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Extreme rainfall and temperature events in Odisha: Trends and vulnerabilities

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सार – यह अध्ययन ओडिशा, भारत में अत्यधिक वर्षा और तापमान की घटनाओं की जांच करता है, जिसमें ओडिशा सरकार के विशेष राहत आयुक्त से 32 वर्षों के वर्षा डेटा (1991-2022) और भारत मौसम विज्ञान विभाग (आईएमडी) से 23 वर्षों के तापमान डेटा (2000-2022) का उपयोग किया गया है। विश्लेषण वार्षिक, मॉनसून और गैर-मॉनसून अवधि के लिए भारी (64.5 से 115.5 मिमी), बहुत भारी (115.6 से 204.4 मिमी), और अत्यधिक भारी (>204.4 मिमी) वर्षा घटनाओं की संख्या की गणना करता है। यह 24 आईएमडी माप स्टेशनों के लिए तापमान चरम सीमाओं की घटना की भी पहचान करता है, जैसे 40 डिग्री सेल्सियस, 45 डिग्री सेल्सियस और 10 डिग्री सेल्सियस। वर्षा और तापमान चरम के रुझानों का पता लगाने के लिए मान-केंडेल परीक्षण लागू किया गया। सुभेद्यता का आकलन करने के लिए, अत्यधिक वर्षा और तापमान मानों को सामान्यीकृत किया गया था। राज्य में कुल मिलाकर 4146 अत्यधिक वर्षा (115.6 मिमी से अधिक) की घटनाएं हुईं, जिनमें से कालाहांडी जिले में सबसे अधिक (257) और देवगढ़ में सबसे कम (42) घटनाएं हुईं। दूसरे दशक (2001 से 2010) में अत्यधिक वर्षा की घटनाओं की अधिकतम संख्या (1458) दर्ज की गई, जिसके बाद पहले दशक में 1267 और तीसरे दशक में 1239 घटनाएँ दर्ज की गईं। प्रवृत्ति विश्लेषण ने दो जिलों जैसे कोरापुट और मलकानगिरी में भारी वर्षा की घटनाओं की आवृत्ति में महत्वपूर्ण वृद्धि और नवरंगपुर में अत्यधिक भारी वर्षा की घटनाओं का संकेत दिया। हालांकि, बालासोर और जाजपुर में भारी वर्षा की घटनाओं के लिए एक घटती प्रवृत्ति; अंगुल, ढेंकनाल, जाजपुर और केंद्रपाड़ा में बहुत भारी वर्षा; और पुरी में अत्यधिक भारी वर्षा की प्रवृत्ति देखी गई । एक दिवसीय संभावित अधिकतम वर्षा (पीएमपी) का मान सबसे अधिक (905 मिमी) कालाहांडी जिले के लिए और सबसे कम (318 मिमी) ढेंकनाल के लिए था। अत्यधिक वर्षा की घटनाओं (115.6 मिमी से अधिक) के भेद्यता विश्लेषण से पता चला कि कालाहांडी और पुरी जिले अत्यधिक सुभेद्य हैं। शीर्ष सात चरम वर्षा घटनाओं के वार्षिक सामान्य वर्षा में योगदान के आधार पर भेद्यता सूचकांक विश्लेषण में पाया गया कि बौध, कटक, जाजपुर, झारसुगुड़ा और खोर्धा अत्यधिक भेद्य थे, जबकि शेष 25 जिले मध्यम रूप से भेद्य थे। बोलंगीर में 40 डिग्री सेल्सियस और 45 डिग्री सेल्सियस दोनों सीमा के लिए सबसे अधिक तापमान की घटनाओं को दर्ज किया गया, इसके बाद संबलपुर और हीराकुंड स्टेशन थे।

