or regional levels. This may be partly due to lack of qualitative long-term data sets compared to other regions. Therefore, the purpose of this analysis of a local series of pan evaporation measurements and other explanatory climatic variables is to explore any time trends found in the light of the hypotheses described above and hence contribute to the on-going discussion from Nigeria, West Africa.

2. Datasets and methods

2.1. The study area

Ibadan, a city in southwestern Nigeria, is located about 110 km northeast of Lagos. The city, reputed to be the largest native city in Black Africa, is located at latitude 7°22′N and longitude 3°54′E (Sangodoyin, 1992). Ibadan grew rapidly in the mid-nineteenth century and her resident population increased from about 1 million in 1963 to about 3.6 million in 2007. The climate is generally monsoon with bimodal rainfall pattern. Average rainfall is about 1300 mm year^{-1} and mean monthly temperature varied from 24.5 °C in August to 28.8 °C in February (Sangodoyin, 1992). The soil type is ferric luvisols and the vegetation is mild-hot farmland and settlements (Jagtap and Alabi, 1997).

2.2. Data source

Pan evaporation (E_{pan}), rainfall (R), solar radiation (S_{R}), wind speed (W_{S}), minimum and maximum temperature (T_{a}) and minimum and maximum relative humidity (R_{H}) data were obtained from the database of the International Institute of Tropical Agriculture (7°30′N, 3°54′E, 243 m amsl), Ibadan. Daily data were available for this location for 36 years (1973–2008). Data collection was done by IITA trained personnel and weather instrument installations conform to WMO standard. Agro-ecological characteristics of the site and instrumentation are presented in Jagtap and Alabi (1997).

2.3. Data analysis

Variability index (VI) for pan evaporation and other variables were calculated as the standardized variable departure (Oguntunde *et al.*, 2006) as:

$$\text{VI}_i = (X_i - \mu)/\sigma \tag{1}$$

where VI_i is variability index for year i, X_i is annual value of the variable for year i, μ and σ are the mean annual value and standard deviation for the period between 1973 and 2008, respectively. Time series of pan evaporation and other climatic factors were examined for trends and slopes on annual and on month-by-month basis. The Mann–Kendall test, which is often used to test for trends in hydrological time series (Salmi *et al.*, 2002; Oguntunde *et al.*, 2006), was used to test for the presence of trends in the time series of the studied variables. The Mann–Kendall test statistic S is given by Salmi *et al.* (2002) as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) \tag{2}$$

where n is the length of the time series $x_i \ldots x_n$, and sgn(.) is a sign function, x_j and x_k are values in years j and k, respectively. The expected value of S equals zero for series without trend and the variance is computed as:

$$\sigma^2(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \tag{3}$$

Here, q is the number of tied groups and t_p is the number of data values in pth group. The test statistic Z is then given as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\sigma^2(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\sigma^2(S)}} & \text{if} \quad S < 0 \end{cases} \tag{4}$$

As a non-parametric test, no assumptions as to the underlying distribution of the data are necessary. The Z statistic is then used to test the null hypothesis, H_0, that the data are randomly ordered in time, against the alternative hypothesis, H_1, where there is an increasing or decreasing monotonic trend. To estimate the true slope of an existing trend Sen's nonparametric method was used (Salmi *et al.*, 2002).

Table I. Summary of climatic variables at Ibadan.

Time series	Minimum	Maximum	Mean	SDEV	CV (%)
Pan evaporation (mm day^{-1})	3.0	4.8	3.9	0.4	11.0
Rainfall (mm year^{-1})	794.3	1655.4	1274.7	219.4	17.2
Solar radiation (MJ m^{-2} day^{-1})	13.3	18.0	15.7	1.4	9.2
Wind speed (km h^{-1})	1.4	4.4	3.4	0.8	24.6
Mean temperature (°C)	25.9	27.7	26.7	0.3	1.3
Diurnal temperature range (°C)	7.58	10.41	9.12	0.74	8.15
Vapour pressure deficit (kPa)	0.78	1.05	0.91	0.07	7.22
Relative humidity (%)	69.9	78.0	74.5	1.8	2.5

SDEV, standard deviation; CV, coefficient of variance.

Principal component analysis (PCA) was used to further analyse the data. PCA helps to identify common modes of variability between variables (Richman, 1986; Jollife, 1990), and can reduce a large number of inter-related variables to a few principal components that capture much of the variance of the original dataset (Hair *et al*., 1998). PCA has been widely and successfully used to help understand, interpret, and reconstruct large, multivariate climate datasets, both with spatial extent (Walsh, 1978) and at single sites (Reusch *et al*., 1999). Here, PCA was applied to identify the meteorological variables that are coupled with the pan evaporation. Statistica software (Statsoft Inc., 2009) using the varimax rotation option to obtain a clear pattern of loadings was used for the analysis.

3. Results

3.1. Annual changes in pan evaporation and other climatic variables

Summary statistics of the temporal series of E_{pan} and other variables are given in Table I. Pan evaporation varied with CV of 11.0%, its value ranged from 1096 to 1753 mm year^{-1} with a mean value of 1442 mm year^{-1}. Rainfall (R) varied between 794 and 1655 mm year^{-1}. Solar radiation (S_R) varies similarly as R with CV of 9.2% and average value of 15.7 MJ m^{-2} day^{-1}. Air temperature, with CV of 1.3% and the least varied of all climatic series examined, range between 25.9 and 27.7 °C.

