Trend analysis of weather variables in Sagar Island, West Bengal, India: a long-term perspective (1982–2010)

S. Mandal[1], B. U. Choudhury[2,*], M. Mondal[3] and S. Bej[4]

[1]Department of Geography, University of Calcutta, Kolkata 700 073, India
[2]Division of Soil Science, ICAR Research Complex for NEH Region, Umiam 793 103, India
[3]Mata Monomohini Madhyamik Vidyalaya, Kolkata 700 108, India
[4]Jeliakhali Vivekananda Vidyapith, North 24 Parganas 743 405, India

Sagar Island, a gargantuan low-lying archipelago setting on the continental shelf of the Bay of Bengal is one of the most vulnerable deltas to climate change. Extreme climate-driven multifarious threats, including tidal gushes, deluge with sea water, permanent submergence of land, occurrence of droughts and water scarcity have taken a toll on food and environmental security of the island. Knowing the trend of long-term weather variables responsible for the climate of the island holds importance in adaptation and mitigation strategies to sustain food production. In the present article, weather variables of the island (1982–2010) have been analysed to detect the changes in trend using Mann–Kendall non-parametric test and the magnitudes of such trends have been estimated using Sen's slope. The island receives an annual average rainfall of 1735 ± 352 mm, with an inter-annual deviation exceeding 40% and exhibits a decreasing trend (–5.79 mm year^{-1}). Significant ($P < 0.05$) anomalies in inter- as well intra-annual rainfall distributions (pre-monsoon, monsoon and post-monsoon months) were observed. Contribution of monsoon and post-monsoon months showed a decreasing trend (–3.84 to –4.42 mm year^{-1}), while pre-monsoon rainfall showed an increasing trend (+ 0.98 mm year^{-1}). Wide variability in inter-annual rainy days (76–139 days) and a decreasing trend (–0.24 days year^{-1}) may further complicate the existing anomalies. The island is experiencing a significant ($P < 0.05$) rising trend of inter-annual mean (+ 0.021°C year^{-1}) and maximum temperatures (+ 0.060°C year^{-1}), with a reverse trend (decline) in minimum temperature (–0.031°C year^{-1}). Other weather variables like sunshine duration, wind speed, atmospheric evaporative demand, etc. also manifested a complex interaction and significant ($P < 0.05$) decreasing trend over the study periods (1982–2010). Implications of these changes were manifested on water balance front: rising trend of water scarcity during post-monsoon months (December–February) in the island.

Keywords: Climate change, trend analysis, water balance, weather variables.

TREND analysis of climate variables on different spatio-temporal scales has been gaining importance ever since IPCC[1] has projected rising trend of Earth's surface temperature (0.74° ± 0.18°C over a period from 1906 to 2005). Mean annual temperature in India has also increased significantly (@ of 0.05°C/10 years) during the period 1901–2003. In the recent past (1971–2003), the warming trend has been accelerated (@ of 0.22°C/10 years)[2]. Future projections of climate change using global and regional climate models, run by the Indian Institute of Tropical Meteorology (IITM) with different IPCC scenarios[3], indicated a temperature change of about 3–5°C and an increase of 5–10% in summer monsoon rainfall[4]. It is also projected that the number of rainy days may decrease by 20–30%, which implies that the intensity of rainfall is likely to increase.

*For correspondence. (e-mail: burhan3i@yahoo.com)

The impact of climate change in future would be quite severe for the mega deltas in Asia. IPCC[5] has projected that with the rise in temperature and subsequent rise in sea level in the coasts of Asia, including the Indian Sundarbans in West Bengal will be exposed to increasing risks like coastal erosion. WWF- INDIA[6] has projected rising trend in surface temperature (0.019°C year^{-1}) for the Sundarbans region and predicted that more than 1.3 million people will be affected by the sea-level rise and permanent submergence of land masses, storm surges and coastal erosions. This will make Sundarbans fall under high-risk area by 2020. The small islands are especially more vulnerable to climatic hazards[7]. One such vulnerable island is the Sagar Island, southeast of Sundarbans. Over the past few decades, continuous inundation of coastal periphery and low-lying areas of the island by saline sea water and the adverse secondary consequences is now posing a serious threat to livelihood, food and environmental security of the rapidly growing population. Although several researchers[8–10] have explored the island in the context of coastal erosion, cyclone, tidal ingression, sea-level rise, etc. there is no comprehensive study on long-term behaviour of climate variables responsible for climate change in the island. Realizing the need to detect the direction of change (+/–) in climate variables and also to quantify the magnitude of such changes (if any), in the present study, we have analysed long-term (1982–2010) climate variables (namely rainfall, temperature, relative humidity, sunshine duration, evaporation, rainy days and wind speed) using non-parametric Mann–Kendall test. The magnitudes of the trends in climate variables were estimated using Sen's slope.

