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Hydroclimatic changes in a climate-sensitive tropical region

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ABSTRACT: In this study, the hydroclimatic variables of Orissa, a tropical region in eastern India, and the cyclonic disturbances over the Bay of Bengal were analysed to assess trends and variations using nonparametric statistical procedures. The trend results revealed pronounced warming pattern in the monthly maximum temperatures and cooling pattern in the monthly minimum temperatures for the period 1987–2001. The differential forcing mechanisms of greenhouse gases and aerosols were considered as a reason for the temperature extremes. For the period 1960–2003, significant upward shift was observed in June rainfall, particularly over the region where orography influences the rainfall. This study provides strong evidence suggesting the occurrence of abrupt shifts in the cyclonic disturbances over the Bay of Bengal. For the period 1901–2003, the monsoon depressions and cyclonic storms, which contribute a substantial amount of rainfall in Orissa and central India, exhibited significant downward abrupt shifts during 1971 and 1950, respectively. However, severe cyclonic storms in the post-monsoon season showed significant upward shift during the 1961–1965 pentad. More cases of non-significant decreasing trends were observed in the monsoon rainfall for the period 1980–2003 in spite of high inter-annual variability. These trends may be attributed to the significant downward shift in the monsoon depression from 1983 onwards analysed for the period 1960–2003. Results also show that the observed trends are highly sensitive to the season of analysis and the period of records. Copyright © 2012 Royal Meteorological Society

KEY WORDS hydroclimatic variables; cyclonic disturbances; Bay of Bengal; anthropogenic activity; nonparametric test

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1. Introduction

Climate change and variability, due to their extensive impacts on society and environment, have attracted the attention of the scientific community and of the general public in recent years. It is projected that global climatic change in the Indian sub-continent would intensify the mean summer monsoon rainfall (June–September), leading to an increase in the inter-annual variability in rainfall (May, 2004; Kumar *et al*., 2006; Kripalani *et al*., 2007). The summer monsoon rainfall primarily modulates the hydrology of the Indian sub-continent. A small change in the monsoon rainfall can have profound economic and environmental impacts due to the dependency of the population in India (∼ 68% of over one billion population) on the climate-sensitive agriculture and allied sectors. The frequent occurrence of climatic extremes in recent years gives rise to the question whether the characteristics of hydroclimatic variables are also changing. Therefore, it is pertinent to identify and ascertain the changes that will help in judicious management of the natural resources in the context of population growth, urbanization, and industrialization.

Previous studies on hydroclimatic changes in India have focused on air temperatures and rainfall, rather than the hydrologic variables. Air temperatures show a general warming trend across the country although the trend magnitudes have exhibited both spatial and temporal differences (Arora *et al*., 2005; Kothawale and Kumar, 2005; Fowler and Archer, 2006). However, extensive studies on rainfall patterns (Rupa Kumar *et al*., 1992; Sen Roy and Balling, 2004; Goswami *et al*., 2006; Basistha *et al*., 2008) provide no evidence of a significant trend in the annual rainfall over the country. However, significant increasing and decreasing trends were observed in different statistics of rainfall in different regions of the country due to the large spatial and temporal variability of the climate of India (Guhathakurta and Rajeevan, 2008). While the climate of the Himalayan range is sub-freezing, the coastal regions experience a tropical climate. Furthermore, the northeastern states are high rainfall regions in contrast to the arid climate of the northwestern parts. While one part of the country experiences a flood, the other part reels under a drought, leading to the masking of the climatic rigours in a country-wide analysis. The lack of consistent patterns, therefore, highlights the need for a more detailed regional analysis to explore the local characteristics of changes in hydroclimatic variables.

In general, the spatial and temporal variability of the monsoon rainfall in India is due to the interaction of synoptic disturbances, which develop over the Bay of Bengal and move towards a west-northwesterly direction along the monsoon trough, and the basic monsoon flow (Mohapatra *et al*., 2003). Therefore, the state of Orissa (Figure 1) is a key area for the hydroclimatic studies as it

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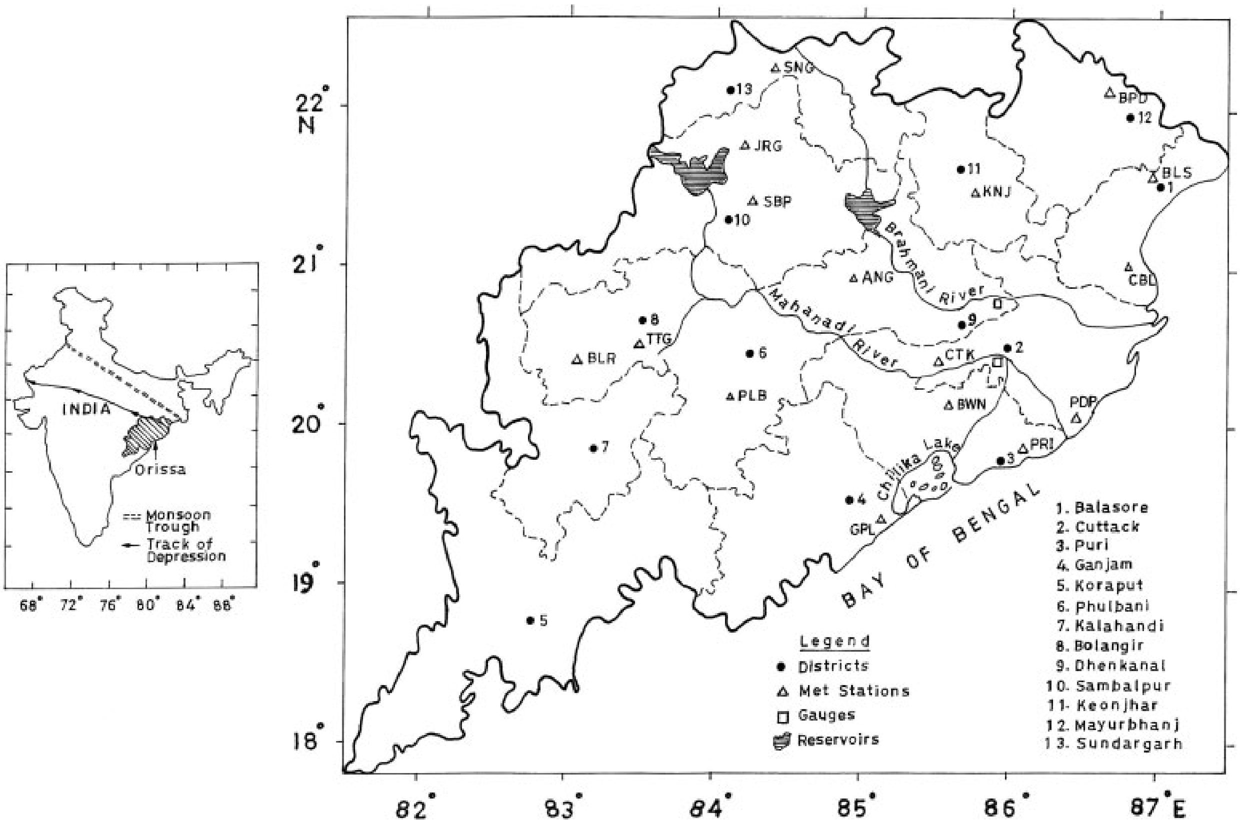

Figure 1. The map shows the geographic location of the study area, Orissa (shaded in the insert map of India) adjacent to the northwest Bay of Bengal.

is located (17°47′–22°33′N latitude and 81°31′–87°30′E longitude) adjacent to the weather-forming zone of the Bay of Bengal within the latitude belt of 15°–25 °N. Since the cyclonic disturbances involve circulations over thousands of kilometres, the atmosphere of Orissa also forms a link with the entire planetary circulation system (CES, 2007). A minor change in the pressure anomaly can have a profound hydrological impact on the landmass of Orissa. The vulnerability of the state of Orissa is evident from the frequent occurrence of climatic extremes in the form of droughts, floods, super cyclone, and heat waves in recent years (Swiss, 2002; Mirza, 2003). Furthermore, Ghosh and Mujumdar (2007) had predicted severe drought conditions for the state of Orissa because of the greenhouse gas warming effect and the coastal position of the region.