Annual time series of E_{pan} and other variables are shown in Figure 1. A summary of the trend estimates are presented in Table II. The observed slopes for E_{pan}, S_R, W_S and VPD are negative, while R, T_a, DTR and R_H showed increasing trends. E_{pan} decreased significantly ($P < 0.01$) at the rate of -0.023 mm day^{-1} year^{-1} (8.3 mm year^{-2}). S_R similarly showed decreasing trends at the rate -0.104 MJ m^{-2} day^{-1} year^{-1} ($P < 0.001$). Wind speed was observed to decrease ($P < 0.01$) with a change of about -28% over the period examined. However, R showed a non-significant ($P > 0.05$) increase of about 2.0 mm year^{-2}. Variability indices for E_{pan}, R, S_R and W_S are presented in Figure 2. The results showed that 1987 was the wettest year while 1998 was the driest. Similarly, 1983 has the highest positive variability while 2004 has the lowest for E_{pan}. In addition, 1983 was the windiest year (VI = +1.08) while 2002 was the least windy (VI = -2.38). The brightest year was 1989 while 2006 was the dimmest.

3.2. Monthly changes in pan evaporation and other climatic variables

Analysis of each calendar month allows the identification of time characteristics peculiar to each month, which may be masked in annual analysis. Table III contains the Z statistic and the levels of significance of slopes for E_{pan}, R, S_R W_S, DTR and VPD, respectively. Monthly average values of E_{pan}, R, S_R and W_S and their respective inter-annual rates of change are given in Table IV. DTR and VPD are omitted in Table IV because there are no detectable significant changes in most of the months. E_{pan} monotonically decreases in all the months with a significant change in 8 months between March and October. However, higher slopes were estimated during the wet season (April to October). Conversely, monthly R showed positive trends for 8 months with February, March, May and October slopes decreasing. However, all the changes were not statistically significant. On average, highest monthly rainfall was recorded in July, whereas September showed an increasing rainfall amount at the rate of 14.6% *per* decade. Similar to E_{pan}, solar radiation decreases in all the months ($P < 0.01$). The reduction ranged from 5.1% *per* decade in March to 9.3% *per* decade in August. Wind speed decreased in 11 months of the year, with only 5 months (June to October) having trends with significant slopes ($P < 0.05$), their respective W_S reduced between 9.5 and 12.2% *per* decade.

4. Discussion and conclusions

The downward trend of pan evaporation in Ibadan is similar to findings reported for many other regions. A decrease of 8.3 mm year^{-2} is lower than 11.4 mm year^{-2} reported for India (Chattopadhyay and Hulme, 1997) and higher than the range of 2–4 mm year^{-2} estimated for most other countries (Peterson *et al*., 1995; Roderick and Farquhar, 2002, 2004; Liu *et al*., 2004; Xu *et al*., 2006). Cohen *et al*. (2002) have also detected an increase of 3.7 mm year^{-2} (2.2% *per* decade) in a similar analysis

