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Trends in reference evapotranspiration in the humid region of northeast India

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Abstract:

In the present study, the trends in the reference evapotranspiration (ET_O) estimated through the Penman-Monteith method were investigated over the humid region of northeast (NE) India by using the Mann-Kendall (MK) test after removing the effect of significant lag-1 serial correlation from the time series of ET_O by pre-whitening. During the last 22 years, ET_O has been found to decrease significantly at annual and seasonal time scales for 6 sites in NE India and NE India as a whole. The seasonal decreases in ET_O have, however, been more significant in the pre-monsoon season, indicating the presence of an element of a seasonal cycle. The decreases in ET_O are mainly attributed to the net radiation and wind speed, which are also corroborated by the observed trends in these two parameters at almost all the times scales over most of the sites in NE India. The steady decrease in wind speed and decline in net radiation not only balanced the impact of the temperature increases on ET_O, but may have actually caused the decreases in ET_O over the humid region of northeast India. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS reference evapotranspiration; Penman-Monteith method; humid; Northeast India; Mann-Kendall; trend

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INTRODUCTION

In recent years, investigations on climate change due to the buildup of greenhouse gases have mushroomed, and climate-related issues have started dominating and influencing policy decisions at various levels of governance in both developed and developing nations. Therefore, global warming due to the anthropogenic-driven emissions of greenhouse gases and land-use and land-cover changes has emerged as one of the important environmental issues of the 21st century. The global mean surface temperature has increased by 0·6 °C over the last 100 years, with 1998 being the warmest year, and most of the increase in the global mean temperature has been observed in two distinct periods: 1910–1940 (0·35 °C) and since 1970 (0·55 °C) (IPCC, 2007). The general expectation is that global warming will lead to an increase in evaporation (E) or evapotranspiration (ET), a key component of the hydrologic cycle. However, some studies reported in the literature show that despite the increase in air temperature, E and/or ET decreased in some regions across the globe. This shows that in addition to air temperature, there are other climatic parameters, like, wind speed, relative humidity, radiation, etc. which may be responsible for the observed decreases in E and/or ET, and which can offset the influence of temperature increases on E and/or ET as well. Also, the attribution analysis of the Penman potential evaporation (Ep) showed that, even though changes in temperature produced the largest change (an increase) in Ep, each remaining variable acted to reduce Ep, resulting in an overall decrease in Ep (Donohue *et al.*, 2010).

Trends in pan evaporation (E_{pan}) or potential evapotranspiration (PET) have emerged in the form of decreasing or increasing, to a small extent, over different parts of the world since the mid 1990s. Peterson *et al.* (1995) reported decreases in E_{pan} over much of Russia and the United States, and Chattopadhayay and Hulme (1997) reported decreasing trends in both E_{pan} and PET over India. Lawrimore and Peterson (2000) witnessed concurrent occurrences of E_{pan} decreases and rainfall increases during the warm-season months in parts of the United States. Golubev *et al.* (2001) reported negative trends in E_{pan} at 6 stations in the United States and the former Soviet Union, and increases in actual ET in some relatively dry parts of southern Russia and Ohio, while there was a decreasing trend of actual evaporation in two wetter places of the Taiga. Roderick and Farquhar (2004, 2005) found decreasing trends in E_{pan} over 14 sites in Australia and 6 sites in New Zealand since the 1970s.

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Gao *et al.* (2006) found decreasing trends in PET in China and for most of the river basins, and a slightly increasing trend in PET in the Songhua River basin. Chen *et al.* (2006) reported decreases in seasonal PET, and also in the average annual ET at a rate of −13·1 mm/decade over entire Tibetan Plateau. Xu *et al.* (2006) witnessed decreasing trends in both ET_O and E_{pan} in the catchment of Changjiang, China. Gao *et al.* (2007) found a decreasing trend in the estimated annual actual ET in most areas east of the 100 °E longitude in China from 1960 to 2002, except for the northeastern Songhua River basin in the northeast. Wang *et al.* (2007) detected decreasing trends in E_{pan} and reference evapotranspiration (ET_O) during summer months over the upper and middle-lower Yangtze River basin. Despite the general rise in annual mean temperature during recent decades over the Yangtze River basin, both E_{pan} and ET_O have decreased. Similarly, Zhang *et al.* (2007) found decreases in E_{pan} and ET_O at 47 and 38% of the respective stations over the Tibetan plateau. Zhang *et al.* (2009) reported ET_O decreases for most parts of the Qinghai-Tibetan Plateau as well. Liu *et al.* (2010) observed ET_O increases in the upper, middle, and the whole of the Yellow River basin. For other areas of Asia, Tebakari *et al.* (2005) found decreasing trends in E_{pan} in the Chao Phraya River basin (Thailand) as Jhajharia *et al.* (2009) showed in humid NE India. Bandyopadhyay *et al.* (2009) also found decreasing trends in ET_O all over India, which was mainly caused by a significant increase in the relative humidity and a consistent significant decrease in the wind speed throughout the country.

Cong *et al.* (2009) reported the existence of E_{pan} paradox in China as a whole with decreases in E_{pan} and increases in air temperature, but not in northeast and southeast China. They reported that E_{pan} decreases were caused by decreasing trends in radiation and wind speed before 1985 and E_{pan} increases were caused by the decreasing trends in vapour pressure deficit due to strong warming after 1986. Liu *et al.* (2010) found increasing and decreasing trends in E_{pan} in 18 and 114 stations, respectively, over China. Liu *et al.* (2010) reported that the changes in sunshine hours and wind speed contributed to the changes of E_{pan} over different parts of China. Wang *et al.* (2010) reported that the wind speed and relative humidity were generally recognized as the main driving forces for the decreasing trends in RET in the plain and the mountain areas of the Haihe River basin (China). However, in the mountainous area of the Haihe basin, in summer the sunshine duration is the most important dominating factor for RET.

Statistically significant increasing trends in E_{pan} mainly in the dry summer half of the year at Bet Dagan in Israel's central coastal plain were noted by Cohen *et al.* (2002). Qian *et al.* (2007) witnessed a tendency for increasing trends in ET over the Mississippi River basin from 1948 to 2004. Walter *et al.* (2004) found an evidence of increasing rates of actual ET in large portions of the conterminous United States over the past 50 years, considering the hydrological cycle more directly. Both precipitation and stream discharge exhibited positive linear trends, with precipitation having increased more rapidly and statistically significant than discharge. Recently, Dinpashoh *et al.* (2011) witnessed both statistically significant increasing and decreasing trends in ET_O over different sites in Iran.

These studies reveal that temperature change alone does not provide a satisfactory explanation for changes in ET as opposed to general expectation. Therefore, we aimed to carry out the present study concerning the analysis of ET_O trends over biodiversity-rich northeastern (NE) India to achieve the following objectives: (1) to estimate ET_O using the Penman-Monteith (PM) method at annual and seasonal time scales over eight sites in NE India and NE India as a whole; (2) to identify the most dominating meteorological variables affecting ET_O using stepwise linear regression analysis; (3) to investigate trends in ET_O using the Mann-Kendall (MK) nonparametric test; (4) to obtain the magnitude of trends in ET_O through Theil-Sen's nonparametric test; (5) to perform trend analysis in the contributing meteorological parameters, i.e. wind speed, vapour pressure deficit, net radiation, and temperature; and finally (6) to test the homogeneity of trends in ET_O over the humid region of NE India.