Materials and methods

Weather data used

Sagar Island (21°37′21″–21°52′28″N and 88°2′17″–88°10′25″E) in the estuary of River Hugli, and the largest island of Sundarbans deltaic complex was selected for the present study. For trend analysis of climatic variables, daily weather data of 29 years (1982–2010) for rainfall, maximum and minimum temperature, pan evaporation, relative humidity, wind speed, sunshine hours, etc. were collected from meteorological observatory of Sagar IMD (station index–42903, altitude ~ 3 m).

Methodology adopted in trend analysis

The southwest monsoon rainfall was classified as deficit when the actual rainfall was < LPA ± CV (LPA, long-period average; CV, coefficient of variation); normal when actual rainfall was within LPA ± CV, and excess when actual rainfall was > LPA ± CV of the corresponding year[11]. Meteorological drought years were considered based on the number of consecutive weeks (CWs) in a year with rainfall less than the water requirements of rice crop during various growth stages, i.e. 55 mm. The degree of severity was assessed in terms of low (2 CWs), moderate (3 CWs), severe (4 CWs) and very severe (> 4 CWs)[11], starting from 1982 to 2010. Climatic water balance (monthly basis from 29 years' average) was estimated based on balance between long-term monthly average Potential evapotranspiration (PET) and rainfall. PET was estimated based on class A pan method[12]. Changing trends of annual and seasonal weather variables were detected in the time series using Mann–Kendall test[13,14]. This is a rank correlation statistic test based on a comparison of the observed number of discordances and the value of the same quantity expected from a random series. Statistically significant trend was evaluated using the Z-statistics. The absolute value of Z was compared with the standard normal cumulative distribution to detect if there is any trend at the selected level of significance (α). The trend is said to be decreasing if Z is negative and increasing if Z is positive. In the second phase of analysis, Sen's non-parametric method was used to estimate true slope (magnitude) of an existing trend (change year^{-1}). To detect the strength of linear relationship between the variables, the correlation coefficient (r) values were also calculated.

Results and discussion

Rainfall distribution pattern

Mean (of 29 years) monthly rainfall varied considerably and July received the highest (372.5 ± 166.0 mm), whereas December received the lowest (4.84 ± 10.5 mm) amount of rainfall. Monsoon months (June–September) received higher monthly rainfall (254–372 mm) with relatively less variability (CV < 30%) compared to pre- and post-monsoon months (> 60%; Table 1). In the last three decades, highest monthly rainfall of 741 mm was received during September 1983. Trend analysis exhibited a significant ($P < 0.05$) increasing trend (@ 3.48 mm/month) of monthly rainfall during July and a reverse trend of significant ($P < 0.05$) decline (@ 4.28 mm/month) during September.

The analysis of LPA (1982–2010) rainfall data established that Sagar Island received an average annual rainfall of 1735.9 ± 352.7 mm (Table 2) with a variability of 20.3% from LPA. Lowest rainfall was received during 1985 (1230.5 mm), while the highest annual rainfall (2514 mm) was received during 1990. The deviation analysis reflected wide inter-annual departure (+44.8% in 1990 to –29.9% in 1985) in the annual rainfall received at Sagar Island. In the last 29 years, 21 years received normal monsoon rainfall (June–September) while 3 years received deficit and 5 years experienced excess rainfall. The mean annual rainfall in 14 non-consecutive years deviated negatively (– 0.37% to – 44.8%) indicating rainfall below LPA, whereas in the remaining 15 of total 29 years (1982–2010), it deviated positively (+ 3.43% to + 29.0%) exhibiting rainfall above LPA. Mann–Kendall test affirmed non-significant decreasing trend ($Z = -0.84$) of average annual rainfall in Sagar Island at the rate of 5.79 mm year^{-1}. The trend was at variance with the findings of WWF-India[6] which reported marginal increase in mean annual rainfall for Sundarbans region during 1990–2000 and 2001–2008 separately.

