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Variability of Surface Air Temperature and Heat wave Incidences Across Coastal Odisha During Summer Season

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Abstract: Over the last few years, increasing attention has been focused on the changes in climate variability and weather extremes, particularly tropical cyclones, unprecedented thunderstorms, heatwaves (1998, 2016), and cold waves (2018, 2019) in coastal Odisha. Heatwaves represent one of the most critical manifestations of regional climate change in India, particularly along the densely populated coastal belt of Odisha. The present study examines five-decadal (1969-2022) variations in surface air temperature and heatwave (HW) characteristics across seven coastal stations Bhubaneswar (BBS), Balasore (BLS), Chandbali (CBL), Cuttack (CTC), Paradeep (PRD), Gopalpur (GPL), and Puri (PRI) using temperature data of stations of India Meteorological Department (IMD). Using homogenised monthly temperature data from 1969 to 2022, the temperature departure index (TDI) was calculated to assess inter-annual and seasonal trends, while a 5-year moving average was applied to identify long-term variability. Heatwave days were determined based on maximum temperature anomalies, following the IMD coastal criteria. The analysis applied the Mann-Kendall test and Sen's slope estimator to identify monotonic trends of surface air temperature and seasonal HW days (March-May) data. Results reveal spatial heterogeneity in temperature variability across stations, such as BLS, CTC, and GPL, which exhibited increasing variability in March and May, while PRI and CTC showed decreasing trends. Significant positive trends were detected at PRD ($Z=2.49$, $p=0.013$, Sen's slope-0.017 days yr^{-1}) and PRI ($Z=2.06$, $p=0.039$, slope $=0.015$ days yr^{-1}) during the pre-monsoon (March-May) season, while other stations exhibited weaker or statistically insignificant trends. The 5-year moving average analysis reveals oscillatory warming episodes corresponding to strong El Niño years (1987, 1998, 2010, and 2016), which coincide with peaks in heatwave occurrences. Analysis of heatwave events reveals that heatwave activity is stronger and slightly increasing toward inland-coastal transition zones (BBS, CBL), whereas true coastal sites exhibit nearly constant or decreasing heatwave frequency. The results highlight a localised modulation of heat extremes by land-sea interactions, urbanisation, and monsoon onset timing. The findings highlight the accelerating risk of heat stress over coastal Odisha and underscore the importance of localised early-warning systems and adaptive urban planning.

Keywords: Surface Temperature variability, Homogeneity, Heat wave, Mann-Kendall trend, Coastal Climate

1. Introduction

Weather and climate are primarily responsible for altering the sources of livelihood, lifestyle, and other day-to-day habits in any location. However, the growth and modernisation of a nation, along with human activities, have also contributed to the process of climate change (Piechota & Garbrecht, 2006). Climate change is now acute and has become a serious threat to the environment due to inadvertent anthropogenic disturbances (Khan et al., 2009). These changes have amplified the frequency and intensity of extreme events such as heatwaves, heavy rainfall, tropical cyclones, and droughts (CRED, 2015).

Now, the influence of climate change and variability on human beings and their activities is a major concern, and its coverage is widespread, particularly in print and electronic media, as well as government organisations. So, there is a need for the study of these hydro-meteorological extremes (either above or below normal). Generally, the studies focus on the issue of whether the climatic trend is warming or cooling.

Globally, the variability of surface air temperature reflects the combined influence of long term anthropogenic forcing and short-term internal climate processes (Deser et al., 2012). Alterations in mean temperature and variability shape the occurrence of climate extremes (Meehl et al., 2000; Katz, 1999). An increase in variability without a change in mean temperature enhances the probability of both hot and cold extremes, whereas simultaneous increases in both mean and variability intensify heat events and suppress cold extremes. These mechanisms directly affect regional hydrology, agriculture, and public health (Lobell & Gourdji, 2012; Patz et al., 2006). During the 1997/98 El Niño event, a record-breaking global temperature was observed for approximately sixteen consecutive months, from May 1997 to August 1998 (Karl et al., 2000).

Adequate knowledge of climate variability will facilitate understanding the future climate change and also strengthen its impact on societal mitigation and adaptation efforts, but understanding of forced variability is fully proven (IPCC, 2021), whereas uncertainty of regional internal variability with persisting society-relevant changes for decades is beyond the range of current scenarios (Hebert et.al, 2022). The occurrence of heat waves, cyclones, floods, severe thunderstorms, and localised flash floods is a recurring phenomenon, and their mitigation and adaptation processes need to be strengthened to minimise loss of life and infrastructure. The eastern Indian state of Odisha provides a unique case study of climate variability and its societal impacts. Bounded by the Bay of Bengal to the east and a continental landmass to the west, coastal Odisha frequently experiences extreme hydro-meteorological events-most notably the 1998 heatwave, which caused over 2,000 deaths, and the 1999 super cyclone, which claimed more than 9,800 lives. However, in recent years, improved disaster preparedness and early warning systems have significantly reduced casualties during major events such as cyclones Phailin (2013), Fani (2019), and Titili (2018).

Coastal Odisha's climate is strongly influenced by the interplay of sea-land breezes, tropical disturbances, and seasonal monsoon dynamics. The region exhibits sharp spatial gradients in temperature and humidity, shaped by both natural processes and anthropogenic drivers such as urban expansion. Population density is comparatively very high in this belt, particularly in urban areas, due to the migration of population from rural areas. Additionally, the location of major cities, ports, airports, and industries in this agriculturally developed region also contributes to this high density. Population density increases proportionately at each of the stations, even though the capital city, BBS, has seen an exponential rise. Understanding long-term trends in surface air temperature variability and heatwave dynamics is therefore critical for predicting future risks and guiding climate adaptation strategies. There is no similarity in the values of annual mean temperature data among all seven stations (Sethi et al., 2024),as verified using raw data through parallel CUSUM plots of equation (1).Using a target station versus the six nearby neighbouring stations based on the techniques of Rhodes & Salinger (1993) is given by

$$\text{cusum}(t) = \sum_{s \le t} \hat{e}_t \qquad (1)$$

Where $\hat{e}_t = x_t - \hat{\mu}_{jt}$, $\hat{\mu}_{jt}$ is the mean of $\{x_s : j_s = j_t\}$ and $j_t$denotes the year corresponding to time t.

Most temperature extremes are observed in various regions of the world (Angell & Korshover, 1978; Asakura & Ikeda, 1981; Jones et al., 1982). Impact of extreme weather events on sectors like health, agriculture & socioeconomic progress and also on comfortable life style of humans in connection with food supply (Lobell & Gourdji, 2012) and water (Zhang &Cai, 2013; Taylor et al., 2013), human health (Patz et al., 2006) by wide spread infectious vector-borne diseases (Epstein,2002; Khasnis & Nettleman, 2005), heat stress (Sherwood & Huber, 2010) and mental illness (Berry et al., 2010), the economy by changes in goods and services (Diaz et al.,2006; Tol, 2002) and the national security by shifting of population, intense competition to achieve natural resources, violent conflict and political agitation (Kloor, 2009). Understanding climate variability and its trends will be very useful for predicting the return periods of intense floods, cyclones, and heatwaves.

Some of the researchers have undertaken studies on long-term trend analysis for the Odisha region in India, and these studies were summarised by trend analysis of data from 1901 to 1980 in the Mahanadi Basin (a Major river basin in Odisha). Their findings showan increase of annual average surface air temperature of 1.1 °C per 100 years (Rao, 1993).There are noteworthy findings in 11-year solar cycles, periodicities of very low frequencies (trends) and quasi-biennial oscillation (QBO) of 2 to 3 years duration of rainfall at some stations, subdivisions and regions of India (Parthasarathy & Dhar, 1974, 1976a and 1976b; Parthasarathy, 1975 and 1984; Mooley & Parthasarathy, 1979 & 1984).Other research findings include a warming trend in coastal districts from 1980 to 2010

(Vijaykumar et al., 2021) and a 0.4 °C increase in the mean annual temperature over the past century in India (Hingane et al., 1985). Moreover, a significant warming trend is observed in Calcutta, Bangalore, and Mumbai, whereas a significant cooling trend is noted in Delhi, but no significant trend is observed in Chennai and Pune (Kumar & Hingane, 1988). In the context of Odisha, the increase in monthly mean temperature in all months at Bhubaneswar, using 46 years of data (Majhi & Rath, 2018), and the increase of 5.1 days per decade in the annual frequency of hot days over Odisha (Srivastava et al., 2014) are also elucidated. Homogeneous temperature & precipitation data series can generate noteworthy results. A homogeneous series refers to a time series that has been adjusted to remove variations due to weather and Climate (Conrad & Pollock, 1950), but not variations caused by non-climatic parameters. In the context of the climate analysis study of Odisha, none of the researchers attempted to use homogenised time series data. Output of non-homogenized time series of temperature data analysis will yield spurious resultas non-climatic parameters, may suppress climate change signal due to change of measuring devices, station site shifting, site exposure conditions like urbanization, land use change and observers' erroneous observation practices (Jones et al, 1985; Karl & Williams, 1987; Gullet et al.,1990; Heino, 1994). Homogenization of temperature time series data for studying climate change and climate variability is necessary, and surface air temperature is a useful indicator, as other meteorological parameters, such as mean sea level pressure, wind speed and direction, rainfall, etc., are directly influenced by it. Several methods have been ascribed by earlier studies to address different factors causing climate data inhomogeneities (Peterson et al, 1998; Jones et al., 1986; Karl & Williams, 1987; Alexandersson, 1986; Gullet et al., 1990; Wang et. al., 2010; Easterling & Peterson, 1995; Vincent, 1998; Perreault et al., 1999, 2000; WMO Technical Note 79, 1966,Climate change; and Szentimrey, 1999). In this study, RH tests (Wang et al., 2013) areemployed to homogenise54-year mean temperature data from 1969 to 2022 for seven stations.