The main objective of this study is to investigate the trend and variability in the hydroclimatic variables of Orissa. To achieve this objective, nonparametric statistical procedures were employed to analyse the air temperatures, relative humidity, rainfall, synoptic-scale disturbances, and streamflow datasets available for different periods of records. The nonparametric methods of trend analysis are robust to the hydroclimatic extremes (outliers) and also do not require the distributional assumptions of the time series. However, the usage of nonparametric method for the analysis of hydroclimatic changes in India is limited (Arora *et al.*, 2005; Narisma *et al.*, 2007; Basistha *et al.*, 2008). It is also important to appropriately characterize the trend in hydroclimatic variables as a monotone change or a step change because of the different physical processes that drive such changes (McCabe and Wolock, 2002). The presence of a monotone trend is likely to continue in the future. However, the presence of a shift suggests that a new climate regime is likely to remain relatively constant until a new shift occurs. Furthermore, the presence of an abrupt shift provides an evidence of climate change (Matalas, 1997). High inter-annual variability in hydroclimatic variables also increases the difficulty involved in detecting trends. In this study, the presence of shifts and changes in variability were examined in the hydroclimatic variables of Orissa. The following section describes the dataset of hydroclimatic variables. The methods for the identification of trends and variability are outlined in Section 3. The results are discussed in three sub-sections under Section 4. The concluding remarks are presented in Section 5.

2. Data

The Indian Meteorological Department (IMD) and the state revenue department maintain the observatories and disseminate the meteorological data in the form of published reports after scrutinizing the data quality. The monthly maximum temperature ($T_{\max}$), monthly minimum temperature ($T_{\min}$), monthly average relative humidity recorded in the forenoon (RH_{fn}) (08 : 30 IST), and monthly average relative humidity recorded in the afternoon (RH_{an}) (17 : 30 IST) were obtained from the report 'Climatological data of Orissa' (published by the Directorate of Economics and Statistics, Government of Orissa). Complete records were available for 16 of the 18 stations for the period 1987–2001. Figure 1 shows the location of these stations. The stations Balasore (BLS), Chandbali (CBL), Paradeep (PDP), Cuttack (CTK), Puri (PRI), Bhubaneswar (BWN), and Gopalpur (GPL) represent the coastal zone of the state; the stations Angul (ANG), Jharsuguda (JRG), Titlagarh (TTG), and Sundergarh (SNG) represent the industrial zone; the stations Phulbani (PLB) and Keonjhar (KNJ) are situated in high topography areas; the stations Sambalpur (SBP) and Bolangir (BLR) represent the parts of the central table physiographic zone; and Baripada (BPD) represents the northern plateau near the monsoon trough.

The monthly rainfall time series of 13 administrative districts of Orissa (Figure 1) available for the period 1960–2003 were obtained from the publication series 'Climatological data of Orissa'. The district average of rainfall data was calculated from 438 rain gauge stations with a proper spatial representation of the study area. This dataset is also used for the identification of vulnerable zones for drought and flood contingency planning in the state. Changes in cyclonic disturbances were investigated as they contribute significantly to the rainfall in Orissa. The IMD has classified these disturbances as depression, cyclonic storm, and severe cyclonic storm based on the maximum sustained wind speed of 17–33 knots, 34–47 knots, and more than 47 knots, respectively. While the depression and cyclonic storm form over the Bay of Bengal in the monsoon season, most of the severe cyclonic storms form in the post-monsoon months of October and November and also in the pre-monsoon month of May. These dataset were extracted from the IMD reports 'Tracks of storms and depressions in the Bay of Bengal and Arabian sea' for the period 1901–1990. Singh and Loe (2007) and Singh (2007) provided the recent dataset of cyclonic disturbances.

The water resource department of Orissa provided the annual maximum streamflow volume data of the Mahanadi (Naraj station) and Brahmani (Pankapal station) Rivers for the period 1964–2003. The Mahanadi is the largest river in Orissa, which drains 42% of the geographical area of the state (155 707 km^2) with a length of 494 km. This river carries an annual runoff volume of 66.88×10^9 m^3. The Brahmani River drains 14% of the geographical area of the state with a length of 541 km. The annual runoff volume of the Brahmani River is 28.48×10^9 m^3. Both the gauging stations are important for flood management in the coastal deltaic region and are also situated at the mouth of the rivers before making deltas and meeting the sea.

3. Methodology

The linear regression method is commonly used to identify the trends in hydroclimatic variables. However, the estimated trend is often affected by the outlying observation or indices of extreme events observed during the drought and flood years. Furthermore, the normality assumption of the parametric method is a limitation for the short time series and thus necessitates the use of nonparametric methods. First, the nonparametric Mann–Kendall (MK) test was used to identify the monotone trends in a hydroclimatic time series, which has been applied widely in literature (WMO, 1988; Zhang *et al.*, 2001). To account for seasonality in the time series and find the overall trend, the seasonal Kendall test was used (Hirsch and Slack, 1984). However, the MK test or the standard regression cannot distinguish an abrupt shift from a monotone trend in a time series (McCabe and Wolock, 2002). Therefore, the nonparametric Pettit test (Pettit, 1979), which is a form of the Mann–Whitney two sample test, was used for the determination of abrupt shifts in the hydroclimatic time series. In addition, the nonparametric Levene test (Levene, 1960) was used to test the equality of variances after dividing the entire time series into distinguished sub-series based on the Pettit test. Unless the significance level is defined, the statistical significance of the trend and variability is assessed at the level $\alpha = 0.05$.

3.1. Mann–Kendall test

For a sample of n independent and identically distributed random variables ($x_1, x_2, \ldots, x_n$), the MK test statistics is defined as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i), \text{ for all } 1 \leq i < j \leq n \quad (1)$$

The sgn() is equal to +1 if x_j is greater than x_i, -1 if x_j is less than x_i, and 0 if x_j is equal to x_i. Under the null hypothesis, the distribution of S can be well approximated by a normal distribution even for a small sample size ($n \geq 10$) with a correction of $\pm$ 1. The mean and variance of S are given by $E[S] = 0$and $\text{var}[S] = \left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)\right]/18$, respectively. Here, m is the number of tied groups and t_i is the extent of the ith tied group. To test the hypothesis, the standard normal variable Z is given by

$$Z = \frac{S + \delta}{\sqrt{\text{var}(S)}} \quad (2)$$

where $\delta = 1$ if $S < 0$ and $\delta = -1$ if $S > 0$. In a two-tailed test performed at the significance level α, the null hypothesis is rejected if $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ is the value of the standard normal distribution having a probability of exceedance of $\alpha/2$. A positive value of Z indicates an upward trend, and a negative value of Z indicates a downward trend in the time series. As the presence of serial correlation influences the trend results, the pre-whitening of the time series was carried out considering the lag-one serial correlation (Zhang *et al.*, 2001). The robust Kendall slope (β) was used to quantify the slope of the monotone trend by calculating the median of $(x_j - x_i)(j - i)-^1$ for all $i < j$.