Seasonal rainfall distribution pattern

Monsoon months (June–September) contributed 73.2% (1271.66 mm) with an average variability of 21.6% to the annual rainfall (1735.9 ± 352 mm), whereas pre-monsoon (MAM, March–May) and post-monsoon (ONDJF, October–February) months contributed 10.5% and 16.2% respectively (Table 2, Figure 1). Seasonal rainfall distribution pattern showed wide variability, particularly

Table 1. Mann–Kendall trend statistics of mean monthly rainfall at Sagar Island (1982–2010)

	Mean monthly rainfall (mm)						
Month	Maximum	Minimum	Mean	SD	CV (%)	*Z*	*Q*
January	87.60	0.10	11.44	24.01	209.88	+0.12	0.00
February	72.1	1.00	20.74	25.55	123.19	–2.40	–0.65**
March	271.7	0.40	21.39	51.23	239.50	0.00	0.00
April	163.3	1.10	40.44	41.23	101.95	–0.47	–0.39
May	471.2	1.00	121.12	93.95	77.50	+ 0.54	+ 0.90
June	363.3	0.80	251.24	145.54	57.93	+ 0.30	+ 0.76
July	700.5	134.9	372.51	166.06	44.58	+ 1.03	+ 3.48
August	380.5	101.8	303.64	104.50	34.42	–0.06	–0.10
September	741.8	78.8	344.27	163.68	47.54	–1.16	–4.26
October	498.1	24.2	182.85	138.00	75.47	–0.02	–0.10
November	307.7	0.40	61.44	90.33	147.02	–1.90	–1.53*
December	33.2	0.10	4.84	10.54	217.77	–1.78	0.00

*Significant at 10%; **Significant at 5%; *Z*, normalized test statistics; *Q*, Sen's slope.

Table 2. Trend analysis of long-period rainfall distribution and rainy days at Sagar Island (1982–2010)

Rainfall (mm)	Total annual	Pre-monsoon (MAM)	Monsoon (JJAS)	Post-monsoon (ONDJF)	Rainy days
Minimum	1230.5	52.1	850.8	46.2	76
Maximum	2514.0	555.1	2018.6	711.0	139
Mean	1735.9	184.7	1271.7	281.3	101.7
SD	352.7	115.8	274.7	182.3	14.7
CV%	20.3	62.7	21.6	64.8	14.5
Z	–0.84	+0.58	–1.14	–0.88	–0.62
Sen's slope	–5.79	0.98	–4.42	–3.84	–0.13

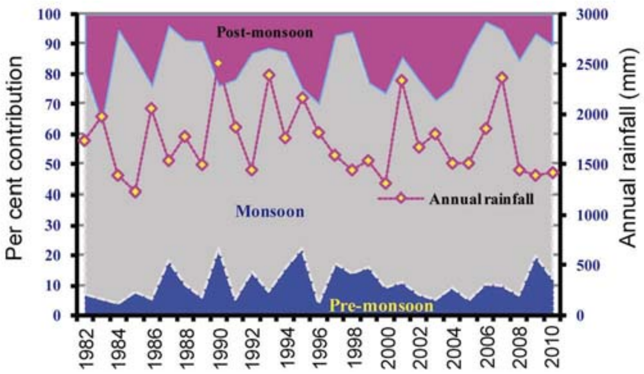

Figure 1. Temporal variation in long-period (1982–2010) annual and seasonal rainfall distributions at Sagar Island.

during pre- and post-monsoon (CV > 62%) periods. Monsoon months also experienced considerable variation in rainfall occurrence: 850.8 mm in 2000 to 2018.6 mm in 2007. Like in other parts of the country[11,15], erratic distribution of rainfall does exist in this vulnerable coastal island as well. Contribution of monsoon and post-monsoon months to the annual rainfall showed a non-significant ($P < 0.05$) decreasing trend (@ 3.84–4.42 mm year^{-1}), but the pre-monsoon months showed an increasing trend (@ 0.98 mm year^{-1}; Table 2). This is in contradiction to the increasing trend reported by WWF-India[6] (1990–2008) for Sundarbans, including Sagar Island. This may be due to the coarser spatial resolution and extrapolation used in the study by WWF-India.

Rainy days and extreme rainfall events

The mean annual rainy days also exhibited non-significant ($P < 0.05$) declining ($Z = -0.62$) trend (0.13 day year^{-1}). A strong positive correlation ($r = +0.47$) between annual rainy days and annual rainfall amount reflects that decreasing trend in annual rainfall may be due to the falling trends in rainy days.