ABSTRACT. This study examines extreme rainfall and temperature events in Odisha, India, using 32 years of rainfall data (1991–2022) from the Special Relief Commissioner, Government of Odisha, and 23 years of temperature data (2000–2022) from the India Meteorological Department (IMD). The analysis calculates the number of heavy (64.5 to 115.5 mm), very heavy (115.6 to 204.4 mm), and extremely heavy (>204.4 mm) rainfall events for annual, monsoon, and non-monsoon periods. It also identifies the occurrence of temperature extremes, such as ≥40 °C, ≥45 °C, and ≤10 °C, for 24 IMD measurement stations. The Mann-Kendall test was applied to detect trends in rainfall and temperature extremes. To assess vulnerability, extreme rainfall and temperature values were normalized. The state as a whole received a total number of 4146 extreme rainfall (≥ 115.6 mm) events, with Kalahandi district experiencing the most (257) and Deogarh the lowest (42) during the period. The 2nd decade (2001 to 2010) realised the maximum number of extreme rainfall events (1458) followed by 1267 number of events in 1st decade and 1239 in the 3rd decade. Trend analysis indicated a significant increase in the frequency of heavy rainfall events in two districts such as Koraput and Malkangiri; and extremely heavy rainfall events only in Nawarangapur. However, a decreasing trend was noticed for heavy rainfall events in Balasore and Jajpur; very heavy rainfall in Angul, Dhenkanal, Jajpur and Kendrapada; and extremely heavy rainfall in Puri. The one-day Probable Maximum Precipitation (PMP) value was the highest (905 mm) for Kalahandi district and the lowest (318 mm) for Dhenkanal. The Vulnerability analysis of extreme rainfall events (≥115.6 mm) revealed the districts namely Kalahandi and Puri to be highly vulnerable. The Vulnerability Index analysis, based on contribution of the top seven extreme rainfall events to annual normal rainfall, found that Boudh, Cuttack, Jajpur, Jharsuguda, and Khordha were highly vulnerable, while the remaining 25 districts were moderately vulnerable. Bolangir recorded the highest number of extreme temperature events for both the ≥40 °C and ≥45 °C thresholds, followed by Sambalpur and Hirakud stations.

Key words – Extreme rainfall, Extreme temperature, Trend, Vulnerability.

1. Introduction

An extreme weather event is defined as ‘an event that is rare at a particular place and time of year’ (IPCC, 2021). Many studies reported that the frequency and intensity of extreme weather events have increased in recent decades under the changing climate (O’ Gormon, 2015; Donat *et al*., 2016). Increasing weather and climate extremes have exposed millions of people to acute food insecurity in many locations including Asia and Africa (IPCC, 2022). Studies on Southwest monsoon rainfall over central India reported a substantial increase in the frequency and magnitude of extreme rainfall events, even though a significant trend was not found (Goswami *et al*., 2006; Rajeevan *et al*., 2006). The year 2024 was ranked as the warmest year on record for India with +0.65 degree Celsius higher than the long-term average (1991 – 2020) with 14 out of 17 warmest years were during the recent seventeen years (2008 - 2024) since 1901 (IMD, 2024). Global warming, the driver of climate change, theoretically increases the convection energy, which is likely to increase the rainfall extremes (Sun *et al*., 2021). The occurrence of these weather aberrations inflicts huge damage to crops, livestock, humans & properties (Bal and Minhas, 2017). Heat-waves impact crop growth and development at different stages and can cause wilting, stunting, or shortened ripening period which reduces the productivity of crops (Bal *et al*., 2022). According to a study by Zhao *et al*., 2017, without CO_2 fertilization, effective adaptation, and genetic improvement, each degree-Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.4%, maize by 7.4%, and soybean by 3.1%.

Extreme precipitation and temperature events, both maximum and minimum, affect agricultural production and productivity in a tropical country like India. Occurrence of heavy to very heavy and extremely heavy rainfall events in an area within a short period causes flash floods leading to soil erosion, siltation of agricultural lands, salinity in coastal areas, and damage to standing crops due to stagnation of water. Odisha state, which lies on the east coast of the Indian peninsula, is one of the most disaster-prone states in India with frequent occurrences of droughts, floods, cyclones, dry spells, heat waves, and other climate extremes occurring alone or in combination in the same year. The state has a normal rainfall of 1451 mm, out of which around 80% is received during the monsoon season i.e. from June to September. Temperatures vary from the mean maximum summer temperature of 40 °C in the West Central Table Zone to the mean minimum winter temperature of 7.5 °C in the Eastern Ghat Highland Zone. The state as a whole mainly has a tropical climate characterized by high temperature, high humidity, medium to high rainfall, and short and mild winters. Most of the heavy rainfall events in the state occur due to the formation of cyclonic circulations over the Bay of Bengal or the land (Pasupalak *et al*., 2017). These weather extremes impact the livelihood of more than 60% population of the state, who gain their employment from agriculture and allied activities.

