INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 1369–1384 (2014)
Published online 16 July 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3761

Trends in temperature over Godavari River basin in Southern Peninsular India

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ABSTRACT: There is little dispute that global surface air temperature has increased and the anthropogenic-induced global warming is likely to play an important role in the management of water resources of a river basin. Therefore, this study was undertaken for Godavari River basin, a large southern peninsular river basin in India. After removing the effect of significant lag-1 serial correlation by pre-whitening procedure, the Mann–Kendall (MK) test was employed to investigate trends in maximum temperature (T_{max}), minimum temperature (T_{min}) and mean temperature (T_{mean}) at 35 stations in the basin. At seasonal (monthly) time scales, a majority of the stations exhibited no trends in T_{mean}, T_{max} and T_{min} in any of the four seasons (12 months) with the exception of post-monsoon (December) for T_{max} and monsoon (July and September) for T_{min}. About 60% (45%) of the stations exhibited increasing trends in T_{max} (T_{min}) in different durations: the month of December and post-monsoon season (the months of July and September and monsoon season) indicating the presence of an element of seasonal cycle in temperature over the Godavari basin. Results of tests of spatial and temporal homogeneity of trends by the Van Belle and Hughes method showed that trends in temperature over the Godavari basin were not homogeneous for different months or at different stations. In spite of the warmer climate in the basin, the evaporation (Epan) has been found to decrease significantly over the Godavari basin. Strong decreases in wind speed and increases in relative humidity may have actually caused the Epan decreases over the southern peninsular region of India.

KEY WORDS temperature; Godavari River basin; Southern Peninsular India; Mann–Kendall test; Theil–Sen's slope; homogeneity of trends

Received 21 October 2011; Revised 29 March 2013; Accepted 19 May 2013

1. Introduction

Water is a fundamental component of Earth's system, providing important controls on the world's weather and climate. Freshwater availability in different parts of Asia, particularly in large river basins, is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standard of living, could adversely affect more than a billion people by the 2050s (Draper and Kundell, 2007). With increasing variability associated with climate change and global warming, the existing water management practices may prove less effective (Vorosmarty, 2002). Similarly, the increasing variability of temperature may affect the production of grains as reported by Riha *et al.* (1996). Increasing temperature variability produces smaller average yield when the growing-season temperatures are outside the optimum range for growth (Riha *et al.*, 1996).

Temperature, one of the most important parameters of climate, is commonly used to detect fluctuations in climate. Because of their linkages to the changes in cloudiness, humidity, atmospheric circulation patterns and soil moisture, Karl *et al.* (1993) employed maximum temperature (T_{max}) and minimum temperature (T_{min}) to denote the sign of warming or cooling. Tayanç *et al.* (2009) reported that minimum temperature series in Turkey show significant warming in almost all over the country indicating the effect of urbanization. Karl *et al.* (1993), Easterling *et al.* (1997) and Vose *et al.* (2005) reported that the

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warming in recent years is associated with much larger increases in T_{min} than in T_{max}, and therefore the diurnal temperature range (DTR) has been decreasing over the globe. However, the observed DTR increases over India were quite different from DTR decreases observed over other parts of the globe (Srivastava *et al.*, 1992; Rupa Kumar *et al.*, 1994). The DTR increases were observed primarily due to higher rates of increase in T_{max} than in T_{min} in the western Himalaya (Yadav *et al.*, 2004), in the Karakoram and Hindu Kush Mountains of the Upper Indus basin (Fowler and Archer, 2006), in the northwestern Himalayas (Bhutiyani *et al.*, 2007), in the river basins of northwest and central India (Singh *et al.*, 2008) and over few sites from the humid region of northeast India (Jhajharia and Singh, 2011). Recently, Yang *et al.* (2012) reported a rise of 0.31 °C/decade for annual mean air temperature over the entire region of the Chinese Himalayas during the period 1971–2007. They also reported that climate was warming and drying in the western Chinese Himalayas.

The spatial and temporal homogeneity of trends is an important aspect of trend analysis of any hydrometeorological parameter in any region. Van Belle and Hughes (1984) developed a method to test the homogeneity of trend by Mann–Kendall (MK) test. The homogeneity test is performed on a data set obtained by combining the data of several stations to obtain a possible single global trend. Several researchers, for example, Gan (1995, 1998), Kahya and Kalayci (2004), Panda *et al.* (2007), Kampata *et al.* (2008), Dinpashoh *et al.* (2011) and Jhajharia *et al.* (2012) applied the test of homogeneity of trends for the time series of precipitation, air temperature, streamflow, groundwater levels and evapotranspiration over different parts of the world.

Little information is available on trends in T_{mean}, T_{max} or T_{min} over the Godavari basin in southern peninsular India. Furthermore, no study concerning the homogeneity of trends in air temperature over a large Indian river basin seems to be available in the literature. Therefore, the main objective of this study was to investigate trends in temperatures (T_{mean}, T_{max} and T_{min}) at annual, seasonal and monthly time scales using data from measuring stations located in or around the transboundary Godavari basin in India. Trends were investigated using the nonparametric MK method after correction for the effect of significant lag-1 serial correlation. We also tested the homogeneity of trends in air temperature over the basin. This study is perhaps the first attempt at determining the homogeneity of temperature trends at a basin-scale in India. Results of this study at the basin scale will help in the planning and management of water resources and their optimal use under the anthropogenic-induced global warming scenario, which has become a matter of the utmost urgency in the 21st century, because the planning and operation of reservoirs may be greatly affected by increases in temperature. Results of study on trends in temperature at the basin scale may help water planners and development agencies incorporate the impact of climate change into decision-making inspite of the fact that some of the agreements are not subject to review, becoming in effect, perpetually valid, for example the Godavari Water Dispute Tribunal (GWDT) award (Richards and Singh, 2002).

2. Material and methods

2.1. Godavari River basin

Godavari River basin (longitudes 73°26′ and 83°07′E; latitudes 16°16′ and 23°43′N) extends over an area of 0.3128 million km^2, which is nearly 9.5% of the total geographical area of India. The Godavari River, the biggest river of Peninsular India, traverses through the states of Maharashtra, Andhra Pradesh, Madhya Pradesh, Karnataka, Orissa and a newly created Chhattisgarh state. Godavari River rises at Triambakeshwar at an altitude of 1067 m a. m. s. l. in the Nasik district of Maharashtra and flows east across the Deccan Plateau from the Western Ghats. After flowing for about 1465 km in southeasterly direction through the states of Maharashtra and Andhra Pradesh, Godavari River falls into the Bay of Bengal. The principal tributaries of the river are Pravara, Mula, Purna, Manjra, Maner, Penganga, Wardha, Wainganga, Pranhita, Indravati and Sabari.

The Godavari basin consists of large undulating plains divided by low flat topped hill ranges. The important soil types found in the basins are black soils, red soils, lateritic soils, alluvium, mixed soils and saline and alkaline soils. The Godavari basin has a tropical climate and the evaporation losses vary from 1800 to 2440 mm over different parts of the basin (CWC, 1999). The Godavari River basin receives an average annual rainfall of about 1132 mm, out of which almost 84% of the total rainfall falls in the monsoon season. The rainfall distribution over the basin is highly uneven and erratic, and there are 13 drought prone districts out of a total 42 districts in the basin (CWC, 1987). Godavari River is purely rainfed and carries enormous quantities of water during the monsoon period, which inundates areas in Andhra Pradesh, Maharashtra, Chhattisgarh and Orissa.

2.2. Temperature data

Monthly data of T_{max}, T_{min} and T_{mean} were obtained from India Meteorology Department (IMD), Pune, for different periods, mainly from 1961 to 2004, at most of the stations. A total of 35 stations were selected from in and around the Godavari River basin. The stations were selected in such a way that all the 6 co-basin states and all the 12 sub-basins, as defined by the GWDT (CWC, 1997) for the sharing of the waters of the Godavari basin were represented in this study (Figure 1). Details of the selected 35 stations are given in Table 1. Missing temperature data at a station for time period were filled by the average values of the nearest stations. Monthly average data of T_{mean} of all the 35 stations of the Godavari basin are given in Table 2, which shows that the average mean temperature varies from 14.5 °C

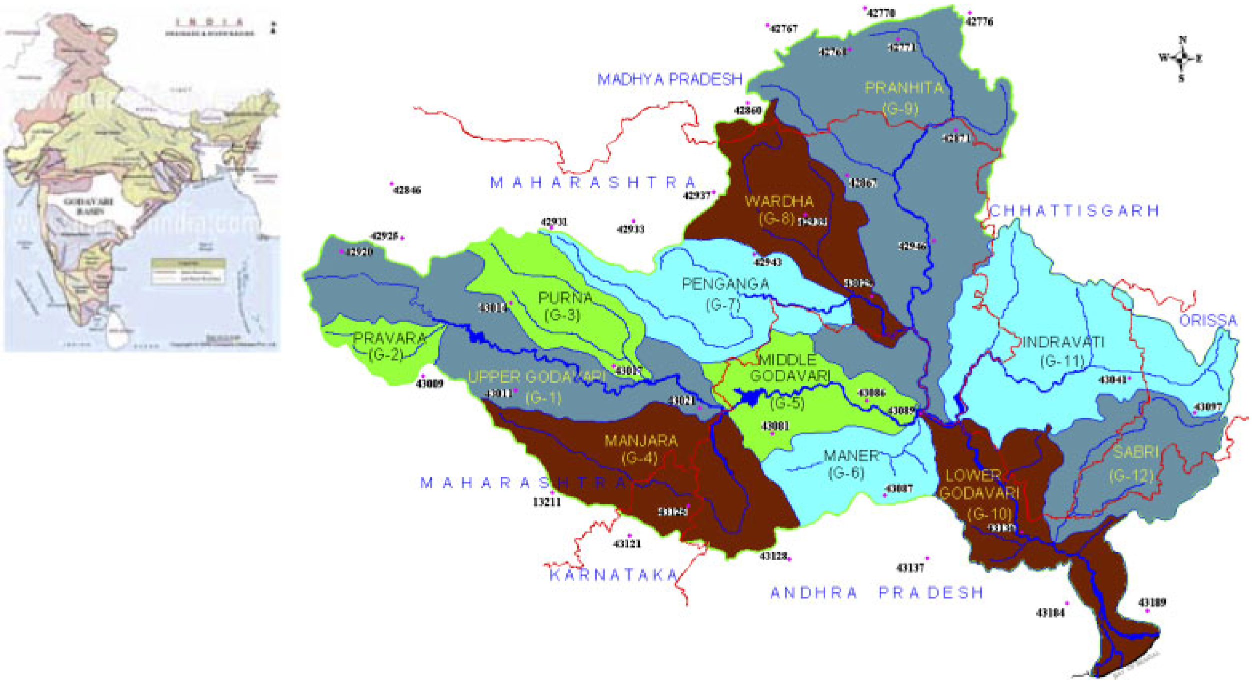

Figure 1. Location map of sites of Godavari river basin. Note: The Godavari basin is shown in white colour in India's river basin map (Source of India map: www.mapsofindia.com).

at Pachmarhi in the month of January to 35.5 °C at Chandrapur in the month of May.