Annual rainy days varied widely from 76 (in 1999) to as high as 139 (in 1990) with LPA (of 29 years) of 101.7 ± 14.7 days (Table 2) The pre-monsoon, monsoon, and post-monsoon months had an average of 14.5, 71.3 and 15.9 rainy days respectively. Nearly 30% of the rainy days was in pre- and post-monsoon months with a wide variability (CV > 35%) compared to relatively more consistent pattern (CV = 12%) with 70% contribution to annual rainy days by monsoon months (Figure 2). Monthly average rainy days during pre-monsoon, monsoon and post-monsoon months were ~4.83, ~3.18 and ~17.75 respectively. Thus, the occurrence of rainy days during the last three decades has more inconsistency during pre- and post-monsoon than monsoon months. Trend analysis of annual rainy days showed a non-significant declining rate (@ 0.24 days year^{-1}), mostly because of the significant ($P < 0.1$) decreasing trend ($Z = -2.12$) at the rate of 0.23 days year^{-1} during post-monsoon months. Rainy days during pre-monsoon and monsoon months have a non-significant increasing trend, which perhaps could not offset the higher declining rate during post-monsoon months and thus, the annual rainy days declined.

Observation of extreme rainfall events indicated that Sagar Island received a total of 59 such events (RX1 day > 100 mm), of which 41 times 1-day maximum was less than 151 mm and for the remaining 18 times, it was higher than 151 mm (RX1 day > 150 mm). Seasonal distribution pattern of 1-day extreme rainfall events (RX1 day > 100 mm) was highest during monsoon months (45 times), whereas pre- and post-monsoon months together experienced this only 14 times.

Rainfall distribution and meteorological droughts during southwest monsoon months

Based on LPA and per cent deviation from LPA, the distribution of rainfall in monsoon months is classified as deficit, normal and excess events[11]. Analysis of 29 years of (1982–2010) monsoon rainfall revealed that the island received 22 normal monsoon years (< LPA ± CV >), while only 7 years received either deficit (<LPA-CV: 4 years) or excess (>LPA + CV: 3 years) monsoon rainfall (Figure 3). Monthly distribution in the monsoon season also exhibited an uneven pattern. July and September consistently received higher rainfall compared to June and August. Rainfall during early June and end of August was comparatively less. As a result, intermittent drought occurred during initial and mid-flowering stages of rice crops.

Meteorological drought years were classified on the basis of weekly water requirement (55 mm) for rice cultivation[11]. Sagar Island experienced different degrees (low to very severe) of meteorological drought 39 times. The years 1982, 1987 and 2000 received < 55 mm rainfall for > 4 consecutive weeks (> 4 CWs) and have been marked as very severe drought years. Similarly, severe meteorological droughts have been observed in 1982, 1988, 1990, 2000, 2007 and 2009 on the basis of 4 CWs with rainfall less than 55 mm. Moderately severe (3 CWs) and severe (2 CWs) meteorological drought events occurred 7 and 22 times respectively, during the last 29 years. The frequent occurrence of different degrees of droughts indicates a water shortage situation in the future for rice cultivation. Hence, rainwater harvesting structures should be initiated to help mitigate water shortage during kharif season rice cultivation and its reuse during subsequent rabi crop production.

Trend analysis of surface temperature

Average monthly temperature was highest during May (29.8°C), and lowest in January (20.43°C). Mean (of 29 years) maximum and minimum temperatures recorded were 33°C (in May) and 22°C (in January). The highest maximum temperature experienced by the island was 43.1°C (June 2010), and the lowest minimum temperature was 11.6°C (January 2010).