The documentation of extreme weather events will be a vital data source for understanding present and future climate risks (Clarke *et al*., 2021). Rajeevan *et al*. (2008) analyzed the trend of extreme rainfall events over India using gridded rainfall data of 104 years. Stephenson *et al*. (1999) studied the daily extreme rainfall events for monsoon months only over the entire country. The above studies on extreme rainfall events were performed at the macro-scale and at the country level. Nevertheless, Pasupalak *et al*. (2017) examined the trend of extreme daily rainfall events for the state of Odisha using the data period 1991-2014. However, no study has been done recently on extreme rainfall and temperature events on daily observed data at micro-level over the entire state. Considering the vulnerability of the state to climate change and livelihood security of about 27 million people dependent on agriculture, this study was made to document the occurrence of extreme rainfall and temperature events, their frequencies, trends, percentage contribution of the top seven rainfall events to total rainfall using the time series data. Furthermore, the district-wise vulnerability index was also worked out for these weather extremes. Such an agro-climatic inventory on a regional level could be employed for taking up climate change adaptation and mitigation measures to combat biotic and abiotic stresses that the crops/livestock experiences during their life cycle.

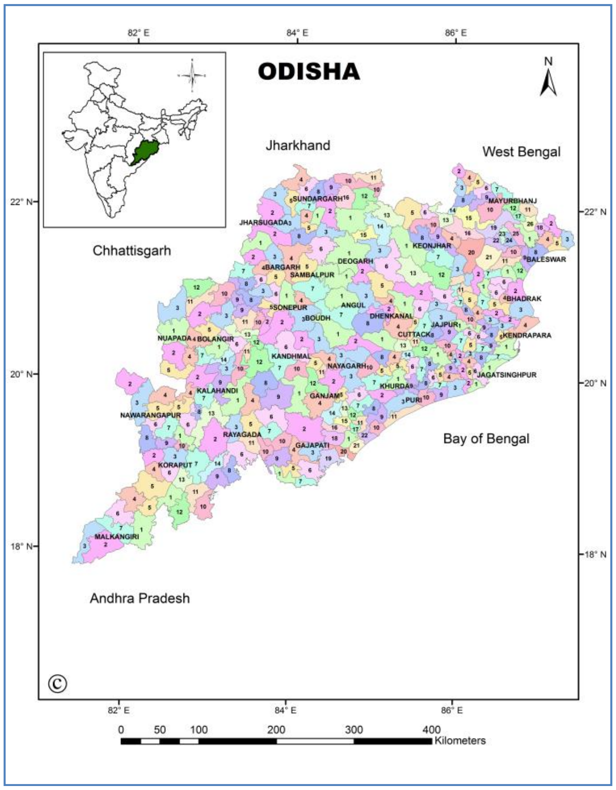

Fig.1. Spatial distribution of rainfall stations (block headquarters) used in the study

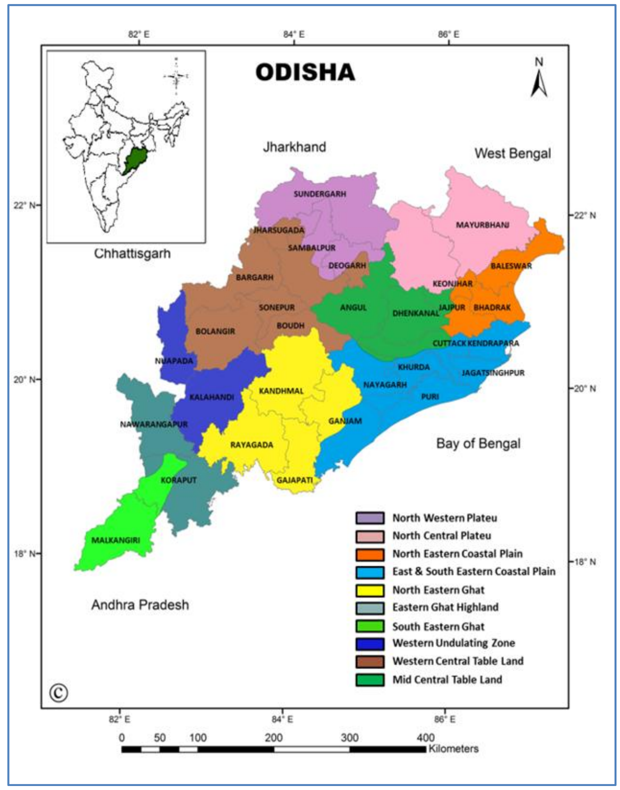

Fig. 2. Agroclimatic zones of Odisha.