MATERIAL AND METHODS

Study area and meteorological data

The main ecosystem in NE India (22°N to 29°N; 88 °E to 97 °E) is a tropical wetland where the annual rainfall, linked with the southwest monsoon, is the heaviest in the world. The total annual rainfall in the region varies from place to place; for example, Cherrapunji (Meghalaya) receives an annual rainfall of about 12000 mm per year, whereas a few places in Assam receive an annual rainfall of only up to 2000 mm (Dev and Dash, 2007). Tea, besides paddy, forest products, like bamboo, different types of fruit crops, and orchids are the main cash crops of NE India. The details and locations of the sites selected from the NE region are given in Table I and Figure 1. The data required for this study were obtained from Tocklai Tea Research Association (Jorhat) and were used to calculate ET_O for a period of 22 years from 1979 to 2000. The data on wind speed are measured using an anemometer installed at a height of 10 feet from the ground surface. The wind-speed measurements were converted to wind speed at 2 metre height by using the wind profile relationship given by Allen *et al.* (1998). The monthly data of selected eight sites were used to obtain the average representative data (hereinafter NE India as a whole) for all the meteorological parameters. Figure 2(a) shows the average annual data of sunshine duration (in hours), morning and afternoon relative humidity (in percent) and wind speed (in km/day) from 1979 to 2000 for NE India as a whole. Figure 2(b) also

Table I. Details of sites of northeast India

S. No.	Name of site	Region of site	Lat. (N)	Long. (E)	Elev., m a.m.s.l.
1	Chuapara	East Dooars, N. Bengal	26°44′	89°28′	190·8
2	Gungaram	Terai, N. Bengal	26°38′	88°48′	123·6
3	Margherita	Upper Assam	27°16′	95°32′	183
4	Nagrifarm	Darjeeling, N. Bengal	26°55′	88°12′	1158·2
5	Nagrakata	Dooars, N. Bengal	26°54′	88°55′	228·6
6	Silcoorie	Cachar, Assam	24°50′	92°48′	39·6
7	Thakurbari	North Bank, Assam	26°48′	92°42′	92·45
8	Tocklai	Jorhat, Assam	26°47′	94°12′	96·5

Figure 1. Location map of sites of northeast India

shows the average data of net radiation ($R_n = (R_{ns} - R_{nl})$, in MJ/m^2 day) and the saturation vapour pressure deficit (VPD $= (e_s - e_s)$, in kPa) from 1979 to 2000 for NE India as a whole on an annual time scale. The net radiation and the VPD values were estimated using the formula introduced by Allen *et al.* (1998) on monthly time scales for the 8 sites of NE India. The net radiation and the VPD varied in the range of about 9–10 MJ m^{-2} day^{-1} and about 0·7–0·9 kPa, respectively, on the annual time scale over NE India as a whole.

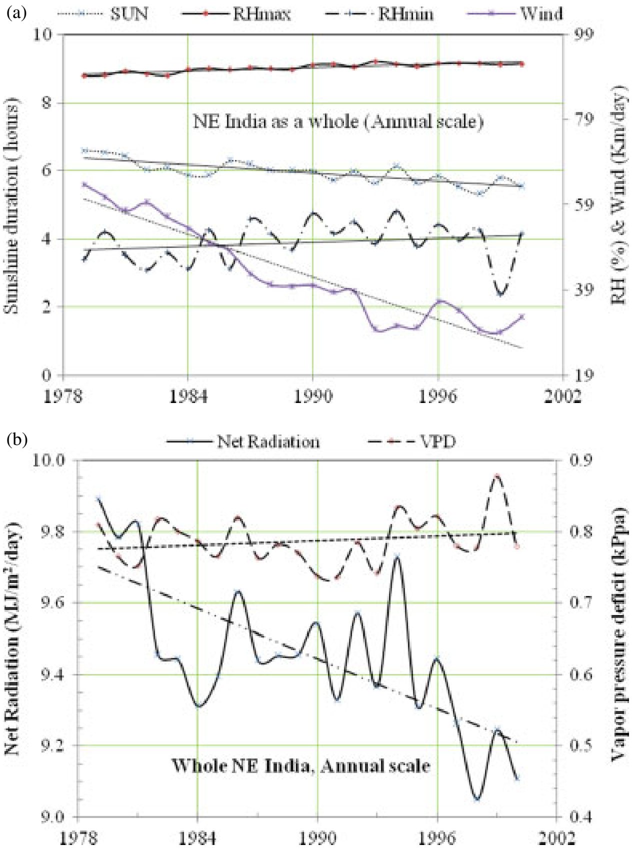

Figure 2. (a) Average climatic data of northeast India as a whole obtained as arithmetic averaging of the data of eight sites (1979–2000) in annual time scale. The straight lines are the linear trend lines of the respective climatic parameter. SUN, RH$_{\max}$, RH$_{\min}$ and Wind denote sunshine duration, morning relative humidity, afternoon relative humidity and wind speed, respectively. (b) Average net radiation (in MJ/m^2 day) and vapor pressure deficit (in kPa) data of northeast India as a whole in the annual time scale The straight lines are the linear trend lines of the respective climatic parameter

Penman-Monteith method

Perhaps the most reliable and universally accepted method to estimate ET_O under various types of climate is the Penman-Monteith (PM) FAO56 method which is physically based and explicitly incorporates both physiological and aerodynamic parameters (Xu *et al.*, 2006). The most recommended form of the PM method in computing ET_O is given as (Allen *et al.*, 1998):

$$ET_O = \frac{0{\cdot}408\Delta(R_n - G) + \gamma\dfrac{900}{\overline{T} + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0{\cdot}34u_2)} \qquad (1)$$

where ET_O is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}); G is the soil heat flux density (MJ m^{-2} d^{-1}); $\overline{T}$ is the mean daily air temperature (°C); u_2 is the wind speed at a 2 m height above the ground (ms^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $e_s - e_a$ is the saturation VPD (kPa); Δ is the slope of vapour pressure *versus* temperature curve at temperature T (kPa°C^{-1}), and γ is the psychrometric constant (kPa°C^{-1}). The reference crop was assumed as green grass with an albedo of 0·23. A complete set of equations, proposed by Allen *et al.* (1998) according to the available weather data and time step computation, constitutes the PM method. Since data of solar radiation is not available for most sites, R_n was estimated based on actual sunshine hours. Recently, Nandagiri and Kovoor (2005), Dinpashoh (2006) and McVicar *et al.* (2007) also applied the PM method for estimating reference evapotranspiration on different time scales for sites located in different types of climatic conditions of India, Iran, China, respectively. Complete details of the parameters and the computation algorithm of the P-M method can also be found in Allen *et al.* (1998).

Methods for trend analysis

Both parametric and nonparametric methods have been employed for identifying trends in data. However, recent studies have shown that nonparametric tests are more suitable for non-normally distributed and censored data, including missing values, which are frequently encountered in hydrological time series. These methods are less influenced by the presence of outliers in the data. Among those, the MK test (Mann, 1945; Kendall, 1975) is one of popular methods for trend analysis. Recently, Kahya and Kalayci (2004), Tebakari *et al.* (2005), Partal and Kahya (2006), Ezber *et al.* (2007), Singh *et al.* (2008), Kumar and Jain (2010), Jhajharia and Singh (2010), Mishra and Singh (2010) and Dinpashoh *et al.* (2011) carried out the MK test, which is also applied in this study, using various hydrologic data. One of the main problems in testing and interpreting trends is the effect of serial dependence. If there is a positive correlation (persistence) in the time series, then the nonparametric test would suggest a significant trend in the time series that is, in fact, random more than specified by the significance level (Zhang *et al.*, 2001). Therefore, we first tested the significance of lag-1 serial correlation (r_1) for all ET_O time series at a 1% significance level to eliminate the effect of serial correlation. If the absolute value of r_1 was less than the significance level value, then ET_O time series was subjected to the original MK test. Otherwise, the effect of serial correlation was removed from the time series by pre-whitening prior to applying the MK test.

Mann-Kendall (MK) test: The MK trend test was first carried out by computing an S statistic as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{2}$$

where n is the number of observations and x_j is the j^{th} observation and $\operatorname{sgn}(\theta)$ is the sign function which can be defined as

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases} \tag{3}$$

Under the assumption that data are independent and identically distributed, the mean and variance of the S statistic are given by (Kendall, 1975)

$$E(S) = 0 \tag{4}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{5}$$

where m is the number of groups of tied ranks, each with t_i tied observations. The original MK statistic, designated by Z, can be computed as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var\ (S)}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{\sqrt{Var\ (S)}} & S < 0 \end{cases} \tag{6}$$

If $-Z_{1-\alpha/2} \le Z \le Z_{1-\alpha/2}$ then the null hypothesis of no trend can be accepted at a significance level of α. Otherwise, the null hypothesis can be rejected and the alternative hypothesis can be accepted at the significance level of α.

Modified Mann-Kendall (MK) method: In the presence of serial correlation, application of the original MK procedure is not recommended for the data set since the effect of lag-1 serial correlation on trend statistic poses a major source of uncertainty. Therefore, prior to applying the MK test, the lag-1 serial correlation component was removed from the time series to eliminate the influence of serial correlation on trend. This treatment is called 'pre-whitening'. The MK test was then used to detect a trend in the residual (or pre-whitened) series. For this purpose the new time series as proposed by Kumar *et al.* (2009) can be obtained as

$$x_i' = x_i - (\beta \times i) \tag{7}$$

where β is Theil-Sen's estimator (Theil, 1950; Sen, 1968) and will be described in the subsequent section. The value of r_1 of the new time series is first computed and later used to determine the residual series as

$$y_i' = x_i' - r_1 \times x_{i-1}' \tag{8}$$

The value of $\beta \times i$ was added again to the residual dataset as

$$y_i = y_i' + (\beta \times i) \tag{9}$$

The y_i series was subjected to trend analysis.