Mann–Kendall trend statistics exhibited significant ($P < 0.01$) rising trend ($Z = +4.45$ to $+2.65$) in maximum temperature for all the months (@ 0.07°C to 0.11°C year^{-1}) with an annual average rise of 0.065°C ($Z = +3.96$; Table 3). On the contrary, minimum temperature revealed a decreasing trend ($Z = -0.02$ to -3.27) for all months (except June), with a declining rate of 0.01 to 0.83°C year^{-1}. Annual average minimum temperature also declined at the rate of 0.03°C year^{-1} (Table 4). The average annual temperature (26.7 ± 0.55°C) increased ($Z = +2.55$) significantly ($P < 0.1$) at the rate of 0.026°C year^{-1}, which is similar to the reported increasing trend (@ 0.019°C year^{-1}) in the Sundarbans region for the period 1965–2000 (ref. 6). Decreasing trend in minimum temperature during winter possibly generated greater number of fog days, which perhaps decreases the sunshine duration during winter

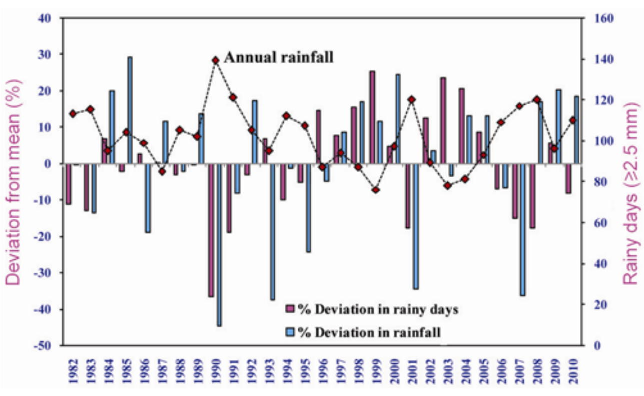

Figure 2. Anomalies of annual rainfall, rainy days and occurrence of total annual rainy days at Sagar Island (1982–2010).

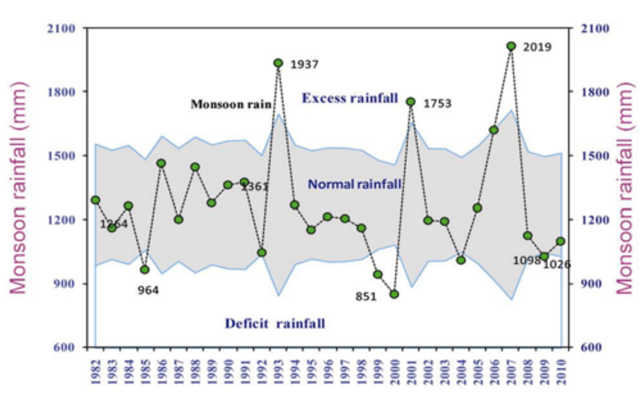

Figure 3. Categorization of long-period (1982–2010) monsoon rainfall as deficit, normal and surplus at Sagar Island.

Table 3. Trend statistics of maximum, minimum and mean monthly temperature at Sagar Island (1982–2010)

	T_{max}		T_{min}		T_{mean}	
Month	*Z*	*Q*	*Z*	*Q*	*Z*	*Q*
January	+1.41	+0.04	–3.27	–0.10***	+1.41	+0.04
February	+1.58	+0.05	–2.27	–0.83**	+1.58	+0.05
March	+3.17	+0.11***	–0.56	–0.01	+3.17	+0.11**
April	+2.72	+0.10***	–0.08	0.00	+2.72	+0.10**
May	+3.55	+0.10***	–1.58	–0.03	+3.55	+0.10**
June	+2.65	+0.07***	+0.39	–0.01	+2.65	+0.07**
July	+3.55	+0.07***	–1.30	–0.02	+3.56	+0.07**
August	+4.45	+0.09***	–0.02	0.00	+4.45	+0.09**
September	+3.74	+0.07***	–1.52	–0.02	+3.74	+0.07**
October	+4.02	+0.09***	–1.82	–0.03*	+4.02	+0.09**
November	+4.33	+0.10***	–0.62	–0.03	+4.33	+0.10**
December	+2.25	+0.07**	–2.40	–0.09***	+2.25	+0.07**

*Significant at 10%; **Significant at 5%; ***Significant at 1%.

Table 4. Statistical analysis of inter- and intra-annual temperature trends at Sagar Island (1982–2010)

Temperature (°C)	Maximum	Minimum	Mean	Summer	Winter
Minimum	28.30	20.62	25.19	26.99	22.67
Maximum	33.21	24.12	28.07	30.86	25.51
Mean	30.67	23.22	26.7	28.99	23.50
SD	1.04	0.81	0.55	0.78	0.81
CV%	3.39	3.49	2.06	2.69	3.49
Z	+3.96	–2.48	+2.55	+3.13	+0.60
Sen's slope	0.060	–0.031	0.021	0.037	0.010

season at Sagar Island. This fact is against the general perception that due to the expansion and intensification of agricultural activities, including irrigation network in the area, Sagar Island has more number of foggy days.