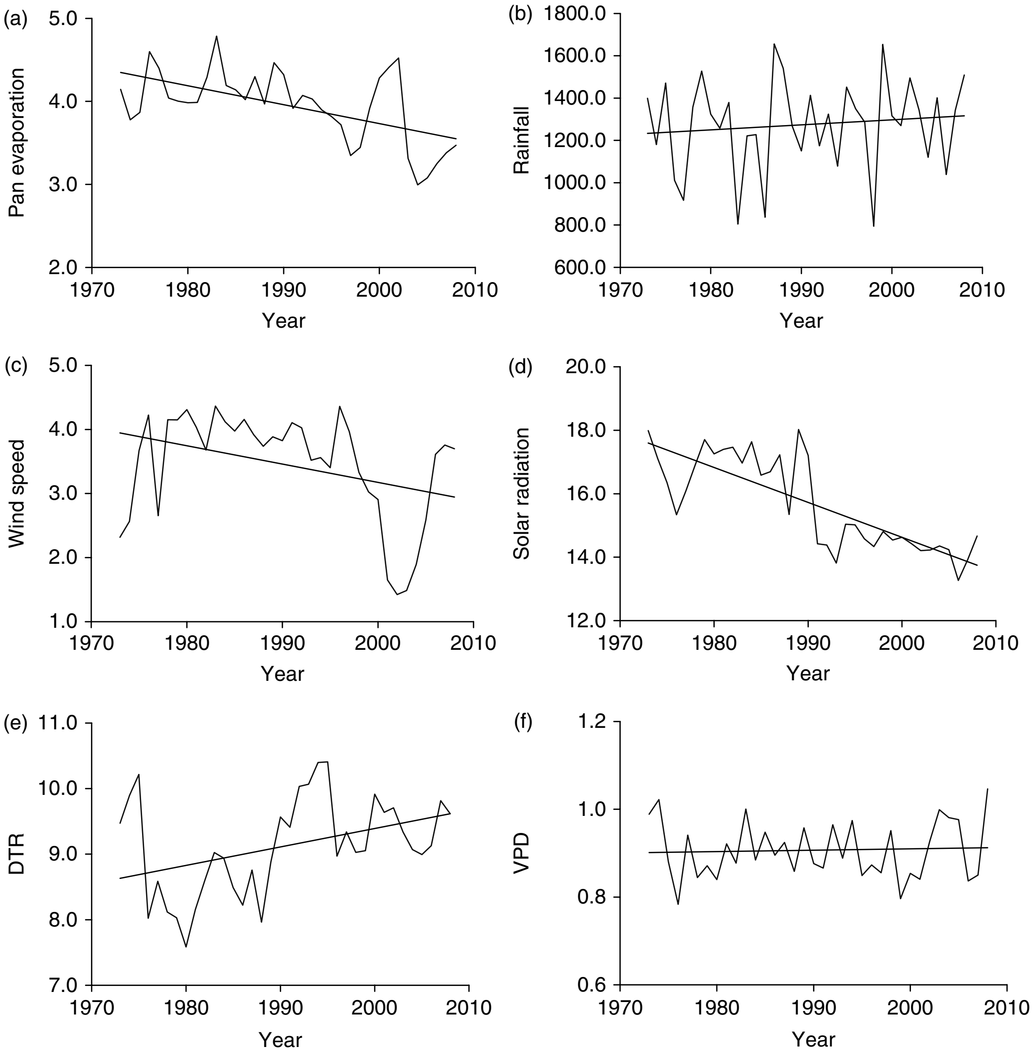

Figure 1. Time series plots and linear trends of (a) pan evaporation, mm day^{-1}; (b) rainfall, mm year^{-1}; (c) wind speed, km h^{-1}; (d) solar radiation, MJ m^{-2} day^{-1} (e) DTR (diurnal temperature range), °C and (f) VPD (vapour pressure deficit), kPa.

Table II. Mann–Kendall and Sen's tests summary statistics for Ibadan climatic variables.

Time series	Test Z	Significance	∂ (/year)	% Δ/36 year	% Δ/decade
Pan evaporation (mm day^{-1})	−2.874	**	−0.023	−20.66	−5.74
Rainfall (mm year^{-1})	0.449		1.998	5.64	1.57
Solar radiation (MJ m^{-2} day^{-1})	−4.863	***	−0.104	−23.78	−6.61
Wind speed (km h^{-1})	−2.656	**	−0.027	−27.87	−7.74
Mean temperature (°C)	0.286		0.002	0.23	0.06
Diurnal temperature range (°C)	2.683	**	0.033	13.16	3.66
Vapour pressure deficit (kPa)	−0.041		−0.0001	−0.45	−0.12
Relative humidity (%)	0.586		0.016	0.76	0.21

*** Significant at the 0.001 level.
** Significant at the 0.01 level.
∂ is trend slope (rate of change *per* year).
Δ is rate of change *per* decade.

of local series in Israel. At Ibadan, a significant decrease in E_{pan} was found in 67% of the months (March to October), with the maximum relative decrease of 10.9% *per* decade occurring in July. In a similar study, an increase of E_{pan} of about 58% of the months, with the maximum relative increase of 7% *per* decade occurring in November was reported for Bet Dagan in Israel (Cohen *et al.*, 2002). However, over the Volta basin in West