2.3. Trend analysis

In this study, the nonparametric MK test was used for the detection of trends in temperature as nonparametric tests are more suitable for non-normally distributed and censored data with missing values, and are less influenced by the presence of outliers in the data (Jhajharia *et al.*, 2009; Wilks, 2011). One of the main problems in testing and interpretation of trends is the effect of serial dependence. Obviously, if there is a persistence in the time series, then the nonparametric test will suggest a significant trend in the series, i.e. more random than specified by the significance level (Zhang *et al.*, 2001). First, the significance of lag-1 serial correlation (r_1) was tested for temperature time series to eliminate the effect of serial correlation. If the absolute value of r_1 was less than the significance level value then the original MK test was used. Otherwise, the effect of serial correlation was removed from the time series by pre-whitening prior to applying the MK test. The interested reader might be referred to Kumar *et al.* (2009), Kahya and Kalayci (2004), Partal and Kahya (2006) and Dinpashoh *et al.* (2011) for the analysis details.

2.3.1. Mann–Kendall (MK) test

The MK test (Mann, 1945; Kendall, 1975) was first carried out by computing S statistic as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \qquad (1)$$

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

$$sgn(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if} \theta = 0 \\ -1 & \text{if} \theta < 0 \end{cases} \qquad (2)$$

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

$$E(S) = 0 \qquad (3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5)}{18} \qquad (4)$$

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

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \qquad (5)$$

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 significance level of α (Jhajharia *et al.*, 2012). For example, if the

Table 1. Details of sites.

S. No.	Name of site	Code of site	State and sub-basin	Lat. (N)	Long. (E)	Elev., m amsl	Duration of data
1	Ahmednagar[a]	43009	MAH	19°05′	74°48′	646.0	1961–2007
2	Akola[a]	42933	MAH	20°42′	77°02′	304.0	1961–2005
3	Amraoti[a]	42937	MAH	20°56′	77°45′	343.0	1961–2006
4	Aurangabad	43014	MAH (G-3)	19°51′	75°24′	579.0	1961–2007
5	Beed	43011	MAH (G-1)	19°00′	75°43′	601.0	1961–1996
6	Betul[a]	42860	MP	21°52′	77°56′	658.0	1961–2006
7	Bhadrachallam	43136	AP (G-10)	17°40′	80°53′	49.00	1961–2002
8	Bidar	43125	KAR (G-4)	17°55′	77°32′	619.0	1961–2004
9	Brahmapuri	42946	MAH (G-9)	20°36′	79°51′	229.5	1961–2004
10	Buldana[a]	42931	MAH	20°32′	76°14′	646.0	1961–2006
11	Chandrapur	43029	MAH (G-8)	19°58′	79°18′	189.0	1961–2006
12	Chindwara	42768	MP (G-9)	22°06′	79°00′	676.0	1961–2006
13	Gondia	42871	MAH (G-9)	21°28′	80°12′	302.0	1961–2006
14	Gulbarga[a]	43121	KAR	17°21′	76°51′	458.0	1961–2006
15	Hanamkonda	43087	AP (G-6)	18°01′	79°34′	269.0	1961–2002
16	Hyderabad[a]	43128	AP	17°27′	78°28′	489.0	1961–2002
17	Jagdalpur	43041	CHH (G-11)	19°05′	82°02′	554.0	1961–2007
18	Kakinada[a]	43189	AP	16°56′	82°13′	2.00	1961–2002
19	Khammam[a]	43137	AP	17°15′	80°09′	107.0	1961–2002
20	Malegaon[a]	42925	MAH	20°33′	74°32′	437.0	1961–2006
21	Mandla[a]	42776	MP	22°35′	80°22′	443.0	1961–2006
22	Nagpur	42867	MAH (G-9)	21°06′	79°03′	310.0	1961–2006
23	Nanded	43021	MAH (G-1)	19°05′	77°20′	381.0	1961–2007
24	Narsinghpur[a]	42770	MP	22°57′	79°11′	356.0	1962–2005
25	Nidadavole[a]	43184	AP	16°55′	81°40′	16.00	1961–2000
26	Nizamabad	43081	AP (G-5)	18°40′	78°06′	395.0	1961–2002
27	Osmanabad[a]	13211	MAH	18°10′	76°03′	647.0	1976–2002
28	Ozar	42920	MAH (G-1)	20°26′	72°51′	579.0	1965–2006
29	Pachmarhi[a]	42767	MP	22°28′	78°26′	1062.0	1961–1992
30	Parbhani	43017	MAH (G-3)	19°16′	76°50′	423.0	1961–2007
31	Ramgundam	43086	AP (G-5)	18°46′	79°26′	179.0	1961–2002
32	Seoni	42771	MP (G-9)	22°05′	79°33′	619.0	1961–2006
33	Sironcha	43089	AP	18°51′	79°58′	118.0	1961–2006
34	Wardha	42939	MAH (G-8)	20°40′	78°35′	255.0	1967–2006
35	Yeotmal	42943	MAH (G-7)	20°24′	75°09′	451.0	1961–2005

Lat, latitude; long, longitude; elev, elevation; m amsl, metre above mean sea level; N, north; MAH, Maharashtra; AP, Andhra Pradesh; MP, Madhya Pradesh; KAR, Karnataka; CHH, Chhattisgarh. [a] Denotes the site, which is located outside the boundary of the basin, but in the close proximity of the boundary.

computed test statistic values lie within limits (−) 1.96 and (+) 1.96, the null hypothesis of no trend in the series can be accepted at the 5% level of significance using a two-tailed test (Jhajharia *et al.*, 2012).

2.3.2. *Theil–Sen's estimator*

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

$$\beta = \text{Median}\left(\frac{x_j - x_l}{j - l}\right) \quad \forall \quad 1 < l < j \tag{6}$$

where, β is Theil–Sen's estimator (Theil, 1950; Sen, 1968). The method of Theil–Sen's estimator has been widely used in identifying the slope of trend line in a hydrological time series. Recently, Jhajharia *et al.* (2012) and Jhajharia *et al.* (2013) also used Theil–Sen's estimator to obtain the magnitude of trends in reference evapotranspiration over different stations in northeast India and in *Plasmodium falciparum* and *Plasmodium vivax* malaria incidence cases in the Thar Desert in the northwest India.

2.4. Testing the homogeneity of trends

To test the homogeneity of trends in temperature ($T_{\max}$, $T_{\min}$ and T_{mean}) of stations, a procedure proposed by van Belle and Hughes (1984), based on the partitioning of the sum of squares, is applied in this study. The procedure uses the chi-square test to determine the homogeneity of trends 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 ($Z^2{}_j$) are 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 degree of freedom (d.f.). Furthermore, if the seasonal observations are far enough apart, then Z_j will be nearly independent. The overall statistics for m months is

$$\chi^2_{\text{Total}} = \sum_{j=1}^{m} Z_j^2 \tag{7}$$

which follows approximately a chi-square distribution with m d.f. under the null hypothesis of no trends for all m months. A large value of such a statistic is

Table 2. Monthly mean temperature over different sites of Godavari River basin.