Atmospheric evaporative demands

Annual evaporation loss (851.7 ± 232.5 mm year^{-1}) reflected a significant ($P < 0.001$) decreasing trend ($Z = -5.12$) at the rate of 16.85 mm year^{-1}. The mean annual evaporation rate (2.35 ± 0.46 mm day^{-1}) also decreased ($Z = -6.12$) significantly ($P < 0.001$) at the rate of 0.048 mm year^{-1} (Table 5). With increasing trend in mean annual temperature (0.021°C year^{-1}), the total evaporative loss was expected to increase. However, it follows a reverse relation ($r = -0.15$) in the present study. Rather, the decreasing trend of annual evaporative demand (difference in water vapour content creates a gradient along soil–plant–atmospheric continuum, which leads to gaseous exchange of water between the given surface and the atmosphere)[16] was closely related and better explained by the declining trend ($Z = -3.13$) in mean annual wind speed at the rate of 0.1 km h^{-1} and mean annual sunshine duration ($Z = -3.13$) by 0.06 h year^{-1}. This was affirmed by correlation studies between atmospheric evaporative demand and other weather parameters, i.e. sunshine duration and wind speed. Similar observations on the strong influence of sunshine duration followed by wind speed on evaporative demand were reported by Choudhury *et al.*[11] at Umiam, Meghalaya. However, in Sagar Island, the atmospheric evaporative demands are more sensitive to wind speed ($r = +0.54$) than sunshine duration ($r = +0.43$). Coastal location and absence of any orographic influences affect evaporative demands to a greater extent than sunshine duration.

Climatic water balance studies

An extreme unevenness and erratic nature in seasonal rainfall distribution pattern at Sagar Island resulted in a wide variability in both inter- and intra-annual climatic water balance (rainfall and PET balance). Acute water shortage was observed during post-monsoon months (December–February), because of inadequate rainfall occurrence which failed to meet even 64% of the monthly PET demand. This water scarcity scenario persists during post-monsoon month, i.e. December till pre-monsoon months, i.e. April, but the magnitude of scarcity is more severe in post-monsoon months. Water surplus situations, on the other hand, have been observed during the remaining seven months (May–November). Mean annual rainfall amount during these months was 1.5–7.5 times higher than the monthly PET requirement (Figure 4). By modifying agronomic management practices like the type of

Table 5. Mann–Kendall test statistics for trend analysis of climate variables at Sagar Island (1982–2010)

Climate variables	E_{pan} (mm day^{-1})	E_{pan} rate (mm day^{-1})	Relative humidity (%) Maximum	Relative humidity (%) Minimum	Relative humidity (%) Mean	Wind speed (km h^{-1})	Sunshine duration (h day^{-1}) Pre-monsoon	Sunshine duration (h day^{-1}) Monsoon	Sunshine duration (h day^{-1}) Post-monsoon	Sunshine duration (h day^{-1}) Mean
Minimum	614.0	1.62	77.3	75.5	76.4	5.60	5.90	2.89	5.02	4.88
Maximum	1740.0	3.04	83.0	80.9	81.9	12.0	8.80	5.05	8.10	7.26
Mean	851.7	2.35	80.4	77.7	79.0	8.24	7.27	3.68	6.32	5.68
SD	232.6	0.46	1.14	1.20	1.09	1.78	0.61	0.60	0.93	0.63
CV%	27.3	19.57	1.42	1.56	1.38	21.6	8.39	16.30	14.72	11.09
Z	–5.12	–6.21	+1.97	+0.66	+1.48	–3.13	–3.27	–1.26	–3.25	–3.13
Sen's slope	–16.85	–0.05	+0.06	+0.03	+0.04	–0.10	–0.04	–0.022	–0.10	–0.06

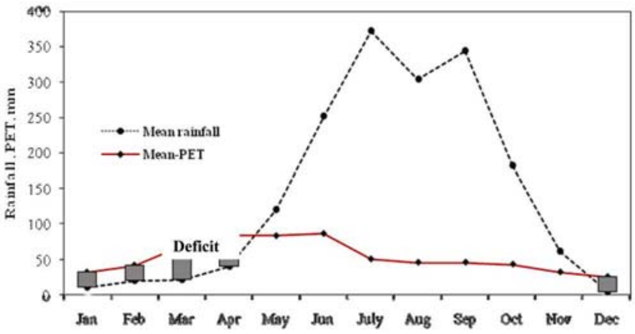

Figure 4. Climatic water balance (rainfall–Potential evapotranspiration) at Sagar Island (1982–2010).

crops grown, date of sowing, growing short-duration varieties, etc., this potential water-surplus period (May–November; Figure 4) can be exploited for intensification as well as diversification of agricultural production system vis-à-vis food security of Sagar Island.