2. Data and methodology

2.1. *Study area*

The study was conducted in Odisha, an eastern Indian state that lies on the Bay of Bengal between 17º 49' to 22º34' N latitude and 81º27’ to 87º 29' E longitude having a480 km long coastline stretching from the borders of West Bengal to the borders of Andhra Pradesh. Administratively, the state is divided into 30 districts which are further subdivided into 314 blocks (Fig. 1). The state is divided into ten agro-climatic zones based on the homogeneity of soil type, climate, topography, elevation, vegetation, and cropping patterns under National Agricultural Research Project (NARP), ICAR (Fig. 2).

2.2. *Rainfall*

The analysis on extreme precipitation events was undertaken over the entire state of Odisha, India using the daily observed rainfall data of 314 stations (located at the block headquarters) spread across the state for 32 (1991 – 2022) years, obtained from the Special Relief Commissioner, Government of Odisha.

The data were subjected to thorough quality checks for missing data, location, typing error etc., before the analysis was carried out. The data used in this study can be considered of good quality as there was less than five percent of missing data (Schafer, 1999). However, missing rainfall data for a block was filled by the Normal Ratio method using rainfall data of three adjacent blocks and normal precipitation data. This method is based on selecting 'm' blocks that are adjacent and approximately evenly spaced around the station with the missing record. The normal ratio method gives Px as:

$$\mathrm{Px} = \frac{Nx}{m}\left[\frac{\mathrm{P1}}{N1} + \frac{\mathrm{P2}}{N2} + \cdots \frac{\mathrm{Pm}}{Nm}\right] \quad (1)$$

where, Px = the missing precipitation data at station X, Nx = the normal precipitation data at station X, P1, P2....Pm are the precipitation values at stations 1, 2.... and m, respectively, N1, N2 .... Nm are the normal precipitation values at stations 1, 2 ....and m, respectively, m = the number of stations

The normal precipitation at a particular station was calculated as the average value of precipitation at a particular date, month, or year over 30 years (1991-2020). We restricted the study period of the present analysis to 1991-2022 since the district-wise data (for 30 districts) were available for this period only.

2.2.1. *Rainfall extreme events*

The IMD classification of 24-hour accumulated rainfall viz. Heavy Rain: 64.5 to 115.5 mm, Very Heavy Rain: 115.6 to 204.4 mm, and Extremely Heavy Rain: >204.4 mm (Standard Operation Procedure - Weather Forecasting and Warning, IMD, 2021), were used for the analysis of extreme rainfall in the present study. The district-wise extreme rainfall events were worked out from the block extreme rainfall data for the respective district. The event for a specific day was considered as one event for that day in the district, if at least one block (location) or multiple blocks in the district experienced the event on that day.

2.2.2. *Probable Maximum Precipitation*

The Probable Maximum Precipitation (PMP) for a district was calculated from the Annual Maximum Daily Precipitation (AMDP) series values using Hershfield (Hershfield, 1965) Method. The maximum daily precipitation value for a specific day at any location (block) in the district was considered as the value for AMDP series for that day in the district. The basic equation used for estimation of PMP is as follows:

$$X_{PMP} = \bar{x}_N + K \times S_N \quad (2)$$

X_{PMP} is the PMP estimate for a particular location. $\bar{x}_N$ is the mean of the Annual Maximum Daily Precipitation Series (AMDP) series for N years at that location. S_N is the standard deviation of the AMDP series at that location. K is the frequency factor for estimating PMP at that location, which was computed using the equation:

$$K = \frac{Xm - \bar{x}_{N-1}}{S_{N-1}} \quad (3)$$

where, X_m is the maximum value in AMDP series at the location, $\bar{x}_{N-1}$ and S_{N-1} are the mean and standard deviation of the AMDP series, respectively for (N -1) years after removing the year with the maximum value.

2.2.3. *Trend analysis*

The non-parametric Mann-Kendall test (Kendall, M.G., 1948 & Mann, H.B., 1945), based on rank system, was used to detect the trends of rainfall extremes. The Mann–Kendall test is a popular non-parametric test for detecting significant trends in time series data. Because it is non-parametric, it is appropriate for all types of distributions. This test was used in our study for trend analysis of rainfall extreme events from 1991 to 2022. This test assumes the absence of a monotonic trend as its null hypothesis. The data need not be normally distributed for this test.