S No.	Name of site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Ahmednagar	21.2	23.1	26.8	30.0	30.8	27.8	25.8	25.1	25.5	25.6	22.9	20.9
2	Akola	21.8	24.3	28.6	32.8	34.9	31.8	28.2	27.0	27.7	27.1	24.1	21.4
3	Amraoti	22.1	24.8	28.8	32.4	34.4	30.6	27.3	26.2	27.0	27.0	24.5	22.1
4	Aurangabad	20.2	22.6	26.8	30.3	31.7	28.8	26.1	25.1	25.6	25.0	22.1	19.8
5	Beed	21.5	23.6	27.5	31.1	32.6	29.8	27.2	26.4	26.4	25.8	22.8	20.7
6	Betul	18.7	20.9	25.1	29.4	32.1	29.7	25.6	24.4	25.0	23.9	20.9	18.7
7	Bhadrachallam	23.9	26.8	29.9	32.3	34.2	31.6	28.6	28.0	28.5	27.7	25.1	23.2
8	Bidar	22.4	25.1	28.7	31.0	32.0	28.1	25.7	25.0	25.5	25.3	23.3	21.8
9	Brahmapuri	21.0	23.8	28.1	32.5	34.8	31.6	27.5	26.8	27.5	26.8	23.4	20.5
10	Buldana	21.1	23.5	27.3	31.0	31.7	28.5	25.3	24.1	25.0	25.4	23.1	21.1
11	Chandrapur	22.3	25.2	29.3	33.3	35.5	32.2	28.2	27.4	28.0	27.0	23.7	21.3
12	Chindwara	17.5	20.1	24.2	29.0	31.8	29.5	25.6	24.5	25.0	23.7	20.3	17.5
13	Gondia	20.6	23.4	27.8	32.3	34.9	32.2	27.9	27.1	27.7	26.9	23.7	20.5
14	Gulbarga	23.5	26.3	29.9	32.5	33.0	29.5	27.3	26.6	27.0	26.7	24.6	22.9
15	Hanamkonda	23.5	26.2	29.4	32.2	34.3	31.5	28.5	27.7	28.1	27.4	24.8	22.8
16	Hyderabad	22.1	24.9	28.4	31.2	32.6	29.2	26.8	26.0	26.4	25.5	23.2	21.4
17	Jagdalpur	20.1	23.1	27.0	29.8	31.2	28.5	25.8	25.4	26.0	25.1	22.1	19.6
18	Kakinada	24.2	26.3	28.9	31.2	32.7	31.5	29.4	28.9	29.2	28.2	26.2	24.3
19	Khammam	24.0	26.7	29.5	32.0	34.1	31.7	28.9	28.2	28.6	27.6	25.3	23.3
20	Malegaon	22.5	24.8	28.7	32.2	32.8	29.4	26.4	25.3	26.2	26.7	24.5	22.5
21	Mandla	17.0	19.8	24.0	28.9	32.3	30.8	26.7	26.0	26.2	24.2	20.2	17.1
22	Nagpur	20.8	23.5	27.8	32.2	35.1	32.1	28.0	27.1	27.6	26.4	23.1	20.4
23	Nanded	22.2	24.6	28.3	32.0	33.5	30.5	27.6	26.6	27.0	26.4	23.5	21.4
24	Narsinghpur	19.0	21.7	26.5	31.7	35.1	33.0	28.4	27.0	27.8	26.8	22.8	19.4
25	Nidadavole	23.9	25.6	27.9	30.3	32.1	30.9	28.5	28.1	28.4	27.7	25.9	24.0
26	Nizamabad	22.7	25.5	29.3	32.5	34.3	30.6	27.6	26.7	27.3	26.5	23.9	21.8
27	Osmanabad	22.2	24.4	28.1	30.6	31.4	27.4	25.1	24.5	25.1	25.0	23.2	21.6
28	Ozar	19.7	21.6	25.5	28.6	29.7	27.8	25.3	24.4	24.8	24.8	22.2	19.8
29	Pachmarhi	14.5	17.0	21.6	26.3	28.9	26.1	22.4	21.4	22.1	20.7	17.2	14.5
30	Parbhani	22.0	24.7	28.7	32.2	33.9	30.5	27.5	26.6	27.0	26.3	23.5	21.4
31	Ramgundam	23.2	26.1	29.7	33.0	35.3	32.1	28.7	27.9	28.6	27.7	24.8	22.3
32	Seoni	19.4	22.1	26.6	31.1	33.2	30.5	26.5	25.7	26.4	25.6	22.5	19.7
33	Sironcha	22.7	26.0	29.9	33.2	35.0	31.6	28.2	27.3	27.8	27.3	24.6	22.0
34	Wardha	21.3	24.0	28.3	32.7	35.1	31.2	27.6	26.5	27.1	26.5	23.6	21.3
35	Yeotmal	22.0	24.6	28.8	32.6	34.4	30.7	26.8	25.7	26.4	26.0	23.5	21.5

not meaningful, as it fails to distinguish heterogeneity between the individual Z^2_j's from the overall trend. This problem is solved by partitioning χ^2_{Total} into $\chi^2_{\text{homog.}}$ and χ^2_{trend} ($\chi^2_{\text{trend}} = mZ^2$; where Z is an average over subscript j). The $\chi^2_{\text{homog.}}$ value can be found by subtracting χ^2_{trend} from the χ^2_{Total}.

Under the null hypothesis of equal Z's for all months, $\chi^2_{\text{homog.}}$ and χ^2_{trend} have a chi-square distribution with (m – 1) and 1 d.f., respectively. The homogeneity of trends can be tested by comparing the calculated $\chi^2_{\text{homog.}}$ by the corresponding χ^2_{m-1} from chi-square tables. If $\chi^2_{\text{homog.}}$ is not significant, then a valid test for the common trend is possible by referring χ^2_{trend} to the corresponding tabulated value. If $\chi^2_{\text{homog.}}$ is significant, then evaluation of χ^2_{trend} is not appropriate. In such a condition, the trend was tested for each month from the individual Z_j. The total chi-square in this condition is $\chi^2_{\text{Total}} = \sum_{j=1}^{m}\sum_{p=1}^{k} z^2_{jp}$, which has approximately, a chi-square distribution with d.f. equal to mk. The following steps were used to test the homogeneity of trends.

Step1: The chi-square values were computed. The $\chi^2_{\text{station-month}}$ were obtained by subtracting the sum of $\chi^2_{\text{month}} + \chi^2_{\text{station}}$ from $\chi^2_{\text{homog.}}$

Step 2: Tested the homogeneity of stations using statistic χ^2_{station}.

Step 3: Tested the homogeneity of months using statistic χ^2_{month}.

Step 4: Tested the homogeneity of month-station interaction using statistic $\chi^2_{\text{station-month}}$.

Step 5: If the test results from steps 2, 3 and 4 were all non-significant, then the test for the overall trend using χ^2_{trend} was performed with d.f. = 1. If months were heterogeneous but stations were homogeneous, trend tests were run for individual months from kZ_j^2 ($j = 1, 2, \ldots, m$). If stations were heterogeneous but months were homogeneous, trend tests were done for individual stations using $mZ_p{}^2$ ($p = 1,2,\ldots,k$). However, if both stations and months were heterogeneous or there was a significant station–month interaction, then only meaningful trend tests were possible for the individual station–months using Z_{jp}. Recently, Dinpashoh *et al.* (2011) and Jhajharia *et al.* (2012) had also used a similar kind of approach for testing the trend homogeneity for data of various stations located in different parts of the globe.

3. Results and discussion

3.1. Analysis of temporal trends in temperature

3.1.1. Trends in maximum temperature

Tables 3 and 4 present the Z statistic obtained through the MK test for $T_{\max}$ at monthly and seasonal time scales, respectively, across the entire Godavari basin. It can be inferred from Table 3 that both upward and downward trends were experienced for $T_{\max}$ at different stations located in twelve different sub-basins of the Godavari basin. More than 75% of the total stations witnessed no trends in $T_{\max}$ obtained through the MK test at 5% level of significance in different durations: Month-January to October; season-winter, pre-monsoon and monsoon (Table 5). However, 19 stations (17 stations) of 35 stations of the Godavari basin witnessed increasing trends in $T_{\max}$ obtained through the MK test at 5% level of significance in the month of December (post-monsoon season). At the annual scale, only eight (6) stations witnessed increasing (decreasing) trends in $T_{\max}$ obtained through the MK test at 5% level of significance. Thus, results of seasonal and monthly analysis indicate that maximum changes in $T_{\max}$ were observed in the post-monsoon season and in the month of December. Figure 2 shows a sample time series of $T_{\max}$ and linear trends in $T_{\max}$ denoted by solid curve and dashed line, respectively, in the month of December over four sites. In addition, the spatial distribution of trends of $T_{\max}$ witnessed at these two time scales (December and post-monsoon season), which witnessed maximum changes, is shown in the Figure 3. Singh *et al.* (2008) also showed that the greatest increase in $T_{\max}$ and T_{mean} was observed in the post-monsoon season over different sites located in northwest and central India. However, Pant and Rupa Kumar (1997) reported significant increasing trends (no trends) in $T_{\max}$ in winter season (pre-monsoon, monsoon, post-monsoon and annual time scales) over the interior peninsula region of India during the period 1901–1987.

Table 3. Z values obtained for maximum temperature over sites of Godavari River Basin.

	Name of site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Ahmednagar	−0.61	−3.58	−1.25	−1.44	**−2.39**	−1.80	**−2.29**	−0.97	−1.24	−1.21	**−4.09**	−1.11
2	Akola	0.12	−0.91	0.44	0.81	0.94	−0.03	0.32	0.14	0.01	−1.34	0.79	1.26
3	Amraoti	−0.32	−1.67	−1.55	−1.35	−0.74	**−2.27**	**−2.08**	−1.42	−1.10	−1.60	−0.33	0.40
4	Aurangabad	1.18	0.05	0.54	0.87	0.02	−0.58	−1.14	−2.09	−0.55	−1.08	0.93	1.54
5	Beed	−0.04	−1.32	−0.42	−1.60	−0.53	−0.79	**−2.87**	−1.73	−1.23	**−2.02**	−1.19	0.31
6	Betul	**2.36**	1.20	1.37	**2.65**	**2.48**	0.75	0.55	0.64	**3.07**	1.80	**2.29**	**3.62**
7	Bhadrachallam	0.21	−1.10	0.33	−0.37	0.77	−0.86	1.33	−0.76	1.50	0.21	1.10	1.84
8	Bidar	**3.93**	**2.53**	**3.04**	**2.89**	1.21	−0.60	1.62	0.44	**2.22**	1.14	**3.45**	**3.33**
9	Brahmapuri	1.35	−0.15	0.21	0.91	0.63	−0.56	0.07	0.49	1.60	1.30	**1.97**	**3.00**
10	Buldana	1.05	0.29	1.27	1.48	1.64	0.09	−0.66	−0.95	0.27	−0.67	0.74	**2.16**
11	Chandrapur	**2.19**	0.73	0.57	1.06	0.25	−0.20	0.47	−0.37	1.73	0.50	0.62	**3.12**
12	Chindwara	−0.51	−1.61	−0.05	0.62	0.94	−0.38	1.02	−0.05	−1.02	−1.42	−0.60	−0.11
13	Gondia	**2.64**	1.34	0.78	0.98	0.68	0.85	1.61	**2.10**	**2.09**	1.78	**2.18**	**3.73**
14	Gulbarga	**3.35**	**3.31**	**2.33**	**2.13**	1.79	1.15	1.27	1.61	**2.06**	0.46	**3.01**	**3.37**
15	Hanamkonda	0.77	−1.23	−0.91	−0.04	1.00	−0.82	1.54	−0.64	1.60	0.50	**1.95**	1.67
16	Hyderabad	**2.40**	0.83	1.75	1.09	1.62	−0.63	1.60	0.09	**2.28**	0.92	**2.32**	**2.09**
17	Jagdalpur	1.92	0.58	0.43	0.61	−0.46	0.09	1.89	0.16	**2.69**	**2.93**	**2.11**	**3.09**
18	Kakinada	**2.92**	−0.27	−0.99	−1.43	−0.07	−1.58	1.40	−0.24	0.52	0.41	**2.84**	**3.56**
19	Khammam	**−3.58**	**−4.03**	**−4.05**	**−3.25**	−1.25	−0.84	1.15	**−1.97**	−0.46	**−2.41**	**−2.10**	**−3.33**
20	Malegaon	1.33	1.18	1.39	1.68	−0.62	−0.79	**−2.27**	**−2.40**	−1.45	−0.75	1.08	**2.71**
21	Mandla	0.82	1.18	0.25	0.15	0.71	−0.01	0.45	−0.46	1.93	1.21	1.60	**2.79**
22	Nagpur	0.73	−0.36	−0.08	0.82	1.42	0.53	−0.21	0.38	1.18	0.36	1.61	**3.18**
23	Nanded	1.61	−1.03	−0.82	0.41	−1.53	−0.55	0.31	−1.36	1.28	−0.11	**2.49**	**2.17**
24	Narsinghpur	0.83	−0.16	−0.43	0.30	1.30	0.42	0.92	0.84	0.86	0.59	1.45	**2.98**
25	Nidadavole	−0.77	−3.61	**−2.93**	−0.14	**−2.14**	−1.18	−0.28	−0.20	0.91	−0.07	0.54	−0.84
26	Nizamabad	1.43	−0.33	−0.76	0.16	0.38	−0.22	0.36	−0.18	0.30	−0.44	1.43	1.41
27	Osmanabad	**4.34**	**2.77**	**3.36**	1.75	0.91	0.02	1.52	1.29	**2.82**	0.36	**4.17**	**4.61**
28	Ozar	1.04	0.81	0.21	−0.64	−1.36	−0.87	−1.36	−1.15	−0.78	−1.15	0.63	**2.51**
29	Pachmarhi	−1.24	−1.38	**−2.10**	−1.81	−1.29	**−2.10**	0.05	−1.54	**2.04**	0.07	−1.90	−0.75
30	Parbhani	0.81	−0.98	−0.32	−0.36	0.33	−0.09	−1.01	−0.98	0.65	−0.34	1.19	**2.17**
31	Ramgundam	−0.49	−1.19	−0.54	−0.43	0.17	−1.52	−0.18	−1.64	0.91	0.18	0.72	1.54
32	Seoni	0.57	0.17	0.06	0.08	−0.08	−0.63	−0.14	0.18	0.73	−0.08	1.00	**3.06**
33	Sironcha	0.15	−0.82	0.25	1.88	0.37	−0.45	1.40	−1.40	−0.82	−0.07	−0.08	0.01
34	Wardha	−0.75	−1.01	−0.47	−0.01	−1.54	−0.75	−0.30	0.32	0.37	−1.06	−0.02	1.24
35	Yeotmal	−0.68	**−1.98**	−1.01	−0.21	−0.88	−1.32	−1.49	−1.49	−0.18	−1.52	0.51	1.40