Mann–Kendall trend statistics also affirmed an increasing trend of water surplus situation during March–August ($Z = +0.47$ to $+2.42$) at the rate of 0.62–4.69 mm $year^{-1}$. The trend of increase was significant ($P < 0.05$) during March and May. September and November, on the other hand, exhibited a decreasing trend ($Z = –0.73$ to $–1.63$) of water surplus at the rate of 1.50–3.09 mm $year^{-1}$. Similarly, December and January also reflected significant ($P < 0.01$–0.10) increasing trend in water deficit situation ($Z = +1.89$ to $+3.00$), which may expand the water deficit condition further during the post-monsoon months.

Relative humidity

LPA mean maximum relative humidity (RH_{max}) was 80.3 (± 1.1)%, whereas minimum relative humidity (RH_{min}) was 77.6 (± 1.2)%, with an average value ($RH_{average}$) of 79.0 (± 1.1)% (Table 5). The Mann–Kendall statistics enumerated a significant ($P < 0.1$) rising trend ($Z = +1.97$) in RH_{max} at the rate of 0.05% $year^{-1}$, while RH_{min} and $RH_{average}$ reflected a non-significant rising trend ($Z = +0.66$ to $+1.48$) at the rate of 0.02–0.03% $year^{-1}$. Relative humidity increases by 7% with every 1 K increase in surface temperature[1,17]. With the rising trend in LPA maximum and average temperatures (Tables 3 and 4) and because of its strategic setting in the delta region (Bay of Bengal), surrounded by coastal lines all around, water vapours are continuously flushing to the atmosphere of Sagar Island. This may be one of the reasons for increasing trend in relative humidity of the island.

Wind speed

Sagar Island experienced a mean annual wind speed of 8.24 (± 1.78) km/h (CV = 21.6%) with wide departure from LPA (–45.9 to +32.0%; Table 5). Maximum wind speed was observed in April (13.2 km h^{-1}), while minimum wind speed was observed in November (4.51 km/h). The annual average wind speed manifested a significant ($P < 0.01$) decreasing trend ($Z = –3.13$) at 0.104 km/year. Mean monthly wind speed also exhibited a significant ($P < 0.1$) declining trend ($Z = –3.13$) at the rate of 0.099 km $month^{-1}$ for the island.

Sunshine duration

Mean annual sunshine duration at Sagar Island varied from 4.88 to 7.26 h day^{-1} with an average of 5.68 ± 0.63 h day^{-1} (Table 5). Monthly LPA was highest in April (7.70 ± 0.68 h day^{-1}) and lowest in July (3.05 ± 0.76 h day^{-1}). The seasonal pattern showed that the pre-monsoon months received the highest duration of daily sunshine hours (7.27 ± 0.61 h day^{-1}) followed by post-monsoon months (6.32 ± 0.93 h day^{-1}), while it was the lowest in monsoon months (3.68 ± 0.60 h day^{-1}).

Annual sunshine duration (average) for all seasons showed a decreasing trend ($Z = –1.26$ to $–3.27$) at the rate of 0.04–0.010 h day^{-1}. The changes were significant ($P < 0.01$) during pre- and post-monsoon months. Regression analysis revealed that sunshine duration was negatively influenced by the number of rainy days at Sagar Island. Similar observations were made by Choudhury *et al.*[11] in North East India. It was assumed that due to the overcast sky condition during monsoon months, sunshine duration has a decreasing trend. Besides, the decreasing trend in sunshine duration during pre-monsoon months is influenced by anthropogenic factors (construction work, emission of GHGs through domestic and commercial activities), which continuously add sufficient amounts of aerosol to the islands atmosphere[18].