3.2. Seasonal Kendall test

The seasonal Kendall test statistic is given by $S' = \sum_{s=1}^{p} S_s$, where S_j is the MK statistic (Equation 1) for season s ($s = 1, 2, \ldots, p$). Under the assumption of independence among the seasons, the variance of S' becomes var $[S'] = \sum_{s=1}^{p} \text{var}[S_s]$. The statistic Z' can be derived in a manner similar to that of the MK test. However, the seasonal Kendall test is appropriate when the trends are homogenous between the seasons (Van Belle and Hughes, 1984). Test of heterogeneity (H) between seasons is given by

$$H = \sum_{s=1}^{p} Z_s^2 - p\overline{Z}^2 \quad (3)$$

where Z_s is the MK statistic Z for season s (Equation 2) and $\overline{Z} = p^{-1} \sum_{s=1}^{p} Z_s$. Here, H follows a chi-square (χ^2) distribution. If H exceeds the critical value of the χ^2 with $(s - 1)$ degrees of freedom at the α level of significance, then the null hypothesis of homogeneous trends between seasons is rejected.

3.2. Pettit test

When the exact time of the change point is not known, the Pettit test detects the significant shift in the mean of the time series. The null hypothesis states that the two samples $(x_1, x_2, \ldots, x_t)$ and $(x_{t+1}, \ldots, x_n)$ are from the same population. The Pettit test statistic is given by

$$U_{t,n} = U_{t-1,n} + \sum_{i=1}^{n} \text{sgn}(x_t - x_i), \text{for } t = 2, \ldots, n \quad (4)$$

For testing the hypothesis, the statistic K_t and the associated probability are given by

$$K_t = \text{Max}_{1 \leq t \geq n} |U_{t,n}| \quad (5)$$

and

$$p \cong 2 \exp\{-6(K_t)^2(n^2 + n^3)^{-1}\}, \text{respectively} \quad (6)$$

The null hypothesis is rejected at the significance level 0.05 if $p \ < 0.05$, and this suggests that a change point has occurred at time t.

3.4. Levene test

In this study, a modification of Levene's original procedure (Brown and Forsythe, 1974) was employed, which considers the distance of the observation from the sample median instead of the mean. Let the sample $(x_1, x_2, \ldots, x_n)$ be divided into g sub-groups, and n_l be the sample size for the lth sub-group. Then the Levene test statistic is defined as

$$W = \frac{(n - g) \sum_{l=1}^{g} n_l (\overline{D}_l - \overline{D})^2}{(g - 1) \sum_{l=1}^{g} \sum_{m=1}^{n_l} (D_{lm} - \overline{D}_l)^2} \quad (7)$$

where D_{lm} is the absolute deviation of the observation from the respective sub-group median $(|x_{lm} - \overline{x}_l|)$; $\overline{D}_l$ and $\overline{D}$ are the sub-group mean and overall mean of D_{lm}, respectively. The null hypothesis of equal variances is rejected at the significance level α if $W > F_{(\alpha,g-1,n-g)}$, where $F_{(\alpha,g-1,n-g)}$ is the critical value of the F distribution with $(g - 1)$ and $(n - g)$ degrees of freedom.

4. Results and discussion

4.1. Temperature and relative humidity trends

Figure 2 presents the time series of monthly maximum temperatures (T_{max}) and monthly minimum temperatures (T_{min}) for a few representative stations to understand the variability of the temperature extremes for the period 1987–2001. The locally weighted scatter plot smooth (LOWESS), a robust nonparametric procedure for estimating the regression surfaces (Cleveland *et al.*, 1988), provided conspicuously increasing and decreasing patterns of T_{max} and T_{min}, respectively, without any abrupt shifts, as shown in Figure 2. Therefore, the monthly temperature range (T_{mtr}), i.e., the difference between T_{max} and T_{min}, resulted in a widening pattern. Table I indicates that the topographic features, location of the station from the coast, and the anthropogenic activities caused the spatial difference in temperatures. The average T_{max} in the coal-based industrial belt [Angul (ANG), Jharsuguda (JRG), Titlagarh (TTG), and Sundergarh (SNG)] was higher in comparison to that in the coastal region [Balasore (BLS), Chandbali (CBL), Paradeep (PDP), Cuttack (CTK), Puri (PRI), Bhubaneswar (BWN), and Gopalpur (GPL)]. However, the average T_{min} of the inland region was less than that of the coastal region. The Yule–Kendall skewness (S_k), a resistance measure of the shape of the distribution, was calculated using the 25th percentile (Q_1), 50th percentile (Q_2), and 75th percentile (Q_3) as $(Q_1 - 2Q_2 + Q_3)(Q_3 - Q_1)^{-1}$ (Ferro *et al.*, 2005). The observed positive and negative S_k suggested the influence of unusually high and low temperatures on the shape of T_{max} and T_{min}.

Figure 3 illustrates the seasonal distribution of the MK test results in terms of increasing (positive) and decreasing (negative) trends in $T_{\text{max}}, T_{\text{min}}$, and T_{mtr}. A pronounced warming trend was observed in T_{max} as 99% of the 192 season-stations (12 seasons for each of the 16 stations) experienced an increasing trend at an average rate of 0.37 °C yr^{-1} (trend magnitude) (Figure 3(a)). About 46% of these season-stations had significant increasing trends. However, 93% of the season-stations showed