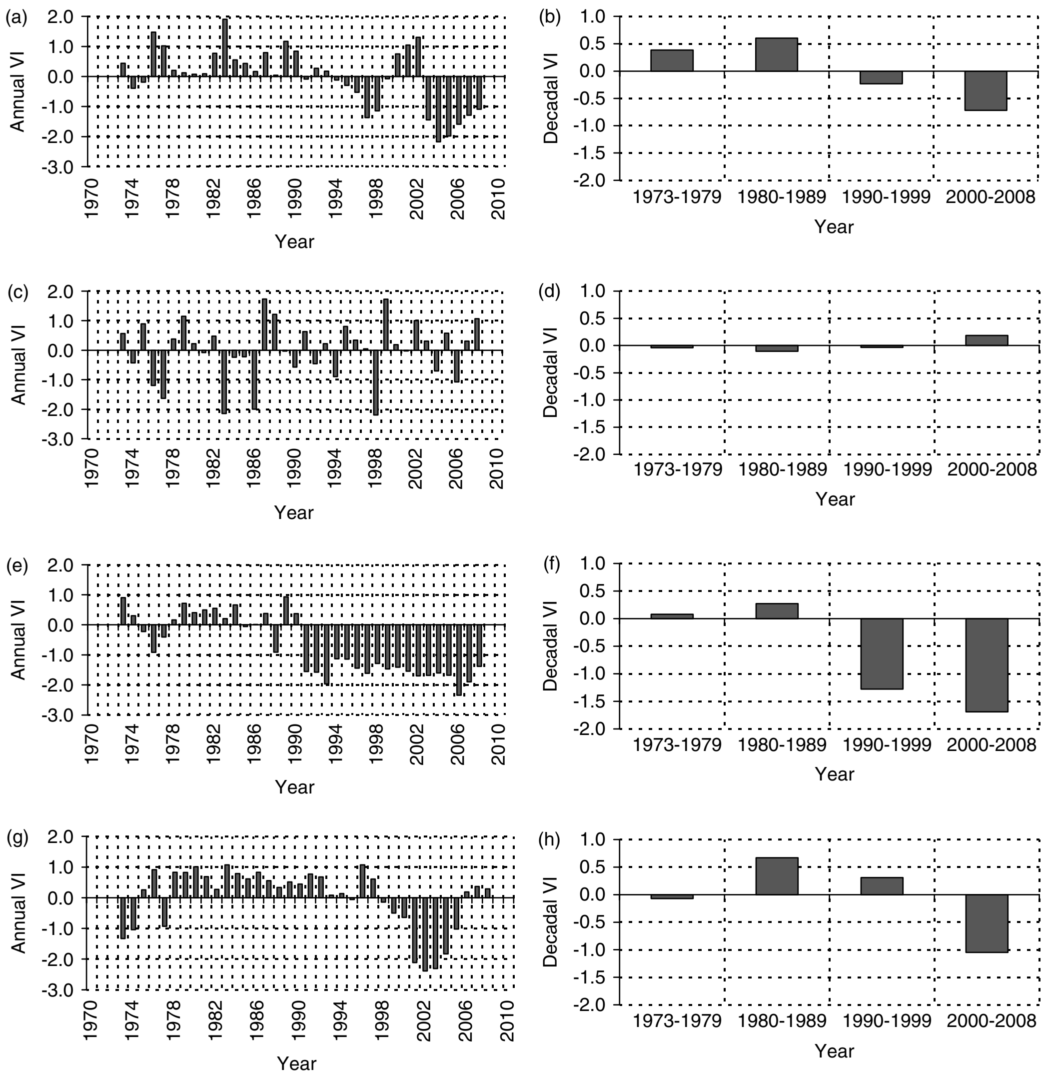

Figure 2. Annual and decadal plots of variability index (VI) for pan evaporation (a, b), rainfall (c, d), solar radiation (e, f) and wind speed (g, h).

Africa, an increase in potential evaporation over the last century (1901–2002) was reported (Oguntunde *et al.*, 2006).

Rainfall did not show any significant trend for both annual and monthly series. An annual increase of 1.6% *per* decade in R was estimated in the study area. Following the descriptions of other authors Nicholson *et al.* (2000) and L'Hote *et al.* (2002), an apparently random succession of dry periods, 'normal' periods and wet periods characterized the rainfall series (Figure 2). Previous studies have reported the absence of any significant trends in rainfall but the presence of large inter-annual variability (Liu *et al.*, 2004; Roderick and Farquhar, 2004; Oguntunde *et al.*, 2006). Monthly and year-to-year S_R significantly reduced for the period examined. This agrees with the widespread decrease, termed 'global dimming', which has been reported (Stanhill and Cohen, 2001). The reduction has been linked to increased cloudiness and/or aerosol concentration (Stanhill and Cohen, 2001; Liu *et al.*, 2004). Average air temperature at Ibadan was found to increase slightly at the rate of 0.06% *per* decade while diurnal temperature range (DTR) increased significantly by 3.7% *per* decade. The global average T_a was reported to have increased by 0.01 °C year^{-1} (Brutsaert, 2006). Increase DTR observed agrees with the pattern reported for India (Chattopadhyay and Hulme, 1997) but contrary to other reports, e.g. for China (Liu *et al.*, 2004), United States and the former Soviet Union (Peterson *et al.*, 1995). To elucidate better on the observed changes in DTR, minimum and maximum air temperature were examined. A reduction in minimum temperature of 0.015 °C year^{-1} and an increase of 0.019 °C year^{-1} in maximum temperature was found. These indicate that Ibadan has experienced colder nights and warmer afternoons in the last four decades. Relative humidity was fairly constant and this concurs with result from elsewhere (Roderick and Farquhar, 2002, 2004). Both VPD and wind speed declined with only W_S showing a highly significant ($P < 0.001$) trend of -7.7% *per* decade. This observation is similar to that of Xu *et al.* (2006) but different from many others (Cohen *et al.*, 2002; Liu *et al.*, 2004).

In agreement with the physical theory, in which evaporation into the atmosphere is directly sensitive to

Table III. Mann–Kendall test summary statistics for Ibadan monthly climatological seires.

Month of year	Pan evaporation (mm day^{-1}) Test Z	Rainfall (mm year^{-1}) Test Z	Solar radiation (MJ m^{-2} day^{-1}) Test Z	Wind speed (km h^{-1}) Test Z	DTR (°C) Test Z	VPD (kPa) Test Z
January	−1.02	0.07	−3.45***	0.15	1.68	1.65
February	−1.74	−0.46	−4.05***	−1.36	1.89	0.86
March	−2.86**	−0.56	−2.87**	−1.51	1.57	−0.01
April	−2.85**	0.04	−4.05***	−0.78	1.54	−0.80
May	−3.50***	−0.16	−3.69***	−1.70	2.34*	−0.69
June	−2.77**	0.83	−3.80***	−2.67**	2.52*	−1.46
July	−3.17**	0.48	−3.61***	−2.93**	1.98*	−1.13
August	−3.83***	0.18	−3.28**	−3.45***	1.54	−2.38*
September	−2.06*	1.76	−3.75***	−2.38*	1.08	−1.02
October	−2.33*	−0.61	−3.42***	−2.47*	1.89	−0.67
November	−0.91	0.38	−3.84***	−1.21	0.56	0.40
December	−0.37	0.48	−3.56***	−0.72	0.86	1.62

*** Significant at the 0.001 level.
** Significant at the 0.01 level.
* Significant at the 0.05 level.

Table IV. Monthly mean (± standard deviation, d), trend (∂) and change *per* decade (Δ/decade) for Ibadan climatological seires.