Bold numbers are statistically significant at 5% level of significance.

Table 4. Z values obtained for maximum temperature and minimum temperature over sites of Godavari River Basin.

		Maximum temperature					Minimum temperature				
	Name of site	ANNU	WINT	PREM	MONS	POST	ANNU	WINT	PREM	MONS	POST
1	Ahmednagar	**−2.80**	**−2.44**	−1.86	**−2.40**	**−2.78**	**−2.46**	−1.80	**−3.67**	0.36	−1.56
2	Akola	0.30	−0.71	1.47	−0.14	0.97	1.75	1.95	0.09	1.65	0.32
3	Amraoti	−1.53	−1.38	−1.16	**−2.26**	−0.01	**−4.22**	−1.14	**−3.28**	**−4.58**	**−2.16**
4	Aurangabad	−0.94	0.60	0.39	−1.83	1.21	**5.28**	**4.38**	**4.46**	**5.16**	**2.01**
5	Beed	**−2.49**	−1.09	−1.10	**−2.79**	−1.24	**3.39**	**2.88**	1.92	**2.79**	0.12
6	Betul	**3.81**	**1.97**	**2.86**	**2.41**	**3.56**	1.70	0.68	1.05	**2.80**	−0.26
7	Bhadrachallam	0.82	0.15	0.50	0.01	1.63	−0.76	−0.04	−0.33	**−2.21**	0.25
8	Bidar	**4.14**	**3.34**	**3.27**	**1.99**	**3.83**	**−2.56**	−1.20	−1.67	−0.19	**−3.11**
9	Brahmapuri	1.14	0.55	1.13	1.01	**3.31**	0.78	0.00	0.56	0.89	0.26
10	Buldana	1.33	0.48	1.87	0.09	1.74	0.76	−0.44	1.17	0.57	−0.25
11	Chandrapur	1.70	1.56	1.10	0.86	2.67	0.66	1.28	−0.55	1.07	0.94
12	Chindwara	−1.52	−1.59	−0.36	−0.04	−0.20	−1.46	−1.34	−1.67	−1.38	−0.53
13	Gondia	**3.28**	**2.26**	1.12	**2.35**	**3.52**	−1.36	−0.35	**−2.03**	−0.34	−1.38
14	Gulbarga	**3.83**	**3.58**	**2.96**	**2.53**	**3.37**	1.04	0.11	−0.11	**2.12**	0.00
15	Hanamkonda	0.80	−0.24	−0.26	0.46	**2.15**	1.02	0.27	0.67	**2.32**	−0.60
16	Hyderabad	**2.56**	1.54	**2.31**	1.48	**2.28**	**3.14**	**2.95**	**2.44**	**2.63**	1.55
17	Jagdalpur	**2.48**	1.75	0.33	1.83	**2.93**	−0.75	−1.61	−0.94	1.56	−1.04
18	Kakinada	0.59	1.66	−1.20	0.00	**3.38**	**5.06**	**3.93**	**3.49**	**3.23**	**2.09**
19	Khammam	**−4.92**	**−4.51**	**−4.15**	−1.38	**−2.88**	0.82	0.77	0.93	0.80	−0.67
20	Malegaon	0.02	1.58	1.46	**−2.54**	**2.10**	−1.23	−0.06	**−2.26**	0.43	−1.14
21	Mandla	1.23	0.86	0.35	0.77	**2.74**	1.29	1.51	1.07	0.79	0.69
22	Nagpur	**2.03**	0.18	0.64	0.99	**2.23**	**2.33**	**2.64**	1.25	**2.40**	1.26
23	Nanded	0.02	−0.26	−1.66	0.12	1.95	1.64	1.15	−0.62	1.90	1.36
24	Narsinghpur	1.63	0.20	0.67	1.07	**2.96**	**2.78**	**2.95**	1.33	**3.16**	1.84
25	Nidadavole	**−2.50**	**−2.33**	−1.83	−0.30	−0.14	−1.74	0.52	**−2.86**	**−3.16**	0.00
26	Nizamabad	−0.09	0.62	0.24	0.17	1.53	0.43	−0.05	0.03	1.26	−0.73
27	Osmanabad	**5.41**	**4.59**	**2.92**	**2.66**	**4.77**	**−4.46**	**−2.12**	**−3.54**	**−3.17**	**−4.00**
28	Ozar	−0.46	0.85	−0.02	−1.51	**2.17**	**2.47**	1.45	0.56	**3.62**	0.80
29	Pachmarhi	**−2.68**	−1.82	**−2.21**	−0.41	−1.06	−1.61	−1.48	**−2.16**	0.03	−0.60
30	Parbhani	0.07	−0.02	−0.03	−0.36	1.82	−0.29	−0.73	−0.13	1.78	−1.32
31	Ramgundam	−1.37	−0.95	−0.60	−0.20	1.06	−1.30	−0.61	−1.31	0.35	−1.93
32	Seoni	0.48	0.38	−0.05	−0.33	**2.35**	**5.98**	**5.39**	**5.07**	**5.28**	**5.03**
33	Sironcha	−1.27	−0.30	1.75	−0.76	0.08	−1.88	−0.15	**−2.11**	**−2.02**	0.07
34	Wardha	−0.99	−0.85	−1.71	−0.26	0.33	−0.64	−1.26	−0.61	0.54	1.00
35	Yeotmal	**−2.69**	−1.66	−1.41	−1.53	1.14	−1.16	0.64	−1.01	−1.57	−0.99

Bold numbers are statistically significant at 5% level of significance.

Figure 4 shows the Box-Plot of Theil–Sen's slopes for T_{max} time series at the monthly time scale. The medians of slopes in the months of January, May, July and September till December were above the zero line. This implies that T_{max} in these months had an upward slope of trend line. The maximum (minimum) of the slope values of about 1.20 °C per decade (−0.70 °C per decade) was observed in December (May). In the months of March, April and October the median of slopes was close to the zero line. This implies that about half of the stations in the Godavari basin had positive T_{max} slopes, whereas the other half experienced negative T_{max} slopes.

Figure 5 shows the Box-Plot of Theil–Sen's slopes for T_{max} time series at annual and seasonal time scales. The medians of slopes of T_{max} in different durations: annual; and seasonal: all but one (Monsoon) are located above the zero line, which implies an increasing slope of trend lines for T_{max} in these different durations in the Godavari basin. The maximum value of slopes in T_{max} at the annual time scale was about 0.58 °C per decade, whereas the minimum corresponding value was about −0.61 °C per decade. At the seasonal time scale, the maximum (minimum) value of slopes in T_{max} observed at Post-Monsoon (Monsoon) was 1.1 °C per decade (−0.6 °C per decade). The maximum (minimum) variance of T_{max} time series trend line slopes belonged to the winter (Monsoon) season, indicating the existence of an element of seasonal cycle in T_{max} in the Godavari basin.

3.1.2. *Trends in minimum temperature*

More than 70% of the total stations witnessed no trends in T_{min} at the 5% level of significance at the following time scales: Month-January to June and November to December; and season-winter and post-monsoon (Tables 4 and 6). Therefore, T_{min} remained stable over the Godavari basin at all these time scales. However, increasing (decreasing) trends were observed at about 30% (20%) of the stations in the Godavari basin in July and September (April). Results of seasonal analysis indicated that about 32% (23%) of the stations witnessed

Table 5. Number of sites which witnessed statistically significant increasing, decreasing or no trends in temperature over the Godavari River Basin.

