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Trends in temperature, diurnal temperature range and sunshine duration in Northeast India

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ABSTRACT: Trends in maximum ($T_{\max}$), minimum ($T_{\min}$) and mean (T_{mean}) temperatures; diurnal temperature range (DTR $= T_{\max} - T_{\min}$); and sunshine duration at eight sites in Northeast (NE) India were investigated. Three sites observed decreasing trends in DTR corresponding to annual, seasonal (pre-monsoon and monsoon) and monthly (September) time scales. On the other hand, DTR increases were also observed at other three sites in monsoon and post-monsoon seasons as well as in the months of June, October and December. The sites showing DTR decreases (increases) witnessed either increasing trends in $T_{\min}$ ($T_{\max}$) or decreasing trends in $T_{\max}$ ($T_{\min}$), with $T_{\max}$ ($T_{\min}$) showing either no trend or increasing at a smaller rate than $T_{\min}$ ($T_{\max}$). Temperature remained practically trendless in winter and pre-monsoon seasons over NE India. However, temperature increases were observed in monsoon and post-monsoon seasons. Decreasing trends in sunshine duration were observed mainly on annual, seasonal (winter and pre-monsoon) and monthly (January, February and March) time scales. Concomitant decreases in sunshine duration may be one of the potential causes of the observed DTR decreases over NE India. Copyright © 2010 Royal Meteorological Society

KEY WORDS trend; temperature; diurnal temperature range; sunshine duration; Northeast India

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1. Introduction

1.1. General

The global mean surface temperature has increased by 0.6 °C over the last 100 years, with 1998 being the warmest year. Most of the increase in global mean temperature has been observed in two distinct periods: 1910–1940 (0.35 °C) and since 1970 (0.55 °C) (IPCC, 2007). Anthropogenic forcing accounts for almost all of the global warming observed between 1946 and 1995, whereas warming between 1896 and 1945 is explained by a combination of anthropogenic and natural forcing and internal variability (Braganza *et al.*, 2004). The warming is very likely the response of the main anthropogenic drivers, such as the population growth, deforestation, industrialization, changes in land use and increasing atmospheric concentrations of greenhouse gases. Atmospheric brown clouds, which are mostly formed due to biomass burning and fossil fuel consumption, also contribute to lower atmospheric heating and surface cooling (Ganguly and Iyer, 2009).

Air temperature is a good indicator of the state of climate globally because of its ability to represent the energy exchange process over the earth's surface with reasonable accuracy. The ease of measurement of temperature with highly standardized thermometers and availability of long, homogeneous records further underline its importance. Braganza *et al.* (2004) also emphasized that changes in mean temperature are an indicator of climate variability, but changes in maximum and minimum temperatures provide more useful information than the mean temperature alone. The changes in mean temperature can be due to trends in either maximum or minimum temperatures, or relative trends in both. The surface warming in recent years is associated with much larger increases in minimum temperature than in maximum temperature (Karl *et al.*, 1993; Easterling *et al.*, 1997; Vose *et al.*, 2005). As a result, the diurnal temperature range (DTR), i.e. the difference between maximum and minimum temperatures, has been decreasing over vast land areas of the world. Therefore, DTR is an important index of climate change and is receiving considerable attention over various regions of the globe in recent times. The mean, maximum and minimum temperatures hereafter will be referred as T_{mean}, $T_{\max}$ and $T_{\min}$, respectively.

Very little information is available on the analysis of DTR, T_{mean}, $T_{\max}$ and $T_{\min}$ over the biodiversity-rich north-eastern (NE) region of India. The objective of the present study, therefore, was to investigate trends in DTR, minimum and maximum temperatures and sunshine

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duration over eight sites of NE India on annual, seasonal and monthly time scales. Since cloud cover data are not available at any of the eight sites, the sunshine duration was used as a proxy to cloudiness. The relationship between DTR and other variables was also explored using Spearman's Rho correlation technique to better understand the origins of observed DTR trends and variability.

1.2. Review of the literature

Temperature changes have not been uniform globally, but have varied over regions and different parts of the Earth's atmosphere. Karl *et al.* (1993) detected increases in $T_{\max}$ and $T_{\min}$ by 0.28 and 0.84 °C, respectively, over a large portion of the earth's surface area, and attributed the decrease of about 0.5 °C in DTR to the possible increase in cloud cover. In the Eastern Mediterranean, Turkes *et al.* (1996) have shown significant decreases in DTR in Turkey due to significant increases in $T_{\min}$. Significant reductions of DTR were also reported by Cohen and Stanhill (1996) in the Jordan Valley, by Ben-Gai *et al.* (1999) in Israel and Price *et al.* (1999) in Cyprus. Easterling *et al.* (1997) and Jones *et al.* (1999) also reported the cases of differential changes in $T_{\max}$ and $T_{\min}$, resulting in both a narrowing of DTR and an increase in T_{mean} over many parts of the world. Rebetez and Beniston (1998) reported that the decrease in DTR at lower elevation sites was found to be associated with a corresponding decrease in the sunshine duration in Swiss Alps, which was inferred to be a consequence of an increase in low-level cloudiness. Recently, Vose *et al.* (2005) reported that historical observations have revealed a substantial decreasing trend in globally averaged DTR for 1950–1990, as $T_{\min}$ has increased at a faster rate than has $T_{\max}$.

Increases in cloudiness, as per the proposition of Easterling *et al.* (1997), are possibly one of the main contributing factors for the observed increases in nighttime temperature in the Southern Hemisphere, because the atmospheric aerosol loading in this hemisphere is comparatively much less than that in the Northern Hemisphere. However, the stronger trace-gas-induced warming observed during the last quarter of the 20th century in the Philippines was one of the main reasons for the larger increase in the annual $T_{\max}$ and $T_{\min}$ than the global trends (Peng *et al.*, 2004). The projected DTR changes are often positively correlated with projections of average temperature changes, because increased cloud cover and soil moisture are negatively correlated with both quantities (Lobell, 2007). However, at higher elevation sites, the DTR trends may be poorly correlated with cloud cover or the sunshine duration. Rebetez and Beniston (1998) put forward the probable reason for the absence of such a relationship between DTR and the sunshine duration as due to the fact that the higher elevation sites lie above the low-level cloud layers and the moisture-laden lower atmospheric boundary layer. Thus, the reported studies recognize the shift in the importance established so far in the T_{mean} changes from the greenhouse gases to the cloud cover. Also, attention is being paid to the signs of global warming in terms of DTR, because the changes in both maximum and minimum temperatures can possibly be linked to the changes in humidity and cloud cover.

In India and other neighbouring countries, several investigators have reported both increasing and decreasing trends in temperature and mostly increasing trends in DTR. Hingane *et al.* (1985) reported an increase of 0.4 °C in annual T_{mean} in India over the past century. However, decreasing trends in temperature were reported from 1950 to 1970 and increasing trends after 1970 in the Qinghai-Xizang (Tibetan) Plateau (Li and Tang, 1986). Srivastava *et al.* (1992) gave the first indications that the DTR decadal trends over India are quite different from those observed over other parts of the globe because of the comparatively large increase in trends in $T_{\max}$ than $T_{\min}$ over a major part of India. Rupa Kumar *et al.* (1994) reported that increases in DTR over the Indian subcontinent are contributed solely by increases (0.6 °C) in $T_{\max}$, with $T_{\min}$ remaining practically trendless, and these trends do not show any urban and altitude bias. They observed that increase in $T_{\max}$ over a major part of India was predominant in winter and post-monsoon seasons.

Kothyari and Singh (1996) and Ahmad and Warrick (1996) observed increasing trends in temperature over the Ganga basin in India and a large region encompassing Bangladesh, respectively. Shrestha *et al.* (1999) found warming trends ranging from 0.06 to 0.12 °C/year in most of the Middle Mountain and Himalayan regions in Nepal. The greatest warming trend in the all-Nepal temperature was observed in the post-monsoon season over all the five regions of Nepal. Yadav *et al.* (2004) observed cooling in pre-monsoon T_{mean} and warming in DTR due to a relatively high decrease in $T_{\min}$ and an increase in $T_{\max}$ in the western Himalayas during the later part of the 20th century.

Roy and Balling (2005) reported significant increases in $T_{\max}$ and $T_{\min}$ over the Deccan plateau; but, in general, DTR trends were not significant except for a decrease in Northwest Kashmir in summer for the time period 1931–2002. Large increases in DTR were observed in all the seasons over the Karakoram and Hindu Kush Mountains of the Upper Indus basin during the period 1961–2000 (Fowler and Archer, 2006). Bhutiyani *et al.* (2007) and Singh *et al.* (2008) observed increasing trends in the temperature range due to a higher rate of increase in $T_{\max}$ than $T_{\min}$ across the northwestern Himalayan region over the majority of river basins of Northwest and Central India, respectively.