Month[a]	Pan evaporation (mm day^{-1})			Rainfall (mm year^{-1})			Solar radiation (MJ m^{-2} day^{-1})			Wind speed (km h^{-1})		
	Mean ± d	∂ (/year)	% Δ/ decade	Mean ± d	∂ (/year)	% Δ/ decade	Mean ± d	∂ (/year)	% Δ/ decade	Mean ± d	∂ (/year)	% Δ/ decade
1	4.4 ± 0.9	−0.01	−2.7	5.2 ± 11.4	0.00	0.0	14.8 ± 1.7	−0.10	−6.6	3.1 ± 1.1	0.00	0.6
2	5.4 ± 0.7	−0.02	−4.4	20.0 ± 24.6	−0.06	−2.8	17.0 ± 2.1	−0.13	−7.4	4.0 ± 1.0	−0.02	−4.9
3	5.3 ± 0.7	−0.03	−5.5	65.8 ± 42.7	−0.43	−6.5	17.9 ± 2.0	−0.09	−5.1	4.5 ± 1.0	−0.02	−4.0
4	4.7 ± 0.7	−0.03	−6.5	120.0 ± 57.3	0.04	0.3	17.9 ± 2.0	−0.12	−6.8	4.2 ± 1.1	−0.01	−2.8
5	4.2 ± 0.6	−0.03	−7.6	150.1 ± 44.3	−0.11	−0.8	17.4 ± 1.5	−0.09	−5.5	3.8 ± 1.0	−0.02	−5.9
6	3.6 ± 0.6	−0.02	−5.7	182.3 ± 73.0	1.06	5.8	16.1 ± 1.9	−0.11	−6.6	3.5 ± 1.1	−0.03	−9.5
7	2.8 ± 0.5	−0.03	−10.9	185.2 ± 76.7	0.66	3.5	13.3 ± 2.1	−0.11	−8.6	3.6 ± 1.2	−0.04	−11.9
8	2.6 ± 0.5	−0.03	−10.3	128.0 ± 85.6	0.20	1.6	12.3 ± 2.1	−0.12	−9.3	3.5 ± 1.1	−0.05	−13.0
9	3.0 ± 0.6	−0.02	−5.9	217.8 ± 93.0	3.18	14.6	14.3 ± 1.9	−0.12	−8.3	3.1 ± 1.1	−0.03	−10.8
10	3.6 ± 0.5	−0.02	−6.3	169.5 ± 62.2	−0.93	−5.5	15.8 ± 1.9	−0.12	−7.5	2.7 ± 1.0	−0.03	−12.2
11	4.0 ± 0.6	−0.01	−2.3	24.1 ± 28.1	0.02	0.6	16.4 ± 1.9	−0.12	−7.5	2.6 ± 0.9	−0.01	−5.2
12	3.9 ± 0.6	−0.01	−1.3	6.8 ± 14.6	0.00	0.0	14.8 ± 1.5	−0.09	−6.1	2.7 ± 0.8	−0.01	−2.4

[a] Month 1–12 represent January to December.

changes in solar radiation, VPD and wind speed, the observed decline in pan evaporation here is related to these factors. A multiple regression analysis between E_{pan} and the three variables indicates that about 30, 15 and 6 of the variance in pan evaporation can be explained by S_R, W_S and VPD, respectively. This is unlike in China where S_R accounted for about 64% of the variations in E_{pan} (Liu *et al.*, 2004). Of all the explanatory variables considered here, S_R played a major role followed by wind speed and VPD. The possibility of W_S playing a role has been previously noted (Roderick and Farquhar, 2004; Xu *et al.*, 2006). At Bet Dagan (Cohen *et al.*, 2002), the aerodynamic surface, which is a combination of functions of wind and VPD, was found to be very important and dictated the trajectory of E_{pan} changes, even when the irradiance was significantly reducing. In India relative humidity was found to play a major role compared to irradiance (Chattopadhyay and Hulme, 1997).

The PCA returns four principal factors (Table V). The principal factor (PF1) shows high loadings (0.62, 0.92 and 0.95) for relative humidity (mean, minimum and maximum, respectively) and a weak loading (0.2) for pan evaporation. The principal factors 2 and 3 (PF2 and PF3) show high loadings for temperature, but negligible loadings for pan evaporation (Table V). Hence, PF2 and PF3 are not of interest in this study. The principal factor 4 (PF4) shows high loadings for pan evaporation (0.81) and solar radiation (0.82): this shows that pan evaporation and solar radiation are well coupled. The time series of PF4 with the anomalies of pan evaporation is shown in Figure 3. Thus, the PCA results further support the

Table V. The principal factors returned by principal component analysis (PCA) for meteorological variables.