Time scale	Sites with (+) trends			Sites with (−) trends			Sites with No trends		
	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}	T_{mean}	T_{max}	T_{min}
Jan	8	8	6	0	1	0	27	26	29
Feb	4	3	7	2	4	3	29	28	25
Mar	4	3	5	4	3	3	27	29	27
Apr	3	3	3	4	1	7	28	31	25
May	4	1	5	4	2	4	27	32	26
Jun	1	0	4	2	2	4	32	33	27
Jul	6	0	10	2	4	4	27	31	21
Aug	2	1	6	3	3	5	30	31	24
Sep	8	8	11	1	0	5	26	27	19
Oct	6	1	8	2	2	4	27	32	23
Nov	5	10	3	1	2	3	29	23	29
Dec	8	19	1	1	1	3	26	15	31
Yearly	9	8	8	5	6	4	21	21	23
Winter	6	5	7	3	3	1	26	27	27
Pre-Mo	5	5	4	5	2	8	25	28	23
Monso	6	5	11	4	4	5	25	26	19
Post-Mo	6	17	3	1	2	3	28	16	29

Trends were obtained through the nonparametric Mann–Kendall (MK) test after the removal of the significant lag-1 serial correlation effect from all the temperature time series by pre-whitening at 5% significance level.

increasing (decreasing) trends in monsoon (pre-monsoon) season over the Godavari basin. At the annual scale, both increasing and decreasing trends obtained through the MK test at the 5% level of significance were observed at 12 stations (increasing trends: 8 stations and decreasing trends: 4 stations) in the Godavari basin. Figure 6 shows a sample time series of T_{min} and linear trends in T_{min} denoted by the solid curve and dashed line in the months of April and September over two sites each. The spatial distribution of trends of T_{min} witnessed significant increasing trends in the month of September over the Godavari basin, as shown in Figure 7. Similar types of results, i.e. T_{min} experiencing the largest variation in the monsoon season were witnessed over different sites located in northwest and central India (Singh *et al.*, 2008).

Figure 8 shows the Box-Plot of Theil–Sen's slopes for T_{min} time series at the monthly time scale over the Godavari basin. At the monthly time scale, the medians of slopes for all but 1 month (December) were located above the zero line, implying an increasing slope of trend lines in T_{min} for these 11 months. The maximum (minimum) of slope values of about 1.83 °C per decade (−1.65 °C per decade) was observed for T_{min} time series in the month of November (December). However in the months of March, April, May and June, the median of slopes was close to zero line. This implies that about half of the stations had positive T_{min} slopes, whereas the other half experienced negative T_{min} slopes over the Godavari basin. However, the variation of slopes was not the same in these months for the two groups of stations.

Figure 9 shows the Box-Plot of Theil–Sen's slopes for T_{min} time series at annual and seasonal time scales. The medians of slopes at all the five time scales are located above the zero line, implying an increasing slope of trend lines for T_{min} time series at the annual scale and four different seasons. The maximum (minimum) of the slope values of about 1.1 °C per decade (−0.60 °C per decade) was observed for T_{min} time series for the annual duration over different sites in the Godavari basin. Similarly, in seasonal time series of T_{min}, the maximum (minimum) of the slope values of about 1.7 °C per decade (−1.1 °C per decade) was observed for T_{min} in the post-monsoon season. The maximum and minimum variance of trend line slopes belonged to the post-monsoon and monsoon seasons, respectively, which indicates the presence of an element of a seasonal cycle in T_{min} over the southern peninsular basin in India.

3.1.3. *Trends in mean temperature*

At least 26 stations (25 stations) out of 35 stations witnessed no trends in T_{mean} in all the 12 months (in all the four seasons). Similarly, about 60% of the total stations witnessed no trends in T_{mean} for the annual duration (Table 5). T_{mean} remained more or less stable at almost all the time scales over the Godavari basin. However, increasing (decreasing) trends in T_{mean} were witnessed at about eight stations (about four stations) at different scales: annual; January, September and December (annual; March to May). Figure 10 shows the Box-Plot of Theil–Sen's slopes for T_{mean} time series at monthly time scale. The medians of slopes for all the 12 months but for June were located above the zero line. This implies that the T_{mean} had an upward slope of trend line in these months. The maximum value of slopes in T_{mean} (1.0 °C per decade) was observed in the months of November and December, whereas the minimum value (−0.55 °C per decade) was observed in the months of June and October. It was observed that the median of slopes was close to the zero line in the months of April, May and August.

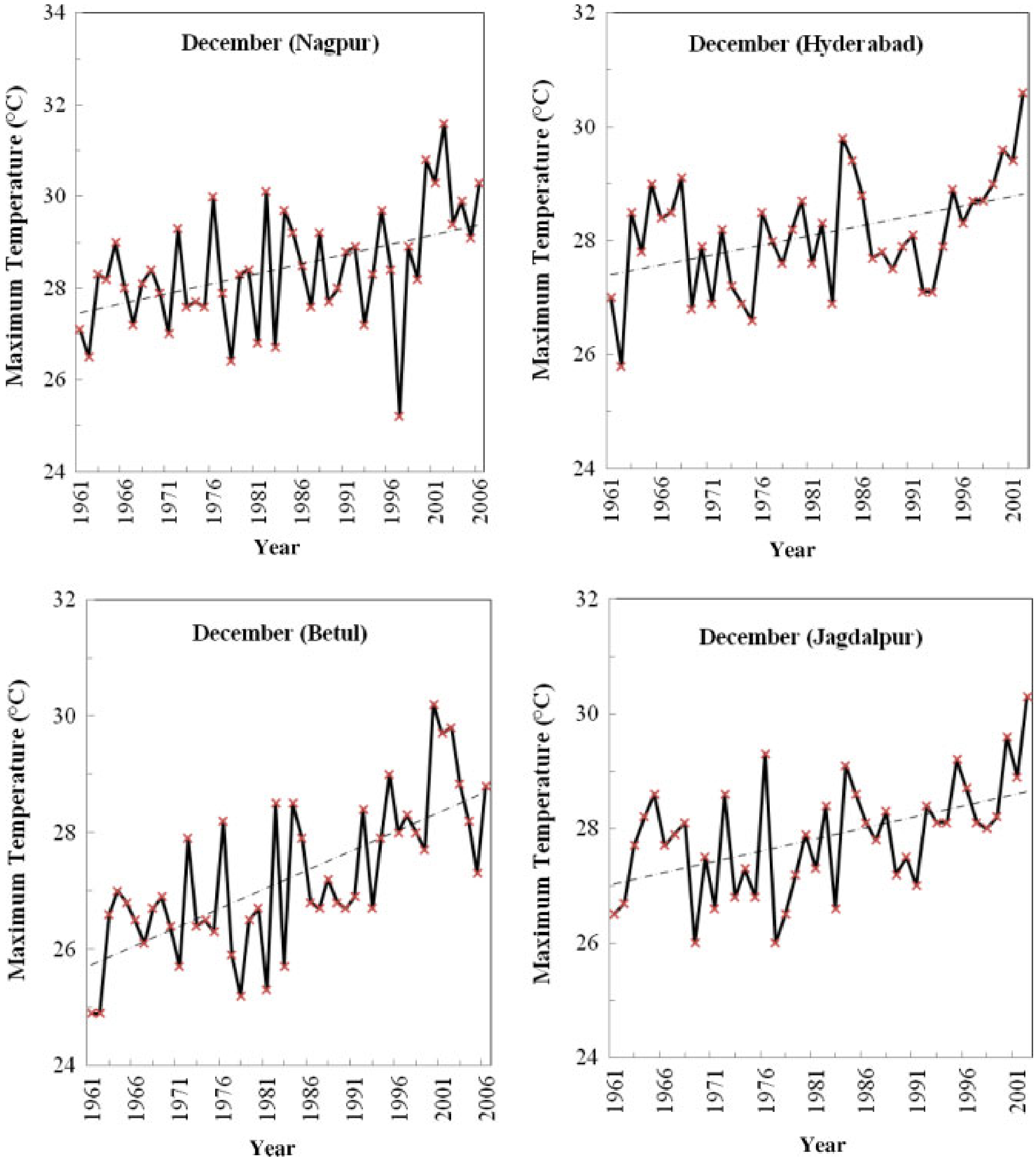

Figure 2. Time series of maximum temperature for different sites in December.

This implies that about half of the stations experienced a positive T_{mean} slope and the other half experienced a negative T_{mean} trend. However, the variation of slopes was great for January–June, August and October–December.

Figure 11 shows the Box-Plot of Theil–Sen's slopes for T_{mean} time series in annual and seasonal time scales. The medians of slopes of T_{mean} for the annual duration and all four seasons were located above the zero line. For the annual duration, the maximum (minimum) value of slope in T_{mean} was about 0.60 °C per decade (−0.41 °C per decade). At the seasonal time scale, the maximum (minimum) value of slope in T_{mean} was found to be about 1.0 °C per decade (−0.57 °C per decade) in the post-monsoon (monsoon) season. The maximum (minimum) variance of the T_{mean} time series trend line slopes belonged to the post-monsoon (monsoon) seasons over the Godavari basin.

3.2. Testing the homogeneity of trend in air temperature

To examine the changes in trends more closely, van Belle and Hughes' test of trend homogeneity was applied to the temperature series at monthly and seasonal time scales. This test was applied to Mann–Kendal's Z statistic and results of homogeneity test for T_{max}, T_{min} and T_{mean} at monthly and seasonal time scales in the Godavari basin are shown in Tables 7 and 8, respectively. It can be seen that for the maximum air temperature, months were found to be heterogeneous, i.e. calculated Chi-square for months, having $12 - 1 = 11$ degrees of freedom, was greater than the corresponding tabulated chi-square value at the 5% level of significance, i.e. $\chi^2_{\mathrm{month},m-1}$ was greater than $\chi^2_{0.95,11}$ (numerically 184.3 > 19.7). Therefore, it can be concluded that trends in maximum air temperature in different months of a year were not

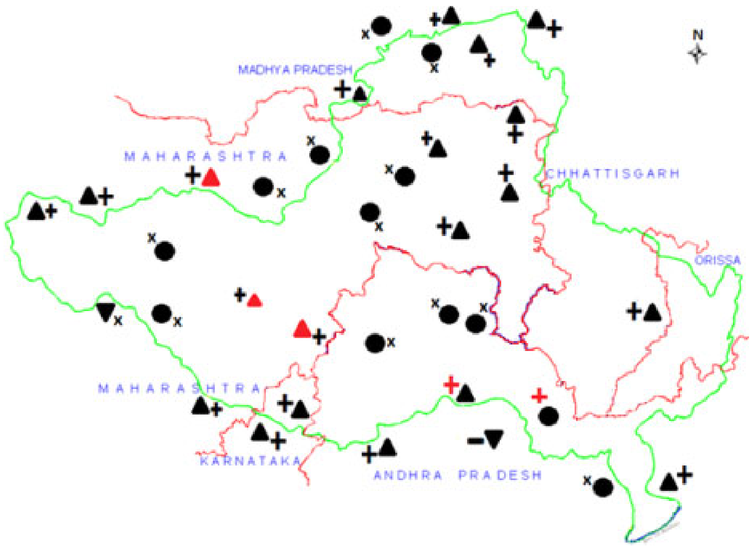

Figure 3. Trends in maximum temperature in the post-monsoon season and in the month of December over Godavari river basin. ▲(▼) and ▲(▼) denote increasing (decreasing) trend obtained through MK test in post-monsoon season at 5 and 10% level of significance, respectively. ●denotes no trend at 10% level of significance in post-monsoon season. ✚(▬) and ✚(▬) denote increasing (decreasing) trend obtained through MK test in the month of December at 5% and 10% level of significance, respectively. ✖denotes no trend at 10 % level of significance in the month of December.