2. Materials and methods

NE India is a unique transitional zone between the Indian, Indo-Malayan and Indo-Chinese bio-geographical zones and also the confluence of the Himalayan region with peninsular India (Rao, 1994). The NE region (22–29°N; 88–97 °E) presents a distinctive geophysical unit set in the Eastern Himalayan Region with high species diversity and a monsoon-dominated climatic system. This region has places like Mawsynram, situated 16 km west of Cherrapunjee (Meghalaya), which recorded the world's highest rainfall of about 13 923 mm in a year (Haridasan and Rao, 1985). Besides paddy and forest products, tea is one of few export items from the region, which contributes to India's net foreign exchange earnings.

2.1. Hydrometeorological data

Eight sites from NE India (Figure 1) were selected for this study: Margherita, Silcoorie, Thakurbari, Tocklai in Assam and Chuapara, Gungaram, Nagrakata and Nagri Farm in North Bengal. Details of these eight sites are given in Table I. Monthly data of rainfall, sunshine duration, $T_{\max}$, $T_{\min}$, morning and afternoon relative humidity (RH) and pan evaporation (E_{pan}) were collected from Tocklai Tea Research Association (Jorhat) for different periods. There was no gap in the data of any of the climatic parameters, except RH and E_{pan}. The RH and E_{pan} data were missing for 2 years (1988 and 1989) for all the stations except Tocklai. The monthly average data of T_{mean} and sunshine duration of the eight sites are given in Table II. The definitions of the four seasons used by Jhajharia *et al.* (2009) were followed: winter (January–February), pre-monsoon (March–May); monsoon (June–September) and post-monsoon (October–December).

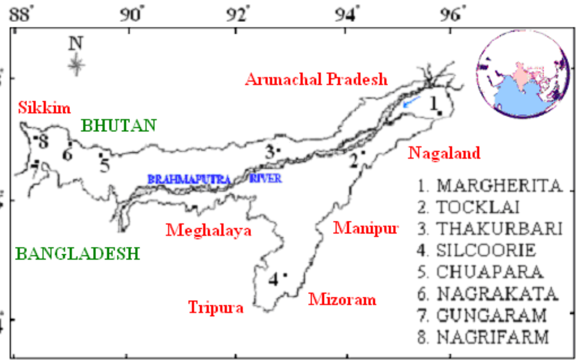

Figure 1. Location of the eight sites in NE India. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

2.2. Methods for trend analysis

Trends in the data can be identified by using parametric or non-parametric methods, and both the methods are widely used. In the recent past, various studies have shown that non-parametric tests are more suitable for non-normally distributed, censored data, including missing values, which are frequently encountered in hydrological time series. These are less influenced by the presence of outliers in the data. In the present analysis, the Mann–Kendall (MK) non-parametric method was applied to establish trends in temperature and DTR over eight sites from NE India using all the available data of individual sites. The description of the MK test can be found in Kothyari and Singh (1996). Most recently, various researchers (Tebakari *et al.*, 2005; Singh *et al.*, 2008; Jhajharia *et al.*, 2009) also used the MK test for trend analysis. In this test, if the computed test statistic values lie within limits -1.96 and 1.96 (-2.326 and 2.326), the null hypothesis of no trend in the series cannot be rejected at the 5% (1%) level of significance using a two-tailed test.

In this study, trend analyses were also carried out using linear regression, a commonly used parametric method. The linear trend is expressed as $y(t) = at + b$, where t is the time and a and b are constants. The trend determined, a, was tested in terms of its statistical significance using the t-test, where $t = a/\sigma_a$ with σ_a being the expected standard deviation of a. If $|t| > t_{(1-\alpha/2;n-2)}$, there is a trend at the α% of significance level. The trend results obtained by the MK test turned out to be nearly identical to those based on the t-test. We also tried to ascertain if there was any change in trend types and their magnitude in the temperature in the last quarter of the 20th century by using the 1976–2000 data to obtain information about warming in NE India.

The relationship between DTR and meteorological variables was also explored using correlation analysis to better understand the origins of observed DTR trends and variability. In order to identify the probable dominant variables responsible for the DTR changes, Spearman's Rho non-parametric test was applied to DTR and sunshine duration, E_{pan}, $T_{\max}$, $T_{\min}$, rainfall, morning and afternoon RH using the SPSS software (Norusis, 1988)

Table I. Details of sites.

S. no.	Name of site	Region of site	Lat. (N)	Long. (E)	Alt. (m amsl)	Duration of data
1	Chuapara	East Dooars, N. Bengal	26°44′	89°28′	190.8	1980–2000
2	Gungaram	Terai, N. Bengal	26°38′	88°48′	123.6	1977–2000
3	Margherita	Upper Assam	27°16′	95°32′	183	1979–2000
4	Nagrifarm	Darjeeling, N. Bengal	26°55′	88°12′	1158.2	1965–1988
5	Nagrakata	Dooars, N. Bengal	26°54′	88°55′	228.6	1965–2000
6	Silcoorie	Cachar, Assam	24°50′	92°48′	39.6	1965–2000
7	Thakurbari	North Bank, Assam	26°48′	92°42′	92.45	1973–2000
8	Tocklai	Jorhat, Assam	26°47′	94°12′	96.5	1965–2000

Lat., Long., Alt., m amsl, N, E denote latitude, longitude, altitude, metres above mean sea level, north and east, respectively.

Table II. Mean temperature (°C) and mean actual sunshine duration (h) in different months.

Name of site	Chuapara		Gungaram		Margherita		Nagrifarm		Nagrakata		Silcoorie		Thakurbari		Tocklai	
	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun	T_{mean}	Sun
January	16.8	6.44	15.7	7.13	15.6	5.74	11.3	5.86	17.0	6.79	18.2	7.67	16.3	7.26	16.2	6.22
February	18.5	6.52	18.6	7.57	17.7	5.70	12.8	5.69	18.8	6.79	20.2	7.98	18.5	7.04	18.1	6.42
March	22.2	6.84	23.3	8.35	20.5	5.14	17.2	6.71	22.8	6.79	23.6	7.78	22.0	6.89	21.6	6.33
April	25.0	6.72	26.6	8.35	23.3	5.23	19.5	5.81	25.2	6.78	25.9	7.34	24.4	6.44	23.8	5.98
May	26.8	6.34	27.8	8.13	25.5	4.91	20.3	5.15	26.3	6.35	27.2	6.37	26.2	5.94	26.2	5.48
June	28.0	3.66	28.3	6.93	28.0	4.15	21.6	3.30	27.3	4.15	28.3	4.76	27.9	4.72	28.2	4.72
July	28.1	2.89	28.0	5.18	27.9	3.37	21.8	2.35	27.3	3.56	28.5	4.27	28.4	4.28	28.6	4.49
August	28.3	3.85	28.6	6.21	28.1	4.51	22.1	3.62	27.6	3.97	28.7	5.01	28.6	4.86	28.7	5.25
September	27.6	4.32	27.9	6.16	27.2	4.09	21.2	3.78	26.9	4.61	28.2	5.34	27.6	4.97	27.8	4.94
October	25.9	7.20	26.3	7.68	24.8	5.90	19.6	6.74	25.0	7.61	27.0	6.75	25.3	6.90	25.7	6.06
November	22.1	7.58	22.6	7.95	20.9	6.93	16.4	7.00	21.5	8.14	23.9	7.66	21.3	7.85	21.4	6.66
December	18.5	7.07	18.8	7.49	17.0	6.53	13.3	6.78	18.3	7.73	19.8	7.93	17.4	7.61	17.2	6.58

T_{mean} and Sun denote mean temperature and sunshine duration, respectively.

and the correlation coefficients were tested for statistical validity at the 5% level of significance as well.

3. Results and discussion

3.1. Analysis of temporal trends in temperature

3.1.1. Annual trends

3.1.1.1 Diurnal temperature range: Three sites (one site), i.e. Chuapara, Nagrakata and Tocklai (Gungaram), observed statistically significant decreasing (increasing) trends in DTR obtained through both MK and t-test in the range of -0.2 to $-0.8\,^{\circ}$C/decade ($+0.3\,^{\circ}$C/decade). The DTR decrease (increase) is caused by increasing trends in T_{min} (T_{max}), with T_{max} (T_{min}) either showing an increasing trend at a smaller rate than T_{min} (T_{max}) at Nagrakata (Gungaram) or showing no trend at Chuapara and Tocklai. Also, Margherita (Thakurbari) observed a significant decreasing (increasing) DTR trend through t-test. A sample time series of DTR and linear trends denoted by solid curves and dashed lines for Nagrakata, Silcoorie and Tocklai are given in Figure 2. The trend analysis, using the 1976–2000 data (results not shown here), reveals that Tocklai (Silcoorie) observed a significant decreasing (increasing) trend in DTR at a comparatively higher rate of $-0.4\,^{\circ}$C/decade (0.6 °C/decade), and the DTR trend at Silcoorie changed from no trend to increasing trend as well.