Theil-Sen's estimator: The slope of n pairs of data points was estimated using Theil-Sen's estimator which is given as:

$$\beta = Median\left(\frac{x_j - x_l}{j - l}\right) \qquad \forall \quad 1 < l < j \tag{10}$$

The slope computed by this estimator is a robust estimate of the magnitude of a trend and has been widely used in identifying the slope of a trend line in a hydrological time series (Yue *et al.*, 2002).

Table II. Mean monthly total ET_O, in mm, obtained through Penman-Monteith method. Chu, Gun, Mag, Ngk, Nfm, Sil, Tha, Toc denote Chuapara, Gungaram, Margherita, Nagrakata, Nagrifarm, Silcoorie, Thakurbari and Tocklai, respectively

	Chu	Gun	Mag	Ngk	Nfm	Sil	Tha	Toc
JAN	59·1	56·0	50·6	57·7	50·2	65·0	54·5	50·5
FEB	68·3	67·6	59·3	66·2	57·1	75·6	65·4	59·3
MAR	102·0	111·8	82·6	99·1	91·3	108·2	99·4	87·1
APR	116·5	132·0	98·0	118·7	103·1	121·8	113·1	102·6
MAY	125·9	145·2	109·3	125·1	104·0	126·1	119·4	114·5
JUN	104·7	133·4	106·1	107·6	89·8	116·1	112·1	113·1
JUL	99·7	119·9	104·2	98·4	86·9	112·0	110·3	115·1
AUG	104·2	123·4	109·5	102·3	92·0	115·3	110·9	116·8
SEP	94·9	108·0	92·0	93·9	80·3	102·3	97·7	98·2
OCT	98·4	99·7	87·4	97·4	83·9	99·6	94·1	88·8
NOV	73·1	71·5	66·2	73·4	65·1	80·4	70·1	67·1
DEC	59·6	56·4	52·6	59·6	54·3	67·0	54·6	52·3

Test of homogeneity of trends: In the present study, a procedure proposed by van Belle and Hughes (1984) to assess the homogeneity of ET_O trends by MK test was used as no such study concerning homogeneity of trend for ET_O is available in the literature. Homogeneity test was performed on a dataset of ET_O obtained by combining the data of ET_O of all the sites of NE India to obtain a possible single global trend. The method proposed by van Belle and Hughes uses the chi-square test to determine the trend homogeneity between months, between stations and station-month interactions. The first step in testing the homogeneity is to calculate the MK statistics Z_j $(j = 1, 2, \ldots, 12)$ for all months, and later its squares $(Z^2{}_j)$ were considered in the analysis. Under the null hypothesis of no trend for month j, each $Z^2{}_j$ has approximately a chi-square distribution with 1° of freedom (d.f.). Furthermore, if seasonal observations are far apart, then Z_j will be nearly independent. The overall statistics for m months is

$$x^2{}_{Total} = \sum\nolimits_{j=1}^{m} Z_j^2 \tag{11}$$

which follows approximately a chi-square distribution with $(m \times k)$ d.f. under the null hypothesis of no trends for all m months and k stations. A large value of such statistics in (11) is not really meaningful, as it still fails to distinguish heterogeneity between individual $Z^2{}_j$'s from the overall trend. This problem can be solved by partitioning $x^2{}_{Total}$ by the following procedure:

$$x^2{}_{Total} = x^2{}_{homog.} + x^2{}_{trend} \tag{12}$$

where

$$x^2{}_{trend} = mZ^2. \tag{13}$$

where Z is an average over subscript j and $x^2{}_{homog.}$ can be found by subtracting $x^2{}_{trend}$ from $x^2{}_{Total}$. Under the null hypothesis of equal Z's for all months, $x^2{}_{homog.}$ and $x^2{}_{trend}$ have chi-square distribution with $(m \times k - 1)$ and 1 d.f., respectively. Homogeneity of trends can be tested by comparing the calculated $x^2{}_{homog.}$ with the corresponding $x^2{}_{mk-1}$ from the chi-square tables. If $x^2{}_{homog.}$ is not significant, then a valid test for the common trend is possible by referring $x^2{}_{trend}$ to the corresponding tabulated value. If $x^2{}_{homog.}$ is significant, then evaluation of $x^2{}_{trend}$ is not appropriate. In such a condition trend tests for each month can be done for individual Z_j.

RESULTS

The monthly data were used to compute seasonal and annual time series of climatic data of sites of NE India. Four seasons of the study area were defined as (Jhajharia *et al.*, 2009): winter (January–February), pre-monsoon (March–May); monsoon (June–September), and post-monsoon (October–December).

Estimation of ET_O and its sensitivity to meteorological variables

The annual total ET_O over 8 sites in NE India, calculated using the PM method, varied from about 900 mm to 1320 mm. The estimated annual total ET_O of NE India as a whole equaled about 1100 mm. Table II presents the average monthly total ET_O obtained through the PM method for 8 sites of NE India. The monthly total ET_O in January and February stayed around 55–65 mm. The monthly total ET_O reached a peak value in May, for most of the sites, in the range of 110–150 mm. ET_O value in July was also comparatively high, and afterwards, ET_O decreased gradually, reaching up to 50 mm in December. On a seasonal time scale, the pre-monsoon and monsoon seasons ET_O values accounted for 25–30% and 35–40% of the annual total ET_O, respectively, in the humid region of northeast India. For NE India as a whole, the average seasonal total ET_O was found to vary from 105 mm in winter to about 470 mm in the monsoon season. The comparatively low temperature (about 10–15 °C), low net radiation (in the range of 10–15 MJ/m^2-day) and moderate wind speed (in the range of 0·3–0·6 m/s) in the winter season over the sites of NE India were responsible for the low values of ET_O witnessed in the winter season. These parameters (temperature, net radiation and wind speed) often overshadowed the effect on ET_O of the occurrence of the lowest values of relative humidity (about 50% in afternoon and 90% in morning) in winter among all the

Table III. Number of times meteorological variables, in order of dominance (i–iii), were significantly related to $\mathrm{ET_O}$ in stepwise regression method in different time scales. VPD, $\mathrm{T_{max}}$ and $\mathrm{T_{min}}$ denote reference vapour pressure deficit, maximum temperature and minimum temperature, respectively

Meteorological variable	Annual			Winter			Pre-monsoon			Monsoon			Post-monsoon		
	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii
Net radiation	7	1	0	8	0	0	6	1	—	8	0	0	6	—	—
Wind speed	1	5	2	0	8	0	2	1	5	0	2	—	1	6	—
VPD	—	2	5	0	0	7	0	6	1	0	6	1	0	1	3
$\mathrm{T_{max}}$	—	—	1	—	—	1	—	—	—	—	—	1	—	—	3
$\mathrm{T_{min}}$	—	—	—	—	—	—	—	—	—	—	—	1	—	—	1

seasons over the humid region of NE India. On the other hand, the comparatively higher values of temperature (of about 30 °C) and net radiation (about 35–50 MJ/m^2-day) in the summer season have led to the occurrence of higher ET_O values in the region in hot and sunny months of the summer season. Comparatively, higher values of VPD in the pre-monsoon season may also be one of the reasons for the occurrence of comparatively higher ET_O in this season in the humid region of northeast India.

In order to identify the dominant variables associated with ET_O, stepwise regression method was adopted. Several researchers, namely, Chattopadhayay and Hulme (1997), Thomas (2000), and Dinpashoh *et al.* (2011) also used a similar procedure to look for the most important variable responsible for ET_O changes under different types of climatic conditions of India, China and Iran, respectively. In the present study, the stepwise regression analysis was performed between ET_O as the dependent variable and the meteorological parameters, i.e. net radiation, wind speed, VPD, and temperature, as independent variables on annual and seasonal time scales by using SPSS (Norusis, 1988) to possibly explain the underlying mechanisms of ET_O changes. The results of stepwise linear regression analysis at annual and season time scales for all the sites of NE India are given in Table III. At the annual time scale, the net radiation was observed to be the most dominating variable which affected the observed changes in ET_O in the humid region of NE India. Wind speed followed by VPD was the other two important contributing variables for the observed trends in annual ET_O. The temperature hardly affected annual ET_O at any of the sites of NE India.