Only seven meteorological observatories, i.e., Bhubaneswar, Balasore, Chandbali, Cuttack, Gopalpur, Paradeep, and Puri, of WMO standard, operated by the IMD, exist in coastal Odisha, and daily long-period data of maximum and minimum temperatures from 1969 to 2022 are available for these stations. The monthly mean temperatures for seven stations were homogenised using RHtests (Wang et al., 2007 & 2008). The problem of homogeneity is addressed by relative comparison of the target station's time series to a (average of neighbouring stations except the target station) composite reference time series. The change points were detected by using RHtests V4 (Wang & Feng, 2013).

However, few researchers have used homogenised long-term temperature series or focused specifically on intra-seasonal variability and heatwave occurrence in the coastal districts of Odisha. The present study bridges this gap by employing homogenised data (1969-2022) from seven IMD observatories to (i) quantify spatial and temporal variability in monthly and seasonal mean temperatures and (ii) assess long-term trends in temperature departure indices. In addition to these, we will generate(iii) statistical trends using the non-parametric Mann-Kendall (MK) test and Sen's slope and (iv) analyse the frequency and intensity of summer heatwaves and associated government mitigation efforts.

2. Materials and Methods

2.1. Study Area

Coastal Odisha, located on the eastern seaboard of India, extends along the Bay of Bengal between latitude 22° 36' N to 17° 49' N and longitude 81° 36' E to 87° 18' E. The coastal belt spans approximately 480 km of shoreline and encompasses ten administrative districts: Balasore, Bhadrak, Jajpur, Kendrapara, Jagatsinghpur, Khurda, Puri, Nayagarh, Ganjam, and Cuttack. This region experiences a tropical monsoon climate with four distinct seasons: Winter (December to February), Pre-Monsoon (summer) (March to May), South-west monsoon (June to September) and Post-monsoon (October to November).

The mean annual rainfall is approximately 1,450 mm, with 75-80% of it occurring during the monsoon season. The mean maximum temperature reaches 37 °C in May over coastal stations such as Bhubaneswar, while inland stations experience values about 41 °C. Coastal Odisha's climate is influenced by interactions between sea-land breezes, cyclonic disturbances, and inland continental heating. The region is one of the most hazard-prone in India, facing frequent heatwaves, cyclones, floods, and thunderstorms. Rapid urbanisation in Bhubaneswar, Cuttack, and Paradeep has altered local land-surface characteristics, intensifying the urban heat island effect and modifying heatwave characteristics.

Seven India Meteorological Department (IMD) observatories representing the ten coastal districts were selected for this study (Table 1). These include four inland-coastal transition stations (Bhubaneswar (BBS), Cuttack (CTC), Chandbali (CBL), and Balasore (BLS)) and three maritime stations (Puri (PRI), Paradeep (PRD), and Gopalpur (GPL)). The region, along with the location of meteorological observatories, is shown in Figure 1.

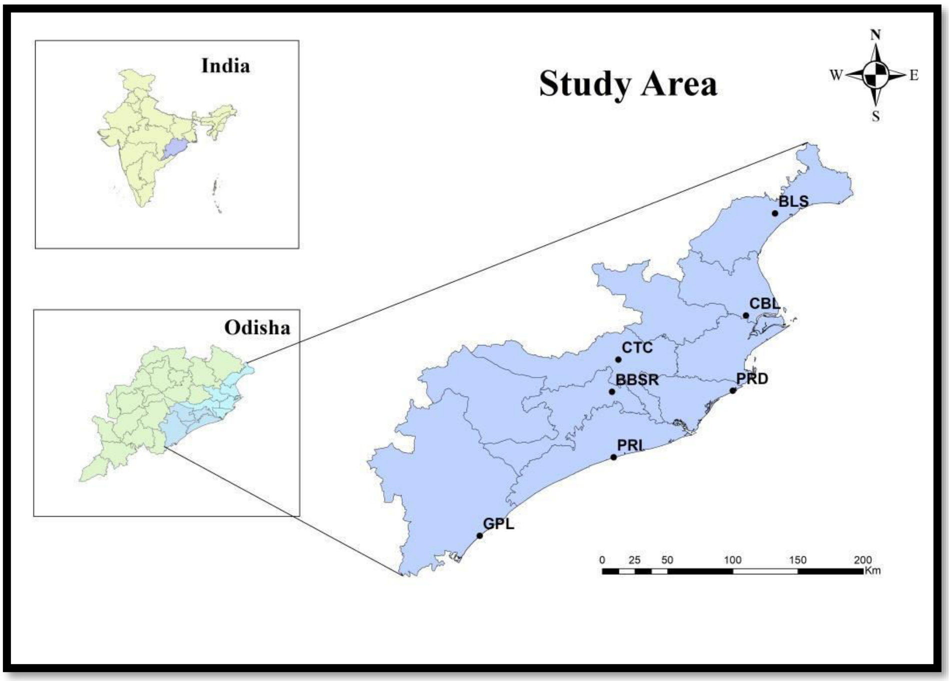


Fig. 1. Location of stations on Odisha map.

2.2 Data

Daily maximum and minimum air temperature data for all seven stations were obtained from the national data centre, IMD Pune, the Special Relief Commissioner, Government of Odisha, and open-source archives (e.g., www.ogimet.com). The dataset spans 54 years from 1969 to 2022. Daily data were screened for quality and continuity. Missing or erroneous entries (≤ 3 consecutive days) were filled using multiple linear regression based on correlations with the two nearest stations. Each completed series was verified to ensure that there was minimal change in standard deviation before and after infilling. Monthly mean temperature values were then computed as the arithmetic mean of daily maximum and minimum temperatures for each station. Daily data from 1969 to 2022 were verified to ensure that the maximum and minimum temperatures are comparable to those of nearby stations in coastal Odisha. All stations are located in the same climatic region, although their locations are in different districts. Geographic information of seven meteorological stations is shown in Table I.

Table 1. Geographical coordinates of seven stations in coastal Odisha

SI. No.	W.M.O ID	Station Name	Latitude	Longitude	hamsl (meters)
1	42971	Bhubaneswar (BBS)	20°15’	85°50’	46
2	42970	Cuttack (CTC)	20°28’	85°56’	27
3	42976	Paradeep (PRD)	20°18’	86°41’	08

4	43053	Puri (PRI)	19°48’	85°49’	06
5	42973	Chandbali (CBL)	20°47’	86°44’	06
6	42895	Balasore (BLS)	21°31’	86°56’	20
7	43049	Gopalpur (GPL)	19°16’	84°53’	17

2.3 Homogenization of mean temperature data

Artificial discontinuities or inhmogeneities are found in the time series temperature data and these are mainly due to non-meteorological factors such as instrumentation, growing trees near observatory site, new observers, shifting of station, procedure of calculation of mean temperature, change in environment surrounding of a station such as urbanization or instrument shelter (Mitchell, 1953; Bradley & Jones, 1985; Quale et al., 1991). Shifting of station sites or other inhomogeneity factors may influence extreme temperatures more than mean values due to topographic contrasts between the old and new sites, or in close proximity to the coast. It is a challenging task to remove inhomogeneity in a climate time series data, so this problem needs to be addressed by comparing the time series of a target station (temperature series of a station to be homogenised) to a time series of a composite reference series, but the composite reference series should be homogeneous.

To develop a homogeneous reference series using data with unknown inhmogeneities, literature review of numerous methods by many researchers to reduce potential inhomogeneity in the time series data (Alexandersson, 1986; Potter, 1981; Gullet et al, 1991; Wang et. al, 2007, 2008; Peterson & Easterling, 1994; Vincent, 1998; Solow, 1987; Kohler, 1949 and Young, 1993) were prepared and finally RHtests V4 of Wang et. al, 2013,2007 & 2008 are brought into use in our research. The problem of homogeneity is addressed by relative comparison of the target station’s time series to a composite reference station’s time series. There are standard techniques proposed by many researchers for developing a composite reference series using data from neighbouring stations (Alexandersson, 1986; Alexandersson & Moberg, 1997; Sugahara et al., 2012; Ducré-Robitaille et al., 2003; Plummer et al., 1995; and Peterson & Easterling, 1994). As there was a very sparse network of stations in coastal Odisha,however, all stations lie in a coastal climatic region.These stations are not highly correlated and dissimilar in their waveforms, so a composite reference series is created for each of the seven target stations by averaging the monthly mean temperature data of the remaining six stations (Allen et al., 1998). Then, change points were detected by using the software package RHtests V4 (Wang & Feng, 2013). As the homogenization of daily data is a challenging task, the monthly mean temperature time series data for seven stations are homogenised in this study, and these were used to study the trend and climatic variability. The recent manual of Rhtests V4 was received from Dr. Y.Feng, Climate Research Division, Science & Technology Branch, Environment Canada. Toronto, Ontario, Canada,via personal communication and occasional email guidance to run the program for achieving homogeneous time series data. This software has been used by many researchers to homogenise time series data of temperature and precipitation (Vincent et al., 2002; Zhang et al., 2005; Wan et al., 2010; Dai et al., 2011; Wang et al., 2014; Xu et al., 2013). The methods of analysis include penalised maximal T-test (PMT) using a reference series and the quantile-matching (QM) adjustment method (Wang et al., 2007; Wang et al., 2010, 2014; Vincent, 2012). Initially, the homogeneity of the composite reference series was tested, and then the homogenised reference series was used to study the relative homogeneity of the target temperature time series data. Then, the monthly mean temperature time series data of the station were tested to find significant breakpoints using PMT at a 5% significance level, based on the composite reference series of the respective station. The relative Penalised Maximal T (PMT) test (Wang et al., 2007) implies a relative test, and a composite reference series was used to identify artificial sudden changes (shifts) in the data records. Here, the reference series was used to estimate the Quantile-Matching (QM) adjustments (Wang et al., 2010) in addition to mean adjustments. The QM adjustments are used to adjust the base series so that the empirical probability distributions of all segments of the detrended base series are consistent with one another. The adjustment values were estimated from the difference (base minus reference) series or from the de-trended base series when the reference series is not used. The adjustment value depends on the empirical frequency of the datum to be adjusted; namely, it varies from one datum to another in the same segment, depending on their corresponding empirical frequencies (Wang et al., 2010, 2014). QM adjusted base series is considered as a homogenised data series, but when the shortest segment is too short, then the QM adjusted series may not be generated, so, in that case, the mean-adjusted series is used as a homogenised series for the target station. Using this method, the mean monthly temperature series of BBS, BLS, CBL, CTC, GPL, PRD and PRI were homogenised.