According to this test: H0 (Null hypothesis): There is no trend in data

H_1 *(Alternate hypothesis)*: There is a trend in time series data

The test statistic S for data points Ri (i = 1, 2, 3...., n) with R_j - R_i denoted as 'x' is:

$$S = \sum_{i=1}^{n-1} \left[\sum_{j=i+1}^{n} \operatorname{sgn}(R_j - R_i) \right] \quad (4)$$

Where sgn(x) = 1 for x > 0, sgn(x) = 0 for x = 0 sgn(x) = -1 for x < 0

If the null hypothesis H_o is true, then S is approximately normally distributed with:

$\mu = 0$

$$\sigma = n\,(n-1)\,(2n+5)\,/\,18 \quad (5)$$

The z-statistic is therefore (critical test statistic values for various significance levels can be obtained from normal probability tables):

$$z = |\,S\,| \,/\, \sigma^{0.5} \quad (6)$$

A positive value of S indicates that there is an increasing trend and vice versa.

2.2.4. *Normal Vulnerability Index*

The vulnerability of a district to extreme rainfall events was worked out by the Normal Vulnerability Index (NVI), which standardizes the disaster values to the ranges between 0 to 1. The NVI was estimated for rainfall extremes (very heavy & extremely heavy rainfall events) for the period 1991-2020. The equation used for estimating the district-wise NVI:

$$NVI = \frac{Mean - Minimum\ Value}{Maximum\ Value - Minimum\ Value} \quad (7)$$

The vulnerability of a district based on NVI values were categorized as:

0	: NIL
0.0 to <0.25	: Low
0.25 to < 0.5	: Moderate
0.5 to < 0.75	: High
0.75 to < 1.0	:Very-High

TABLE 1

District-wise extreme rainfall (≥ 115.6 mm) events (annual)

Sl. No.	District	1991-2000 (number)	2001-2010 (number)	2011-2020 (number)	2021-2022 (number)	1991-2022 (number)
1	Angul	34	48	19	2	**103**
2	Balasore	64	70	47	9	**190**
3	Bargarh	49	57	54	5	**165**
4	Bhadrak	45	28	31	4	**108**
5	Balangir	34	67	56	3	**160**
6	Boudh	21	29	26	6	**82**
7	Cuttack	51	99	71	11	**232**
8	Deogarh	13	16	11	2	**42**
9	Dhenkanal	44	22	26	3	**95**
10	Gajapati	25	18	27	5	**75**
11	Ganjam	33	31	43	6	**113**
12	Jagatsinghpur	69	40	44	8	**161**
13	Jajpur	70	46	43	7	**166**
14	Jharsuguda	21	24	26	2	**73**
15	Kalahandi	75	101	74	7	**257**
16	Kandhamal	55	79	41	11	**186**
17	Kendrapara	76	46	39	8	**169**
18	Keonjhar	29	44	43	6	**122**
19	Khordha	35	45	31	5	**116**
20	Koraput	34	62	62	11	**169**
21	Malkanagiri	32	36	36	7	**111**
22	Mayurbhanj	68	70	61	10	**209**
23	Nawarangpur	36	72	57	7	**172**
24	Nayagarh	26	32	27	5	**90**
25	Nuapada	15	23	23	2	**63**
26	Puri	72	61	64	10	**207**
27	Rayagada	16	38	31	4	**89**
28	Sambalpur	45	60	47	4	**156**
29	Subarnapur	22	35	35	4	**96**
30	Sundargarh	58	59	44	8	**169**
	Odisha	**1267**	**1458**	**1239**	**182**	**4146**

2.2.5. Contribution of high-intensity rainfall events

The percentage contribution of the top seven high-intensity rainfall events to annual normal rainfall (Source: IMD, Pune) for a district was calculated from daily data at the block level. The district-wise NVI for the contribution of top seven rainfall extremes (very heavy & extremely heavy rainfall events) was estimated for the period 1991-2022.

2.3. *Temperature*

Temperature data for the period 2000-2022 (23 years) was collected from the Meteorological Centre, IMD, Bhubaneswar for 24 stations spread across the state. The list of stations with their spatial distribution in the state is depicted in Fig. 19. The missing data of a station were determined by calculating the simple arithmetic average of the temperatures of the preceding and succeeding days. This method was used as there were no missing data for a consecutive period of more than one day in the data series.

$$Ti = \frac{1}{2}[T_{i-1} + T_{i+1}] \quad (8)$$

where, Ti = missing temperature data at station 'X' on i^{th} day; Ti-1 = temperature data at station 'X' of the preceding day, and Ti+1 = temperature data at station 'X' of the succeeding day Trends of temperature extreme events viz. ≥40ºC and ≥45ºC were calculated using trend/change detection software *ver.* 1.0.2. (non-parametric Mann-Kendall test).