Conclusion

Trend analysis of weather variables of Sagar Island manifested significant changes over the last three decades (1982–2010). Inter-annual rainfall distribution varied from 44.8% deficit to 29.1% excess over LPA rainfall (1735.9 ± 352.7 mm). Similarly, intra-annual rainfall distribution also reflected significant ($P < 0.05$) anomalies. Contribution of monsoon months varied from 69% to 80% while pre- and post-monsoon months were 2–36%. The island experienced decreasing trend in mean annual (–5.79 mm $year^{-1}$) and seasonal (monsoon and post-monsoon months: –3.84 to –4.42 mm $year^{-1}$) rainfall, with an increase in pre-monsoon rainfall. The island is getting warmer with wider diurnal variations: significant ($P < 0.05$) rising trend in mean maximum and average temperature, and a declining trend in minimum temperature. Other climate variables (evaporation, wind speed, relative humidity, sunshine hours, etc.) also reflected significant changes (+/–) at different magnitudes over the last three decades. Imbalance in climatic water balance, particularly prevailing surplus in monsoon and water scarcity during post-monsoon months was found to increase further. All these changes and complex interactions among them are bound to influence the vulnerability of the island to climate change. Therefore, findings of this study may be useful in implementing adaptation and mitigation strategies for alleviating the environmental and livelihood threats of this fragile island in the Bay of Bengal from extreme climatic hazards.

1. IPCC, *Climate Change 2001, The Scientific Basis*, Contribution of Working Group I to the third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2001, pp. 1–881.
2. Kothawale, D. R. and Rupa Kumar, K., On the recent changes in surface temperature trends over India. *Geophys. Res. Lett.*, 2005, **32**, L18714.
3. Nakicenovic, N. *et al.*, *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2000, p. 599; http://www.grida.no/climate/ipcc/emission/index.htm
4. NATCOM, India's initial national communication to the United Nations Framework Convention on Climate Change. National Communication Project, Ministry of Environment and Forests, Government of India, 2004.
5. IPCC, Climate Change, *Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change., Cambridge University Press, Cambridge, UK, 2007, pp. 1–976.
6. WWF-India, Sunderbans: future imperfect, climate adaptation report. 2010, pp. 1–29.
7. IPCC, *Climate Change 2007. Climate Change Impacts, Adaptation and Vulnerability*, Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report, Summery for Policy Makers, Cambridge University Press, Cambridge, UK, 2007, p. 23.
8. Gopinath, G., Critical coastal issues of Sagar Island, east coast of India. *Environ. Monit. Assess.*, 2010, **160**, 555–561.
9. Bandyopadhyay, S., Natural environmental hazards and their management: a case study of Sagar Island, India. *Singapore. J. Trop. Geogr.*, 1997, **18**, 20–45.
10. Majumder, R. K. and Das, D., Hydrological characterization and estimation of aquifer properties from electrical sounding data in Sagar Island region, South 24 Parganas, West Bengal, India. *Asian J. Earth Sci*., 2011, **4**, 60–74.
11. Choudhury, B. U. *et al.*, Trend analysis of long-term weather variables in mid-altitude Meghalaya, North- East India. *J. Agric. Phys.*, 2012, **12**, 12–22.
12. Dorrenbos, J. and Pruitt, W. O., *Guidelines for Predicting Crop Water Requirements*. FAO Irrigation and Drainage Paper 24. Food and Agriculture Organization of the United Nations, Rome, 1977.
13. Mann, H. B., Nonparametric tests against trend. *Econometrica*, 1945, **13**, 245–259.
14. Kendall, M. G., *Rank Correlation Methods*, Charles Griffin, London, 1995.
15. Subhas, N. *et al.*, An investigation into observational characteristics of rainfall and temperature in Central Northeast India – a historical perspective 1889–2008. *Theor. Appl. Climatol*., 2011, **103**, 305–319.
16. de Jager, J. M. and van Zyl, W. H., Atmospheric evaporative demand and evaporation coefficient concepts. Water SA, 1989, **15**, 103.
17. Sun, D. and Held, I. M., A comparison of modeled and observed relationships between inter-annual variations of water vapor and temperature. *J. Clim.*, 1996, **9**, 665–675.
18. Deką, R. L., Mahanta, C. and Nath, K. K., Trends and fluctuations of temperature regime of North East India. In *Impact of Climate Change on Agriculture* (eds Panigrahy, S., Ray, S. S. and Parihar, J. S.), ISPRS Archives XXXVIII-8/W3 Workshop Proceedings. Space Application Centre, Ahmedabad, 2009, pp. 376–380.

Received 11 March 2013; revised accepted 2 July 2013