2.4 Methodology

2.4.1 Computation of Temperature Departure Index (TDI)

A station-wise study is attempted,taking into account the variation in temperature and precipitation from station to station in recent years. For each station and month, the temperature departure index (TDI) was computed to quantify deviations from the long-term mean:

$$\mathrm{TDI} = \frac{X_i - \bar{X}}{\sigma} \qquad (2)$$

Where X_i is the monthly mean temperature for year i, X is the long-term mean monthly temperature (1969-2022), and σ is the standard deviation of the monthly mean temperature series.

A 5-year moving average of TDI values was then applied to reveal low-frequency variability. High positive TDI values indicate unusually warm conditions, while negative values indicate cooler periods.

For a given region or zone, the climatic variability index of Tavakol and Jones can be adopted (Lamb, 1982), and it is computed as follows

Climate Variability Index$=\frac{1}{n}\sum_{i=1}^{n}\frac{|X_i-\bar{X}|}{\sigma}$ (3)

where n is the number of sites in the region being assessed, and summation is made for all stations in the region.

To detect general trends in temperature variability, 5-year moving averages of temperature departure index values were calculated. Results of the index values for 5-year moving averages, presented monthly from January to December, along with graphs for all the seven stations, depict the trend of temperature departure index values over the years. The index values range from 0 to 2.5. Five-year running means are actually plotted for the middle year, i.e., the five-year average of 1969-1973 is plotted at 1971, similarly, the 5-year average of 1970-1974 is plotted at 1972, and so on, with the last point plotted being 2020, representing the 5-year period of 2018-2022. The 5-year moving averages are plotted as solid lines while individual yearly index values are indicated by dots. Low index values represent near-average temperature conditions for the station, and higher index values indicate exceptionally unusual conditions, either well above or well below normal values. A study of index values for 5-year moving averages, covering both annual and seasonal data for the entire coastal Odisha (averaged across all seven observatories), has been conducted using graphs and analysis.

2.4.2 Heatwave Identification

Heatwave and severe heatwave (HW/SHW) days were determined following IMD's coastal criteria:

Heatwave (HW): Maximum temperature ≥37 °C and departure from normal 4.5-6.4 °C

Severe Heatwave (SHW): Maximum temperature ≥ 37°C and departure >6.4 °C

In this study, heat wave criteria are applied to a particular station, so, criteria of two stations for at least two consecutive days in a region are not considered because one sample station is taken to find out HW and SHW days in a year as an extreme weather affecting climate variability of a place or region. The total number of HW and SHW days is combined and plotted season-wise, with separate plots for March to May and March to June, covering the period from 1969 to 2022. This enabled correlation with temperature variability indices and identification of inter-annual heatwave tendencies. 5-year moving average and Mann-Kendall trend applied to observe the seasonal trend.

Climate change is increasing the likelihood of many extreme weather events, which in turn contribute to climate variability. Therefore, the study of heat waves during the pre-monsoon season in coastal Odisha has been analysed. In this regard, all stationswere selected, and the maximum temperature data from these stations for the period from 1969 to 2022 were used. Although heat waves were a recurring phenomenon in Odisha, awareness programs were not established until 1998. About 2042 people died in 1998 due to heat wave-related hazards (SRC report), and public awareness campaigns by the government and NGOs were strengthened thereafter. In light of the 1998 heat wave tragedy, it was deemed necessary to study the trend of heat wave analysis for the seasons March-May and March-June, spanning from 1969 to 2022, using maximum temperature data at individual stations.

2.4.3 Trend analysis using Mann-Kendall Test and Sen's slope Estimator

To statistically assess whether observed changes in temperature or heatwave frequency are significant, the non-parametric Mann-Kendall (MK) trend test (Mann, 1945; Kendall, 1975) was applied. It evaluates the null hypothesis (no monotonic trend) against the alternative (existence of an increasing or decreasing trend) without requiring the data to follow any specific distribution. Test statistic (S is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}\ (x_j - x_i) \qquad (3)$$

Where sign $(x_j-x_i) = +1$ if $x_j > x_i$, 0 if equal, -1 if $x_j < x_i$.

The variance of S is computed considering tied values, and a Z-statistic is derived:

$$Z = \sum \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S>0 \\ 0, & S=0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S<0 \end{cases} \qquad (4)$$

A two-tailed test at $\alpha = 0.05$ was used; $|Z| > 1.96$ indicates a statistically significant trend.

To estimate the magnitude of change, Sen's slope estimator (Sen, 1968) was applied:

$$\beta = \text{Median}\ \left(\frac{x_j - x_i}{j-i}\right) \quad \forall\ i<j \qquad (5)$$

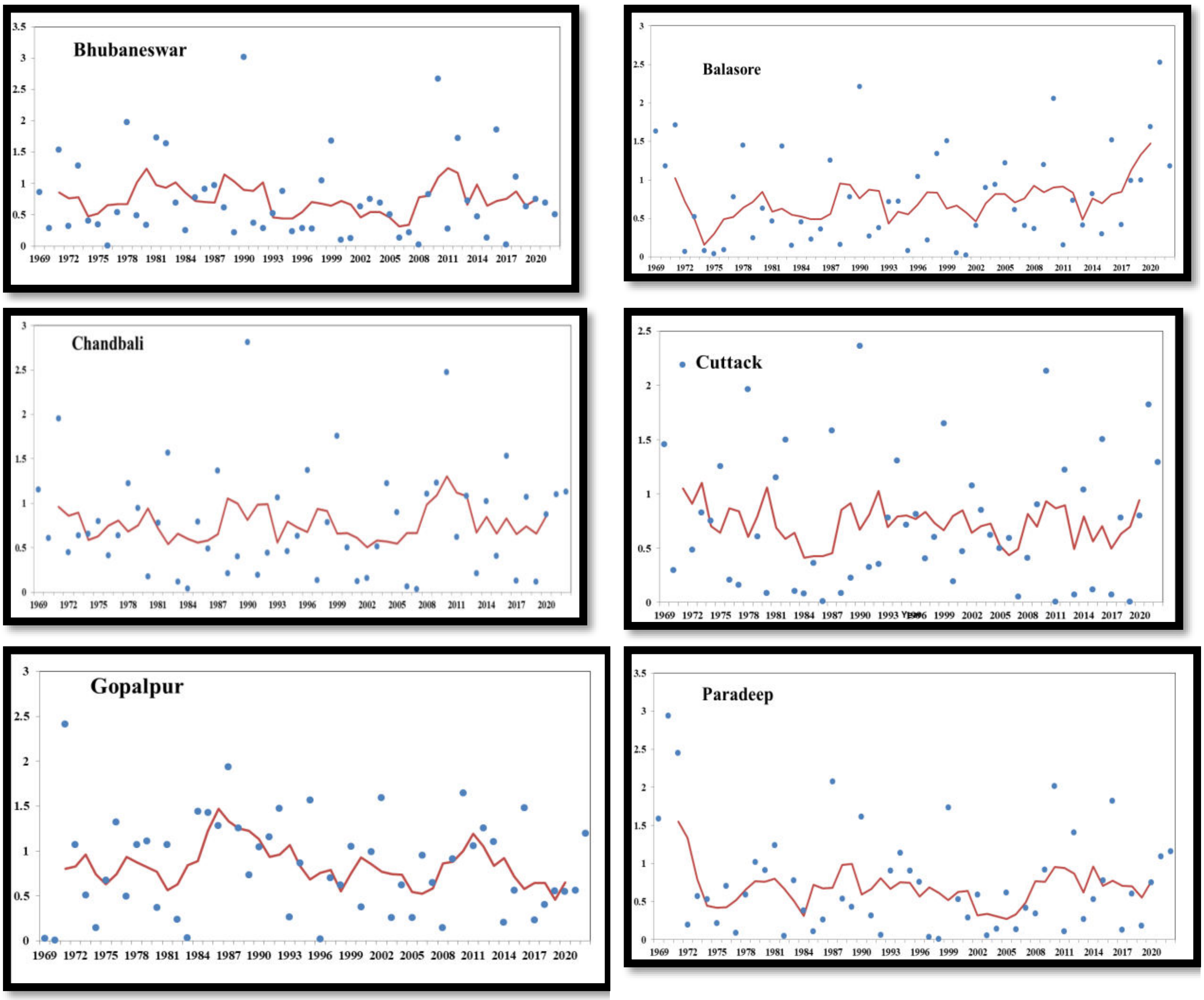
Here, β represents the rate of change per year (°C yr^{-1} for temperature or days $yr^{-1}$for heat waves). Positive β values indicate warming/increasing frequency; negative values show cooling/decrease.

