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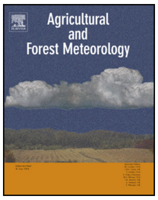

Statistical analyses of potential evapotranspiration changes over the period 1930–2012 in the Nile River riparian countries

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A R T I C L E I N F O

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A B S T R A C T

Changes in potential evapotranspiration (PET) in the Nile Basin tend to be analyzed mostly based on short-term remotely sensed annual data. In this study, long-term country-wide series from 1930 to 2012 were used to assess changes in annual and seasonal PET in all the Nile River Riparian Countries (NRRCs). Variability was investigated using the nonparametric anomaly indicator method. Trend was assessed both graphically and statistically using the cumulative rank difference method. The PET totals from 1930s to 1970s (from around 1980 to early 2000s) were generally below (above) the mean of the long-term data. Moreover, for this period from around 1980 to early 2000s, both annual and seasonal PET totals in most of the NRRCs were characterized by an increase significant at 5% level. This increase in the PET influenced the long-term trend based on the full time series from 1930 to 2012 towards positive direction. For instance, the long-term annual PET exhibited increasing trend significant at 5% level in 2 of the 6 countries in the equatorial region. However, the positive trends in the PET of Sudan, Ethiopia, Eritrea and Egypt were insignificant at 5% level. It was found that the temporal changes in PET especially during rainy seasons can be explained at the significance level of 5% by the rainfall variation. Sampling uncertainties on the PET trend magnitudes are quantified and provided. The findings in this study are important for determining the crop water requirements especially in arid conditions where rainfall is unreliable and low in volume.

1. Introduction

Analyses of the changes in potential evapotranspiration (PET) are vital to obtain acumen about the influence of land-atmosphere interactions and/or climate system on hydro- and agro-meteorology. The unswerving dependence of majority of the people within the Nile Basin on agriculture for their livelihoods (International Water Management Institute [IWMI], 2014), and the effect of climate variability on hydro-meteorological variables make food insecurity a formidable challenge that the Nile River Riparian Countries (NRRCs) have to deal with. One form of support in tackling such a challenge is a comprehensive study of the historical PET changes and the possible associated driving forces. Such support would be valuable for determining the crop water requirements especially in arid conditions where rainfall is unreliable and low in volume. Apart from the Ethiopian Highlands and the equatorial region which receive large amounts of rainfall annually, other parts of the study area experience both hyper-arid and sub-humid conditions.

Analyses of the changes in hydro-meteorological variables require long-term series of historical or observed data to minimize bias on the statistical results (Onyutha et al., 2015). However, due to the data limitation in the Nile Basin, the analyses of PET changes conducted in studies by e.g. Alemu et al. (2014), and Bashir et al. (2008) have been based on short-term remotely sensed data. For an insight into the temporal variability and long-term trends, it is vital to analyze changes in the PET based on rather long-term historical series than the remotely sensed data.

In this study, detection of changes in the long-term historical PET was two-fold. Firstly, long-term trend was assessed in terms of the significance of the non-zero slope of a linear variation of the PET with time. Secondly, variability was investigated in terms of the short-durational changes in the PET totals relative to the mean of the full time (long-term) series. Some of the nonparametric trend detection methods include the Mann-Kendall (MK) (Mann, 1945; Kendall, 1975), Spearman's rho (SMR) (Lehmann, 1975; Sneyers, 1990; Spearman, 1904), and the Cumulative Rank Difference (CRD) (Onyutha, 2016a) tests. These methods were demonstrated to perform comparably by Yue et al. (2002) for MK and SMR, and Onyutha (2016a) for MK and CRD. Thus, the CRD deemed to be representative for the analyses of PET trends was adopted in this study. On the other hand, some of the key methods

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for computing variability include: (1) the autocorrelation spectral analysis (Blackman and Tukey, 1959; World Meteorological organization [WMO] 1966), and (2) empirical orthogonal functions. To assess variability in the PET, the Nonparametric Anomaly Indicator Method NAIM (Onyutha, 2016b), as will be presented in Section 3.1.3, was adopted in this study based on its suitability for non-normally distributed data and the robustness to deal with the influence of outliers in the series.

In statistical analyses of trends, a number of data related uncertainty sources exist some of which include: (1) data structure characterized by ties, serial correlation, etc which jointly invalidate the change-detection test assumption of the independence of observations; (2) data limitation in the form of short record length; and (3) data quality resulting from erroneous observations that can falsify the trend analyses results. In this study, the uncertainties on the trends are quantified by employing a technique herein coined as the Exclude-one and Estimate Slope (EES).

2. Study area and data

2.1. Study area

The study area (see Fig. 1) comprises the River Nile which is the world's longest river under arid condition and has a drainage area of about 3,400,000 km^2. The River Nile has two sources including the White Nile (from the equatorial region), and the Blue Nile (from the Ethiopian Highlands). About 50% of the River Nile flow is lost by evaporation in the Sudd region of South Sudan. The coverage of the NRRCs as a percentage of the total area of the Nile Basin (Food and Agriculture Organization [FAO], 1997) is: Uganda (7.4%), Kenya (1.5%), Tanzania (2.7%), Rwanda (0.6%), Burundi (0.4%), Democratic Republic of Congo (DRC) formerly known as Zaire (0.7%), Sudan (inclusive of the current South Sudan) (63.6%), Ethiopia (11.7%), Eritrea (0.8%), and Egypt (10.5%). The climate of the NRRCs is characterized by a strong latitudinal wetness gradient (Camberlin, 2009; Onyutha, 2016b). Whereas some parts of the study area such as the Ethiopian Highlands and Equatorial region receive annual rainfall in excess of 1000 mm, the areas which are not reached by the inter-tropical convergence zone (ITCZ) i.e. the northern most part of Sudan up to Egypt experience arid condition (Camberlin, 2009).