TABLE 2

District-wise extreme rainfall (≥ 115.6 mm) events (monsoon)

Sl. No.	District	1991-2000 (number)	2001-2010 (number)	2011-2020 (number)	2021-2022 (number)	1991-2022 (number)
1	Angul	33	46	15	2	96
2	Balasore	46	53	31	6	136
3	Bargarh	49	56	53	5	163
4	Bhadrak	29	20	23	1	73
5	Balangir	33	63	53	3	152
6	Boudh	21	29	23	6	79
7	Cuttack	38	87	54	10	189
8	Deogarh	13	16	10	1	40
9	Dhenkanal	35	19	18	3	75
10	Gajapati	16	13	16	4	49
11	Ganjam	22	21	26	3	72
12	Jagatsinghpur	53	31	29	5	118
13	Jajpur	57	37	29	5	128
14	Jharsuguda	21	22	26	2	71
15	Kalahandi	75	98	71	7	251
16	Kandhamal	42	74	35	11	162
17	Kendrapara	56	37	22	5	120
18	Keonjhar	24	39	38	5	106
19	Khordha	21	41	19	5	86
20	Koraput	30	53	58	11	152
21	Malkanagiri	29	31	32	5	97
22	Mayurbhanj	56	58	50	7	171
23	Nawarangpur	30	69	53	7	159
24	Nayagarh	17	29	15	5	66
25	Nuapada	15	23	22	2	62
26	Puri	52	48	40	7	147
27	Rayagada	13	33	25	3	74
28	Sambalpur	44	58	47	4	153
29	Subarnapur	22	35	33	4	94
30	Sundargarh	55	57	43	6	161
	Odisha	1047	1296	1009	150	3502

The extreme temperature events categorized as ≥ 40 °C were identified based on the criteria used by the India Meteorological Department for declaring a heat wave, which stipulates that the maximum temperature at a station must reach at least 40 °C or higher for plains (Meteorological Monograph: Heat and Cold Waves in India. Processes and Predictability). Further, Heat Wave is declared by IMD when the temperature is ≥ 45 °C based on 'Actual Maximum Temperature'.

The NVI for temperature thresholds viz. ≥40 ^{o}C and ≥45 ^{o}C were worked out using the same formula which was used in calculating NVI for rainfall extremes.

3. Results and discussions

3.1. *Extreme Rainfall Occurrence*

The state as a whole received a total of 4146 extreme rainfall events during the 32 years (Table 1). The annual incidence of the number of events was maximum in Kalahandi (257) followed by Cuttack district (232). Deogarh district received the minimum of 42 events followed by Nuapada (63) and Jharsuguda (73). Events were maximum in number (1458) during 2001-2010 (2nd decade) and then decreased. The monsoon period analysis

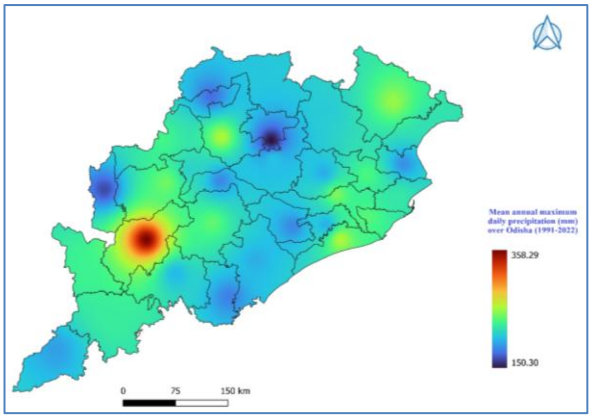

Fig. 3. Mean annual maximum daily precipitation (mm) over Odisha (1991-2022)