Together, MK and Sen's tests quantify both the significance and the magnitude of temperature and heatwave trends.

3. Results and Discussion

3.1 Inter-annual Temperature variability by month (Mar-May)

To detect trends in the index values over time, five-year moving averages were calculated using temperature departure index values for each of the seven stations during the summer months (March to May) for the period 1969-2022 incoastal Odisha. Results are presented in a series of maps/graphs in Fig.2 to Fig.4. Low index values of individual years indicate near average temperature for the district based on index values of the station in the district concerned, but high index values indicate exceptionally unusual conditions with either much warmer or much colder than average temperatures. Standard deviation σ, in the denominator, normalises TDI values, so some regions might experience extreme temperatures in a particular year (either well above or well below) of 2 to 3°C or more from the record mean value, whichmay not be reflected in the index.



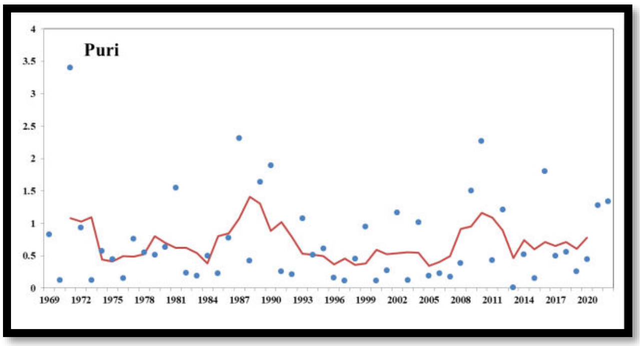
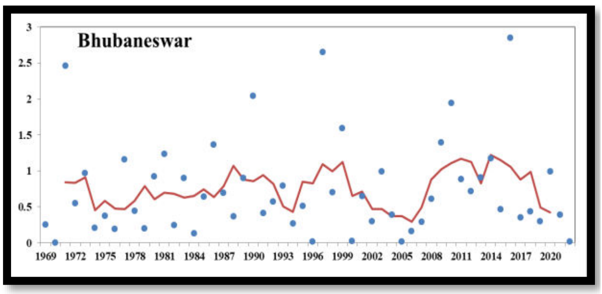


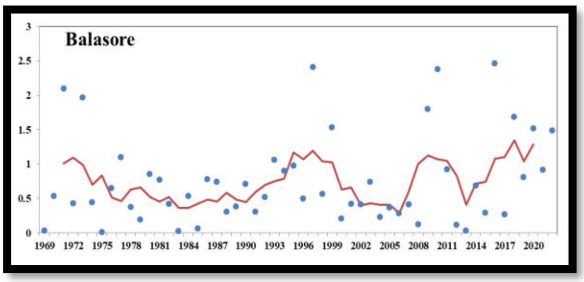
Fig.2. Temperature variability index values for the month of March for the period 1969-2022 (plotted as dots) and 5-year moving averages (plotted as solid red line) for BBS, BLS, CBL, CTC, GPL, PRD, and PRI

March, April, and May constitute the summer season, during which day temperatures rise, with the occurrence of heatwave days; however, the number of these days is less compared to April and May.

For March (Fig. 2), a peak in the trend line for temperature departure index values is evident in the early 2010s for BBS, CBL, GPL, and PRI, but a weaker peak is recorded at CTC and PRD. This peak was caused by the high index value (the second-highest) of 2010. Another peak over the trend line of the 5-year moving average is seen in the early 1980s for BBS, BLS, CBL, and CTC, whereas a prominent peak over the trend line exists in the mid-1980s for GPL and PRI, and it is caused due to the high index value of 1987 (2nd highest in March). There are ups and downs in the trend line for the GPL site, but a similar characteristic is absent at the other sites. The TDI trend line of the 5-year moving average for recent years indicates a trend toward increased temperature variability for BLS and CTC. The highest index value is observed in March 1990 for BBS. There was an El Niño in 2010 and a moderate El Niño in 1987. Heat waves were experienced for four days in 2010 at the representative station BBS in coastal Odisha, but no heat wave was recorded in 1987. During a 54-year period, the highest number of heat wave days was observed in March 1999; however, no such remarkable indication is evident in the trend line of TDI in a 5-year moving average, and no higher index value is noted. March temperatures across coastal Odisha exhibit a general warming tendency with positive Sen's slopes observed at all stations. Statistically significant warming trends ($p<0.05$) are observed at CBL and PRD, indicating clear evidence of temperature rise during March at these locations. The other stations (BBS, BLS, CTC, GPL, and PRI) show positive but non-significant trends. The strongest warming is evident in Paradeep, followed by CBL, whereas Gopalpur remains almost stable. This pattern suggests that northern and central coastal regions of Odisha have undergone more pronounced warming in March than the southern coast, possibly reflecting differences in urbanisation, coastal convection, and land-sea thermal contrast.

April is a part of the pre-monsoon season (Hot weather season), and heat waves are prevalent during this season. The trend line of 5-year moving average in April (Fig. 3) of TDI shows peak between mid- 1990s and late 1990s for BBS, BLS, CBL, CTC, PRD and PRI due to highest index value in the year 1997 (2.99 of CBL, 2.65 of BBS, 2.67 of PRD & 2.4 of BLS) but the weaker peak in recorded at PRI and no Peak is noticed at GPL. A sharp peak exists on the trend line of the 5-year moving average in the mid-1980s for GPL due to the highest index values in the year (2nd highest in 2.29 in April 1986 and 3rd highest 2.27 in April 1987). A weak peak in the trend line for TDI is evident for PRI & BBS. No trend is observed for PRD, CTC, and BLS based on the trend line for TDI of 5-year moving averages between the early 1980s and the early 1990s, whereas a trend is evident from the late 1970s to the mid-1990s for CBL. It suggests the variability is low during the period. A distinct peak is found in the trend line of TDI for the 5-year moving average in the late 2000s and early 2010s for BBS, BLS and CBL. The trend line shows a clear increasing trend in recent years for GPL, whereas BBS shows a decreasing trend. The lowest index values are observed in the early 1980s for PRI. The highest index value is evident in the year 2016, and a sharp peak in the mid-2010s of the trend line of TDI in a 5-year moving average is observed for BLS. There are ups and downs in the trend line, indicating a similar periodic nature for BLS from the early 1990s to the end of the 5-year moving average trend line, and a similar feature with less pronounced characteristics is noticed for BBS, CBL, and CTC. The periodic type of feature in the trend line may be due to internal variability, such as ENSO cycles of LA Niña and El Niño, and forced greenhouse-induced trend (Rantanen & Laaksonen, 2024). 2015-2016was a very strong El Niño year, and a higher number of heatwave days were recorded in April 2016 for the entire 54-year dataset at the representative station BBS in coastal Odisha. Moderate positive but non-significant trends are observed at BBS and PRD, while BLS, CTC, and GPL display weak or negligible cooling tendencies. Only PRI exhibits a statistically significant increasing trend ($p=0.035$), suggesting localised warming. The Sen's slope values range between -0.009 °C yr^{-1}(GPL) and +0.019 °C yr^{-1} (PRI), suggesting that the rate of change varies spatially along the coast. Overall, April temperatures show mild warming tendencies, most evident in central and southern coastal Odisha (Puri and Paradeep), whereas the northern sector (Balasore) remains relatively stable or slightly cooler. This spatial heterogeneity likely arises from land-sea thermal contrasts, urban heat effects and coastal atmospheric circulation differences, with southern coastal sites exhibiting stronger warming signals.