The DTR decreases observed at the sites of NE India are in total contrast to the findings for India (Rupa Kumar *et al.*, 1994), but are consistent with the global trends in DTR (Easterling *et al.*, 1997; Vose *et al.*, 2005). Easterling *et al.* (1997) reported that trends in T_{min} were considerably less than those found by Karl *et al.* (1993), which resulted in a smaller trend in DTR. This finding was not surprising, as most of the sites included in the data of a previous study were selected from tropical and subtropical regions where temperature changes are not expected to be as large as in regions of higher latitude. However in the present study, the sites of NE India, which are from the tropical/subtropical region, witnessed significant changes in DTR due to changes in either T_{min} or T_{max} (Tables III–V).

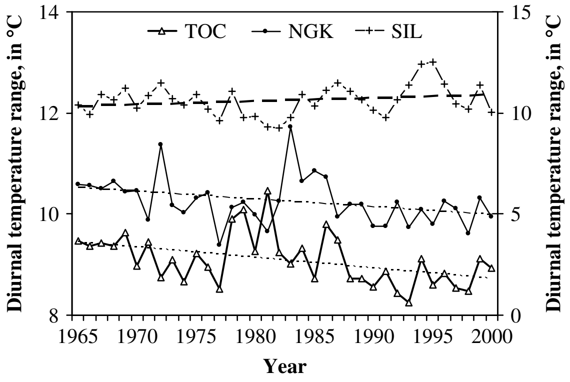

Figure 2. Annual time series and linear trends in DTR. SIL, TOC, NGK denote Silcoorie, Tocklai and Nagrakata, respectively. The solid curves and the dashed lines represent the time series and the linear trends, respectively. SIL values are shown on the secondary Y-axis.

3.1.1.2 Maximum temperature: Three sites, namely, Gungaram, Nagrakata and Silcoorie, observed significant increasing trends in T_{max} through the MK test, which varied from 0.1 to 0.9 °C/decade, and the remaining five sites observed no trends. The analysis using the 1976–2000 data produced exactly similar types of trends (results not shown). The results, however, suggest a temperature increase at a comparatively high rate, i.e. T_{max} increased from 0.1 to 0.2 °C/decade at Nagrakata and 0.2 to 0.6 °C/decade at Silcoorie.

3.1.1.3 Minimum temperature: Five sites, i.e. Chuapara, Gungaram, Margherita, Nagrakata and Tocklai, observed significant increasing trends through the MK test in the range of 0.1–0.6 °C/decade, and the remaining three sites observed no trends even at the 10% level of significance through the MK test. However, Thakurbari witnessed

Table III. Trends and the rate of changes (°C/decade) in DTR in different durations.

Time scale	Chu	Gun	Mag	Nfm	Ngk	Tha	Sil	Toc
January	−0.9 (−1.67)	0.1 (0.001)	−0.4 (−0.42)	0.7* (2.7)	−0.1 (−0.63)	0.3 (−0.16)	0 (0.19)	−0.1 (−0.27)
February	−0.1 (−0.08)	−0.2 (−1.22)	−1.0 (−0.85)	0.7* (2.44)	0 (−0.20)	0.2 (0.06)	−0.2 (−0.46)	−0.4** (−1.85)
March	−0.2 (0.19)	−0.1 (−0.77)	−0.8 (−1.57)	0.5 (1.3)	−0.3 (−1.17)	−0.1 (−0.79)	−0.4 (−1.4)	−0.6* (−2.46)
April	−0.4 (−0.49)	−0.1 (−0.62)	−0.3 (0.43)	0.3 (0.43)	0.1 (0.27)	0.6 (1.01)	−0.1 (−0.27)	−0.2 (−1.11)
May	−0.9* (−2.1)	0.3 (0.75)	−0.9* (−1.90)	0.5* (2.2)	−0.1 (−0.99)	0.4 (0.95)	0.1 (0.18)	−0.1 (−0.71)
June	−0.8* (−3.04)	0.2 (0.49)	−0.5* (−2.27)	0.5* (2.9)	−0.1 (−1.07)	0.5* (1.54)	0.3** (1.82)	−0.1 (−0.31)
July	−0.2 (−0.69)	0.1 (0.92)	0.5 (0.6)	0.3 (1.57)	−0.2* (−2.02)	0.6* (0.68)	0.3* (2.02)	−0.1 (−1.47)
August	−0.4 (−0.98)	0.3 (1.30)	−0.7* (−2.15)	0.2 (1.15)	−0.2 (−0.93)	0.7* (0.33)	0.4* (2.29)	−0.2* (−2.60)
September	−0.3 (−0.76)	0.7* (3.25)	−0.2 (−0.5)	−0.4* (−1.65)	−0.3* (−2.1)	0.5 (0.14)	0.2 (1.5)	−0.1** (−1.72)
October	−0.6 (−1.25)	0.9* (2.01)	−0.3 (−0.91)	−0.1 (−0.91)	−0.1 (−0.7)	1.1* (2.07)	0.3** (1.71)	−0.3** (−1.76)
November	−2.1* (−2.93)	0.5 (0.15)	−0.7** (−1.85)	−0.3 (−0.34)	−0.1 (−0.46)	1.2* (2.39)	0.4* (2.4)	−0.1 (−0.98)
December	−0.3 (−0.57)	0.4 (0.25)	2.0* (2.68)	0.2 (0.06)	0 (−0.05)	1.3* (1.67)	0.4** (1.72)	0 (0.31)
Yearly	−0.8* (−3.15)	0.3* (2.21)	−0.3** (−1.53)	0.3 (1.56)	−0.2* (−2.53)	0.6* (0.63)	0.2 (0.87)	−0.2* (−2.95)
Winter	−1.4* (−2.63)	0 (−0.77)	−0.7 (−1.20)	0.7* (3.96)	−0.1 (−0.83)	0.3 (0.17)	−0.1 (−0.25)	−0.3 (−1.39)
Pre-monsoon	−0.5** (−1.44)	0 (0.72)	−0.7* (−2.11)	0.4** (1.58)	−0.1 (−0.98)	0.3 (0.49)	−0.1 (−0.88)	−0.3* (−2.32)
Monsoon	−0.4* (−2.19)	0.3 (1.69)	−0.2 (−0.75)	0.1 (1.36)	−0.2* (−2.32)	0.6** (0.39)	0.3* (2.23)	−0.1* (−2.41)
Post-monsoon	−1.0* (−2.69)	0.8* (2.34)	0.3 (0.36)	−0.1 (−0.32)	−0.2 (−0.88)	1.2* (1.94)	0.4* (2.74)	−0.1 (−0.94)

Value in bracket denotes the test statistic value obtained through Mann–Kendall's non-parametric test.

Chu, Gun, Mag, Nfm, Ngk, Tha, Sil and Toc denote Chuapara, Gungaram, Margherita, Nagri Farm, Nagrakata, Thakurbari, Silcoorie and Tocklai, respectively.

* and ** denote trends at 5% and 10% significance level, respectively, using Student's t-test. '−' sign indicates decreasing trend.

a decreasing trend in $T_{\min}$ through the t-test at a rate of −0.5 °C/decade. The trend analysis using the data of 1976–2000 produced almost similar types of trends for all sites except Tocklai, which showed no trend in $T_{\min}$.

3.1.1.4 Mean temperature: Four sites, namely, Gungaram, Margherita, Nagrakata and Silcoorie, observed significant increasing trends through the MK test in the range of 0.2–0.8 °C/decade, and the remaining sites observed no trends through the MK test (Table VI). However, Thakurbari witnessed a decreasing trend in T_{mean} through the t-test at a rate of −0.2 °C/decade. The T_{mean} increases are contributed by increasing trends in either (both) $T_{\max}$ or (and) $T_{\min}$. The trend analysis using the 1976–2000 data produced exactly similar results.

3.1.2. Seasonal trends

3.1.2.1 Diurnal temperature range: DTR remained practically trendless in winter season, as six sites observed no trends in DTR and remaining two sites, i.e. Chuapara and Nagri Farm, observed decreasing and increasing trends obtained through both the MK test and the t-test at the 1% level of significance, respectively. In the pre-monsoon season, three sites, i.e. Chuapara, Margherita and Tocklai, observed decreasing trends in DTR. In the monsoon season, three (two) sites observed decreasing (increasing) trends in DTR obtained through the MK test in the range of −0.1 to −0.4 °C/decade (0.3 °C/decade each). In the post-monsoon season, three (one) sites observed increasing (decreasing) trends in DTR obtained through the MK test in the range of 0.4–1.2 °C/decade (−1.0 °C/decade).

The DTR trend analysis using the data of 1976–2000 reveals almost similar types of trends except for Thakurbari (Tocklai), which observed an increasing trend of 0.8 °C/decade (no trend) in the monsoon (winter) season. Also, Nagrakata and Tocklai (Silcoorie and Thakurbari) witnessed comparatively higher decreases (increases) in

Table IV. Trends and the rate of changes (°C/decade) in T_{max} in different durations.