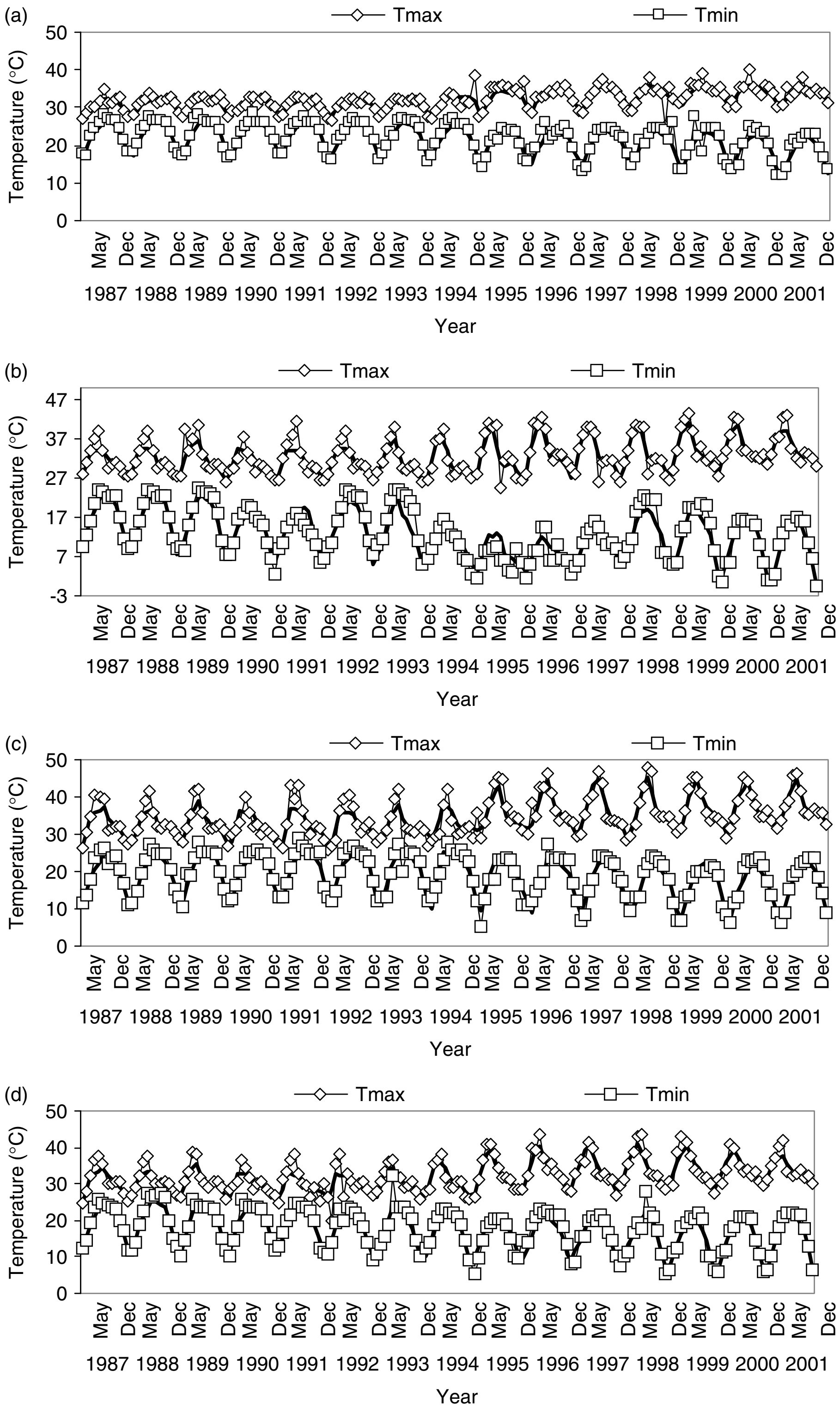

Figure 2. Temporal and spatial differences in the monthly maximum temperature (T_{max}) and monthly minimum temperature (T_{min}) for the stations (a) Gopalpur in the coastal region, (b) Phulbani in the high topography areas with minimum temperature below 0 °C, (c) Jharsuguda, and (d) Keonjhar in the industrial belt. The LOWESS smooth curve (thick line) shows an increasing trend in the monthly temperature range (T_{mtr}).

a negative trend (cooling) of −0.32 °C yr^{-1} in T_{min} (Figure 3(b)); a significant negative trend was observed in 39% of the season-stations. Figure 3(c) indicates that T_{mtr} exhibited an increasing trend in 98% of the 192 season-stations with significant increases in 44% of the season-stations. An overall increasing trend of 0.69 °C yr^{-1} was observed in T_{mtr}. The observed increase in the T_{mtr} suggested that the trends in T_{max} are stronger than the trends in T_{min}. The significant trends in T_{max} and T_{mtr} are more concentrated in the non-monsoon dry seasons

Table I. Descriptive statistics of monthly maximum temperature (T_{max}) and monthly minimum temperature (T_{min}) in °C for the period 1987–2001.

Station Name (Station ID)	Altitude (m MSL)	Variable	Mean	Standard deviation	Minimum	Q_1	Q_2	Q_3	Maximum	S_k
Balasore (BLS)	18.8	T_{max}	33.37	3.79	25.10	30.85	33.20	35.35	44.00	−0.04
		T_{min}	20.55	4.81	9.60	16.55	22.20	24.50	27.10	−0.42
Chandbali (CBL)	4.8	T_{max}	33.96	3.80	23.90	31.40	33.65	36.20	44.60	0.06
		T_{min}	20.46	4.54	10.30	16.95	22.20	24.00	29.90	−0.49
Paradeep (PDP)	7.6	T_{max}	31.91	2.78	25.20	30.55	31.80	33.75	41.90	0.22
		T_{min}	21.32	4.22	7.80	18.60	22.65	24.50	29.60	−0.37
Cuttack (CTK)	25.7	T_{max}	34.25	3.59	24.80	31.65	33.90	36.55	44.10	0.08
		T_{min}	19.10	4.68	7.50	16.00	20.00	22.20	36.90	−0.29
Puri (PRI)	4.8	T_{max}	32.02	2.39	20.80	30.50	32.25	33.65	40.80	−0.11
		T_{min}	22.92	4.00	13.30	19.80	23.95	26.40	37.60	−0.26
Bhubaneswar (BWN)	45	T_{max}	34.25	3.60	27.60	31.75	34.10	36.10	44.60	−0.08
		T_{min}	20.82	4.66	9.50	17.65	22.40	24.60	29.90	−0.37
Gopalpur (GPL)	16	T_{max}	32.28	2.65	25.00	30.55	32.25	34.15	40.30	0.06
		T_{min}	21.92	4.06	12.00	19.05	22.85	25.40	28.40	−0.20
Phulbani (PLB)	462.6	T_{max}	32.65	4.59	24.40	29.35	31.65	35.30	43.50	0.23
		T_{min}	13.00	6.51	−0.60	8.30	12.30	17.95	24.60	0.17
Angul (ANG)	138	T_{max}	36.60	4.74	28.50	33.23	35.40	40.05	47.00	0.36
		T_{min}	17.37	4.73	4.00	13.50	18.80	21.03	26.50	−0.41
Bolangir (BLR)	189.2	T_{max}	34.10	5.82	23.10	29.50	33.63	37.90	47.70	0.02
		T_{min}	16.33	5.58	3.10	13.30	16.40	20.10	27.10	0.09
Jharsuguda (JRG)	228	T_{max}	34.71	5.16	26.00	31.00	33.55	38.10	48.00	0.28
		T_{min}	19.33	5.91	5.50	13.85	20.20	24.15	39.50	−0.23
Sambalpur (SBP)	148	T_{max}	34.89	4.96	25.20	31.45	34.10	38.45	47.50	0.24
		T_{min}	18.82	5.87	3.60	14.35	20.45	23.55	31.60	−0.33
Titilgarh (TTG)	210	T_{max}	36.61	5.90	27.00	31.40	36.10	40.90	49.80	0.01
		T_{min}	20.15	5.43	4.50	16.30	22.00	23.95	32.00	−0.49
Baripada (BPD)	53.5	T_{max}	33.90	4.41	24.90	31.05	33.40	36.60	44.60	0.15
		T_{min}	19.75	5.45	8.40	15.55	21.55	24.45	33.70	−0.35
Keonjhar (KNJ)	485	T_{max}	32.21	4.37	20.10	29.30	31.40	34.90	43.60	0.25
		T_{min}	17.79	5.61	5.20	13.27	19.10	22.22	32.30	−0.30
Sundargarh (SNG)	240	T_{max}	34.13	5.39	22.30	30.40	33.00	37.80	46.00	0.30
		T_{min}	15.05	5.50	1.90	10.52	16.76	19.25	28.20	−0.43

Q_1, 25th percentile; Q_2, 50th percentile (median); Q_3, 75th percentile; S_k, Yule-Kendall skewness.

(Figure 3). The seasonal Kendall test indicated significant warming trends in T_{max} and T_{mtr} for all the 16 stations. Furthermore, a significant cooling trend in T_{min} was also observed for 87% of the stations. The observed opposite trends in T_{max} and T_{min} suggested that the underlying governing factors could be different. However, averaging the time series might have resulted in the masking of the underlying pattern and also low-scale variability.