Variable	PF1	PF2	PF3	PF4
Rainfall	0.33	−0.28	−0.04	0.07
Pan evaporation	0.20	0.04	−0.06	**0.81**
Wind speed	0.29	0.51	−0.05	0.31
Solar radiation	−0.17	0.24	0.30	**0.82**
Minimum mean temperature	0.09	0.21	**0.94**	0.17
Maximum mean temperature	−0.01	**−0.96**	0.17	−0.10
Mean temperature	0.06	**−0.59**	**0.79**	0.04
Diurnal temperature range	−0.07	**−0.82**	−0.49	−0.18
Minimum relative humidity	**0.92**	0.08	−0.02	0.14
Maximum relative humidity	**0.63**	0.10	0.43	−0.28
Mean relative humidity	**0.95**	0.11	0.21	−0.05
Total variance (%)	21	20	20	15

Significant values are in bold face.

notion that changes in pan evaporation at Ibadan are best explained with variations in solar radiation.

In this study, no data on aerosol concentration or cloudiness was available for the attribution of the observed trends in S_R. However, the months from December to February are usually characterized with the 'harmattan', a hot and highly dust laden wind from the Sahara Desert. In this period, the dust haze from the Northeastly Trade Wind tends to prevent all possible solar radiation from reaching the soil surface (Ogunjobi *et al.*, 2002). In addition, the monsoon months are generally known to have low clearness indices and, hence, the annual increase in these convective clouds could be responsible for the decreasing S_R during these months. Related studies at similar tropical sites, Ile-Ife in Nigeria and Ejura in Ghana, have elucidated on the role of convective clouds in attenuating solar radiation and hence evaporation during the monsoon months (Jegede, 1997; Oguntunde and van de Giesen, 2005). Furthermore, the cause of decreasing W_S may not be easily ascertained especially as it has not been widely documented, but it may be connected with changes in local or mesoscale circulation occasioned by either climate change or land cover changes that occurred due to population explosion, or both.

For further examination of the trends, annual and decadal variability indices were computed for E_{pan} and other climatic variables (Figure 2). One could easily observe an increase in E_{pan}, S_R and W_S in the first two decades (1973–1989) whereas the actual reduction in E_{pan} started since the 1990s and that of W_S began around the year 1998. Therefore, the E_{pan}, R, S_R and W_S series were divided into two periods, 1973–1989 and 1990–2008. The same trend analyses were applied to the two periods separately as shown in Figure 4. Whereas E_{pan} was increasing by 3.3% *per* decade before 1990, it was rapidly increasing by 12.6% *per* decade since 1990. Average R of 1257 mm year^{-1} was observed in the first period compared to 1290 mm year^{-1} in the second period. Rainfall, S_R and W_S also showed no significant change between 1973 and 1989 whereas R increased slightly by 4.4% *per* decade. However, S_R and W_S decreased significantly by 3.4% *per* decade and 26.2% *per* decade, respectively, since the 1990s. It seems that the complementary relationship hypothesis can only fairly explain the trends in E_{pan} given the trends and magnitude of changes in the surfaces concerned. Firstly, for this hypothesis to hold true between actual evaporation and pan evaporation, VPD would be expected to have a positive correlation with E_{pan} (Liu *et al.*, 2004), this was observed in this study. Secondly, within the complementary relationship hypothesis, potential evaporation (pan evaporation) must be negatively correlated to rainfall. This was also observed to some extent. For example, when E_{pan} increased during 1973–1989, rainfall decreased but both reduced during the 1990–1999 decade. In addition, the magnitude of the changes observed for R was lower compared to that of E_{pan}. Nevertheless, this increase in R may be attributed to possible increase in terrestrial evaporation and may as

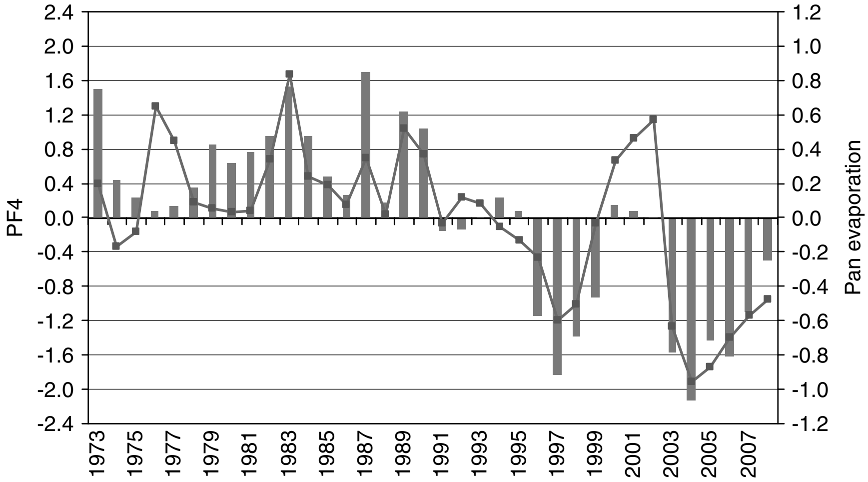

Figure 3. The time series of principal factor 4 (PF4, line) with the anomalies of pan evaporation (bars).