Time scale	Chu	Gun	Mag	Nfm	Ngk	Tha	Sil	Toc
January	−0.9	0	0.2	0.6	−0.1	0.2	0	−0.2
	(−1.37)	(−0.12)	(0.0)	(1.39)	(−0.79)	(0.77)	(0.13)	(−1.34)
February	0.2	0.3	−0.3	0.2	0	0.1	−0.2	−0.3
	(−0.15)	(−0.32)	(−0.20)	(0.17)	(−0.38)	(−0.03)	(−0.94)	(−0.99)
March	−0.2	1.4*	−0.2	0.1	−0.3	−0.6	−0.1	−0.5*
	(−0.04)	(2.72)	(−0.9)	(−0.08)	(−1.61)	(−1.62)	(−0.49)	(−2.23)
April	0.3	1.3*	0.2	−0.1	0	−0.1	0.2	−0.1
	(0.34)	(3.08)	(0.94)	(−0.23)	(0.59)	(0.22)	(0.65)	(−0.46)
May	0.2	1.3*	−0.4	−0.2	0.2	0.1	0.1	0
	(0.57)	(2.86)	(−1.0)	(−0.34)	(0.9)	(0.33)	(0.35)	(0.09)
June	−0.8*	0.7*	−0.2	0.5*	0.3*	−0.1	0.4*	0.1
	(−2.93)	(1.74)	(−1.71)	(2.4)	(1.79)	(−0.36)	(2.46)	(0.71)
July	0	0.5	0.9	0	0.1	0	0.3*	0
	(−0.19)	(1.42)	(1.03)	(0.03)	(1.33)	(0.19)	(1.84)	(−0.18)
August	−0.2	0.4**	−0.5	0.5	0.2	−0.1	0.4*	0
	(−0.60)	(1.65)	(−1.79)	(1.50)	(1.28)	(−0.55)	(2.5)	(0.0)
September	0.1	0.8*	0.6*	−0.4*	0.1	0.2	0.2	0
	(0.0)	(2.89)	(1.91)	(−1.84)	(1.41)	(0.77)	(1.46)	(−0.64)
October	−0.1	1.4*	0.4	0.1	0.3*	0.5*	0.4*	0
	(−0.42)	(4.14)	(1.53)	(−0.59)	(2.88)	(1.42)	(2.24)	(0.18)
November	−0.4	1.4*	0.3	−0.1	0.3*	0.6*	0.6*	0.2
	(−0.79)	(4.30)	(0.57)	(−0.33)	(2.04)	(2.09)	(4.07)	(1.19)
December	0.1	1.1*	1.7*	−0.2	0.2	0.8*	0.5*	0
	(0.19)	(3.16)	(3.09)	(−0.59)	(0.63)	(2.73)	(2.64)	(−0.13)
Yearly	−0.1	0.9*	0.2	0.1	0.1*	0.1	0.2*	−0.1
	(−0.72)	(3.59)	(1.06)	(0.31)	(1.82)	(0.0)	(2.51)	(−1.02)
Winter	−0.3	0.1	0	0.4	−0.1	0.1	−0.1	−0.3**
	(−0.75)	(−0.29)	(−0.61)	(1.58)	(−1.16)	(0.16)	(−0.76)	(−1.49)
Pre-monsoon	0.1	1.3*	−0.1	−0.1	0	−0.2	0	−0.2
	(0.19)	(3.54)	(−0.76)	(−0.65)	(0.12)	(−0.59)	(0.22)	(−1.49)
Monsoon	−0.2	0.6*	0.2	0.2	0.2*	0	0.3*	0
	(−1.74)	(2.75)	(0.09)	(0.68)	(2.61)	(−0.0)	(3.04)	(−0.28)
Post-monsoon	−0.1	1.3*	0.8*	−0.1	0.3*	0.6*	0.5*	0
	(−0.19)	(4.69)	(3.02)	(−0.34)	(2.88)	(2.41)	(3.86)	(0.52)

Value in bracket denotes the test statistic value obtained through Mann–Kendall's non-parametric test.
Chu, Gun, Mag, Nfm, Ngk, Tha, Sil and Toc denote Chuapara, Gungaram, Margherita, Nagri Farm, Nagrakata, Thakurbari, Silcoorie and Tocklai, respectively.
* and ** denote trends at 5% and 10% significance level, respectively, using Student's t-test. '−' sign indicates decreasing trend.

monsoon at a rate of −0.5 and −0.4 °C/decade (0.6 and 0.8 °C/decade). Silcoorie and Thakurbari witnessed higher rates of increases in the post-monsoon season, i.e. 0.7 and 1.5 °C/decade. The DTR changes have been greatest mainly during the monsoon and post-monsoon seasons and least during the winter season, which suggest the presence of a seasonal cycle in NE India.

3.1.2.2 Maximum temperature: T_{max} remained practically trendless in winter and pre-monsoon seasons, as all sites and all sites but one (Gungaram), respectively, observed no trends in T_{max} through the MK test. Increasing trends in T_{max} obtained through the MK test at the 1% level of significance were witnessed by three and five sites ranging from 0.2 to 0.6 °C/decade and 0.3 to 1.3 °C/decade in monsoon and post-monsoon seasons, respectively. A sample time series of T_{max} and linear trend denoted by the solid curve and dashed line in winter season at Tocklai is given in Figure 3. The trend analysis using the data of 1976–2000 reveals that Silcoorie (Tocklai) witnessed an increasing (a decreasing) trend in T_{max} in the pre-monsoon (monsoon) season at a rate of 0.6 °C/decade (−0.2 °C/decade). No trend was observed in T_{max} in the monsoon season at Nagrakata, which earlier was a case of 'increasing trend'. The results suggest warming in the post-monsoon season during 1976–2000 at a higher rate, i.e. T_{max} increases rose from 0.3 to 0.5 °C/decade at Nagrakata, 0.5 to 0.7 °C/decade at Silcoorie and 0.6 to 0.9 °C/decade at Thakurbari.

3.1.2.3 Minimum temperature: T_{min} remained practically trendless in winter season, as seven sites observed no trends. Five sites witnessed increasing trends in T_{min} in the range of 0.2–0.4 °C/decade in monsoon season. Three and four sites witnessed increasing trends in the range of 0.6–1.3 °C/decade and 0.2–0.9 °C/decade in

Table V. Trends and the rate of changes (°C/decade) in T_{min} in different durations.

Time scale	Chu	Gun	Mag	Nfm	Ngk	Tha	Sil	Toc
January	0.1	−0.1	0.6**	−0.1	0	−0.1	0	−0.1
	(0.30)	(−0.15)	(1.6)	(−0.96)	(−0.35)	(−0.09)	(0.23)	(−0.90)
February	0.3	0.5	0.7	−0.5**	0	−0.2	0	0.1
	(0.72)	(1.24)	(1.91)	(−1.76)	(0.28)	(−0.55)	(0.0)	(0.94)
March	0	1.4*	0.7*	−0.4	0	−0.4	0.3	0.1
	(−0.0)	(3.06)	(2.4)	(−1.33)	(−0.0)	(−0.74)	(1.34)	(0.77)
April	0.7**	1.4*	0.5*	−0.4	−0.1	−0.7*	0.2	0
	(1.22)	(3.62)	(1.67)	(−0.82)	(−0.90)	(−1.99)	(0.79)	(0.15)
May	1.1*	1.0*	0.5*	−0.7*	0.3**	−0.3	0	0.1**
	(2.9)	(2.8)	(1.48)	(−2.63)	(1.69)	(−1.41)	(−0.38)	(1.22)
June	0.1	0.5	0.2	0.1	0.4*	−0.7*	0.1	0.2*
	(0.54)	(1.21)	(0.98)	(0.54)	(4.08)	(−1.51)	(1.19)	(2.86)
July	0.2	0.3	0.4*	−0.3	0.4*	−0.6*	−0.1	0.1**
	(1.78)	(0.18)	(2.2)	(−1.17)	(4.19)	(−1.61)	(−0.81)	(1.58)
August	0.2	0.2	0.2	0.3*	0.4*	−0.7*	0	0.3*
	(1.43)	(0.94)	(1.03)	(1.98)	(4.86)	(−1.87)	(0.28)	(3.42)
September	0.4*	0.2	0.8*	0	0.4*	−0.3	−0.1	0.1**
	(1.95)	(1.47)	(2.64)	(0.3)	(3.65)	(−0.01)	(−0.67)	(1.81)
October	0.5	0.6	0.7*	0.2	0.5*	−0.6*	0.1	0.3**
	(1.53)	(1.57)	(2.00)	(0.88)	(2.58)	(−1.67)	(1.19)	(1.86)
November	1.7*	0.9*	1.1*	0.2	0.4*	−0.5**	0.2	0.3
	(3.03)	(2.24)	(2.51)	(0.0)	(2.15)	(−1.43)	(1.07)	(1.64)
December	0.5	0.7*	−0.2	−0.4	0.2**	−0.5	0	0
	(1.37)	(1.96)	(−0.52)	(−1.16)	(1.96)	(−1.29)	(0.38)	(−0.09)
Yearly	0.5*	0.6*	0.5*	−0.2	0.3*	−0.5*	0.1	0.1*
	(2.80)	(3.17)	(2.51)	(−1.44)	(3.49)	(−1.21)	(1.28)	(2.2)
Winter	0.2	0.2	0.6*	−0.3	0	−0.1	0	0
	(0.56)	(0.59)	(2.09)	(−1.3)	(0.24)	(−0.55)	(0.0)	(−0.02)
Pre-monsoon	0.6*	1.3*	0.6*	−0.5*	0.1	−0.5*	0.2	0.1
	(1.91)	(4.52)	(1.99)	(−1.87)	(0.69)	(−1.61)	(1.56)	(1.31)
Monsoon	0.2*	0.3	0.4*	0	0.4*	−0.6*	0	0.2*
	(2.05)	(1.97)	(1.99)	(0.14)	(4.55)	(−0.92)	(0.34)	(3.33)
Post-monsoon	0.9*	0.7*	0.5	0	0.4*	−0.6*	0.1	0.2**
	(2.23)	(2.56)	(1.42)	(0.34)	(2.79)	(−1.48)	(0.86)	(1.48)

Value in bracket denotes the test statistic value obtained through Mann–Kendall's non-parametric test.