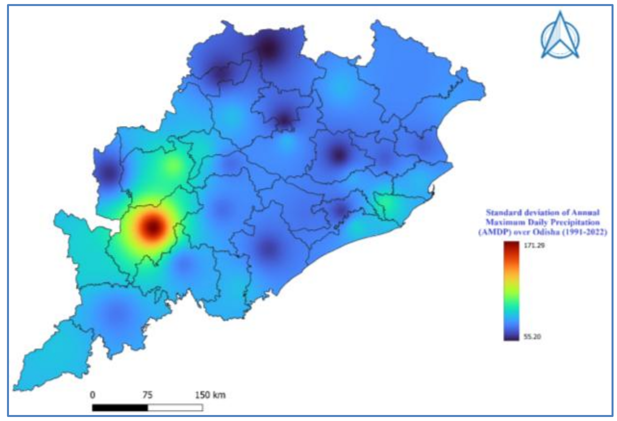

Fig. 4. Standard deviation of Annual Maximum Daily Precipitation (AMDP) over Odisha (1991-2022).

revealed that Kalahandi experienced the maximum number of events (251) followed by Cuttack (189); minimum number of extreme rainfall events occurred in Deogarh (40) followed by Gajapati (49). Decade-wise analysis for monsoon months revealed that the state received maximum events (1296) during 2001-2010 period (Table 2). During the non-monsoon months, the number of events was maximum in Puri (60) followed by other coastal districts namely, Balasore (54), Kendrapada (49), Cuttack (43), Jagatsinghpur (43), and Ganjam (41) (Table 3). The incidence of events was minimal in western districts with Nuapada district receiving the lowest occurrence (01) followed by Subarnapur, Jharsuguda, Baragarh and Deogarh with three number of events each. The recent decadal period (2011-2020) experienced the maximum number of extreme rainfall events (230) during non-monsoon months in the state as compared to the preceding two decades.

3.2. *Probable maximum Precipitation*

The highest mean annual maximum daily precipitation was recorded in Kalahandi at 358 mm, followed by Puri with 259 mm, Sambalpur with 258 mm, and Mayurbhanj with 253 mm. Deogarh had the lowest value at 150 mm (Fig 3 & 4). Regarding the one-day probable maximum precipitation, Kalahandi again topped the list with 905 mm, followed by Bolangir (618 mm), Koraput (613 mm), and Jagatsinghpur (610 mm). The lowest value was observed in Dhenkanal at 318 mm (Fig 5).

3.3. *Extreme rainfall trend*

The trend of annual and monsoon extreme rainfall revealed that two districts namely, Koraput, and Malkangiri showed an increasing trend of Heavy Rainfall events, whereas Balasore & Jajpur districts displayed a decreasing trend significantly (Fig 6 & 9). As regards the trend of Very Heavy Rainfall events, four districts namely, Angul, Dhenkanal, Jajpur & kendrapara showed a significant decreasing trend in annual & monsoon extreme rainfall (Fig 7 & 10) and only Korpaut district displayed a significant increasing trend in monsoon extreme rainfall. The trend of Extremely Heavy Rainfall events was found to be significantly increasing in Nawarangapur district whereas it showed a declining trend in Puri district for both annual and monsoon period (Fig 8 & 11). The trend analysis of rainfall extremes during non-monsoon months revealed that districts namely, Boudh & Puri showed an increasing trend of Very-Heavy Rainfall events (Fig 13). No significant trend was observed for both heavy and extremely heavy rainfall events during non-monsoon period (Fig 12 & 14).

3.4. *Normal Vulnerability Index*

The analysis of the Normal Vulnerability Index (NVI) for rainfall extremes across districts revealed that Kalahandi and Puri are moderately vulnerable to rainfall extremes during both the annual and monsoon periods (Fig 15 & 16). Among the 30 districts, 28 exhibit moderate vulnerability during the annual period, while 27 show moderate vulnerability during the monsoon season. In contrast, only four districts namely, Cuttack, Jagatsinghpur, Ganjam, and Koraput are moderately vulnerable to rainfall extremes in the non-monsoon period, with the remaining districts classified as having low vulnerability (Fig 17).