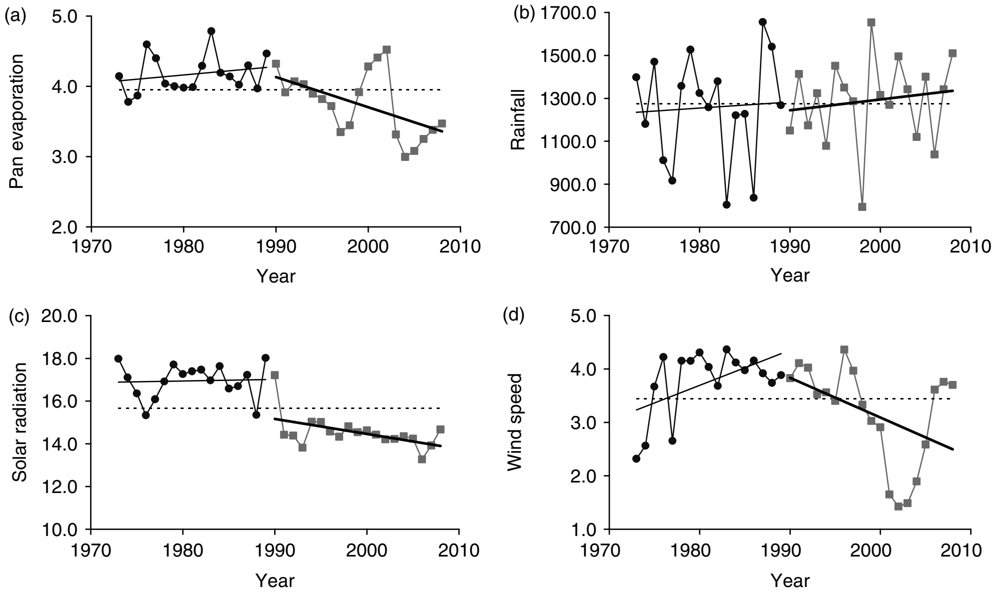

Figure 4. Time series plots (a) pan evaporation, mm day^{-1}; (b) rainfall, mm year^{-1}; (c) solar radiation, MJ m^{-2} day^{-1} and (d) wind speed, km h^{-1}. Estimated trends for the sub-series 1973–1989 (thin lines) and 1990–2008 (thick lines) are shown together with the whole-series average (horizontal dashed thin lines).

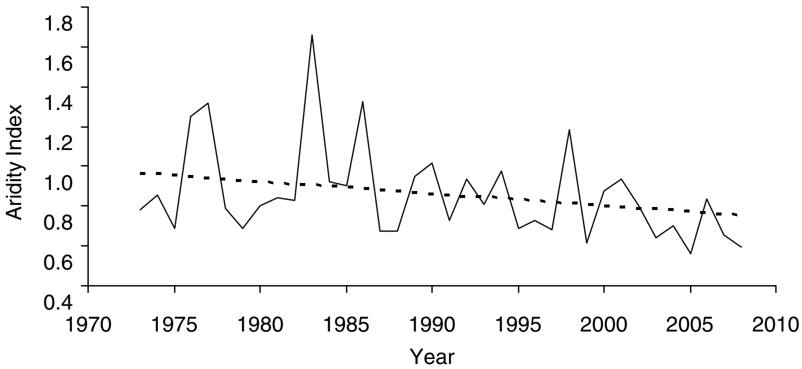

Figure 5. Time series plot of aridity index with estimated linear trend (dashed line).

well be an indication of an accelerating hydrological cycle in the study area. Therefore, this result agrees more with others that attributed declining E_{pan} with the solar dimming.

The aridity index (I_A) showed a significant decreasing trend (6.9% *per* decade). Ibadan is getting wetter as the I_A reduces from about 1.8 in 1983 to less than 1.0 in the last decade of the time series (Figure 5). Similar results of less aridity have been reported for many places, including Australia, to indicate that the Earth's surface is getting warmer and wetter (Roderick and Farquhar, 2004). Finally, the analysis of variability and trends of pan evaporation and other climatological series presented here showed a significant reduction in E_{pan} with slight increase in rainfall. The implication of this is an overall reduction in aridity as the supply of water is more capable of meeting the atmospheric water demand. Hence, this result has important consequences for plant productivity and the understanding of how the study area has changed over time.

Acknowledgements

The authors thank the management of International Institute of Tropical Agriculture, Ibadan, for providing the climatic data for this study. The second author was partly supported by National Research Foundation, South Africa. Computing facility was provided by the Centre for High Performance Computing (CHPC, South Africa). Comments from the two anonymous reviewers and the Editor are greatly appreciated.

Acronyms

CV coefficient of variance
DTR diurnal temperature range
E_{pan} pan evaporation
PCA principal component analysis
R rainfall
R_H humidity

S_R radiation
T_a temperature
VI variability index
VPD vapour pressure deficit
W_S wind speed

References

Asanuma J, Kamimera H, Lu M. 2004. Pan evaporation trends in Japan and its relevance to the variability of the hydrological cycle. *Tenki* **51**: 667–678.

Brutsaert W. 2006. Indications of increasing land surface evaporation during the second half of the 20th century. *Geophysical Research Letters* **33**: L20403.

Brutsaert W, Parlange MB. 1998. Hydrologic cycle explains the evaporation paradox. *Nature* **396**: 30.

Chattopadhyay N, Hulme M. 1997. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agricultural and Forest Meteorology* **87**: 55–73.

Cohen S, Ianetz A, Stanhill G. 2002. Evaporative climate changes at Bet Dagan, Israel, 1964–1998. *Agricultural and Forest Meteorology* **111**: 83–91.