Chu, Gun, Mag, Nfm, Ngk, Tha, Sil and Toc denote Chuapara, Gungaram, Margherita, Nagri Farm, Nagrakata, Thakurbari, Silcoorie and Tocklai, respectively.

* and ** denote trends at 5% and 10% significance level, respectively, using Student's t-test. '-' sign indicates decreasing trend.

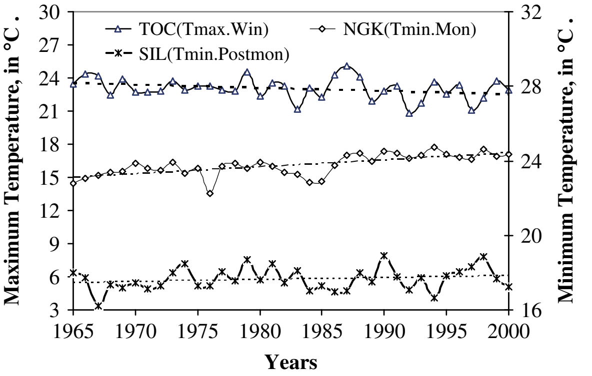

Figure 3. Trends in temperature in different seasons. SIL, TOC, NGK, T_{max}, T_{min}, Win, Mon, Postmon denote Silcoorie, Tocklai, Nagrakata, maximum temperature, minimum temperature, winter, monsoon and post-monsoon, respectively. The solid curves and the dashed lines represent the time series and the linear trends, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

pre-monsoon and post-monsoon seasons, respectively. Decreasing trends in T_{min} were also observed at Nagri Farm in pre-monsoon and at Thakurbari in pre-monsoon, monsoon and post-monsoon seasons (Table V). A sample time series of T_{min} and linear trends denoted by solid curves and dashed lines in monsoon and post-monsoon seasons for Nagrakata and Silcoorie, respectively, is given in Figure 3. The trend analysis results obtained from the data of 1976–2000 were similar to those obtained from the complete data for all sites except Nagrakata. An increasing trend (0.3 °C/decade) in pre-monsoon season was witnessed at Nagrakata when using the 1976–2000 data, which earlier was a case of 'no trend'.

3.1.2.4 Mean temperature: T_{mean} remained trendless in winter and pre-monsoon seasons, as all sites and all but one site (Gungaram) observed no trends in these

Table VI. Trends and the rate of changes (°C/decade) in T_{mean} in different durations.

Time scale	Chu	Gun	Mag	Nfm	Ngk	Tha	Sil	Toc
January	−0.4 (−0.76)	0 (−0.47)	0.4** (1.87)	0.2 (0.39)	0 (−0.5)	0.1 (0.36)	0 (0.19)	−0.1 (−1.47)
February	0.2 (0.57)	0.4 (0.1)	0.2 (0.48)	−0.1 (−0.76)	0.1 (0.22)	0 (−0.27)	−0.1 (−0.95)	−0.1 (−0.59)
March	−0.1 (−0.34)	1.4* (3.37)	0.3 (0.30)	−0.2 (−0.59)	−0.2 (−0.8)	−0.4** (−2.14)	0.1 (0.09)	−0.2** (−1.69)
April	0.5 (1.69)	1.3* (3.53)	0.4 (1.12)	−0.3 (−0.25)	0 (0.14)	−0.4 (−1.46)	0.2 (0.83)	−0.1 (−0.31)
May	0.6* (2.3)	1.1* (3.72)	0 (0.06)	−0.4 (−1.67)	0.2** (1.77)	−0.1 (−0.62)	0 (0.28)	0.1 (0.41)
June	−0.3* (−1.87)	0.6* (1.94)	0 (−0.60)	0.3 (1.87)	0.4* (4.1)	−0.4* (−1.89)	0.3* (2.2)	0.2 (1.38)
July	0.1 (0.46)	0.4 (1.06)	0.7* (1.72)	−0.2 (0.08)	0.2* (3.2)	−0.3** (−1.31)	0.1 (1.18)	0 (0.37)
August	0 (−0.15)	0.3 (1.39)	−0.2 (−0.24)	0.4 (1.47)	0.3* (2.96)	−0.4* (−1.89)	0.2* (2.2)	0.1** (1.19)
September	0.2 (0.19)	0.5* (2.21)	0.7* (2.42)	−0.2 (−0.74)	0.3* (2.93)	−0.1 (−0.02)	0.1 (1.36)	0 (0.26)
October	0.2 (0.15)	1.0* (3.33)	0.6** (1.82)	0.1 (0.28)	0.4* (3.20)	−0.1 (−0.43)	0.2* (2.02)	0.1 (1.06)
November	0.6* (2.2)	1.2* (3.47)	0.7* (1.75)	0.1 (−0.25)	0.4* (3.57)	0 (0.06)	0.4* (2.95)	0.2 (1.49)
December	0.3 (0.53)	0.9* (3.61)	0.8* (2.15)	−0.3 (−1.42)	0.2* (1.51)	0.1 (0.97)	0.3* (2.26)	0 (0.05)
Yearly	0.2 (1.06)	0.8* (3.47)	0.4* (1.93)	0 (−0.45)	0.2* (3.24)	−0.2* (−1.48)	0.2* (3.8)	0 (0.84)
Winter	−0.1 (−0.45)	0.2 (0.32)	0.3 (1.12)	0 (0.06)	0 (0.17)	0 (0.09)	−0.1 (−0.80)	−0.1 (−1.22)
Pre-monsoon	0.3 (1.55)	1.3* (4.66)	0.2 (0.73)	−0.3 (−1.35)	0 (0.73)	0.1 (−0.88)	0.1 (1.02)	−0.1 (−0.58)
Monsoon	0 (−0.45)	0.4* (2.23)	0.3 (1.18)	0.1 (0.45)	0.3* (4.51)	−0.3* (−2.23)	0.2* (2.91)	0.1** (1.35)
Post-monsoon	0.4 (1.1)	1.1* (3.93)	0.7* (2.03)	0 (−0.01)	0.3* (3.84)	0 (−0.14)	0.3* (3.50)	0.1 (1.42)

Value in bracket denotes the test statistic value obtained through Mann–Kendall's non-parametric test.

Chu, Gun, Mag, Nfm, Ngk, Tha, Sil and Toc denote Chuapara, Gungaram, Margherita, Nagri Farm, Nagrakata, Thakurbari, Silcoorie and Tocklai, respectively.

* and ** denote trends at 5% and 10% significance level, respectively, using Student's t-test. '−' sign indicates decreasing trend.

two seasons, respectively (Table VI). In monsoon and post-monsoon seasons, four sites observed increasing trends in T_{mean} in the range of 0.1–0.4 °C/decade and 0.3–1.1 °C/decade, respectively. Only one site (Thakurbari) observed a decreasing trend in T_{mean} in the monsoon season. The trend analysis using the data of 1976–2000 produced results similar to those obtained from the complete dataset for all seasons except pre-monsoon. Nagrakata and Silcoorie witnessed increasing trends (0.3 °C/decade) in the pre-monsoon season. The results suggest warming in the post-monsoon season at a higher rate, i.e. T_{mean} increased from 0.3 to 0.4 °C/decade at Nagrakata and Silcoorie, when using the 1976–2000 data.

3.1.3. Monthly trends

3.1.3.1 Diurnal temperature range: A sample time series of monthly DTR over Tocklai, Silcoorie and Nagrakata and linear trends denoted by solid curves and dashed lines, respectively, is given in Figure 4. DTR trend analysis using the data of 1976–2000 (results not shown here) reveals that all the sites, except Nagri Farm, remained practically trendless during January–April. The DTR trends in July, August and December are affected by the change of dataset to 1976–2000, as the DTR changes, in terms of magnitude, are comparatively high now. Also, DTR decreases (increases) varied from −0.3 to −0.7 °C/decade (0.5–1.5 °C/decade) in July–September (July, August, October and November) at Tocklai and Nagrakata (Silcoorie and Thakurbari). Thus, the above results suggest an element of a cycle in the DTR changes, i.e. the strongest changes in July, August and December and the least changes during January–April.