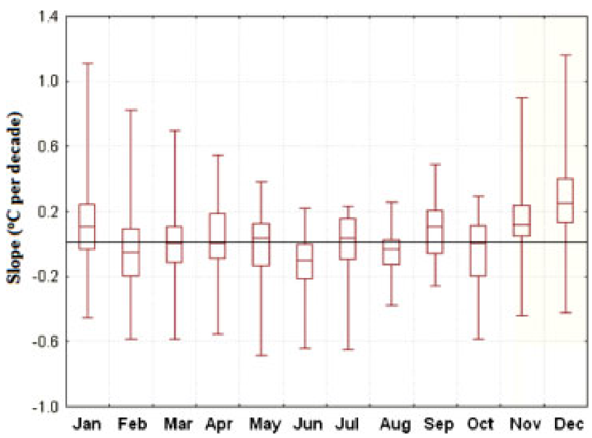

Figure 4. Box-Plot of Theil–Sen's slopes for T_{max} time series in monthly time scale.

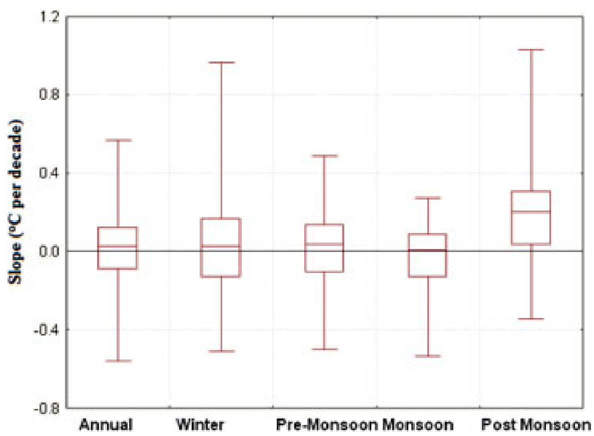

Figure 5. The Box-Plot of Theil–Sen's slopes for T_{max} in different time scales.

homogeneous in the Godavari basin; that is, trends in January were different from those in February or March, and so on. It is worthwhile to note that 27 of 35 stations had witnessed negative trends in the month of June, while 30 stations experienced positive trends in December. This implies that temperature trends of a particular month were different from the trends witnessed in temperature in other months, for example, trends in June were different than the trends in December for the entire Godavari basin.

Similarly, stations were also found to be heterogeneous in the case of maximum temperature, i.e. calculated Chi-square for stations (478), having 34 (=35 − 1) degrees of freedom, was greater than the corresponding tabulated Chi-square value (48.6) at the 5% level of significance, i.e. $\chi^2_{\text{station},k-1}$ was greater than $\chi^2_{0.95,34}$ (numerically 478.1 > 48.6). Therefore, it can be concluded that the trends of maximum air temperature were not homogeneous for different stations during the year. This is noticeable from the Z (test statistic) values of various stations, for example, the mean Z of station Osmanabad (2.33) was positive and significant at the 1% level of significance, but the corresponding value for station Khamam (−2.18) was negative and significant at 5% level of significance. Such opposite signs yielded heterogeneity in the trends for the selected stations in the Godavari basin. However, no significant station–month interaction was detected, i.e. calculated Chi-square for 374 (= (35 − 1) × (12 − 1)) degrees of freedom was less than the corresponding tabulated Chi-square value (48.6) at the 5% level of significance. This seems to be the effect of existence of serial correlation in the temperature

Table 6. Z values obtained for minimum temperature over sites of Godavari River Basin.

S. No.	Name of site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Ahmednagar	−1.32	**−1.98**	**−4.35**	**−3.65**	−0.32	−0.45	−0.06	0.26	1.38	−0.94	−0.18	**−2.29**
2	Akola	1.69	1.73	0.23	0.45	0.60	−0.16	1.39	0.44	**2.24**	1.91	0.38	−0.15
3	Amraoti	−1.00	−1.22	−1.41	**−3.52**	**−3.67**	**−3.75**	**−4.75**	**−4.89**	**−3.37**	**−4.60**	**−2.50**	−1.19
4	Aurangabad	**3.64**	**3.95**	**3.88**	**2.92**	**4.73**	**3.84**	**4.37**	**4.28**	**4.77**	**2.82**	1.84	1.44
5	Beed	**2.97**	**2.05**	1.78	−0.11	**2.46**	1.62	**2.39**	**2.26**	1.90	**2.00**	1.20	0.15
6	Betul	0.53	0.44	−0.49	0.48	**2.71**	1.67	**2.10**	1.26	1.66	1.40	0.81	−0.64
7	Bhadrachallam	0.16	0.64	0.29	−0.28	−1.33	−1.84	**−2.13**	−1.89	−1.84	−1.45	0.29	0.84
8	Bidar	−0.41	−1.35	−1.90	−0.75	−1.23	0.51	1.42	1.46	0.83	**−2.90**	**−2.38**	**−2.16**
9	Brahmapuri	−0.21	0.37	−0.03	−0.13	0.99	0.50	1.80	0.46	1.23	0.25	0.92	−0.36
10	Buldana	−0.26	−0.58	0.32	0.47	1.05	1.14	0.87	0.76	1.42	−0.56	0.03	−0.55
11	Chandrapur	1.32	0.70	0.38	−1.33	0.01	−0.83	−0.59	−0.56	0.93	**2.10**	1.25	0.81
12	Chindwara	−0.98	−1.51	−1.72	−0.80	−1.51	**−2.39**	−1.94	−1.15	−0.42	0.61	−0.13	−0.63
13	Gondia	−0.83	−0.26	−0.20	**−2.27**	−1.72	−0.53	−1.09	−1.55	**−2.44**	0.57	0.44	−1.42
14	Gulbarga	0.31	−0.40	0.89	−1.12	−1.06	−0.40	**2.15**	1.91	**2.39**	0.53	1.03	−0.34
15	Hanamkonda	−0.09	0.75	1.50	0.80	0.16	−0.43	1.67	1.02	**3.21**	**3.23**	0.65	−0.96
16	Hyderabad	**2.45**	**3.01**	**2.55**	1.78	**2.09**	1.48	1.45	0.73	**3.22**	**2.76**	**2.48**	0.51
17	Jagdalpur	−0.88	−1.39	−1.36	−0.22	−0.58	0.72	**2.25**	1.54	1.69	0.46	−0.20	−1.39
18	Kakinada	**3.95**	**2.73**	**3.54**	**2.21**	1.40	1.21	**2.26**	**2.01**	**3.28**	**3.66**	**2.88**	1.47
19	Khammam	0.30	1.50	1.35	0.69	−0.16	−0.59	1.68	−0.66	**2.63**	1.08	0.30	−0.22
20	Malegaon	−0.24	0.03	**−2.18**	**−3.04**	−1.50	−0.86	0.21	0.23	0.37	0.14	−0.13	−1.42
21	Mandla	0.74	1.86	1.59	0.90	0.85	0.40	0.41	−0.29	−0.19	0.46	0.71	1.13
22	Nagpur	1.54	**2.89**	**2.26**	0.55	0.23	0.81	**2.72**	0.85	**2.05**	1.86	1.36	1.10
23	Nanded	1.26	−0.47	−0.71	0.06	−0.53	0.37	1.14	0.70	0.77	1.63	1.71	0.16
24	Narsinghpur	**1.97**	**2.30**	1.16	0.41	1.06	0.51	1.92	**2.45**	1.92	**2.48**	1.55	0.76
25	Nidadavole	1.48	1.22	−1.69	**−3.25**	**−3.27**	−1.73	−1.53	**−2.81**	**−2.75**	**−2.27**	0.82	−0.08
26	Nizamabad	−0.14	−0.40	−1.02	−0.02	0.90	−0.44	1.68	0.95	1.00	0.91	−0.41	−1.41
27	Osmanabad	−0.78	**−4.13**	**−2.17**	**−2.09**	**−3.75**	**−3.42**	**−4.21**	**−3.86**	**−3.44**	**−2.29**	**−3.04**	**−4.54**
28	Ozar	0.76	1.40	0.56	−0.33	1.94	**2.90**	**3.73**	**2.74**	**3.32**	1.79	0.99	−0.33
29	Pachmarhi	−0.72	−1.38	0.05	**−1.96**	−0.97	−1.08	0.49	0.39	0.08	1.36	0.24	−0.36
30	Parbhani	0.26	−0.38	−1.85	−0.99	1.63	**2.45**	**2.25**	1.38	**2.27**	−0.95	−0.29	−1.02
31	Ramgundam	−0.65	−0.78	−1.60	−1.29	−0.85	0.03	1.73	0.66	0.93	−0.44	−0.82	−1.67
32	Seoni	**5.47**	**3.94**	**3.88**	**4.84**	**3.90**	**3.51**	**4.69**	**4.16**	**4.66**	**4.48**	**4.47**	**5.22**
33	Sironcha	−1.23	0.18	−0.27	−1.23	**−3.04**	**−2.16**	**−3.01**	**−2.15**	**−2.28**	0.13	0.06	−0.41
34	Wardha	−0.78	**−2.07**	−1.29	−0.10	−0.12	−0.43	−0.28	−0.55	0.25	0.55	1.07	1.02
35	Yeotmal	0.23	0.27	−0.55	−1.52	−0.76	−0.77	−0.97	**−2.01**	−0.85	−1.14	−1.32	−0.63

Bold numbers are statistically significant at 5% level of significance.

series for consecutive months. In this study, the monotonic trends of months were heterogeneous and the trends for stations were also heterogeneous. It is not impossible to have the interaction of stations and months to be homogeneous for the whole basin.