On examining the results of stepwise regression to determine the causal mechanisms of ET_O changes at the seasonal scale, the net radiation was found to be the most dominating variable for all the sites in all the four seasons over NE India. After net radiation, wind speed (VPD) was the second (third) most important variable responsible for the observed ET_O changes mainly in winter, pre-monsoon and post-monsoon (pre-monsoon and monsoon) seasons. However, temperature was found to be the most insignificant causative variable for the observed ET_O changes in any of the seasonal time scales.

Chattopadhayay and Hulme (1997) reported that although most parts of India except Gujarat and a few parts on the west coast have witnessed temperature increases, however, both $\mathrm{E_{pan}}$ and PET have witnessed decreasing trends over a majority of sites in India. They also found that the relative humidity was strongly associated with changes in $\mathrm{E_{pan}}$. The increasing trends in RH have counterbalanced the effect of rising temperature on $\mathrm{E_{pan}}$ by hampering the evaporative process. Bandyopadhyay *et al.* (2009) also found decreasing trends in ET_O over various sites in India. They report that the main causes of such downward trends in ET_O are the significant steady decrease in wind speed and significant increase in air relative humidity. Wind is strongly related to $\mathrm{E_{pan}}$ decreases in the pre-monsoon and the monsoon seasons over NE India. Sunshine duration is also found to be the most influencing variable responsible for the observed changes in $\mathrm{E_{pan}}$ in winter, pre-monsoon and monsoon seasons (Jhajharia *et al.*, 2009).

Trend analysis of ET_O and governing meteorological variables

Trends in ET_O and governing meteorological variables over NE India were analysed on annual, seasonal, and monthly (results not shown here) time scales. The test statistic (Z) values obtained through the nonparametric MK test after the removal of the significant lag-1 serial correlation effect from the time series of ET_O, net radiation and wind speed (temperature: Tmax, Tmin, and Tmean) by pre-whitening are given in Table IV (Table V). We also estimated the trends using the MK test in actual vapour pressure (e_a), saturation vapour pressure (e_s) and VPD ($e_s - e_a$) following the works of Xu *et al.* (2006) and McVicar *et al.* (2007), and the trend results are shown in Table VI. The results of trends in ET_O and the governing meteorological parameters under the humid climatic conditions of NE India are discussed as below.

Annual time scale: A sample annual time series (denoted by solid lines) of ET_O, Tmax, and Tmin, and linear trends (denoted by the dashed lines) of the NE Indian sites are given in Figure 3. Six sites observed statistically significant decreasing trends in ET_O in the range of about (−) 18 to (−) 71 mm/decade. NE India as a whole witnessed significant annual ET_O decreases at a rate of (−) 38·5 mm/decade as well. Figure 4 shows

Table IV. Test statistic (*Z*) values obtained from the MK test in the time series of ET_O, net radiation and wind speed over sites of northeast India at different durations. ET_O, R_{net} and Wind denote reference evapotranspiration, net radiation and wind speed, respectively

Name of site	Different Durations														
	Year			Winter			Pre Monsoon			Monsoon			Post Monsoon		
	ET_O	R_{net}	Wind	ET_O	R_{net}	Wind	ET_O	R_{net}	Wind	ET_O	R_{net}	Wind	ET_O	R_{net}	Wind
Chuapara	−2·65	−3·34	−3·51	−2·37	−1·33	−3·19	−2·54	−3·99	−3·12	−1·27	−2·6	−3·45	−2·37	−1·69	−2·67
Gungaram	−4·34	0·73	−5·3	−3·44	−2·26	−4·51	−4·17	0·79	−4·91	−1·69	1·24	−4·85	−4·23	0·08	−4·68
Margherita	−4·4	−2·14	−5·53	−2·65	−2·2	−5·08	−1·97	−2·37	−4·51	−2·71	−1·41	−4·79	−3·61	−0·17	−5·22
Nagrakata	−1·41	−3·53	−0·73	−1·18	−0·85	−0·96	−1·07	−1·97	−1·75	−1·97	−3·19	−1·3	−1·13	0·03	−1·21
Nagrifarm	−2·26	−1·27	−4·19	−2·71	−0·37	−4·3	−2·48	−0·93	−4·74	1·02	−0·85	−3·73	−2·2	−2·43	−4·22
Silcoorie	−1·47	−3·22	−2·79	−1·69	−2·23	−2·29	−1·24	−2·48	−2·59	−1·3	−2·09	−2·59	−0·06	−2·23	−0·45
Thakurbari	−4·23	−3·67	−5·98	−3·67	−1·38	−5·58	−3·38	−2·54	−5·13	−3·89	−2·85	−5·33	−4·23	−2·4	−5·64
Tocklai	−3·61	−2·71	−4·91	−2·48	−2·06	−3·87	−2·48	−1·66	−3·78	−4·23	−2·14	−4·46	−3·16	−0·99	−4·74
NE India	−3·33	−3·24	−5·53	−2·99	−2·36	−4·91	−3·33	−3·04	−5·36	−4·00	−1·92	−5·62	−3·33	−1·46	−5·08

Table V. Test statistic (Z) values obtained from the MK test in the time series of temperature in annual and seasonal time scales. T_{max}, T_{min}, T_{mean} and NE India denote the maximum, minimum and mean temperatures, and northeast India as a whole, respectively

Name of site	Different Durations														
	Year			Winter			Pre Monsoon			Monsoon			Post Monsoon		
	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}	T_{mean}
Chuapara	0·10	2·93	1·41	−1·56	0·49	−1·04	0·91	2·12	2·22	−1·33	1·70	−0·29	0·23	1·65	1·56
Gungaram	1·80	2·91	3·10	−0·14	0·62	0·37	4·75	4·27	4·49	2·60	1·72	1·83	3·05	2·88	3·58
Margherita	1·19	2·65	2·12	−0·59	2·23	1·19	−0·73	2·23	0·87	0·20	1·70	2·03	3·13	1·75	2·20
Nagrakata	1·04	2·71	2·57	0·06	0·23	0·06	0·45	2·20	1·61	−0·54	2·82	2·12	1·58	1·47	1·81
Nagrifarm	3·30	1·52	2·65	2·83	0·88	2·00	1·27	−0·17	0·73	2·90	1·78	2·09	0·42	1·78	0·76
Silcoorie	3·44	−0·40	2·91	0·51	0·03	0·00	1·50	0·08	1·61	2·43	−1·67	1·16	2·88	0·03	1·72
Thakurbari	2·77	−1·64	−1·24	0·68	−1·16	0·28	0·28	−1·21	−0·76	0·34	−2·03	−3·53	3·61	−1·50	0·08
Tocklai	−1·02	1·92	0·11	−0·71	0·90	−0·06	−0·40	0·79	0·45	−3·11	1·13	−1·86	0·00	1·75	0·48
NE India	2·99	2·00	3·02	0·39	0·90	0·45	2·09	1·89	2·51	2·03	0·68	1·52	2·77	1·24	2·20

Table VI. Test statistic (*Z*) values obtained from the MK test for saturation vapour pressure, actual vapour pressure and vapour pressure deficit over sites of NE India. e_s, ea and VPD denote saturation vapour pressure, actual vapour pressure and vapour pressure deficit, respectively

Name of site	Different Durations														
	Year			Winter			Pre Monsoon			Monsoon			Post Monsoon		
	e_s	e_a	VPD	e_s	e_a	VPD	e_s	e_a	VPD	e_s	e_a	VPD	e_s	e_a	VPD
Chuapara	1·44	−0·16	1·96	−1·31	−1·30	−0·88	1·95	0·84	1·27	−0·89	−1·63	1·31	0·78	−0·55	0·91
Gungaram	2·97	3·87	0·77	0·20	1·11	−0·60	3·78	4·91	−0·28	1·81	1·84	1·30	3·90	2·82	1·78
Margherita	1·33	1·25	1·23	0·28	0·03	0·54	0·23	0·45	0·08	0·80	0·40	−0·09	2·77	1·39	2·46
Nagrakata	2·87	3·70	−2·15	0·28	2·47	−2·00	1·38	2·76	−1·86	1·83	2·97	−2·11	2·00	2·72	−0·68
Nagrifarm	1·70	2·92	0·51	2·12	0·43	1·11	0·90	1·69	0·51	2·20	2·43	0·97	0·54	0·90	−0·17
Silcoorie	3·49	1·47	1·42	0·60	1·25	−1·30	1·69	1·13	0·45	1·48	0·34	1·56	2·60	1·62	0·82
Thakurbari	−0·57	−0·57	−0·45	0·28	0·51	−0·68	−0·14	0·34	−0·45	−2·94	−2·04	−0·82	1·61	−0·23	3·00
Tocklai	−0·40	0·95	−1·97	−0·25	0·40	−0·82	0·39	1·30	−0·79	−2·07	−0·09	−2·24	0·54	−0·03	0·63

the box and whisker plot of slopes of annual ET_O time series in NE India. The median of ET_O slopes at the annual time scale is located below zero. Also, the maximum of β at the annual time scale is located below the zero line. This means that all the sites at the annual time scale had downward trends, which created a reverse slope. The median of β was about −18 mm/decade. The variability of β above the median was less than the corresponding values below the median. The lower point at the annual time scale was located about (−) 45 mm/decade,