The results of the pronounced warming trend are in general agreement with the reported increases in seasonal and annual temperatures in different regions of India (Rao, 1993; Arora *et al.*, 2005; Fowler and Archer, 2006). We speculate that the build-up of greenhouse gases from the coal-based industries of the study area (Rao, 1993; Khatua and Stanley, 2006) might be primarily responsible for the observed warming trends. About 22×10^6 t of coal is consumed annually to meet the energy requirements of Orissa (CES, 2007). Garg *et al.* (2001) observed a direct correlation between coal consumption and the high greenhouse gas build-up in Orissa. Recently, the Washington-based Centre for Global Development has identified the Talcher power plant complex (production capacity 4000 MW) in Angul (ANG) as the largest CO_2 emitter in India. Our results also showed relatively higher temperatures (Figure 2) and strong increasing trends in T_{max} for the coal-based industrial regions [Angul (ANG), Jharsuguda (JRG), and Titlagarh (TTG)] in comparison to other regions of the state. In addition, the aluminium production process with a capacity of 0.58×10^6 t yr^{-1} might have contributed to the warming trends in Orissa by emitting the SO_2, perflourocarbon, and hexaflouroethane. Moreover, biomass burning and construction activities are also the probable sources of warming. More than 80% of the population in Orissa (36 million in 2001) resides in rural areas where biofuel primarily meets the domestic energy requirement. The Cuttack (CTK) district is identified as one of the hotspots of biofuel consumption in India (Garg *et al.*, 2001).

It is interesting to note the simultaneous decrease in the night temperatures (T_{min}) in Orissa, which is consistent with the findings on the cooling trends in other parts of India (Yadav *et al.*, 2004; Gadgil and Dhorde, 2005;

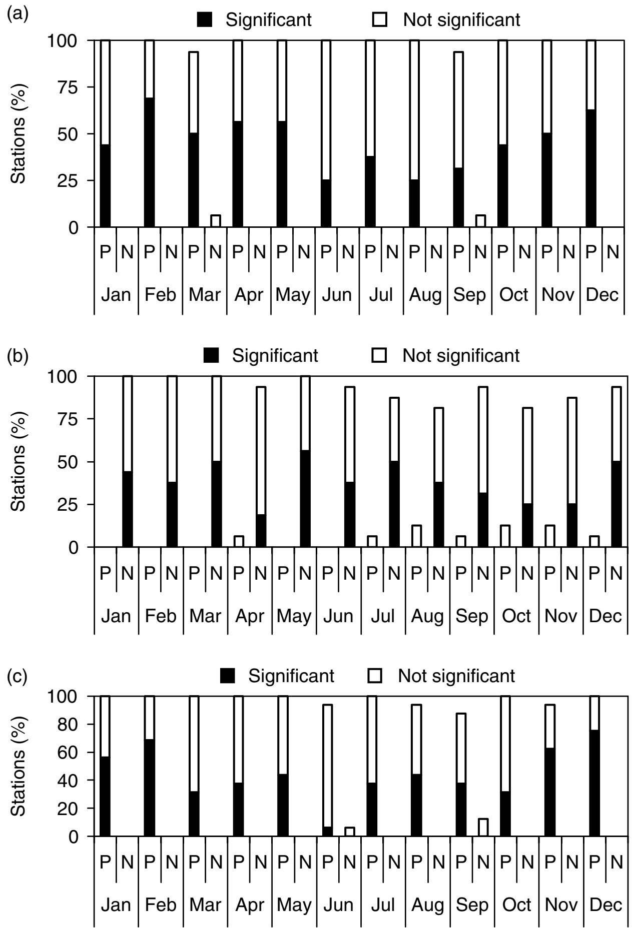

Figure 3. Seasonal distribution of the positive (P) and negative (N) trends in (a) monthly maximum temperature (T_{max}), (b) monthly minimum temperature (T_{min}), and (c) monthly temperature range (T_{mtr}) for the period 1987–2001. The percentage of stations with significant ($\alpha = 0.05$) trend is shaded.

Fowler and Archer, 2006). Gadgil and Dhorde (2005) attributed the cooling trends to the absorbing aerosols in atmosphere. In Orissa, the coal-based industries and the anthropogenic activities (mining and biofuel use) are also the sources of both absorbing and reflexive aerosols such as black carbon, dust, fly ash, sulphates, and nitrates (SER, 2006). Annually, the industrial activities produce about 10×10^6 t of fly ash and 1.4×10^6 t of blast furnace slag in the state. The Talcher power plant complex in Angul (ANG) was reported as one of the aerosol polluted regions in India with significantly high aerosol optical depth (Prasad *et al.*, 2006). The back trajectory analysis of the National Oceanic and Atmospheric Administration HYSPLIT model showed that the outflow of wind at around 21°N (adjacent to Orissa) carries sub-micrometre and fine mode aerosols from the north and central India to the Bay of Bengal, causing high optical aerosol depth in the coastline of Orissa (Niranjan *et al.*, 2005).

In general, both absorbing and reflective aerosols have reduced the amount of sunlight reaching the ground and, thus, have caused local cooling in India (Menon *et al.*, 2002; Ramanathan *et al.*, 2005). Therefore, we reason

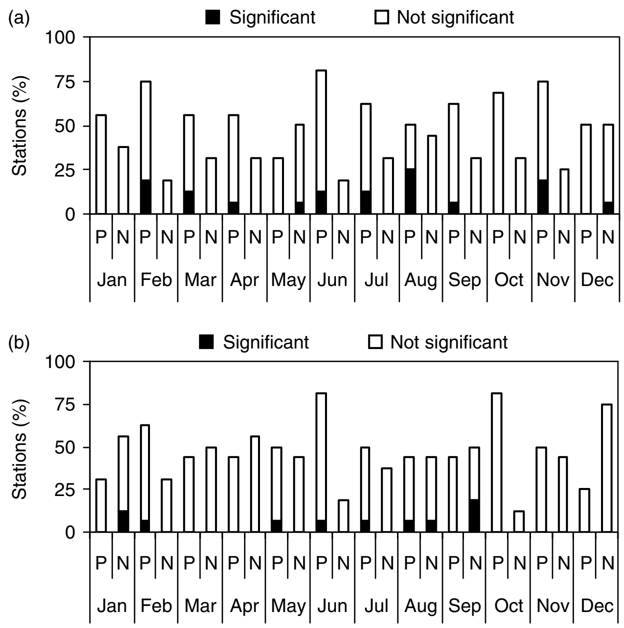

Figure 4. Seasonal distribution of the positive (P) and negative (N) trends in (a) monthly average relative humidity recorded in the forenoon (RH_{fn}) (08 : 30 IST), and (b) monthly average relative humidity recorded in the afternoon (RH_{an}) (17 : 30 IST) for the period 1987–2001 The percentage of stations with significant ($\alpha = 0.05$) trend is shaded.

that the aerosol loads could be one of the major causes of the observed cooling trends in Orissa. However, the quantification of the influence of greenhouse gases and aerosols requires a process-based modelling study, which is beyond the scope of this study. It is important to note that while most parts of the world experienced a narrowing of daily temperature range (DTR), an increasing DTR pattern was observed in different regions of the Indian sub-continent (Yadav *et al.*, 2004; Fowler and Archer, 2006). This study, however, confirmed a significant increasing pattern in the monthly temperature range (T_{mtr}).