3.1.3.2 Maximum temperature: The T_{max} trends obtained through two datasets were almost similar, except change

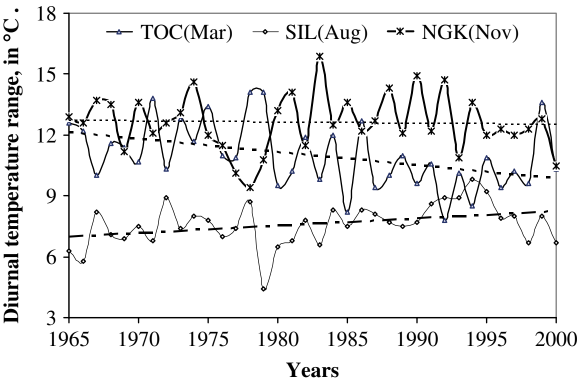

Figure 4. Time series and linear trends in monthly DTR. SIL, TOC, NGK denote Silcoorie, Tocklai and Nagrakata, respectively. The solid curves and the dashed lines represent the time series and the linear trends, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of 'no trends' obtained through the complete data to increasing trends obtained through the 1976–2000 data: May (Nagrakata); April and September (Silcoorie); December (Nagrakata), and a decreasing trend in August (Tocklai). Increasing trends in $T_{\max}$ using 1976–2000 data were observed at Silcoorie during April–December (0.5–0.8 °C/decade); Thakurbari during October–December (0.8–0.9 °C/decade); and Nagrakata in May, October and December (0.5–0.6 °C/decade). Also, eight sites and seven sites observed no trends in $T_{\max}$ in January and February and March and April, respectively. Three sites and four sites observed increasing trends in May and November and June and October, respectively. Decreasing trends were witnessed at Chuapara (−0.8 °C/decade) in June, Tocklai (−0.3 °C/decade) in August and Nagri Farm (−0.4 °C/decade) in September as well. The temperature rise was found to be the greatest in December, as five sites witnessed increasing trends in the range of 0.6–1.7 °C/decade.

3.1.3.3 Minimum temperature: $T_{\min}$ remained practically trendless in January, February, March and December, as seven and six sites each observed no trends (Table V). At least three sites witnessed increasing trends in $T_{\min}$ in May and July–November in the range of 0.1–1.7 °C/decade. Using the 1976–2000 data, the rates of increasing (decreasing) trends were found to be comparatively higher (lower) than the rates obtained through the complete dataset, i.e. $T_{\min}$ increases (decreases) varied from 0.5 to 07 °C/decade (−0.7 to −1.0 °C/decade) during May–October (June–August) at Nagrakata (Thakurbari).

3.1.3.4 Mean temperature: T_{mean} remained practically trendless in January and February at all sites except Margherita, which witnessed an increasing trend in T_{mean} in January. Comparatively large magnitudes of T_{mean} increases were witnessed in the months of October–December in NE India (Table VI). T_{mean} decreases were observed at Thakurbari (March, June–August), Tocklai (March) and Chuapara (June) as well. The results of the trends obtained from the 1976–2000 data matched with the trends obtained from the complete dataset for all the sites except Silcoorie (August), Tocklai (March) and Nagrakata (August), where no trends were observed in T_{mean} during the last quarter of 20th century.

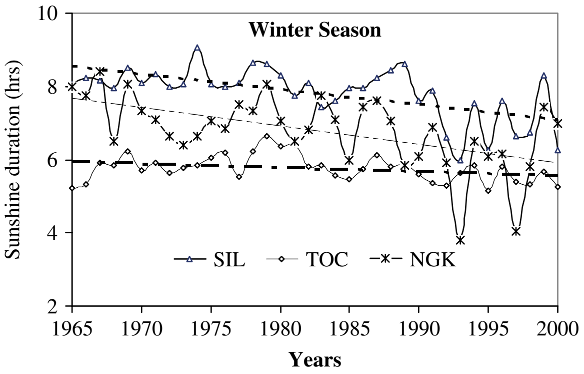

Figure 5. Time series and linear trends in sunshine duration in winter season. SIL, TOC, NGK denote Silcoorie, Tocklai and Nagrakata, respectively. The solid curves and the dashed lines represent the time series and the linear trends, respectively. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

3.2. Analysis of temporal trends in sunshine duration

On a yearly basis, seven sites witnessed significant decreasing trends in the sunshine duration over NE India. A sample time series of sunshine duration and linear trends denoted by solid curves and dashed lines in the winter season is given in Figure 5. Five sites and three sites observed significant decreasing trends in the sunshine duration in winter, pre-monsoon, monsoon and post-monsoon seasons, respectively (Table VII). The sunshine duration decreases caused possibly by the blocking/absorption of solar radiation suggest an increase in cloudiness over NE India and support the findings of solar dimming (Kumari *et al*., 2007).

Five sites each witnessed significant decreasing trends in the sunshine duration in January–March over NE India. Significant increasing trends in the sunshine duration were also observed, i.e. in monsoon season (Gungaram) and September (Gungaram); and December (Chuapara and Margherita). The sunshine duration remained practically trendless at Nagri Farm (Darjeeling). Nagri Farm being a high elevation site is situated above the low-lying clouds which block sunshine radiation, and thus the results of no trends in sunshine duration at this hill station are justifiable.

3.3. Correlation analysis between DTR and other meteorological parameters

The relationship between DTR and other meteorological parameters (E_{pan}, $T_{\max}$, $T_{\min}$, rainfall, cloud cover, morning RH and afternoon RH) was explored in order to identify the genesis of observed DTR trends in NE India. Because the cloud cover data were not available, the sunshine duration was used in place of cloud cover as

Table VII. Trends and the rate of changes in sunshine duration (h/decade).

Time scale	Chu	Gun	Mag	Nfm	Ngk	Tha	Sil	Toc
January	−0.5	−1.3*	−0.6	−0.1	−0.5*	−0.5*	−0.3*	−0.3*
	(−0.75)	(−2.18)	(−1.56)	(−0.74)	(−2.93)	(−3.10)	(−2.03)	(−1.76)
February	−0.4	−0.7*	−0.4	−0.5	−0.5*	−0.2	−0.5*	−0.4*
	(2.06)	(−2.19)	(−0.85)	(−1.41)	(−2.80)	(−0.79)	(−2.89)	(−2.20)
March	−0.4	−0.4	−1.0*	−0.3*	−0.7*	−0.7*	−0.4*	−0.4*
	(−0.99)	(−1.02)	(−1.78)	(−2.16)	(−4.18)	(−3.04)	(−2.34)	(−2.66)
April	−0.7*	−0.1	0.2	0	−0.2	−0.2	−0.2	0
	(−2.35)	(0.23)	(0.87)	(−0.03)	(−1.29)	(−1.18)	(−1.22)	(0.04)
May	−2.1*	0.3	−1.1*	−0.4	−0.4*	−0.3	−0.3	0
	(−3.41)	(0.97)	(−2.27)	(−0.55)	(−2.38)	(−0.96)	(−1.04)	(−0.15)
June	−1.1**	0.6	−1.1*	0.4	−0.1	−0.3	−0.3	0.1
	(−1.74)	(1.74)	(−2.07)	(1.01)	(−0.05)	(−0.91)	(−1.52)	(−0.42)
July	−0.5	0.5	0.5	−0.2	−0.1*	−0.3	−0.1	0
	(−0.79)	(1.34)	(1.01)	(−0.18)	(−1.73)	(−1.42)	(−0.65)	(−0.24)
August	−1.5*	0.5	−0.2	0.7	−0.2	−0.6*	−0.1	−0.1
	(−3.35)	(1.44)	(−0.58)	(−0.08)	(−1.48)	(−2.14)	(−0.53)	(−0.56)
September	−0.4	0.6**	−0.2	0	−0.3*	−0.2	−0.3*	−0.1
	(−1.21)	(1.59)	(−0.87)	(−1.45)	(−2.18)	(−1.23)	(−2.09)	(−0.67)
October	−0.2	−0.1	−0.5	−0.3	−0.2	−0.2	−0.3*	−0.2**
	(−0.67)	(−0.47)	(−1.59)	(−2.75)	(−1.13)	(−1.20)	(−2.06)	(−1.70)
November	−0.7*	−0.5**	−0.2	−0.2	−0.3*	−0.2	0	0.1
	(−1.90)	(−1.81)	(−0.58)	(−1.51)	(−1.67)	(−1.28)	(−0.04)	(−0.04)
December	0.7**	−0.3	1.2*	−0.4	−0.4*	−0.4*	−0.1	0
	(1.60)	(−1.11)	(2.99)	(−0.42)	(−3.30)	(−2.06)	(−0.10)	(−0.09)
Yearly	−0.6*	−0.1	−0.3*	−0.1*	−0.3*	−0.3*	−0.2*	−0.1**
	(−2.97)	(−0.59)	(−2.01)	(−2.11)	(−4.55)	(−3.73)	(−2.47)	(−1.94)
Winter	−0.5	−1.0*	−0.5	−0.3	−0.5*	−0.4*	−0.4*	−0.1*
	(−0.83)	(−2.88)	(−1.68)	(−1.55)	(−3.19)	(−2.05)	(−3.30)	(−2.68)
Pre-monsoon	−1.1*	−0.1	−0.6*	−0.3	−0.4*	−0.4*	−0.3*	−0.2
	(−3.99)	(−0.23)	(−2.66)	(−1.91)	(−4.13)	(−2.51)	(−2.18)	(−1.32)
Monsoon	−0.9*	0.5*	−0.3	0.2	−0.2	−0.3*	−0.1	0
	(−2.43)	(1.41)	(−1.59)	(−0.14)	(−1.99)	(−2.98)	(−0.43)	(−0.69)
Post-monsoon	−0.1	−0.3*	0.2	−0.3	−0.3*	−0.3*	−0.1	0
	(−0.29)	(−2.01)	(1.01)	(−2.10)	(−4.25)	(−2.17)	(−0.83)	(−0.81)