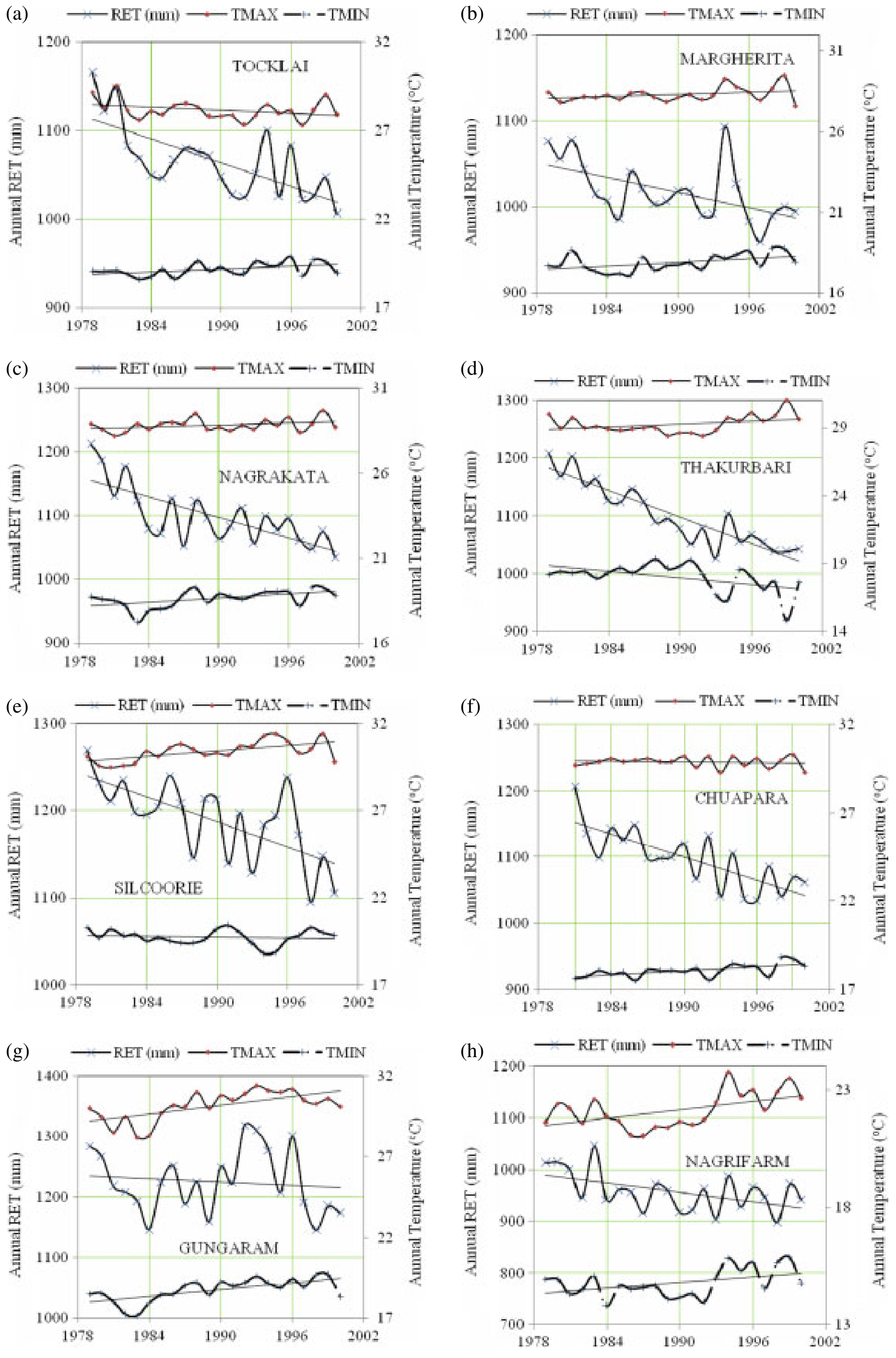

Figure 3. Time series of ET_O, maximum and minimum temperatures over sites of NE India
Note: RET, TMAX and TMIN denote reference evapotranspiration, maximum temperature and minimum temperature, respectively

indicating that the amount of crop water requirements have become less in the last few decades in NE India.

The trend analysis of temperature for the duration 1979–2000 produced results which were almost similar to those of Jhajharia and Singh (2010). Significant increasing trends in T_{max}, T_{min} and T_{mean} were observed at the annual time scale over five and six sites each, respectively, including NE India as a whole (Table V). It is striking to note that almost all the sites witnessed the occurrence of concomitant ET_O decreases and temperature increases, which indicates the involvement of the other meteorological parameters in the observed ET_O trends in the humid region of northeast India at the annual time scale. Thus, the trends in wind speed and net radiation (saturation vapour pressure, actual vapour pressure and VPD) were also analysed, and the results obtained through the nonparametric MK test are presented in Table IV (Table VI). Decreasing trends in wind speed (net radiation), mostly at a 1% level of significance, were observed in all but one site (all but two sites) and the NE region as a whole at the annual scale. On the other hand, four (three) sites of NE India witnessed statistically

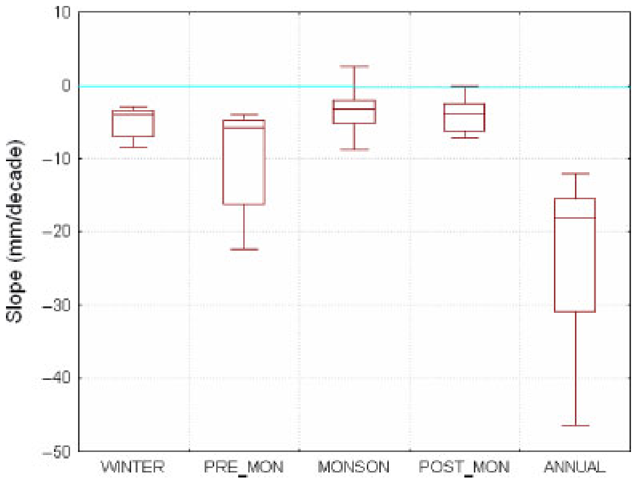

Figure 4. Box plots of trend slopes of the seasonal and annual ET_O time series. The lower and upper ends of the box denotes the 25 and 75 percentile values, the line inside the box represents the median and the whiskers show the 5 and 95 percentile values. PRE_MON, MONSON and POST_MON denote pre-monsoon, monsoon and post-monsoon, respectively

significant increasing trends in saturation vapour pressure, i.e. e_s (actual vapour pressure, e_a) in annual duration. Also, one site (two sites) witnessed statistically significant increasing (decreasing) trends in VPD in the annual scale. The decrease in VPD at Nagrakata is caused due to the comparatively stronger increases in e_s than e_a (Table VI). The occurrence of ET_O decreases in spite of the observed warming over NE India is caused mainly due to the decrease in wind speed and net radiation over almost all the sites. The reasonably stronger decreases in wind speed and sunshine duration not only compensated for the affect of observed warming on the rate of ET_O, but may have caused the decline in ET_O in the humid region of NE India. The results of stepwise regression analysis reveal that ET_O decreases are mainly attributed to the net radiation and wind speed, which are also corroborated by the observed trends in these two parameters. Therefore, the decreases in net radiation along with all-pervading wind speed decreases strongly favoured the annual ET_O decreases for the humid sites of NE India.