During the study period, the monthly average relative humidity in the forenoon (RH_{fn}) and afternoon (RH_{an}) were 78% and 73%, respectively, in the coastal region of Orissa in comparison to 71% and 60%, respectively, in the inland region. Several stations exhibited negative skewness (S_k), indicating the presence of unusually low values. About 67% and 50% of the 192 season-stations exhibited increasing trends in RH_{fn} and RH_{an}, respectively (Figure 4). The trend magnitude indicated an overall increasing (moistening) trend of 0.07% yr^{-1} and 0.01% yr^{-1} in RH_{fn} and RH_{an}, respectively. Comparatively more cases of positive trends suggested an increasing moisture load in the atmosphere. Figure 4 displayed that the significant increasing trends are more concentrated in the monsoon months. The seasonal Kendall test indicated significant increasing trends in RH_{fn} for six stations in the coastal region (except Balasore (BLS)) and two stations at higher elevation [Phulbani (PLB) and Keonjhar (KNJ)]. Similarly, two stations in the coastal region [Puri (PRI) and Bhubaneswar (BWN)] and Balasore (BLR) experienced significant increase in RH_{an}. The abundant moisture supply from the Bay of Bengal, particularly in the monsoon season, might have contributed to the increasing trend of the relative humidity in the coastal region of Orissa. The predictions of May (2004) and Kripalani *et al.* (2007) also suggested an increased moisture flux from the warmer Indian Ocean. Furthermore, the pronounced warming trend could also be one of the causes of the moisture load through the evaporative demand of atmosphere. The combustion of coal and other fossil fuels also produce water vapour although in small quantity. Nevertheless, the uncertainty in both the temporal and spatial distribution of water vapour continues to be a hindrance while attributing the trends and variability in relative humidity (Gaffen and Ross, 1999).

4.2. Rainfall and cyclonic disturbances trends

Preliminary inspection of the LOWESS plots (not shown) indicated an increasing mean rainfall pattern in the pre-monsoon (February to May) and post-monsoon (October to January) seasons for the state of Orissa as a whole. The monsoon season rainfall, which contributes about 80% of the long-term annual rainfall of 1482 mm, showed high inter-annual variability without any noticeable changes. An increasing trend was observed in the June rainfall in contrast to a decreasing trend in the September rainfall. A station (district) level analysis indicated a change in the mean and the associated variability in rainfall during the early 1980s. We, therefore, calculated the descriptive statistics for the pre-monsoon, June, July, August, September, and post-monsoon season rainfall over the districts for the sub-periods 1960–1979 and 1980–2003 in order to examine the changes in the location parameters. Table II illustrates an unstable rainfall distribution for the recent (1980–2003) period in comparison to the pre-1980 period, as evident from the high standard deviation and location parameters. Increase in the Q_3 (75th percentile) and maximum rainfall were observed for the recent period. However, the mean and median (Q_2) of rainfall in the monsoon months were less than the long-term normal rainfall. The July and August rainfall, which contributes largely to the success of agriculture, showed a decrease in the lower percentile [minimum and Q_1 (25th percentile)] and an increase in the higher percentile (Q_3 and maximum). Positive skewness (S_k) was also observed for most of the cases, suggesting the influence of a few unusually heavy rainfall events on the shape of the distribution.

For the state as a whole, the Pettit test indicated the presence of non-significant shifts in the mean rainfall for different seasons. However, the standard deviation (variability) of the pre-monsoon season rainfall exhibited a significant ($\alpha = 0.1$) upward shift around the year 1980. The Levene test also showed a significant change in the variability in the September and post-monsoon season mean rainfall. However, the MK test exhibited non-significant trends in the mean rainfall of Orissa in different seasons for the sub-periods as well as the whole period. This suggested that the high inter-annual variability might have obscured the underlying pattern (Matalas, 1997). Station level analysis indicated that the Balasore district experienced a significant upward shift during the year 1980 in the pre-monsoon season rainfall. This result is noteworthy as the Balasore district is situated near the northwestern Bay of Bengal along the monsoon trough. In general, the coastal region showed a non-significant upward shift in the rainfall in comparison to the inland region. The significant ($\alpha = 0.1$) upward shift was observed for four stations in the June rainfall and one station each in July and August rainfall around the year 1980. A majority of these stations are situated in the western and southwestern parts of Orissa where orography influences the rainfall. Yet, no shift occurred in the post-monsoon rainfall. The significant ($\alpha = 0.1$) change in variability was observed in the pre-monsoon (one station), June (one station), August (six stations), September (two stations), and post-monsoon rainfall.

Figure 5 illustrated the MK test results of the 78 season-stations rainfall time series (six seasons for each of the 13 stations) for the periods 1980–2003 and

Table II. Descriptive statistics of the seasonal rainfall (mm) in for the period 1 (1960–1979) and period 2 (1980–2003) in Orissa.

Season	Period	Mean	Standard deviation	Minimum	Q_1	Q_2	Q_3	Maximum	S_k
Pre_monsoon	1	110.06	67.91	1.53	61.80	96.00	142.00	442.50	0.15
	2	144.97	102.46	2.60	78.05	118.48	192.60	667.65	0.29
June	1	178.56	97.09	12.60	110.90	154.50	226.95	592.70	0.25
	2	216.10	92.95	30.50	150.45	202.45	274.95	501.00	0.16
July	1	306.70	99.86	33.60	237.80	304.00	375.70	676.50	0.04
	2	308.06	117.93	32.40	232.05	292.65	364.40	774.50	0.08
August	1	325.30	105.19	53.50	256.85	325.75	393.50	594.40	−0.01
	2	341.23	124.60	38.90	249.13	326.85	411.07	786.20	0.04
September	1	224.11	85.76	23.90	163.60	218.85	270.90	569.80	−0.03
	2	217.45	97.30	13.40	148.90	205.00	272.55	745.00	0.09
Post-monsoon	1	129.31	100.58	0.00	62.50	105.50	165.40	698.00	0.16
	2	143.18	133.75	3.80	48.44	99.75	183.75	669.20	0.24

Q_1, 25th percentile; Q_2, 50th percentile (median); Q_3, 75th percentile; S_k, Yule-Kendall skewness.

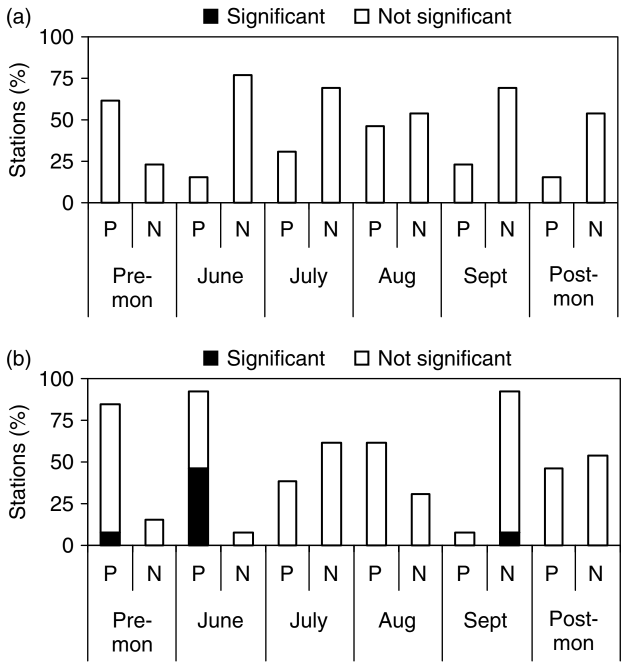

Figure 5. Seasonal distributions of the positive (P) and negative (N) trends in rainfall for the periods (a) 1980–2003 and (b) 1960–2003, respectively. The percentage of stations with significant ($\alpha = 0.05$) trend is shaded.