* and ** denote trends at 5% and 10% significance level, respectively, using Student's t-test. '−' sign indicates decreasing trend.
Value in bracket denotes the test statistic value obtained through Mann–Kendall's non-parametric test.
Chu, Gun, Mag, Nfm, Ngk, Tha, Sil and Toc denote Chuapara, Gungaram, Margherita, Nagri Farm, Nagrakata, Thakurbari, Silcoorie and Tocklai, respectively.

suggested by Angell (1990). The correlation coefficient values between DTR and other meteorological parameters were obtained from Spearman's Rho test through SPSS, a commercial package for statistical analysis, by keeping DTR as a dependent variable and meteorological parameters as independent variables. The correlation coefficient values lie in the range of 1.0 to −1.0, where −1.0 represents a perfect negative relationship between DTR and a meteorological parameter and 0 represents no relationship.

3.3.1. Factors responsible for DTR decreases

Almost all the cases of DTR decreases were in a strong and positive relationship with the sunshine duration as indicated by high values of correlation coefficients (in the range of 0.46–0.92) between these two variables, as observed in Table VIII. Karl *et al.* (1987, 1993) and Dai *et al.* (1999) have argued that much of the widespread decreasing trends in DTR since 1950 can be attributed to an increase in cloudiness. Rebetez and Beniston (1998) showed a strong correlation between DTR and the sunshine duration at lower elevation sites in the Swiss Alps. Durre and Wallace (2001) reported that the spatial pattern of DTR trends are physically consistent with the pattern of trends in cloud cover areas; i.e. areas of decreasing DTR are found where the sunshine duration had also been decreasing. Roy and Balling (2005) observed that rising $T_{\min}$ in NE India was a result of increasing cloud cover in winter, a view supported by DTR decreases at Tocklai in February and Chuapara in winter in the present study (Table VIII). Almost all the cases of DTR decreases were in strong and positive relationship with $T_{\max}$ (correlation coefficients varied from 0.47 to 0.92) and in moderate and negative relationship with $T_{\min}$ (correlation coefficients varied from −0.36 to −0.88). The increased cloud cover reduces

Table VIII. Correlative analysis of sites observing DTR decreases in different durations.

Name of site	SUN	E_{pan}	T_{max}	T_{min}	RAIN	AN.RH	MO.RH
Annual duration							
Chuapara	**0.77**	0.47	0.34	***−0.81***	***−0.69***	*−0.20*	0.40
Nagrakata	**0.46**	**0.56**	0.20	***−0.65***	*−0.07*	***−0.53***	***−0.54***
Tocklai	**0.58**	0.31	**0.71**	***−0.50***	*−0.20*	***−0.82***	***−0.50***
Winter							
Chuapara	**0.68**	0.39	**0.47**	*−0.17*	*−0.39*	***−0.66***	0.22
Pre-monsoon season							
Margherita	**0.54**	0.41	**0.69**	***−0.68***	*−0.32*	*−0.42*	0.01
Tocklai	**0.62**	**0.80**	**0.86**	*−0.21*	***−0.43***	***−0.93***	***−0.68***
Monsoon season							
Chuapara	**0.92**	0.40	**0.92**	***−0.49***	*−0.69*	*−0.34*	0.36
Nagrakata	**0.60**	**0.50**	0.24	***−0.69***	*−0.22*	***−0.47***	***−0.48***
Tocklai	**0.67**	**0.38**	**0.75**	*−0.25*	0.27	***−0.61***	***−0.36***
Post-monsoon							
Chuapara	**0.69**	0.11	**0.60**	***−0.61***	0.09	*−0.47*	0.32
February							
Tocklai	**0.86**	**0.42**	**0.81**	***−0.36***	***−0.58***	***−0.77***	***−0.45***
March							
Tocklai	**0.66**	**0.82**	**0.88**	***−0.39***	***−0.67***	***−0.96***	***−0.72***
May							
Chuapara	**0.79**	**0.68**	**0.59**	***−0.55***	***−0.66***	***−0.78***	*−0.33*
Margherita	**0.75**	0.15	**0.82**	***−0.64***	***−0.58***	*−0.33*	*−0.19*
June							
Chuapara	**0.78**	0.32	**0.81**	***−0.55***	***−0.58***	*−0.49*	0.02
Margherita	**0.62**	**0.65**	**0.89**	*−0.38*	***−0.54***	*−0.45*	*−0.41*
July							
Nagrakata	**0.62**	**0.52**	**0.48**	***−0.51***	*−0.15*	***−0.59***	***−0.50***
August							
Margherita	**0.48**	0.25	**0.62**	***−0.66***	*−0.19*	***−0.53***	*−0.43*
Tocklai	**0.65**	0.17	**0.63**	*−0.30*	0.06	***−0.47***	*−0.32*
September							
Nagrakata	**0.76**	**0.48**	**0.48**	***−0.47***	*−0.09*	***−0.71***	***−0.38***
Tocklai	**0.69**	**0.68**	**0.80**	0.13	*−0.01*	***−0.67***	*−0.02*
October							
Tocklai	**0.63**	**0.36**	0.23	***−0.76***	***−0.58***	***−0.74***	0.14
November							
Chuapara	**0.57**	*−0.01*	**0.68**	***−0.88***	***−0.50***	***−0.69***	0.36
Margherita	0.35	0.50	0.34	***−0.70***	*−0.39*	0.15	0.08

SUN, E_{pan}, T_{max}, T_{min}, RAIN, AN.RH and MO.RH denote sunshine duration, pan evaporation, maximum temperature, minimum temperature, rainfall, afternoon relative humidity and morning relative humidity, respectively.

Bold numbers denote statistically significant value at 5% significance level through Spearman's Rho non-parametric test. The negative values are in italics.

The correlation coefficient value is rounded off to two decimal places.

incoming solar radiation during the day and retards outgoing longwave radiation at night, which can lead to a reduction in T_{max} and increase in T_{min}.

Correlation analysis between DTR and E_{pan} demonstrated a positive and strong to moderate relationship between these two variables in different durations: annual; seasonal: pre-monsoon and monsoon; and monthly: February, March, May, June, July, September and October (Table VIII). Peterson *et al.* (1995) and Roderick and Farquhar (2002) suggested that decreases in solar irradiance, resulting from increasing cloud coverage, and decreases in DTR would cause the observed decreases in E_{pan}. Jhajharia *et al.* (2009) observed decreasing trends in E_{pan} over NE India in pre-monsoon and monsoon seasons, which support the experience of decreased DTR and decreased E_{pan} at Tocklai and Nagrakata in this study. Thus, pan evaporation shows a coherent relationship between decreased DTR and decreased E_{pan} mainly in pre-monsoon and monsoon seasons over a few sites of NE India.

Correlation analysis between DTR and rainfall demonstrated negative and strong relationship in February, March and October (May and June) at Tocklai (Chuapara and Margherita). Also, DTR decreases had a negative and strong to moderate correlation with the afternoon and morning RH. A radiative-convective model study by Stenchikov and Robock (1995) suggests that water vapour reduces DTR through its absorption of solar radiation in the near-infrared zone. Increasing trends in relative humidity in winter and pre-monsoon seasons over NE India, as reported by Jhajharia *et al.* (2009), may lead to warming over the surface because of more heat trapping caused by the increase in water vapour in the atmosphere.

3.3.2. Factors responsible for DTR increases

All the significant DTR increases over Gungaram, Silcoorie and Nagri Farm have witnessed a strong and positive relationship with T_{max}, and DTR increases over Thakurbari have witnessed a strong and negative correlation with T_{min}. The temperature trends, i.e. T_{max} increases at Gungaram and Silcoorie and T_{min} decreases at Thakurbari, support the results of correlation analysis between DTR and T_{max} and T_{min}.