Seasonal time scale

Statistically significant decreasing trends in ET_O, mostly at a 1% level of significance, were observed over 7 sites, 6 sites each and 5 sites in the winter, the pre-monsoon, the post-monsoon and the monsoon seasons, respectively. For NE India as a whole, statistically significant decreasing trends in ET_O, in the range of (−) 6·5 mm/decade in the post monsoon season to (−) 13·6 mm/decade in pre-monsoon season, were witnessed. Almost all the sites of NE India witnessed higher magnitude of ET_O decreases in the pre-monsoon season (in the range of (−) 11 mm/decade to (−) 26 mm/decade) in comparison to other three seasons. A sample time series of the total ET_O in pre-monsoon season at four sites of NE India is shown in the Figure 5. The broken lines on the bar diagrams represent linear trends in the total ET_O in pre-monsoon season over these NE Indian sites. The box and whisker plot denoting the slopes of ET_O time series in different seasons is shown in Figure 4 as well. The 50 percentile (median lines) and 75 percentile

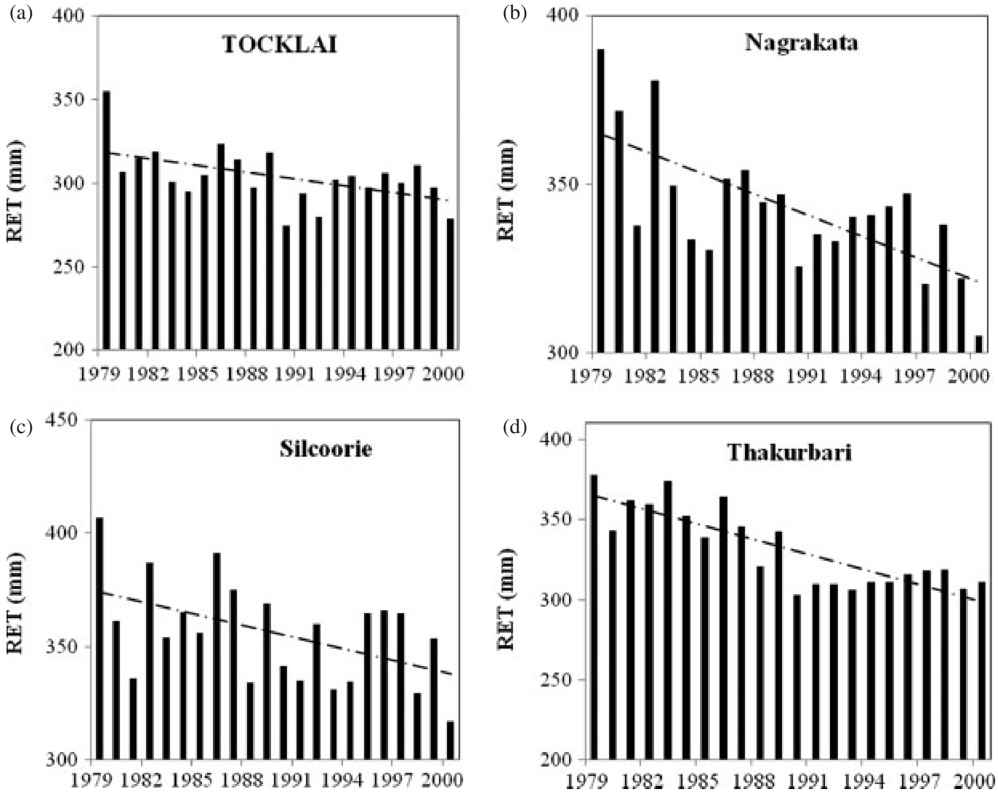

Figure 5. Time series of ET_O over sites of NE India in pre-monsoon season

(i.e. third quartile) of slopes were located below zero for all the seasons. The end point of whisker line from the top was also located below the zero line for all but one (monsoon). This implies that seasonal ET_O time series in NE India exhibit decreasing trends. The pre-monsoon season has the lowest median of slopes of ET_O in comparison to the other three seasons. It can be seen from Figure 4 that the distance between the median and the upper line of rectangles was lower than the corresponding distance between median and lower part of rectangles. This means that the variability of slopes for the median till 75 percentile (i.e. third quartile) was smaller than that of 25 percentile till 50 percentile (i.e. second quartile) at the seasonal time scale. In all the seasons, the distance between the median and the top of boxes (i.e. 75 percentile) was smaller than the corresponding distance between the median and the bottom of boxes (i.e. 25 percentile). This is especially true for winter and pre-monsoon seasons. This means that the variability of slopes for the median till 75 percentile is smaller than that of 25 percentile till 50 percentile.

Results of trends in air temperature indicate that T_{max}, T_{min} and T_{mean} remained practically trend-less in winter, and T_{max} and T_{mean} in the pre-monsoon season. Increasing trends in T_{max} and T_{mean} were observed at four and five sites including NE India as a whole in the monsoon and the post-monsoon seasons, respectively. Five sites each, inclusive of NE India as a whole, witnessed increasing trends in T_{min} in the pre-monsoon, the monsoon, and the post-monsoon seasons, respectively. In the monsoon season, decreasing trends in T_{max}, T_{min} and T_{mean} were witnessed over one and two sites each, respectively, as well (Table V). Therefore, concomitant ET_O decreases and temperature increases were witnessed at only two sites (Margherita and Nagri Farm) in winter; at four sites (Margherita in Upper Assam and three sites of north Bengal region) in pre-monsoon; at two sites (north Bengal region) in monsoon; and at six sites in the post-monsoon season. Similarly, concomitant ET_O decreases and temperature increases were witnessed in the pre-monsoon, the monsoon and the post-monsoon seasons for NE India as a whole. On the other hand, two sites witnessed simultaneous decreases in ET_O and temperature in the monsoon season.

Trends in wind speed and net radiation (saturation vapour pressure, actual vapour pressure, and VPD) obtained through the MK test in seasonal time scales are presented in Table IV (Table VI). Eight sites, seven sites each and six sites witnessed significant decreasing trends in wind speed in pre-monsoon, winter and monsoon, and post-monsoon seasons, respectively. Similarly, decreasing trends in the net radiation were also witnessed at six and five sites (four sites each) in the pre-monsoon and monsoon (winter and post-monsoon) seasons, respectively. On the other hand, no trends were observed in VPD over seven sites each (six and five sites) in the winter and pre-monsoon (monsoon and post-monsoon) seasons. Only one site, i.e. Nagrakata (two sites, i.e. Gungaram and Margherita) witnessed a decreasing (increasing) trend(s) in VPD, which was caused mainly due to the occurrence of larger increases in the actual vapour pressure (saturation vapour pressure) in comparison to the saturation vapour pressure in winter, pre-monsoon and monsoon (post-monsoon) seasons. However, one site, i.e. Tocklai, witnessed a decreasing trend in VPD, which was caused mainly due to the decrease in the saturation vapour pressure in the monsoon season (see Table VI). In winter (pre-monsoon) season, all but one site (all but two sites) of NE India witnessed significant decreases in ET_O which were caused mainly due to the occurrence of steady wind speed decreases and significant net radiation decreases over NE India. In post-monsoon season, ET_O decreases occurred in spite of the observed temperature rise over most of the sites of NE India because of decreases in wind speed and net radiation. The combination of decreasing trends in wind speed and net radiation not only neutralized the effect of observed warming on ET_O, but might have actually caused ET_O to decline further in the post-monsoon season under the humid climatic conditions of northeast India.

Trends in rainfall were obtained in the same way as for other meteorological parameters in the region under study. No significant trends in rainfall were observed at all the sites of northeast India at all the time scales (see Table VII). Jhajharia *et al.* (2009) also found no concurrent occurrences of decreases in E_{pan} and increases in rainfall at almost all the eleven sites of northeast India except two cases (Agartala in winter and at Chuapara in annual and pre-monsoon). Similarly, Bandyopadhyay *et al.* (2009) reported significant decreasing trends in ET_O and no significant trend in rainfall over India during 1971–2002, which is in total agreement with the findings of the present study for NE India. Figures were drawn between total ET_O and total rainfall in annual and seasonal time scales in order to verify the relationship between ET_O and rainfall over all the eight sites of

Table VII. Number of statistically significant decreasing (increasing) trends obtained through the Mann-Kendall test in various meteorological parameters of eight sites of NE India and NE India as a whole. The value in brackets denotes the number of statistically significant increasing trend (at 10% or higher) of that variable

Time scale	WIND	Rnet	VPD	T_{max}	T_{min}	T_{mean}	Rainfall	ET_O
ANNUAL	8	6	2(1)	(5)	(6)	(6)	0	7
WINTER	8	4	1	(1)	(1)	(1)	0	8
PRE MONSOON	9	6	1	(2)	(5)	(3)	0	7
MONSOON	8	5	2	1(4)	2(5)	2(4)	0	6
POST MONSOON	7	4	(3)	(5)	(5)	(5)	0	7