2.2. Data

Country-wide total monthly PET series (Harris et al., 2014) for the period 1930–2012 were obtained via the British Atmospheric Data Centre (BADC) (2014). Harris et al. (2014) computed the PET (mm/day) as a variant of the Penman-Monteith method using half degree gridded absolute values of mean temperature (°C), maximum temperature (°C), minimum temperature (°C), vapor pressure (hPa), cloud cover (%), and wind speed (m/s). The Penman-Monteith method was proposed by Food and Agriculture Organization as the standard method to calculate PET or Reference evapotranspiration (Allen et al., 1989). Long-term country-wide monthly rainfall data over the period 1930–2012 were also obtained from the same source as that for the PET i.e. (BADC, 2014; Harris et al., 2014). Rainfall data were obtained mainly for two reasons: firstly, to confirm whether the patterns of monthly rainfall totals in the study area are consistent with those known from past studies. Secondly, rainfall was also used to assess whether its variation can be used to explain the changes in PET. Because the series from the Climatic Research Unit (CRU) were already quality controlled (BADC, 2014), it was confirmed in this study that the data sets of both rainfall and PET had no missing values. Note should be taken that although South Sudan recently got independence from Sudan in 2011, the data under the name Sudan comprised averages over both Sudan and South Sudan.

Fig. 2 shows the monthly rainfall and PET patterns of all the NRRCs based on the data from 1930 to 2012. The rainfall pattern of the equatorial region (countries labeled (1) to (6) in Fig. 1) is bimodal and the "long-rains" and "short-rains" occur over the months of March–May (MAM) and October–December (OND) respectively (Nicholson, 1996). The long and short dry periods respectively occur over the months of June–September (JJAS) and January–February (JF) (Fig. 2a–f). The rainfall over the countries (7) to (9) is of a unimodal pattern with the JJAS (MAM) as the main (slight) rainy season (Camberlin, 2009), and October–February (ONDJF) the dry season (Fig. 2g–i). For Egypt, the long-term mean monthly rainfall is of more unclear patterns than for other countries (1–9); however, the wet (dry) season can be identified as MAM, ONDJF (JJAS). On the other hand, it is noticeable that Egypt's PET (Fig. 2j) is more distinctively of a unimodal pattern than that for the rest of the NRRCs (Fig. 2a–i). Fig. 2 suggests that the patterns of the monthly rainfall data obtained from Harris et al. (2014) and/or BADC (2014) are consistent with those from past studies. Because of the importance of rainfall seasonality for agriculture in the study area, the seasonal PET totals were computed based on the seasons of the rainfall (Fig. 2). However, annual time scale was also considered for the statistical assessment of changes in the PET.

3. Methodology

3.1. Cumulative rank difference (CRD) method

Although it was already mentioned in Section 1 that the CRD was adopted because it is comparable to both the SMR and MK in terms of performance, another reason for its use in this study also followed the fact that it employs both the statistical and graphical approaches for trend detection. Instead of testing for hydro-meteorological change in a purely statistical or mathematical way which can give meaningless results in some cases (Kundzewicz and Robson, 2000), graphical technique of exploratory data analyses is important to reveal hidden features such as sub-trends. The CRD method of change detection considers rescaling of the given time series of size n nonparametrically in terms of the difference d (Eq. (1)) between the exceedance and non-exceedance counts of data points.

$$d_i = u_i - v_i = 2u_i - (n - w_i) \text{ for } 1 \le i \le n \tag{1}$$

where u_i is the number of times the i^{th} data point is exceeded, v_i the number of times the i^{th} data point exceeds others, and w_i the number of times the i^{th} data point appears within the given sample. To determine u_i, v_i or w_i, each data point is counted as if it was not considered before (Onyutha, 2016b). For illustration, consider the hypothetical data set of $n = 10$ with data points 33, 14, 33, 29, 20, 33, 14, 27, 31, 50; the values of w_i and u_i at $i = 1, 2, \ldots.,$ 10 are (3, 2, 3, 1, 1, 3, 2, 1, 1, 1) and (1, 8, 1, 5, 7, 1, 8, 6, 4, 0) respectively. Correspondingly, the rescaled series d_i is (−5, 8, −5, 1, 5, −5, 8, 3, −1, −9). The cumulative sum (s_i) of the difference d_i in the ranks is obtained using Eq. (2).

$$s_i = \sum_{j=1}^{i} d_i \text{ for } 1 \le i \le n \tag{2}$$

For the above hypothetical series, the values of s_i would be (−5, 3, −2, −1, 4, −1, 7, 10, 9, 0). Because $\sum_{j=1}^{n} d_j = 0$, s_n must be zero.