Most of the DTR increases had a weak correlation with E_{pan} and rainfall, in contrast to the results of DTR decreases. Also, almost all DTR increases have witnessed a weak correlation with sunshine duration except in the months of the monsoon season, i.e. June–September. Only Gungaram experienced simultaneous increases in DTR and the sunshine duration in the monsoon season and in September (Tables VII and IX). Roy and Balling (2005) reported a significant increase in DTR in those places of NE India where cloud cover decreased in the summer monsoon season. However, other sites, i.e. Nagri Farm and Silcoorie, do not support the findings of Roy and Balling (2005). All the significant DTR increases have witnessed a negative correlation with the afternoon RH, although statistically significant mainly during the months of May–December.

Table IX. Correlative analysis of sites observing DTR increases in different durations.

Name of site	SUN	E_{pan}	T_{max}	T_{min}	RAIN	AN.RH	MO.RH
Annual duration							
Gungaram	0.33	*−0.18*	**0.65**	0.18	*−0.14*	***−0.48***	0.03
Winter season							
Nagrifarm	0.12	0.06	**0.65**	*−0.14*	0.02	*−0.30*	*−0.04*
Monsoon season							
Gungaram	**0.45**	*−0.18*	**0.60**	0.07	*−0.21*	−0.18	0.38
Silcoorie	0.21	0.05	**0.83**	***−0.54***	*−0.19*	***−0.46***	***−0.50***
Post-monsoon season							
Gungaram	*−0.08*	0.21	**0.52**	*−0.13*	*−0.02*	*−0.32*	*−0.23*
Thakurbari	*−0.06*	0.00	**0.77**	***−0.78***	*−0.12*	***−0.48***	**0.45**
Silcoorie	0.09	0.26	**0.76**	***−0.51***	*−0.24*	*−0.09*	*−0.17*
January							
Nagrifarm	**0.52**	**0.49**	**0.86**	0.16	*−0.17*	*−0.38*	*−0.29*
February							
Nagrifarm	0.37	0.35	**0.65**	0.01	0.01	*−0.38*	*−0.06*
May							
Nagrifarm	0.26	0.14	**0.55**	*−0.27*	*−0.29*	***−0.73***	*−0.32*
June							
Nagrifarm	**0.68**	**0.54**	**0.88**	0.23	0.05	*−0.46*	*−0.34*
Silcoorie	**0.66**	0.25	**0.75**	*−0.18*	***−0.59***	***−0.72***	***−0.71***
July							
Silcoorie	**0.34**	0.16	**0.79**	*−0.30*	*−0.24*	***−0.51***	***−0.36***
August							
Silcoorie	**0.37**	0.17	**0.86**	*−0.29*	*−0.27*	***−0.59***	***−0.61***
September							
Gungaram	**0.44**	***−0.45***	**0.54**	*−0.01*	*−0.14*	***−0.69***	0.15
October							
Gungaram	0.24	0.06	**0.42**	***−0.53***	*−0.36*	***−0.61***	0.10
Thakurbari	0.28	0.16	**0.65**	***−0.74***	*−0.13*	***−0.67***	0.21
Silcoorie	0.17	**0.57**	**0.63**	***−0.39***	*−0.29*	***−0.36***	***−0.41***
November							
Thakurbari	0.34	0.02	**0.67**	***−0.70***	***−0.55***	***−0.56***	0.33
Silcoorie	0.29	0.24	**0.50**	***−0.52***	***−0.50***	***−0.42***	*−0.21*
December							
Margherita	**0.74**	*−0.05*	**0.82**	***−0.50***	***−0.88***	***−0.84***	0.08

SUN, E_{pan}, T_{max}, T_{min}, RAIN, AN.RH and MO.RH denote sunshine duration, pan evaporation, maximum temperature, minimum temperature, rainfall, afternoon relative humidity and morning relative humidity, respectively.

Bold numbers denote statistically significant value at 5% significance level through Spearman's Rho non-parametric test. The negative values are in italics.

The correlation coefficient value is rounded off to two decimal places.

3.4. Implications for agriculture, water resources and human health

The rise in temperature may have a large bearing on agriculture and water availability besides human health. High temperatures are a major constraint to crop productivity, especially when temperature extremes coincide with critical stages of the plant development (McWilliam, 1980). Crop yields would be negatively affected owing to increased insect damages and plagues by all kinds of pathogens, which are likely to occur with increasing temperature. Crops, like paddy and tea and fruit crops, such as banana, jack fruit, olive, orange, passion fruit, pineapple, etc., are grown extensively in NE India. Thus, there is a need to carry out research to ascertain whether the observed warming is affecting the growth and production of these crops.

Mall *et al.* (2006) indicated practical difficulties in convincing water planning and development agencies to incorporate the impact of climate change into their projects because of suggestions of no clear role of global warming in the variability of monsoon rainfall over India from a recently concluded study by Kripalani *et al.* (2003). However, they stated the usefulness of conducting more in-depth studies and analyses to judge the potential adverse impacts on water resources by climate change. Man-made changes affecting climate, such as changes in cropping patterns and land-use patterns, over-exploitation of water storages and changes in irrigation and drainage in the Gangetic basin showed a reduction in the Ganges discharge by 60% over a period of 25 years (Adel, 2002). This has led to an almost 50% drop in the water availability in the surface water resources and a drop in groundwater table. Also, Chattopadhyay and Hulme (1997) and Goyal (2004) reported increases in potential evaporation over different places of India due to temperature increases and concluded that an increase in the evapotranspiration (ET) demand due to global warming would have a larger impact on the water resources of India and Rajasthan in particular.

Natural ecosystems, such as forests, are generally less adaptable than agricultural systems to rapid change and can prove more susceptible to global warming. NE India, a floristic rich and a high bio-diversity rich region, contains about 550 orchid species, i.e. 55% of total orchid species found in India, and about 8000 species of flowering plants, including prehistoric angiosperms (Rao, 1994; Khan *et al.*, 1997). Deforestation level is quite high due to various anthropogenic activities, such as rise in population and illegal immigration from neighbouring countries, rise in shifting cultivation, industrialization, logging for fuel-wood, hydroelectric projects, etc. Anthropogenically induced climate changes have severe adverse impacts on the country's ecosystems, agricultural potential, forests as well as water and marine resources, and thus large-scale planning would be needed for adaptation measures to accommodate climate change impacts (National Environment Policy, 2004).

Climatic variables exhibit impacts on the incubation rate of *Plasmodium* parasites and the breeding of *Anopheles*, and are important environmental contributors to the malaria transmission (McMichael and Martens, 1995). Temperature is one of the critical variables in malaria epidemiology, as the malaria vectors are poikilothermic and a change in temperature by 1 °C in the range of 18–26 °C can change a mosquito's life by more than a week (Jepson *et al.*, 1947). Githeko *et al.* (2000) also found that the average global temperature, with a rise of 1.0–3.5 °C, increases the likelihood of many vector-borne diseases in new areas. Several researchers (Loevinsohn, 1994; Peng *et al.*, 2003; Devi and Jauhari, 2006) found that temperature, especially T_{min}, is strongly correlated with the transmission dynamics of malaria. Dev *et al.* (2004) reported that malaria is endemic in NE India under the influence of *Anopheles minimus* (perennial), *A. Dirus* (monsoon) and *A. fluviatilis* (winter). Malaria accounts for much of the morbidity and mortality associated with the disease, and it is important to assess the impact of warming on the increased likelihood of spread of malaria in new areas in NE India.

4. Conclusions

DTR decreasing trends are observed at four sites, i.e. Chuapara, Margherita, Nagrakata and Tocklai, for almost all time scales; however, the DTR trends are significant mainly at annual, seasonal (pre-monsoon and monsoon) and monthly (May, June, August, September and November) time scales. Significant increasing trends in DTR are observed at three sites, i.e. Gungaram, Thakurbari and Silcoorie, in the month of October and in the monsoon and post-monsoon seasons as well. Temperature remains practically trendless in winter and pre-monsoon seasons. Four sites each observed significant increasing trends in T_{mean} in monsoon and post-monsoon seasons. Also, the post-monsoon changes in T_{max} and T_{min} are more than the monsoon changes, indicating the presence of an element of a seasonal cycle. Rupa Kumar *et al.* (1994) reported predominant T_{max} increases over India in the post-monsoon season. Significant decreasing trends in the sunshine duration are observed at annual, seasonal (winter and pre-monsoon) and monthly (January–March) time scales.

Correlation analysis reveals that different meteorological parameters influence DTR in different seasons over different sites. DTR increases are found to have a strong positive correlation with T_{max} and moderate negative correlation with T_{min}. However, DTR decreases are found to have a positive correlation with the sunshine duration, T_{max} and E_{pan} and a negative correlation with T_{min} and afternoon relative humidity. Concomitant decreases in sunshine duration may be one of the potential causes of observed DTR decreases over NE India. Decreases in sunshine duration could be indirectly related to the observed warming caused possibly by the increases in anthropogenic greenhouse gases over NE India.

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