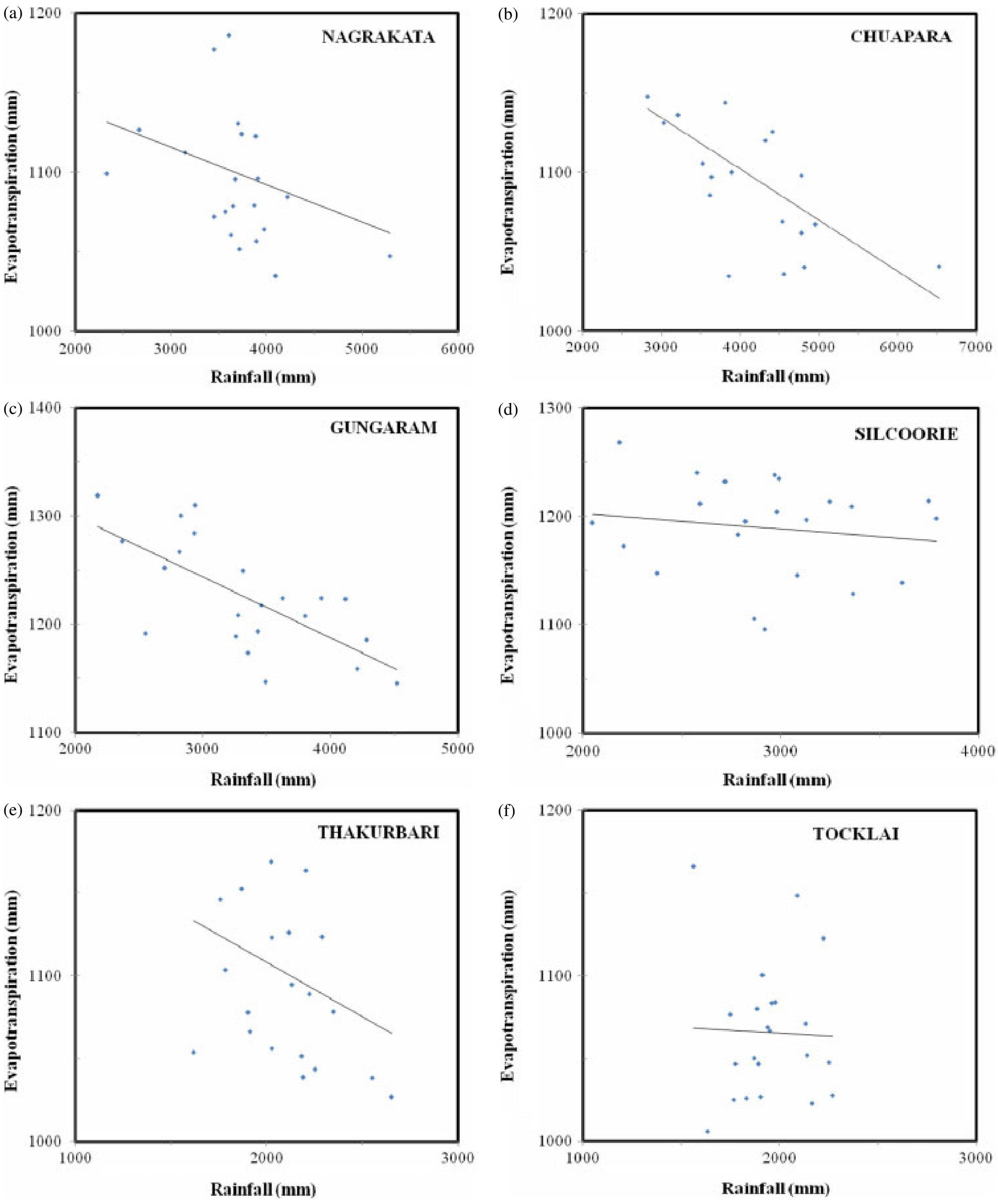

Figure 6. Relationship between RET and Rainfall for different sites of NE India in annual time scale

NE India. Figure 6 shows the relationship between total rainfall and total ET_O at six different sites of northeast India for the annual duration. A negative relationship exists between annual total rainfall and annual total ET_O over these six sites. Similarly, negative relationships in winter, pre-monsoon and monsoon seasons (post-monsoon season) were also obtained for different sites of NE India, and are shown in Figure 7 (Figure 8). Under the given situation of ET_O decreases and relatively stable rainfall in the northeastern region of India, one would expect an increase in runoff under the assumed condition of no changes in other parameters under the humid climatic conditions. Also, the water requirements of various crops and vegetation will decrease on account of the observed ET_O decreases in the crop-growing seasons over NE India.

Homogeneity tests of ET_O

Table VIII presents the results of homogeneity test of monthly ET_O trends. The value of $x^2{}_{Total}$ equal to 485·9

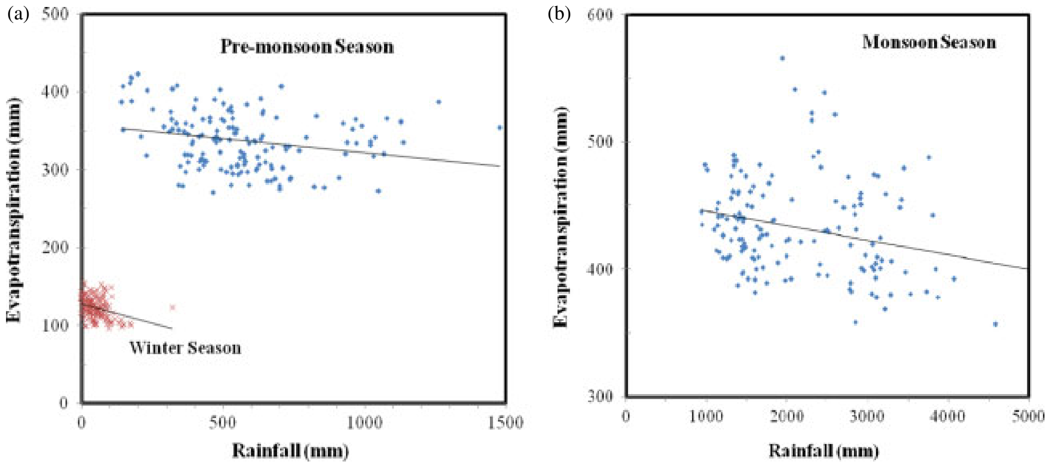

Figure 7. Relationship between RET and Rainfall for eight sites of NE India in different seasons