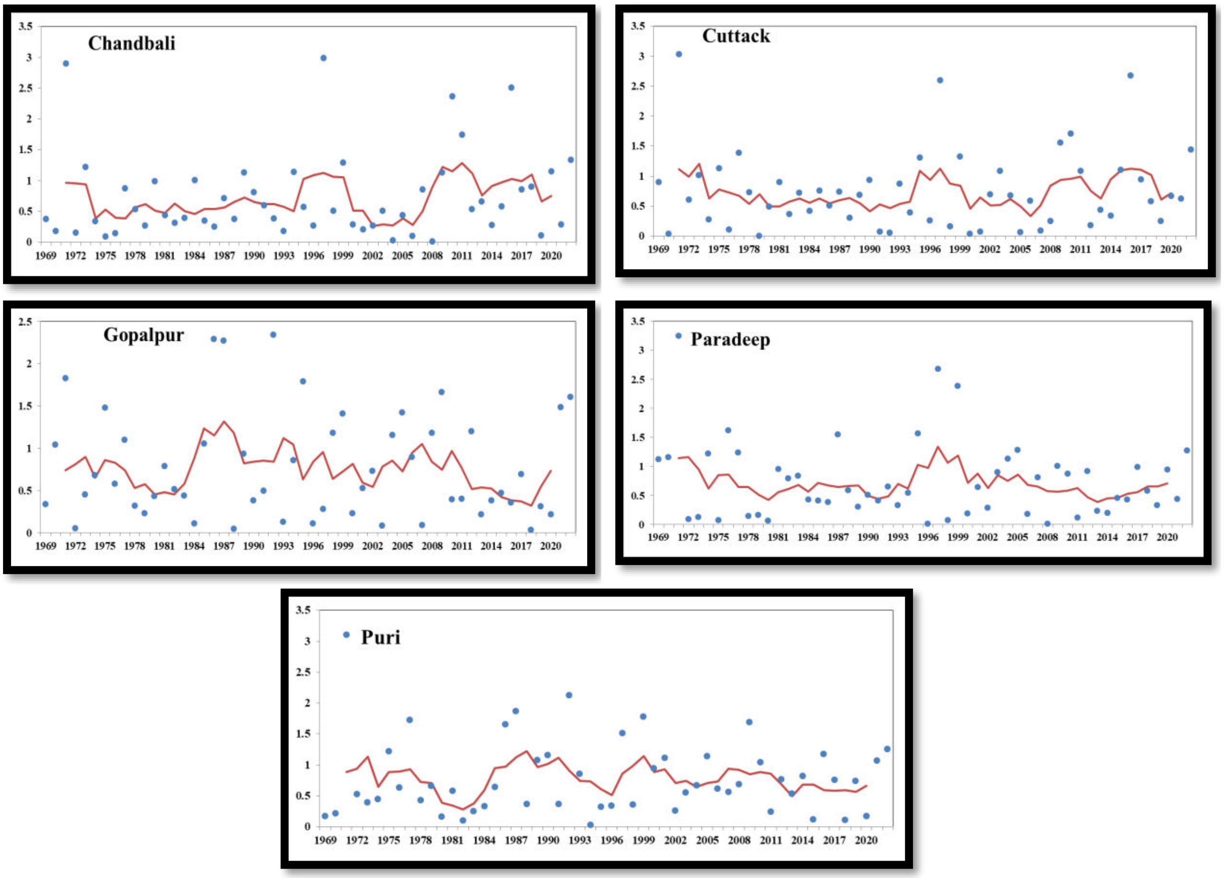
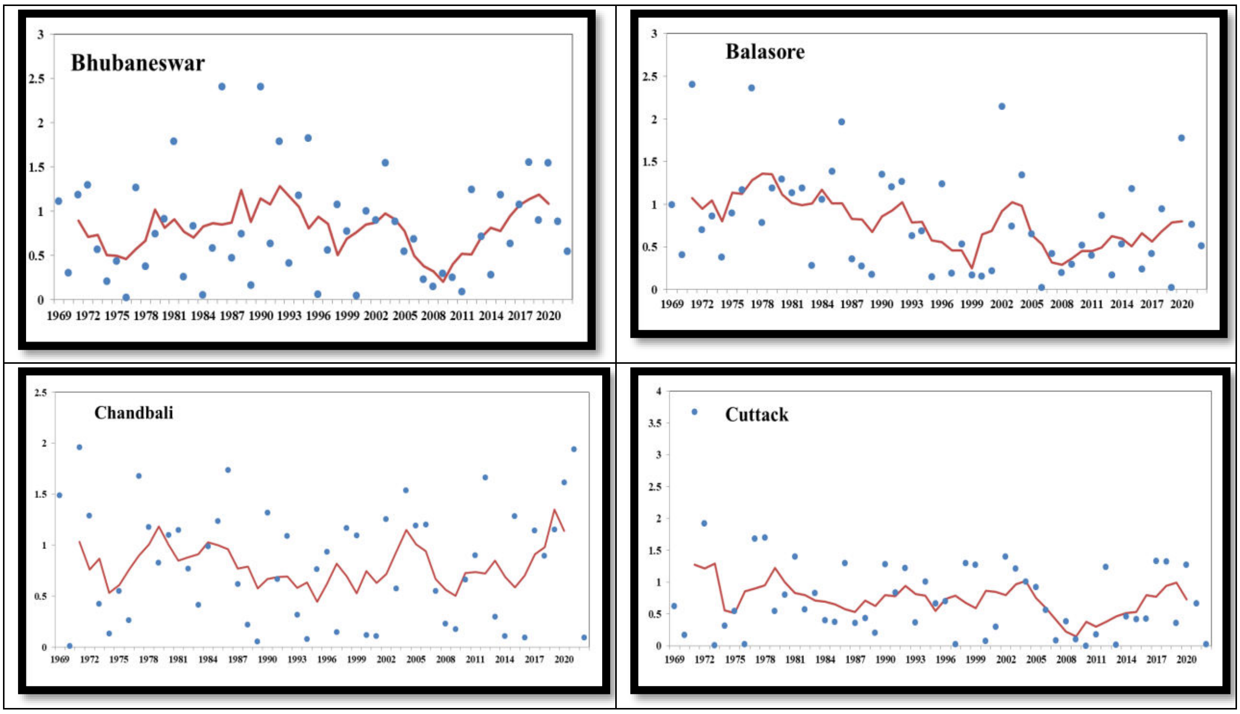


Fig.3.Temperature variability index values for the month of April for the period 1969-2022 (plotted as dots) and 5-year moving averages (plotted as solid red line) for BBS, BLS, CBL, CTC, GPL, PRD, and PRI.



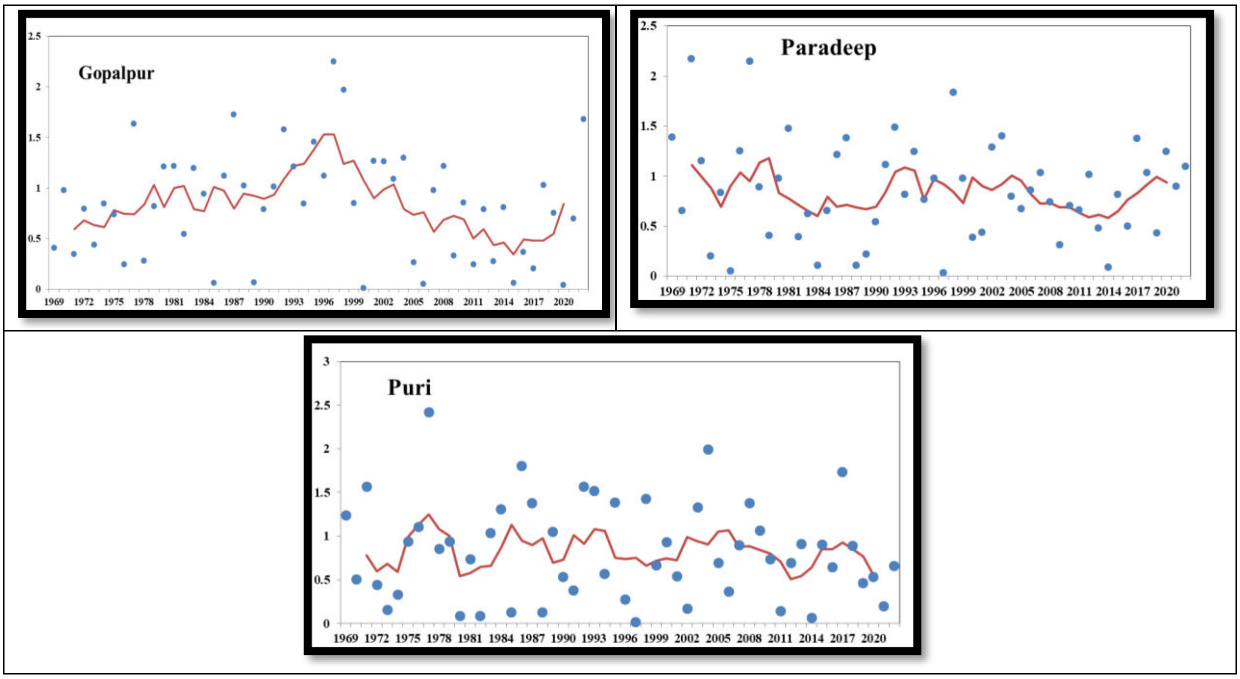


Fig.4.Temperature variability index values for the month of May for the period 1969-2022 (plotted as dots) and 5-year moving averages (plotted as solid red line) for BBS, BLS, CBL, CTC, GPL, PRD, and PRI.

Among the months of the pre-monsoon (hot weather) season, May is the middle month, and the occurrence of heatwaves is a frequent phenomenon due to low humidity during the daytime and the prevalence of westerly or north-westerly dry, hot winds. The trend line of the 5-year moving average for all seven stations is shown in Fig. 4. The trend line in TDI of the 5-year moving average shows a peak in the early 1990s for BBS, but a comparatively weak peak for BLS, PRD, and PRI. Another prominent peak exists in the late 2010s on the trend line of 5-year moving averages in TDI for CBL, BBS, and PRD. The index values for this peak are not high. A sharp peak on the trend line of the 5-year moving average is evident in the mid-2000s for CBL, but the peaks are weak for BBS, BLS, and PRI due to the high index values of 2002 at BLS and 2004 at CBL. Another peak is evident in the late 1970s for CBL, whereas a weaker peak is observed for BBS, BLS, CTC, PRD, and PRI. This peak is attributed to a high index value in 1977 (2.42) at PRI, as well as for BLS, PRD, and PRI. The trend line shows an increasing upward trend up to the mid-1990s, followed by a downward trend for GPL; however, other trend lines don't exhibit this feature. The trend line of TDI in 5 5-year moving averages shows a decreasing trend in recent years for PRI and CTC, whereas an increasing trend for BLS and GPL. It is evident that the variability or index values are not homogeneous at all stations in coastal Odisha. Only one distinct peak exists in the mid-1990s for GPL due to the highest index value of 2.25 in 1997. May 1997 is the beginning of the El Niño cycle. 2002 & 2004 are neutral periods, though high index values are recorded for BLS & CBL, respectively. Heatwave days are observed every year from 2011 to 2017, coinciding with two El Niño years (2014-2015 & 2015-2016) and two La Niña years

(2011-2012 & 2016-2017) at the beginning and end of the period. No such remarkable heat wave days are experienced during the peak index value of TDI in May. The Sen's slope values range from -0.011 °C yr^{-1}(GPL) to +0.015 °C yr^{-1}(PRI), indicating low spatial variability and subdued temperature change in May compared to the rest of the months of the pre-monsoon season. PRD and PRI show positive slopes (+0.0142 and +0.015 °C yr^{-1}, respectively), suggesting mild warming tendencies along the central and southern coasts. Conversely, BLS and GPL exhibit weak cooling trends (-0.0100 and -0.0112 °C yr-1, respectively), although not statistically significant. The absence of statistically significant trends implies that May temperatures over coastal Odisha have remained relatively steady over the last five decades, with localised warming in industrialised zones (PRD) and stable or slightly cooling tendencies elsewhere. This subdued thermal response may reflect increased convective activity, pre-monsoon cloudiness, and maritime moderation during late summer, which collectively dampen long-term warming signatures in May.