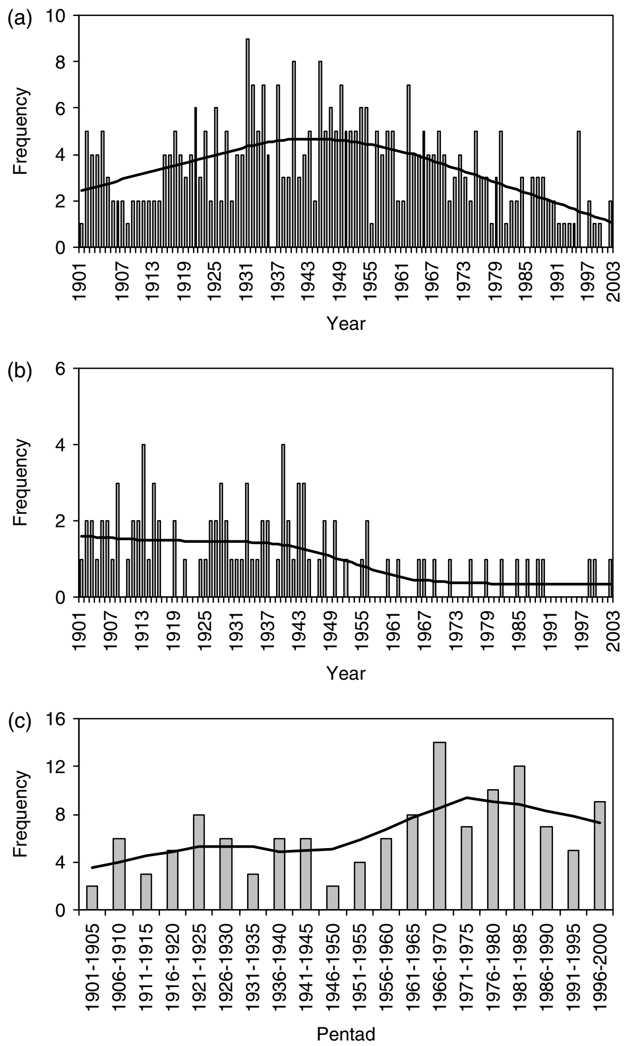

Figure 6. Frequency of (a) depression, (b) cyclonic storm in the monsoon season, and (c) severe cyclonic storms total in the pre- and post-monsoon season over the Bay of Bengal. The LOWESS smooth curve (thick line) exhibits a discernible pattern. The significant ($\alpha = 0.05$) abrupt downward shift in the monsoon depression and cyclonic storm is observed during 1971 and 1950, respectively.

1960–2003. For the periods 1980–2003, about 59% of the 78 season-stations exhibited decreasing rainfall trends in comparison to 33% that exhibited increasing trends with an overall trend of -1.54 mm yr^{-1}. However, none of the stations experienced a significant trend. Figure 5(a) shows that most of the rainfall decreases occurred in the monsoon and post-monsoon season. It is interesting to note the change in the trend direction (sign) as 56% of the 78 season-stations exhibited increasing rainfall trends for the period 1960–2003 (Figure 5(b)). Out of the seven stations having significant increasing trends in the pre-monsoon and June rainfall, five stations exhibited significant ($\alpha = 0.1$) upward shifts during 1980. The test of heterogeneity was carried out for the monsoon months only as the governing factors for the monsoon rainfall are different from those for other seasons. For the period 1980–2003, the seasonal Kendall test also indicated the occurrence of non-significant trends for all the stations. For the period 1960–2003, however, a significant increase in the monsoon rainfall was observed in the Balasore, Koraput, and Dhenkanal districts. In contrast, the Sundergarh district experienced a significant decreasing trend. A significant change in variability was observed for Puri, Ganjam, Phulbani, and Balangir, leading to the occurrence of the non-significant trends.

The synoptic disturbances over the Bay of Bengal contribute a substantial amount of rainfall in Orissa and adjacent central India. Therefore, the possible changes in the frequency of cyclonic disturbances were investigated to understand the influence of large-scale circulation. Figure 6(a) and (b) shows clear changes in the depression and cyclonic storm frequency for the period 1901–2003. The depression, which occurs in the monsoon season, exhibited significant decreasing trend of -0.01 yr^{-1}. This trend was due to the significant downward shift during 1971 (Figure 6(a)). The mean as well as the percentiles (Q_1, Q_2, and Q_3) of depression frequency also dropped in the post-1971 period (1972–2003) in comparison to that in the period 1901–1971. Furthermore, the Levene test indicated a significant change in depression variability between the sub-periods. However, the depression exhibited a significant increasing trend of 0.03 yr^{-1} for the period 1901–1971 in contrast to a significant decreasing trend of -0.06 yr^{-1} for the period 1972–2003. The depression frequency also exhibited a significant decreasing trend for the period 1960–2003 (rainfall study period). This trend was also characterized by the presence of a significant downward shift during 1983. Although the post-change point period (1984–2003) exhibited a non-significant decreasing trend, a significant decreasing trend was observed for the period 1960–1983.

The cyclonic storms exhibited a significant decreasing trend of -0.01 yr^{-1} for the period 1901–2003 (Figure 6(b)) due to the presence of a significant downward shift during the year 1950. The sub-periods from the change point year, however, exhibited non-significant decreasing trends. Furthermore, the change in variability was also non-significant. Figure 6(c) indicated a general increasing pattern with a slight reversal from 1971 onwards in the total severe cyclonic storms (in the pre- and post-monsoon season) for the period 1901–2000. The total and the post-monsoon severe cyclonic storm exhibited significant increasing trends. The severe cyclonic storm in November showed a significant trend due to the occurrence of an upward shift during the 1961–1965 pentad. However, the pre-monsoon season experienced a non-significant increasing trend, which could be due to the significant ($\alpha = 0.1$) change in variability between the sub-periods 1901–1965 and 1966–2000.

Using a linear regression method, several studies observed a decreasing trend in the monsoon depression over the Bay of Bengal (Rajeevan *et al*., 2000; Dash *et al*., 2004; Rao *et al*., 2004). These studies attributed the decreasing trend to the weakening of the atmospheric dynamical parameters and tropical easterly jet. This weakening of the summer monsoon circulation had been linked to the weakening of sea surface temperature (SST) gradients due to the warming of SST accompanied by the aerosol-induced dimming of the north Indian Ocean (Chung and Ramanathan, 2006). For example, the aerosols reduced the heating gradient along the meridional monsoon circulation in 2002 (Patra *et al*., 2005). This led to a widespread drought in India as not even a single depression and cyclonic storm was formed over the Bay of Bengal. Recently, model experiments also showed that increases in SST beyond a certain threshold have resulted in anti-cyclonic circulation anomalies over the Indian sub-continent and Bay of Bengal regions, leading to below-normal rainfall from west central India to the central east coast of India (Rao *et al*., 2010). Furthermore, significant increasing trends in the severe cyclonic storm and hurricane over the north Indian Ocean were linked to the warming induced significant increasing trend in SST (Webster *et al*., 2005; Hoyos *et al*., 2006; Singh, 2007).

Our results are in agreement with the findings of the previous studies, and a general consensus emerges regarding the direction of the trends. However, this study provides the evidence that most of the trends in the cyclonic disturbances are due to the occurrence of abrupt shifts in the time series, which is important because of the nature of its evolution. The occurrences of these shifts imply that the climate system has been enforced to cross a certain threshold, thus triggering an abrupt transition to a new state. The LOWESS plots (Figure 6) also showed a marked nonlinear pattern of cyclonic disturbances, which might not be distinguished using the linear regression. Significant decreases in the monsoon cyclonic disturbances imply a reduction in rainfall, whereas increases in the severe cyclonic storm incur economic and environmental losses in the coastal regions. The identification of the change point year is important for future research to precisely assess the driving factors of the observed changes. We showed that the sign and significance of the observed trends were altered by adding the cyclonic disturbances over the seasons, suggesting the masking of trends and variability. Because of the presence of shifts, the trend results were also sensitive to the period of record, as evident from the difference in trend results for the sub-periods.