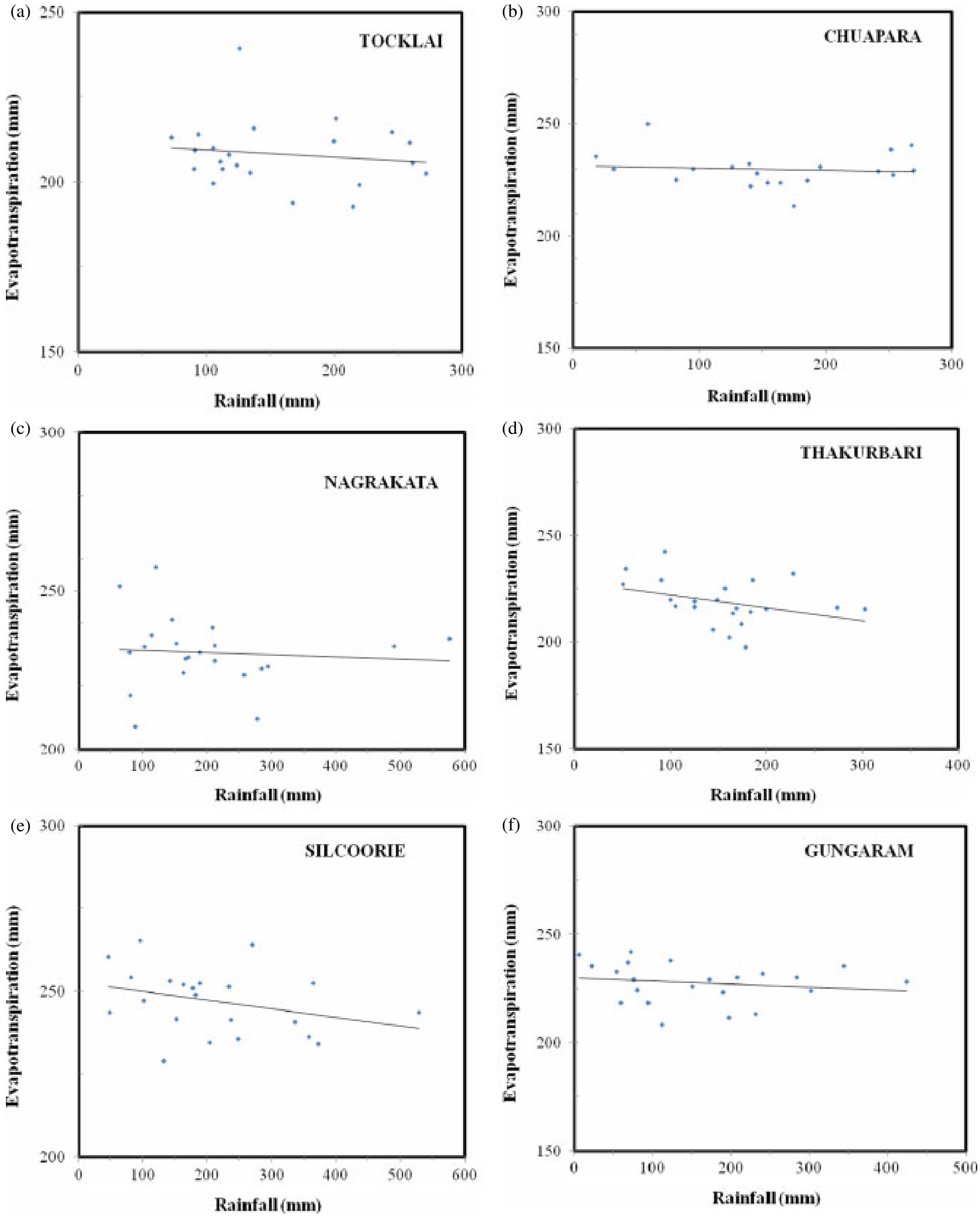

Figure 8. Relationship between RET and rainfall for two sites of NE India in post-monsoon season

Table VIII. Partitioning of sums of squares for testing monthly ET_O trend heterogeneity of NE India. (S: significant; NS: not significant)

Source	Chi-square (calculated)	d.f.	Critical Chi-sq. in 5% (from Table)	Significance
Total	485·91	96	119·8	S
Homogeneity	150·01	95	118·7	S
Month	12·32	11	19·68	NS
Station	70·67	7	14·07	S
Station-Month	67·02	77	98·48	NS
Trend	335·90	1	3·84	S

(i.e. $\sum_{j=1}^{m}\sum_{p=1}^{k} Z_{jp}^2$) is higher than the corresponding chi-square table value (119·8), indicating that the other four tests show the existence of an overall significant trend in NE India, which is heterogeneous across the study area (Table VIII). The $x^2{}_{Total}$ value was partitioned into two major sources of variation, such as $x^2{}_{homog.}$ and $x^2{}_{trend}$ with (*mk*-1) and 1 d.f., respectively. Again, $x^2{}_{homog.}$ was partitioned into assignable sources, such as $x^2{}_{(station,k-1)}$, $x^2{}_{(month,m-1)}$ and $x^2{}_{(station-month,(m-1)(k-1))}$ for the time series of ET_O. At $\alpha = 0{\cdot}05$ level, $x^2{}_{homog.}$ was found to be 150. Referring to the table of the x^2 distribution with 95 [= (*mk*-1)] d.f., the critical value at $\alpha = 0{\cdot}05$ was 118·7. Since $x^2{}_{homog.}$ was greater than the critical value at $\alpha = 0{\cdot}05$, the null hypothesis of homogeneity of stations was rejected. It was concluded that the stations were heterogeneous for ET_O trends as well. Partitioning $x^2{}_{homog.}$ into three other sources as in Table VIII, it was found that stations were heterogeneous for ET_O data, i.e., $x^2{}_{station,k-1} > x^2{}_{.95,7}$ (70·67 > 14·07)].

Since ET_O trends across stations were not homogeneous, the significance of the overall ET_O trend of each month could not be further tested. However, it was found that months were homogeneous for ET_O data, i.e. $x^2{}_{month,m-1} < x^2{}_{.95,11}$ (12·32 < 19·68). In other words, one can assume a monotonic trend between months, or trends in January are the same as those in February or March, etc. Since ET_O trends of NE India in months are homogeneous, one can further test the significance of the overall ET_O trend of each station. Also the value of the interaction between station and month, i.e. $x^2{}_{(station-month,(0{\cdot}95,77))} = 67{\cdot}02$ was less than the corresponding tabulated value, i.e. $x^2{}_{.95,77}$ (= 98·48), indicating that this term is insignificant. It is reasonable to conclude that the meaningful trend tests are said to be not for the individual site-seasons, i.e. Z_{jp} ($j = 1, \ldots, 12$; and $p = 1, \ldots, 8$). In other words, there is homogeneity in ET_O trends in the interaction between stations and months. This conclusion is surprising for the study area that ET_O is a complex phenomenon which can be affected by many variables even for a small area. In this area, although sites were heterogeneous but months were homogeneous. All monthly ET_O in the study area witnessed decreasing trends (results not shown here) and were statistically significant and homogeneous at a 5% level of significance.

SUMMARY AND CONCLUSIONS

In the present study, first we estimate ET_O using the universally accepted PM method over the eight sites in NE India and NE India as a whole under the humid climatic conditions of biodiversity-rich northeastern region of India. The total annual ET_O of the eight sites of NE region is found to be in the range of about 900–1320 mm. The total monthly ET_O stays around 50–65 mm in December to February, reaches its peak in summer and remains in the range of about 110–150 mm, and thereafter gradually decreases over sites of NE India. The average seasonal total ET_O varies from 105 mm (in winter) to 470 mm (in monsoon) for NE India as a whole.

We also investigate trends in ET_O and governing meteorological parameters through the MK test and obtain the magnitudes of trends in ET_O through Theil-Sen's nonparametric test. The effect of significant lag-1 serial correlation is removed from the data by pre-whitening prior to trend analysis. Statistically significant decreasing trends in ET_O are observed for the annual duration; winter, pre-monsoon and post-monsoon seasons and to some degree in the monsoon season under the humid climatic conditions of NE India. When considering the entire study domain for analysing the homogeneity of ET_O trends using the method of Van Belle and Hughes (1984), we find the existence of homogeneity in ET_O trends in the interaction between months and the interaction between station–month, but not in the interaction between stations. Temperature remains practically trendless in winter and pre-monsoon seasons, and witnesses increasing trends in monsoon and post-monsoon seasons. On the other hand, decreasing trends in net radiation are witnessed mainly for the following durations: annual; and seasonal: pre-monsoon and monsoon over NE India. Decreasing trends in wind speed are observed at almost all the time scales over most of the sites of NE India. Bandyopadhyay *et al.* (2009) relate the steady wind speed decreases witnessed over India to the obstruction of wind flow offered by the ever-increasing construction works. Also, Vautard *et al.* (2010) and McVicar and Roderick (2010) mention about the possible role played by the increases in terrestrial surface roughness in the global wind speed decreases.

The concomitant occurrences of ET_O decreases and the temperature increases are witnessed for the annual duration and the post-monsoon season under the humid climatic conditions of NE India. The contribution of the temperature rise to ET_O is offset mainly by the impact of steady wind speed decrease and decreases in net radiation over NE India, which is also confirmed by the strong and high sensitivity of net radiation and wind speed with ET_O through the stepwise regression analysis at almost all the time scales. Donohue *et al.* (2010) also find that the overall contribution from increases in temperature is almost entirely cancelled out by the decreases in wind speed alone over Australia. The observed ET_O decreases are also influenced, to some degree, by the VPD over a few sites of NE India. The findings of this study are also supported by the observed ET_O decreases over the Yangtze River basin (Xu *et al.*, 2006). They find the net radiation and wind speed as the main two variables responsible for the observed ET_O decreases in the Yangtze River catchment in China. However, Goyal (2004) finds that temperature followed by radiation; wind speed and vapour pressure have an effect on ET_O over an arid zone of Rajasthan in India. Thomas (2000) reports that sunshine duration (wind speed, relative humidity and maximum temperature) is (are) found to be the main parameter(s), which affect PET in south China (the northwest, central, and northeast China, respectively). Similarly, decreases in ET_O caused by the wind speed decreases are also witnessed over Canada (Burn and Hesch, 2007), over parts of China (Chen *et al.*, 2006; Xu *et al.*, 2006; Zhang *et al.*, 2007; Zhang *et al.*, 2009) and over most parts of Australia (Roderick *et al.*, 2007). Dinpashoh *et al.* (2011) also report wind speed as the main contributory parameter for the observed ET_O trends over different parts of Iran.

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