The station-by-station differences demonstrate that temperature variability in coastal Odisha is not spatially homogeneous. Inland/Urbanised stations (BBS, CTC, and BLS) generally record larger TDI magnitudes than maritime stations (GPL, PRD, and PRI), consistent with the moderating effects of sea. The observed periodicity in the 5-year moving averages likely reflects the interplay of internal climate modes (ENSO, IOD) and forced warming.El Niño years often precede or coincide with heightened heatwave occurrence in this region.

3.2 Temperature Variability Trends during the Pre-Monsoon/Summer Season

The inter-annual trend of temperature variability for all seven stations was obtained by averaging the monthly index values of each season to obtain a seasonal index value. From the average of the seasonal index values of all seven stations, the index values for coastal Odisha for the season were obtained. The 5-year moving average has been calculated using index values for the summer seasons representing the pre-monsoon (March-May) period over coastal Odisha. To address general trends of temperature, graph representing line using 5-year moving average against year has been plotted similar to monthly 5-year moving average where plotting began from initial middle of the year of 5-year moving average till end of the 5-year moving average group i.e., from 1971 to 2020 and also individual year's seasonal index values from 1969 to 2022 are presented as dots for the summer or pre-monsoon season (Fig. 5)

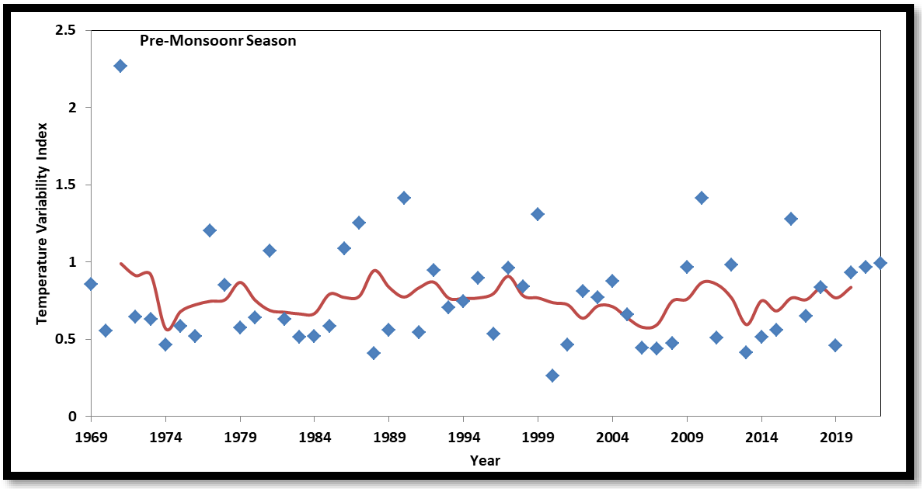


Fig.5. Temperature variability index values for the summer or Pre-monsoon season for the period 1969-2022 (plotted as dots) and 5-year moving averages (plotted as a solid red line).

The trend line of the 5-year moving average (Fig.5) does not show a clear trend in temperature departure index values. However, TDI index values for the recent three years are neither the highest nor the lowest values in the 54-year period index data. The highest index value, 2.27,occurred in 1971, and most of the index values for the respective years were close to the 5-year moving average trend line.

The pre-monsoon seasonal analysis reveals that five of the seven stations exhibit positive Sen's slopes, indicating an overall warming tendency across coastal Odisha during March-May especially in central and southern costal Odisha. The Sen's slopes (~0.015 to 0.017 °C yr^{-1}) correspond to an approximate 0.8 to 1.0 °C increase over 50 years, indicating a gradual but meaningful pre-monsoon warming. Sea breeze modulation and enhanced pre-monsoon convection may limit warming in southern coastal areas explaining weak or mixed signals at Gopalpur. However, only PRD and PRI demonstrate statistically significant increasing trends at the 95% confidence level, while the remaining stations show weak, non-significant changes. The Z-statistics further corroborate this pattern with higher Z values at PRD (2.49) and PRI (2.06), confirming the robustness of warming trends at these locations. The observed warming in PRD and PRI aligns with increased anthropogenic forcing, such as urban growth, port-related industrialization, and surface modification, which amplify localized heat accumulation. In contrast, the relative stability of northern stations likely stems from open agricultural land cover, less urban density, and enhanced ventilation due to prevailing winds. This regional warming may serve as a precursor to increased heatwave frequency, thermal discomfort and energy demand escalation in coastal urban zones.

3.3 Annual Temperature Variability Trends

Similar to the calculation of monthly and seasonal index values, annual index values are obtained by averaging the 12-monthly index values of each year across all stations in coastal Odisha. To get the trend characteristics for the whole year, 5-year moving average trend line of TDI was generated, which is depicted in Fig.6. It seems that this approach of studying variability of yearly index values is much more appropriate than making an average of mean annual temperatures because annual temperature averages are found out by taking the cold and warm extremes in a given year.

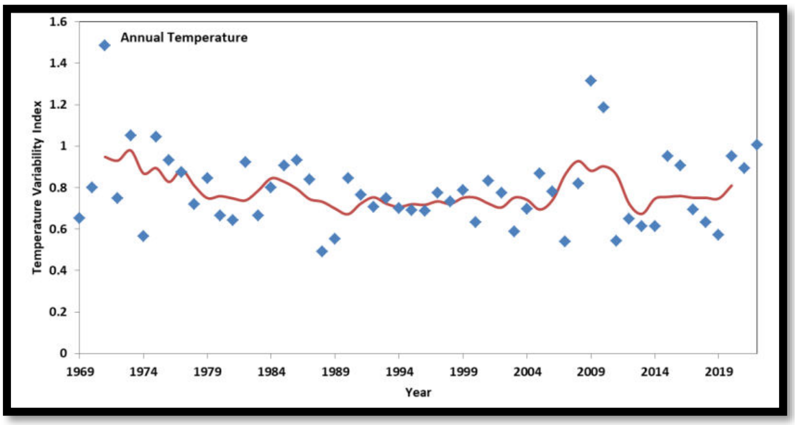


Fig.6. Annual temperature variability index values for the period 1969-2022 (plotted as dots) and 5-year moving averages (plotted as solid red line).

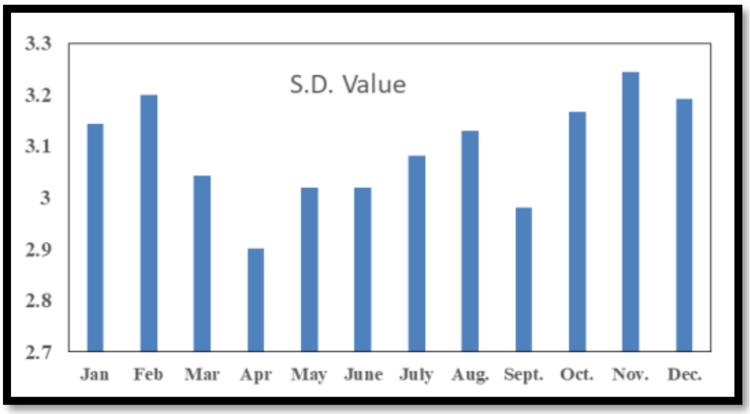


Fig.7. Month-wise Standard Deviation (SD) values computed based on index values from 1969 to 2022 for the coastal Odisha

Moreover, standard deviation is incorporated in the temperature variable index (TDI) when calculating the average of 12-monthly index values, which gives equal weight to July, i.e., one standard deviation from its mean, compared to January, with one standard deviation from its mean. The monthly standard deviation graph (Fig. 7) suggests that temperature variability is highest in November, followed by February, then December, October, and January. It is implied that winter and post-monsoon months in coastal Odisha as a whole have much more temperature variability than other months of the year, as indicated by higher S.D. values for these months for the whole coastal Odisha. Annual temperature departure index values are plotted as dots in Fig.6 for the entire coastal Odisha for the period 1969-2022. Moreover, 5-year moving averages are plotted as a solid trend line in the same Fig.6. Analysingthe annual temperature departure index trend line in 5-year moving average, The largest annual index values occur around 1971 and 2009-2010 (El Nino period), but recent years do not consistently show the highest indices. The highest index values for 2009 (1.31) and 2010 (1.19) cause the peak in the mid-2000s. The trend line initially dropped downwards and then rose again from the early 1980s. The 5-year moving average line does not indicate a clear trend from the early 1990s to the mid-2000s, and moreover, index values of individual years are also recorded close to the 5-year moving average line during this period. In recent years, no clear trend is anticipated, and it is noted that 2009-2010 was an El Niño year. The prominence of variability outside the pre-monsoon season suggests that while pre-monsoon months host the extreme high temperatures (heatwaves), interannual variance can be higher during cooler months due to greater sensitivity to regional circulation anomalies and episodic weather systems.