The formation of the low-pressure system over the northwestern Bay of Bengal along with the activity of the monsoon trough increases the formation of cloudiness over the region. Rajeevan *et al*. (2000) observed a decrease in the activity of low cloudiness over the Bay of Bengal from 1977 onwards. This finding may be linked to the observed downward shift in the frequency of depression from 1983 onwards. It is also noteworthy to observe the simultaneous non-significant decreasing trends in the monsoon rainfall for the period 1980–2003 (Figure 5(a)). The growing body of evidence has suggested that warmer climate accelerates the hydrologic cycle with a consequent occurrence of extreme rainfall and increased climate variability (Trenberth *et al*., 2003). It can also be inferred from our results that the observed pronounced warming in conjunction with a comparatively moist trend (in previous section) might have provided the necessary background for enhancing the process of moisture convergence into storm and extreme rain events in Orissa. Moreover, a general increase in higher percentiles of rainfall and positive skewness (Table II) in the monsoon season were indicative of the heavy rain events. Several previous studies also noted significant increasing trends in the frequency and magnitude of heavy rain events over the western and central India (including Orissa) due to greenhouse gas warming (Sen Roy and Balling, 2004; Goswami *et al*., 2006). Therefore, the decrease in the rainfall due to the downward shift in the cyclonic frequency might have been partially compensated for by the increase in the heavy rain events. Nevertheless, both the situations do not balance in a given season, leading to the occurrence of floods and droughts (Trenberth *et al*., 2003). It appears that the observed high variability in monsoon rainfall is due to the imbalance between the warming induced excess rainfall and the reduction in the cyclonic disturbances.

The rainfall on monthly and seasonal timescales might not have segregated the opposite mechanisms, leading to the identification of non-significant trends in Orissa. It can be noted that the stations having orographic influence on the rainfall exhibited significant upward shifts in the pre-monsoon and June rainfall for the period 1960–2003. The elevated heat pump mechanism of the absorbing aerosol in the pre-monsoon and early June, which brings warm and moist air from the adjacent ocean with increased convection over north India (Lau *et al.*, 2006), could be one of the plausible factors. Furthermore, the increasing trend in severe cyclone frequency in the pre-monsoon season might have partially contributed to the increasing rainfall trend. Salahuddin *et al.* (2006) also reported an enhancement in June rainfall in comparison to other monsoon months in Bangladesh due to the increasing SST of the Bay of Bengal along with the orographic effect. However, Maity and Nagesh Kumar (2007) attributed the pre-monsoon and early monsoon rainfall variability in the sub-divisions of eastern India (including Orissa) to the relative influence of ocean–land temperature contrast in comparison to that of the SST.

4.3. Streamflow trends

Figure 7 indicates the presence of high variability without a noticeable pattern in the annual maximum streamflow of the Mahanadi River for the period 1964–2003. This was in correspondence with the observed high inter-annual variability in the monsoon rainfall. To compare with the rainfall changes, the descriptive statistics of the peak flow were calculated for the sub-periods 1964–1979 and 1980–2003. The lower quartiles (minimum and Q_1) decreased while the higher quartiles increased for the period 1980–2003 in comparison to those for the pre-1980 period. This suggested that the streamflow extremes of the Mahanadi River have become severe in recent years, leading to the occurrence of both the high- and low-flow years. Furthermore, positive skewness (S_k) was observed, implying the influence of unusually high-flow years on the shape of the streamflow distribution. Although no abrupt shift was observed, the Levene test indicated a significant change in variability between the sub-periods. The pre-1980 period streamflow exhibited significant increasing trend of 22×10^3 m^3 s^{-1} in contrast to the non-significant decreasing trend of -6×10^3 m^3 s^{-1} for the period 1980–2003. The observed high variability in the streamflow might have led to the identification of the non-significant trend.

The annual maximum streamflow of the Brahmani River showed a sharp reduction for the period 1980–2003, as evident from the LOWESS curve in Figure 7.

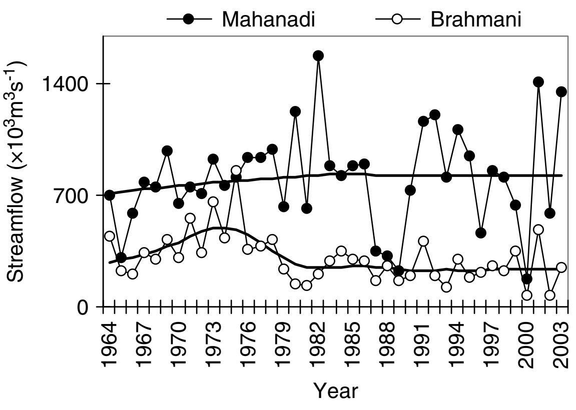

Figure 7. Annual maximum streamflow in the Mahanadi and Brahmani Rivers of Orissa. The thick line denotes the LOWESS smooth curve.

This reduction is due to the construction of a dam to mitigate floods and also to meet the industrial water requirements. Therefore, the streamflow exhibited a significant decreasing trend of -5×10^3 m^3 s^{-1} for the period 1964–2003 due to the downward shift during 1978. However, non-significant increasing trends were observed for the sub-periods 1964–1977 and 1978–2003. The ecosystem develops resilience to the monotonic changes in the hydroclimatic variables, and the occurrence of an abrupt shift fundamentally alters the ecosystem function (Genkai-Kato, 2007). A recent study by the India-based Institute of Minerals and Materials Technology showed that the streamflow reduction in the Brahmani River increased the salinity of the Bhitarkanika estuary with a consequent change in the composition of plant species and the retardation of growth in the mangrove forest. It was also predicted that continuous loss of the mangrove forest may increase the risk of seawater intrusion.

5. Conclusions

This study revealed noticeable changes in the hydroclimatic variables of Orissa and in the cyclonic disturbances over the Bay of Bengal. Significant monotone trends, abrupt shifts, and changes in variability were observed in several hydroclimatic variables than would be expected to occur by chance. It is interesting to note that the observed trends and variability showed correspondence among the hydroclimatic variables. The monthly maximum temperatures exhibited significant warming trend, whereas the minimum temperatures exhibited significant cooling trend in many stations. A significant increasing pattern was observed in the monthly temperature range, which suggested that the increases in monthly maximum temperatures were more pronounced than those in the monthly minimum temperatures. We hypothesize that the differential forcing mechanisms of greenhouse gases and aerosols might be mainly responsible for the observed changes in the temperature extremes. Furthermore, the coastal region experienced a significant increasing trend in the monthly average relative humidity, which appears to be consistent with the predicted increases in the moisture flux from the adjacent ocean. The rainfall of Orissa showed a variety of trends and variability in different seasons and stations. The annual peak flow in the major rivers of Orissa also showed high variability in terms of extremes.

For the first time, this study provides strong evidence suggesting the occurrence of abrupt shifts in the cyclonic disturbances over the Bay of Bengal. This is important as the evolution and implication of the abrupt shifts are different from the monotone trends. The monsoon depression and cyclonic storm exhibited a significant downward shift, whereas the post-monsoon severe cyclonic storms exhibited a significant upward shift. This might be due to the influence of differential forcing mechanisms on the different categories of cyclonic disturbances. The occurrence of more non-significant decreasing trends in the monsoon rainfall for the period 1980–2003 might be accompanied by a significant downward shift in the frequency of depression from 1983 onwards. Furthermore, this study revealed that the trend results were highly sensitive to the season of analysis and the period of records. If the observed changes in the hydroclimatic variables and in the synoptic disturbances continue, then they would have severe ecological and economic implications. Further research is needed to identify and quantify the driving factors of the observed monotone trends and abrupt shifts.

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