Table 7 also shows the results of analysis of the homogeneity of trends for monthly minimum temperature and monthly mean temperature for the entire study area. Exactly similar kinds of results of homogeneity of trends for the monthly minimum and mean temperatures (heterogeneous trends for stations and months, but non-significant station–month interaction) were obtained over the whole Godavari basin. These findings for maximum, minimum and mean temperatures in the Godavari basin are in the agreement with Gan (1995) who found heterogeneous trends in maximum air temperature for either stations or months but homogeneous trends for station–month interaction in six groups of stations located in Canada and north-eastern United States. However, Table 8 presents results from testing the homogeneity of trends in maximum, minimum and mean air temperatures at the seasonal time scales in the Godavari basin. The seasons for trends in the maximum temperature were found to be heterogeneous, i.e. trends in maximum temperature in the pre-monsoon season were not the same as the corresponding trends in maximum temperature in the post-monsoon season at the % level of significance (Table 8). The trends in the maximum temperature in the post-monsoon were comparatively larger than the trends in the maximum temperature in the pre-monsoon season. Similarly, the stations were found to be heterogeneous, i.e. the trends in seasonal maximum air temperature of a particular station, for example, Osmanabad (having an overall average value of Z as 3.73), differed from the trends at other stations, i.e. Khamam (having overall average value of Z nearly −3.23). Such opposite trends, detected at different stations, yielded heterogeneity in the air temperature trends for the entire Godavari basin. However, the station–season interaction was homogeneous. These results were similar to the results of trend homogeneity for monthly air temperature for the whole basin. Similarly, the same kinds of results of homogeneity tests for the seasonal minimum and mean temperatures (heterogeneous trends for stations and seasons, but non-significant

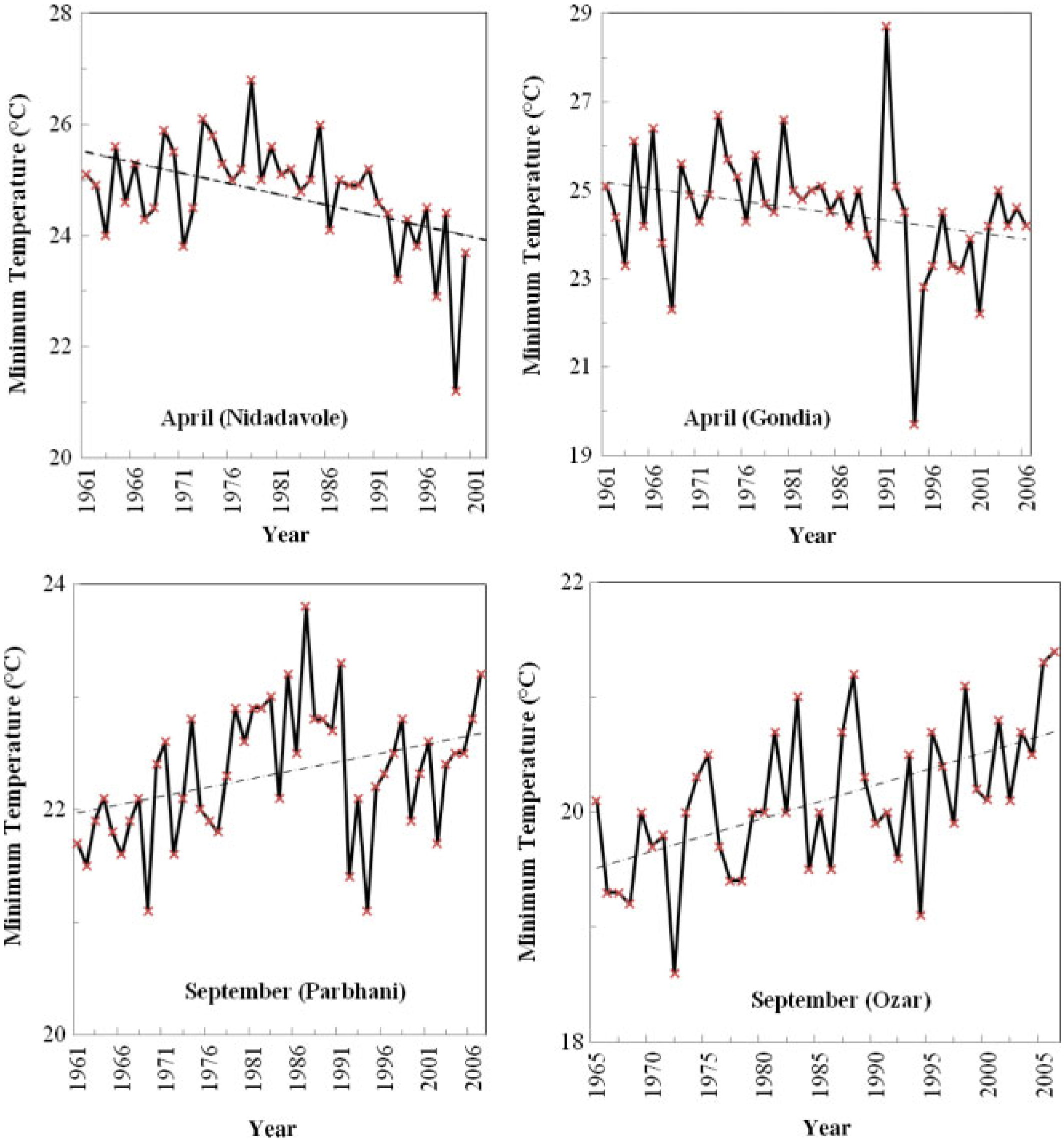

Figure 6. Time series of minimum temperature in different time scales for different sites.

station–season interaction) were obtained over the entire Godavari basin.

3.3. Global warming, climate change and water availability in the Godavari basin

It is worthwhile to mention that the six sub-basins of the Godavari River, i.e. the Pranhita, the Manjara, the Upper Godavari, the Lower Godavari, the Maner and the Indravati, witnessed warmer climate during the month of December because of T_{max} increases over these sub-basins. Similarly, few other sub-basins witnessed warmer climate in different time scales over the Godavari river basin. It may be interested to see if warmer climate in the Godavari basin may lead to any water-shortage for about 65 million people who depend on the waters of the Godavari River for their well-being and livelihood. Also, the projected basin-population, i.e. about 101 million in the 2051, will further put pressure on the river, and may ultimately threaten the existing water-sharing agreements of this peninsular river basin among the six co-basin states for the beneficial uses of the Godavari waters (Jhajharia, 2012). Thus global warming will have far reaching consequences on the general public, mainly the people living below poverty line, and the indigenous societies who depend more on the natural resources. Providing clean drinking freshwater to the under-privileged or common public will be one of the important societal, environment and political issues of the 21st century, and more so when the freshwaters through the transboundary river basins are involved.

It is generally expected that an increase in evaporation, an important component used in yield estimation of a basin, will take place in the warmer climate over the river basin. The rate of evaporation in the storage reservoirs is very useful in estimation of basin's present and future water requirements, and therefore, the evaporation in any river system plays an important role in the reservoir design and the operation of reservoirs especially in the

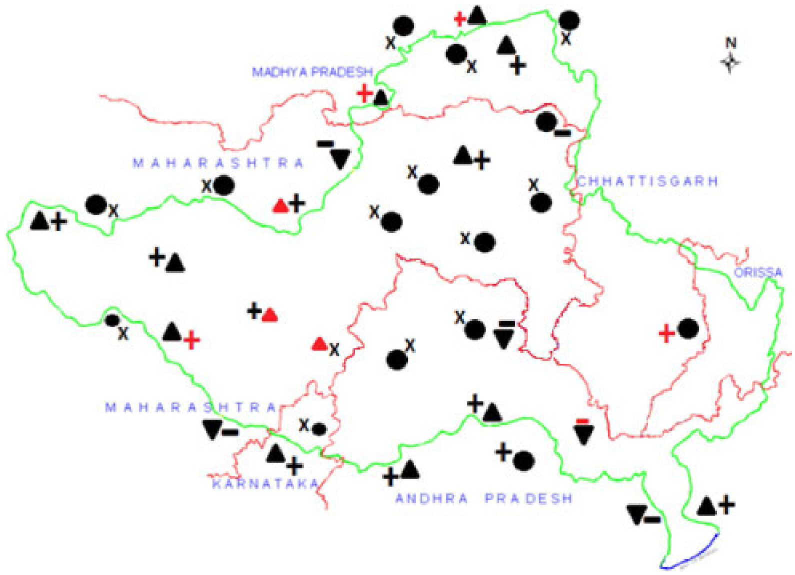

Figure 7. Trends in minimum temperature in the monsoon season and in the month of September over Godavari river basin. ▲(▼) and ▲(▼) denote increasing (decreasing) trend obtained through MK test in post-monsoon season at 5 and 10% level of significance, respectively. ●denotes no trend at 10% level of significance in the monsoon season. +(−) and +(−) denote increasing (decreasing) trend obtained through MK test in the month of September at 5 and 10% level of significance, respectively. ×denotes no trend at 10 % level of significance in the month of September.