3.4 Heat wave and its precautionary measures

3.4.1 Analysis and synoptic factors

High temperatures satisfying the criteria of heatwave (HW) and severe heatwave (SHW) events are recurring phenomena in Odisha, particularly over the coastal districts during the pre-monsoon season (March-May) and occasionally in the first fortnight of June. The total number of HW and SHW days computed over the coastal stations (Fig.8) shows pronounced inter-annual variability, with SHW conditions most frequently observed in May and June.This underscores the importance of robust summer heatwave disaster management across coastal Odisha.The Fig.8 shows the temporal variation of seasonal heatwave (HW) days (combination of heatwave (HW) and severe heatwave (SHW)) during March-May for the seven coastal stations-BBS, BLS, CBL, CTC, PRD, GPL and PRI for the period 1969-2022). The March-May season represents the core pre-monsoon heat period in coastal Odisha, when solar heating is at its maximum and land-sea contrast peaks.

BBS shows a gradual rise in HW days since the 1980s, with several prominent events after 2000. The positive slope (~0.037 days yr^{-1}, p=0.10) indicates a weak but increasing trend, suggesting growing frequency of pre-monsoon heat extremes in the urbanized interior-coastal zone. BLS shows flat trend, implying no significant long-term change in Mar-May HW frequency, inter-annual variability dominates, controlled mainly by synoptic systems and sea-breeze moderation. CBL shows moderate inter-decadal variability and a small positive slope. This reflects episodic increases in HW days since the late 1990s, but not statistically significant at 95% confidence. CTC stands out with a significant decreasing trend (slope=-0.053 days yr^{-1}, p=0.004). The decline in Mar-May HW days may relate to urban expansion, increased vegetation, and changing local humidity that modify the threshold exceedance conditions. PRD has negligible slope, showing little systematic change. Being a coastal port station, maritime influence strongly dampens temperature extremes. GPL shows slight decline in HW days with near zero slope and marginal significance (p=0.04). This type of phenomena is attributed due to dominant sea-breeze cooling and increased coastal humidity.

PRI exhibits minimal variability and no clear trend (slope≈0, p≈0.62). The frequency of March-May HW days remains almost stationary through the record.

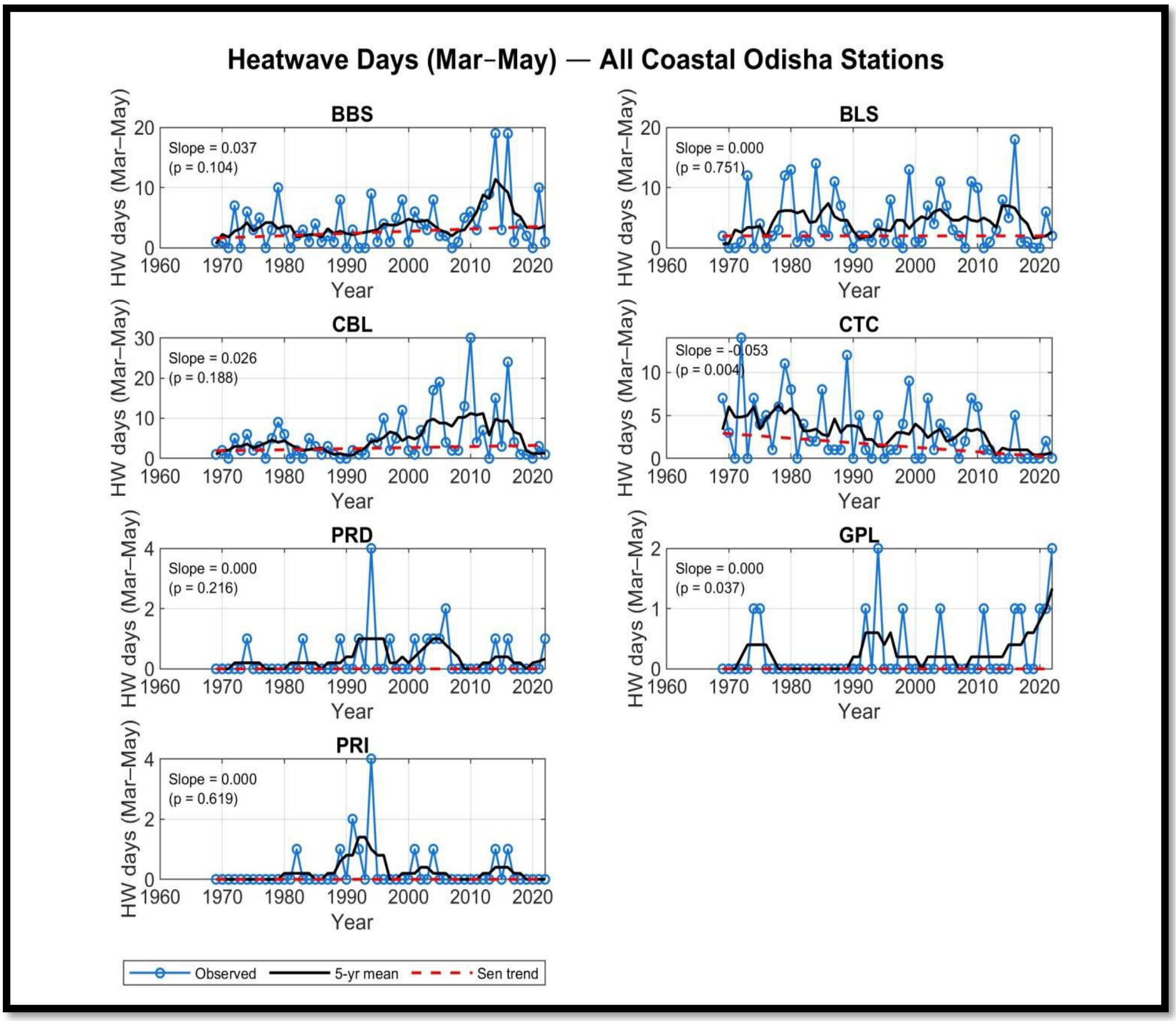


Fig.8 Heatwave (HW) days (observed blue colour) recorded over stations at Bhubaneswar (BBS), Baleswar (BLS), Chandbali (CBL), Cuttack (CTC), Paradeep (PRD), Gopalpur (GPL), and Puri (PRI) during Pre-Monsoon season (March-May). 5-year Mean days (thick black curve) along with Sen's trend (dotted red line) plotted on respective stations.

In summary, Mar-May HW activity increases slightly inland (BBS, CBL) and decreases or remains stable along the immediate coast (CTC, PRD, GPL, PRI). Only CTC shows a statistically significant downward trend, highlighting spatial heterogeneity of coastal influences. In some years, HW days are recorded in month of June (till onset of monsoon in Odisha). To understand the heatwave dynamics, analysis HW days Mar-June has been attempted and the data are shown in Fig.9 in respect of all stations being used in this study.

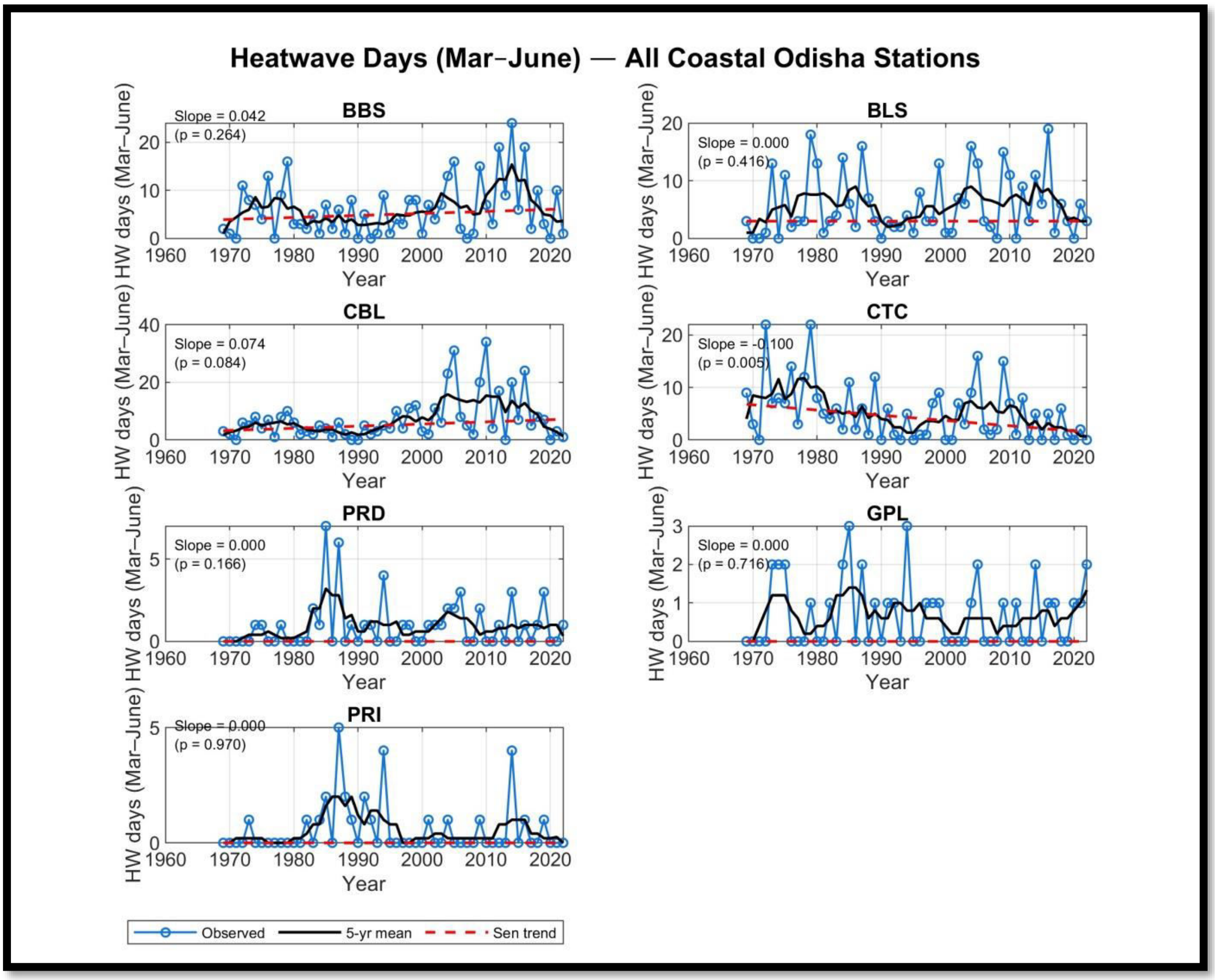


Fig.9 Heatwave (HW) days (observed blue colour) recorded over stations at Bhubaneswar (BBS), Baleswar (BLS), Chandbali (CBL), Cuttack (CTC), Paradeep (PRD), Gopalpur (GPL), and Puri (PRI) during Pre-Monsoon season (March-June). 5-year Mean days (thick black curve) along with Sen's trend (dotted red line) plotted on respective stations.