Farquhar GD, Roderick ML. 2005. The pan evaporation paradox – an overview of the scope of the problem. In *Pan Evaporation: An example of the Detection and Attribution of Trends in Climate Variables*, Gifford RM (ed.). Proceedings of a Workshop held at the Shine Dome. Australian Academy of Science: Canberra; 20–22.

Golubev VS, Lawrimore JH, Groisman PY, Speranskaya NA, Zhuravin SA, Menne MJ, Peterson TC, Malone RM. 2001. Evaporation changes over the contiguous United States and the former USSR: a reassessment. *Geophysical Research Letters* **28**: 2665–2668.

Hair JF, Anderson RE, Tatham RL, Black WC. 1998. *Multivariate Data Analysis*, 5th edn. Prentice Hall: Upper Saddle River, NJ.

Jagtap SS, Alabi RT. 1997. Reliability of daily, weekly and monthly grass evapotranspiration using hourly estimates by Penman method in three agroecological zones of West Africa. *Nigerian Meteorological Journal* **2**(1): 59–68.

Jegede OO. 1997. Diurnal variation of net radiation at a tropical station of Osu Nigeria. *Theoretical and Applied Climatology* **58**: 161–169.

Jollife IT. 1990. Principal component analysis: a beginner's guide. Part I: introduction and application. *Weather* **45**: 375–382.

Lawrimore JH, Peterson TC. 2000. Pan evaporation in dry and humid regions of the United States. *Journal of hydrometeorology* **1**: 543–546.

L'Hote Y, Mahe G, Some B, Triboulet JP. 2002. Analysis of a Sahelian annual rainfall index from 1896 to 2000; the drought continues. *Hydrological Science Journal* **48**(3): 489–496.

Liu B, Xu M, Henderson M, Gong W. 2004. A spatial analysis of pan evaporation trends in China, 1955–2000. *Journal of Geophysical Research* **109**: D15102, DOI: 10.1029/2004JD004511.

Liu C, Zeng Y. 2004. Changes in pan evaporation in the recent 40 years in the Yellow River basin. *Water International* **29**: 510–510.

Nicholson SE, Some B, Kone B. 2000. An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years. *Journal of Climate* **13**(14): 2628–2640.

Ogunjobi KO, Kim YJ, Adedokun JA, Ryu SY, Kim JE. 2002. Analysis of sky condition using solar radiation data at Kwangju and Seoul South Korea and Ile-Ife Nigeria. *Theoretical and Applied Climatology* **72**: 265–272.

Oguntunde PG, Friesen J, van de Giesen N, Savenije HHG. 2006. Hydroclimatology of the Volta River Basin in West Africa: trends and variability from 1901 to 2002. *Physics and Chemistry of the Earth* **31**: 1180–1188.

Oguntunde PG, van de Giesen N. 2005. Water flux measurement and prediction in young cashew trees using sap flow data. *Hydrological Processes* **19**: 3235–3248.

Peterson TC, Golubev VS, Groisman PY. 1995. Evaporation losing its strength. *Nature* **377**: 687–688.

Reusch DB, Mayewski PA, Whitlow SI, Pittalwala II, Twickler MS. 1999. Spatial variability of climate and past atmospheric circulation patterns from central West Antarctic glaciochemistry. *Journal of Geophysical Research* **104**: 5985–6001.

Richman MB. 1986. Rotation of principal components. *Journal of Climatology* **6**: 293–335.

Roderick ML, Farquhar GD. 2002. The cause of decreased pan evaporation over the past 50 years. *Science* **298**: 1410–1411.

Roderick ML, Farquhar GD. 2004. Changes in Australian pan evaporation from 1970 to 2002. *International Journal of Climatology* **24**: 1077–1090.

Roderick ML, Farquhar GD. 2005. Changes in New Zealand pan evaporation since the 1970s. *International Journal of Climatology* **25**: 2031–2039.

Salmi T, Määttä A, Anttila P, Ruoho-Airola T, Amnell T. 2002. Detecting Trends of Annual Values of Atmospheric Pollutants by the Mann-Kendall Test and Sen's Slope Estimates – The Excel Template Application MAKESENS. Publication on Air Quality, no. 31. Finnish Meteorological Institute: Helsinki.

Sangodoyin AY. 1992. Wastewater applications: changes in soil properties, livestock response and crop yield. *Environmental Management and Health* **3**(1): 11–19.

Stanhill G, Cohen S. 2001. Global dimming: A review of the evidence for a widespread and significant reduction in global radiation. *Agricultural and Forest Meteorology* **107**: 255–278.

Statsoft Inc. 2009. Electronic Statistics Textbook. http://www.statsoft.com/textbook/ (accessed 13 December 2010).

Tebakari T, Yoshitani J, Suvanpimol C. 2005. Time-space trend analysis in pan evaporation over kingdom of Thailand. *Journal of Hydrological Engineering* **10**: 205–215.

Walsh JE. 1978. Temporal and spatial scales of Arctic circulation. *Monthly Weather Review* **106**(11): 1532–1544.

Xu C, Gong L, Jiang T, Chen D, Singh VP. 2006. Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze River) catchment. *Journal of Hydrology* **327**: 81–93.