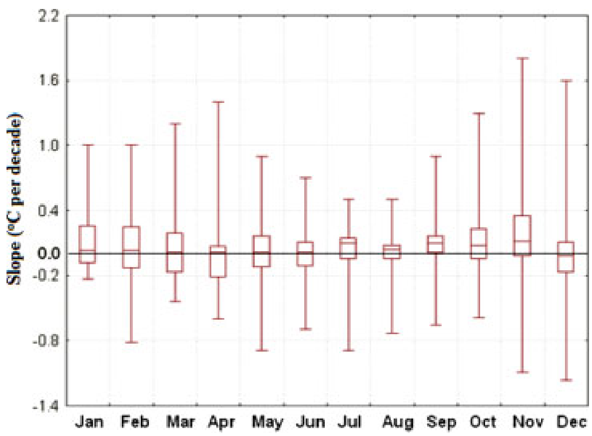

Figure 8. Box-Plot of Theil–Sen's slopes for the monthly time series of T_{min} over Godavari basin.

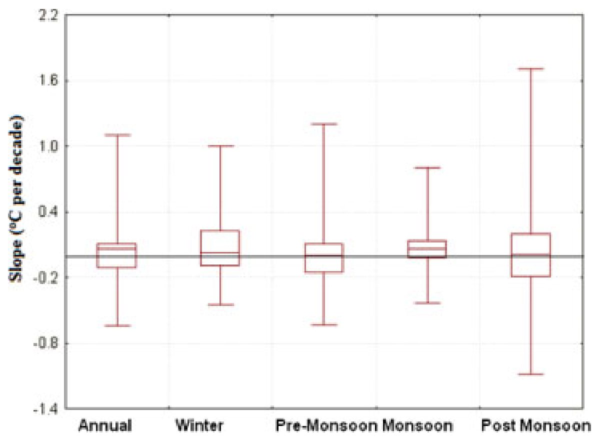

Figure 9. Box-Plot of Theil–Sen's slopes for T_{min} in different time scales over Godavari basin.

regions of high evaporation (Loaiciga, 2002). Recently, McVicar *et al.* (2012) also carried out the global review on evaporation and reference evapotranspiration (ET) in view of the importance of the evaporation in various activities, like, irrigation planning and reservoir's yield estimation, etc. In the Godavari basin, the rate of pan evaporation (Epan) is measured at six different sites, namely, Aurangabad, Betul, Hyderabad, Jagdalpur, Nagpur and Ramagundam. The records of the Epan provided by the IMD show that the rate of Epan varies from 1800 to 2440 mm on annual time scale in different parts of the Godavari basin.

It is worthwhile to note that the Epan decreases are witnessed at all but one (Jagdalpur) sites in annul and almost all the four seasons over the Godavari basin. McVicar *et al.* (2012) report that the Epan have decreased over the Godavari River basin at the rate of 25.3 mm annum^{-2} during the last three decades. It is interesting to note that the Epan deceases are observed in all the four seasons in spite of the general rise in temperatures over the basin, which indicates that some other climatic parameters may be more strongly influencing the process of evaporation over the Godavari basin. To solve this paradoxical situation, we first searched the trends in the wind speed over the Godavari basin. Strong deceases in wind speed were observed in all the four seasons and in the annual time scale for all the above-mentioned six sites located in the basin. The strong decreases in wind speed indicate the presence of the 'stilling' phenomenon over the Godavari basin, which may possibly be one of the reasons

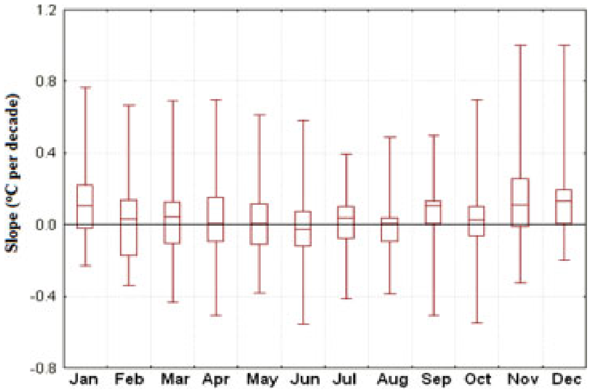

Figure 10. Box-Plot of Theil–Sen's slopes for T_{mean} time series in monthly time scale.

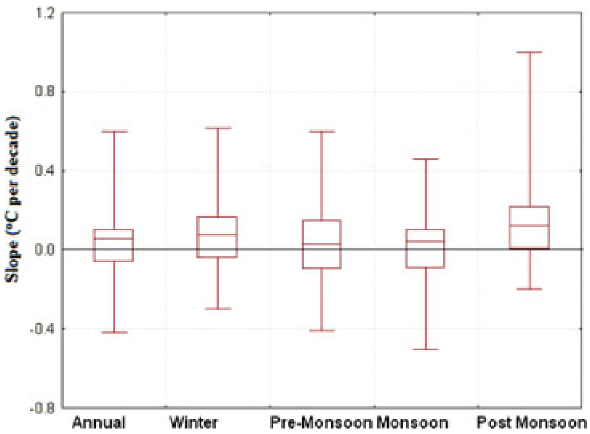

Figure 11. The Box-Plot of Theil–Sen's slopes for T_{mean} in different time scales.

for the observed decreases in Epan. McVicar *et al.* (2012) also report that the wind speed decreases at the rate of (−) 0.035 m s^{-1} $annum^{-1}$ during the period from 1961 to 2004 over 17 different sites of Godavari River basin are an important contributing factor to the observed decline in Epan over the southern peninsular basin of India (see Supplementary Material Table 4 of McVicar *et al.*, 2012). Trends in mean relative humidity were also examined at all the six sites located in the Godavari River basin. All but one (Hyderabad) site witnessed statistically significant increasing trends in mean relative humidity, mostly at 1% level of significance, over the Godavari basin. The observed increases in humidity may lead to the decrease in evaporation process as the atmosphere over and above the Godavari basin may already be saturated with the water molecules leaving less scope for the evaporation process. Similarly some other studies showed that despite increase in temperature, evaporation have decreased in different parts of the world. McVicar *et al.* (2012) reports that observations of Epan are found to have declining trends across the globe as well. Therefore in view of the above fact, it is imperative to mention that the decreases of evaporation in the reservoirs of the Godavari River basin under the well-reported warming, 'stilling' phenomenon and increases in mean relative humidity taking place over the entire peninsular river basin of India may have slightly increased the total yield of the Godavari basin. Recently, Jain and Kumar (2012) reported statistically significant decreasing trends in total rainfall (4.0 mm decade in pre-monsoon season) and rainy days (3 and 2 d $decade^{-1}$ in annual time scale and in monsoon season, respectively) over the Godavari River basin. They reported statistically non-significant decreasing trends in rainfall in annual duration (monsoon season) at the rate of about 27.3 (26.4) mm/decade over the entire Godavari basin. Therefore, the rainfall decreases along with the increase in air temperature proved that the climate over the Godavari basin is warming and drying, which may affect the water availability in the basin. However, the Epan decreases may slightly compensate the decrease in water availability caused due to the rainfall decreases in different time scales over the Godavari River basin.

4. Conclusions

We investigated trends in temperature data at annual, monthly and seasonal time scales over the Godavari basin, a southern peninsular river basin, India, using the nonparametric MK test after removing the effect of significant lag-1 serial correlation by pre-whitening. T_{max} (T_{min}) remains practically trendless at different time scales: monthly-all except December (all except July and

Table 7. Partitioning of the sums of squares for testing trend homogeneity in monthly temperature.

Source	Chi-square T_{max}	Chi-square T_{min}	Chi-square T_{mean}	d.f.	Chi-square Table	Significance
Total	991.7	1486	1088	420	468.3	sig-5%
Homogeneity	953.2	1451	1034	419	467.3	sig-5%
Months	184.3	64.3	81.7	11	19.7	sig-5%
Stations	478.1	997.6	704.1	34	48.6	sig-5%
Station-month	290.8	389	248.2	374	419.7	ns-5%
Trend	38.5	35.2	53.8	1	3.8	sig-5%

d.f., denotes degree of freedom.

Table 8. Partitioning of the sums of squares for testing trend homogeneity in seasonal temperature

Source	Chi-square			d.f.	Chi-square table	Significance
	T_{max}	T_{min}	T_{mean}			
Total	486.5	569.4	486.9	140	168.2	sig-5%
Homogeneity	447.9	555.2	449	139	167.1	sig-5%
Seasons	53.2	26.5	15.6	3	7.8	sig-5%
Stations	321.0	434.7	362	34	48.6	sig-5%
Station- season	73.7	93.9	71.4	102	125	ns-5%
Trend	38.6	14.2	37.9	1	3.8	sig-5%

d.f., denotes degree of freedom.

September); and seasonal-all four seasons except post-monsoon (all the four except monsoon) over Godavari basin. Rupa Kumar *et al.* (1987) also reported that the warming in the Indian temperature mainly resulted from increasing temperatures up to the late 1950s, after which temperature remained nearly stable over India. Significant increasing trends witnessed in T_{max} (in December and post-monsoon) and T_{min} (in July and September and monsoon) indicate the presence of an element of seasonal cycle in temperature over the Godavari basin. However, decreasing trends are witnessed in T_{min} in April and in the pre-monsoon season at seven and eight stations, respectively, out of 35 selected sites in the Godavari basin. Results of the spatial and temporal homogeneity of trends tested by the method of Van Belle and Hughes showed that both months and stations trends were not homogeneous for temperature in the basin. The Epan decreases were witnessed at all but one site in almost all the time scales over the Godavari basin. In spite of the general rise in temperatures over the basin, the Epan deceases were observed in all the four seasons because of strong deceases in wind speed and significant increases in mean relative humidity over the Godavari basin.

Our results may have potential for the adoption of climate-related changes in the GWDT in future by the policy makers as currently the award related to the optimal utilization of Godavari River, currently shared by six states, is adopted permanently. Singh *et al.* (2008) stated that the awareness about the hydrological response of a river basin under changed climatic conditions may be helpful in modifying the present practices of planning, designing and management of water resources projects. Moreover a climate related study at the basin scale will help in combating the adverse impacts, if any, on rainfed agriculture and forest dependent tribal local communities due to climate change induced changes in the Godavari basin.

Acknowledgements

The authors acknowledge the India Meteorological Department, Pune for providing the data used in this study. The authors also gratefully acknowledge the kind help of Mr. Olgay Sen (ITU, Istanbul) Turkey in the revision work. The authors thank the three anonymous reviewers and Professor D. G. Mcgregor (Editor, IJOC) for constructive comments, which ultimately helped in improving this article.

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