For most stations, the slope values decrease or turn negative, indicating that HW activity during the extended season is either weakening or showing no trend. The example from Cuttack (CTC) shows a significant negative trend (-0.10 days yr^{-1}, p=0.005), confirming that post-1990, HW occurrences in the extended season are notably fewer than in earlier decades. Stations like BBS and CBL show minor positive trends for Mar-May but flatten or reverse when June is included, implying that the onset of monsoon rainfall curtails prolonged heat events. Coastal stations (PRD, GPL, and PRI) remain nearly trend-neutral through both periods due to consistent maritime moderation.

The comparison confirms that the core heatwave period (March-May) shows spatially heterogeneous trends, with weak inland increases and coastal stability or declines. In the extended season (March-June), most stations experience trend flattening, signifying the onset of monsoon damping. The observed regional differences are shaped by both synoptic scale and local-scale processes such as (1) land-sea breeze circulation and sea surface temperature of Bay of Bengal modulate daily maximum temperatures at PRD, GPL, and PRI., (2) urban expansion and land-use change around BBS and CTC intensify local heat retention, potentially elevating pre-monsoon HW frequency despite no comparable changes along the coast., (3) pre-monsoon rainfall variability directly affects soil moisture and surface energy balance, reducing HW persistence in wet years, and (4) monsoon onset shifts can alter the duration of the HW window, delayed onset years often correspond with higher HW counts during May, consistent with multi-decadal climate oscillations.

Moderate to strong heat waves have been experienced in the year following the El Niño event, as observed in 1998, when a very strong El Niño occurred. In contrast, heat waves in 1999, 2003, and 2004 were moderate, while 2015 saw a moderate to very strong El Niño, followed by more heat waves in 2016. Due to unawareness about the impact of heat waves on human and animal bodies, around 2042 (SRC data) people lost their lives in 1998 during the pre-monsoon and first fortnight of June month. A heat wave was caused in Odisha due to the advection of north-westerly dry hot wind from the northwest part of India towards coastal Odisha, blocking of sea breeze from the Bay of Bengal by the northeast-southwest trough along the Odisha coast in the lower atmosphere, and, in addition, clear sky conditions being one of the important factors. Besides these meteorological factors, the levels of trace gases such as sulphur dioxide, nitrous oxide, ozone, ammonia, and black carbon have increased in the lower atmosphere, but the neutralising capacity of soil has decreased. Moreover, there is a strong correlation between the occurrence of heat waves and short-lived trace pollutants at higher altitudes in the atmosphere, which is also related to heat-trapping greenhouse gases of continental origin.

3.4.2 Government Preparedness and Mitigation Measures

Realizing the severity of heat wave and its related phenomenon after 1998 heat wave tragedy, a lot of preparatory measures have been adopted by Government of Odisha prior to occurrence of heat waves in coastal as well as whole Odisha every year and these are listed as functioning of control room round the clock in each district from 1st March to till end of June, uninterrupted power supply to citizens in urban as well as rural areas, adequate arrangement for uninterrupted drinking water supply, distribution of ORS (oral rehydration solutions) packets, construction of rest shed at work/construction site, closing of cinema /video halls during noon hours, facility of cold drinking water supply at specific locations in the city-peripheral areas of industry-long route buses etc.,drinking water provision for cattle, deployment of mobile vehiclesin citiesand nearby areas for shifting sun stroke-heat wave affected patients to nearby hospitals, restrictions for engagement of labourers between 11.0 hrs. IST to 15.30 hours IST, air conditioner room facility in district HQ hospitals, city hospitals, telecast of precautionary measures to protect from heat waves by electronic media along with awareness clips or instructions in local as well as national newspapers, regulating as well as restricting overcrowdings in buses, water supply through mobile tankers, regulating morning classes in schools/colleges and rescheduling of examination timings if any and also classes in colleges. Public-place management has been implemented particularly restriction of noon-time shows in cinema halls, regulation of crowding in buses and public spaces, and provision of shade in marketplaces.

Implementation of these measures has dramatically reduced heatwave mortality, bringing fatalities close to zero in recent years despite increasing frequency of hot days. Odisha's proactive approach is now widely recognized as a national model for heatwave management.

3.4.3 Climatic Variability and Future Outlook

Month-wise variability in the 5-year moving average of heatwave days (March-June) reveals alternating phases of increase and decrease, reflecting natural climatic oscillations superimposed on a long-term warming trend. Not every year experiences heatwaves in all pre-monsoon months, which explains the irregularity of the seasonal trend line. Nevertheless, the persistence of extreme events emphasizes the need for continued public awareness, infrastructure resilience, and data-driven climate forecasting to mitigate future impacts in this coastal region.

4.0 Disaster Management and Adaptation Strategies

The analysis of long-term temperature variability and heatwave patterns over coastal Odisha reveals clear implications for disaster risk management (DRM) and climate adaptation. The region's exposure to extreme heat, cyclones, and hydro-meteorological hazards makes integrated planning essential to safeguard lives and livelihoods.

Odisha has emerged as a model state in disaster preparedness through the institutionalization of the Odisha State Disaster Management Authority (OSDMA) and Special Relief Commissioner (SRC). The state operates a multi-tier early warning system that disseminates heat alerts, cyclone forecasts, and rainfall earnings through district control rooms and the Odisha Disaster Rapid Action Force (ODRAF). For heatwave risk reduction, the IMD's real-time temperature monitoring combined with OSDMA's outreach initiatives enables rapid public communication. These alerts are disseminated via SMS, twitter, community radio, and social media platforms to ensure last-mile communication. After 1998 heatwave, Odisha implemented comprehensive Heat Action Plans (HAPs) at state and district levels. These plans are now a central component of its disaster risk reduction strategy. For long-term sustainability, climate-smart disaster management should focus on the following aspects:

(a) Mainstreaming climate information into district-level development planning

(b) Integrating heatwave risk into land-use zoning, especially in expanding urban centres.

(c) Developing heat-health early warning systems (HHEWS) integrating meteorological, health, and remote sensing data
(d) Scaling local adaptation strategies such as urban forestry, rooftop greening, and reflective building materials.
(e) Enhancing local capacity through continuous training of disaster volunteers, school programs, and women's self-help groups.

By aligning scientific understanding with policy implementation, Odisha's model demonstrates how data-driven climate risk management can effectively reduce disaster impacts in vulnerable coastal environments.

5.0 Conclusion:

In the wake of climate change and global warming, a regional study of temperature variability is urgently needed. Keeping this in mind, it is being conducted over the coastal parts of the state of Odisha. Mean monthly temperature data of the stations following homogenization have been utilised in this study, and therefore, no attempt has been made for the interpretation of the variability of temperature extremes associated with weather events on individual days. However, monthly mean temperature values have been used to assess climatic temperature variability through the temperature departure index for each of the seven stations, both seasonally and annually, forthe entire coastal Odisha region. An effort has been made in this study to assess trends in temperature departures from average, irrespective of whether the departures are positive (higher than normal/mean) or negative (lower than normal/mean) with respect to individual stations for month-wise, seasonal cases during the summer time and also annual indexes for the whole coastal Odisha. The 54-year analysis (1969-2022) of homogenised IMD temperature data reveals spatially varied but discernible warming across coastal Odisha. The TDI and 5-year moving averages highlight periodic fluctuations superimposed on an overall rising trend, especially during the pre-monsoon months. Mann-Kendall and Sen's slope analyses confirm significant positive trends at PRD and PRI, while other coastal stations show weaker or mixed signals, likely due to maritime moderation. Heatwave frequency (March-May) exhibits increasing tendencies inland (BBS and CBL) and stable or declining trends near the coast (PRD and GPL). The extended seasonal assessment (March-June) suggests a partial suppression of heatwave activity following the early onset of the monsoon. Years of peak TDI values (1987, 1998, 2010, and 2016) align with severe El Niño events, reinforcing the linkage between large-scale oceanic forcing and regional heat extremes. No clear trend is discernible in the annual temperature departure index trend line. Moreover, the trend line of TDI for the monthly 5-year moving average indicates higher variability with respect to BBS, BLS, CBL, and CTC compared to GPL, PRD, and PRI. The summer season trend line doesn't indicate any remarkable variability, whereas ups and downs on monthly analysis at station sites suggest the existence of variability in the individual month, March, April, or

May, from year to year, during the 54-year period. The findings underscore the importance of sustained heatwave monitoring, regional early-warning systems, and integrated climate-health data strategies for mitigating heat-related mortality.

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