3.5. *Contribution of high-intensity rainfall events to annual normal rainfall*

The percentage contribution of the top seven rainfall events to the total annual normal rainfall was maximum (41.1) for Kalahandi district followed by Puri

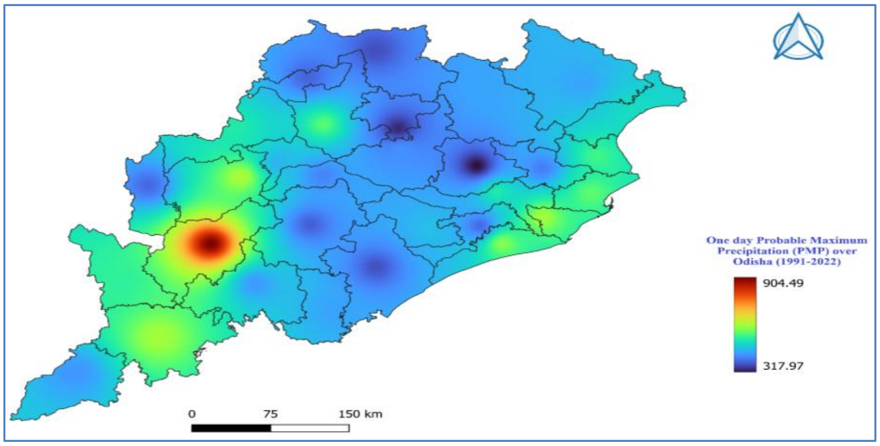

Fig. 5. One day Probable Maximum Precipitation (PMP) over Odisha (1991-2022).

TABLE 3

District-wise extreme rainfall (≥ 115.6 mm) events(non-monsoon)

Sl. No.	District	1991-2000 (number)	2001-2010 (number)	2011-2020 (number)	2021-2022 (number)	1991-2022 (number)
1	Angul	1	2	4	0	**7**
2	Balasore	18	17	16	3	**54**
3	Bargarh	0	1	1	0	**2**
4	Bhadrak	16	8	8	3	**35**
5	Balangir	1	4	3	0	**8**
6	Boudh	0	0	3	0	**3**
7	Cuttack	13	12	17	1	**43**
8	Deogarh	0	0	1	1	**2**
9	Dhenkanal	9	3	8	0	**20**
10	Gajapati	9	5	11	1	**26**
11	Ganjam	11	10	17	3	**41**
12	Jagatsinghpur	16	9	15	3	**43**
13	Jajpur	13	9	14	2	**38**
14	Jharsuguda	0	2	0	0	**2**
15	Kalahandi	0	3	3	0	**6**
16	Kandhamal	13	5	6	0	**24**
17	Kendrapara	20	9	17	3	**49**
18	Keonjhar	5	5	5	1	**16**
19	Khordha	14	4	12	0	**30**
20	Koraput	4	9	4	0	**17**
21	Malkanagiri	3	5	4	2	**14**
22	Mayurbhanj	12	12	11	3	**38**
23	Nawarangpur	6	3	4	0	**13**
24	Nayagarh	9	3	12	0	**24**
25	Nuapada	0	0	1	0	**1**
26	Puri	20	13	24	3	**60**
27	Rayagada	3	5	6	1	**15**
28	Sambalpur	1	2	0	0	**3**
29	Subarnapur	0	0	2	0	**2**
30	Sundargarh	3	2	1	2	**8**
	Odisha	220	162	230	32	644

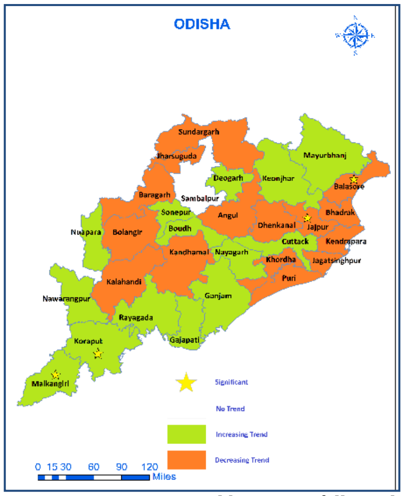

Fig.6 District-wise annual heavy rainfall trend

Fig.7 District-wise annual very-heavy rainfall trend

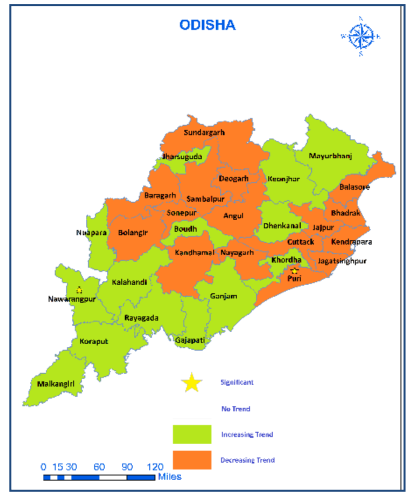

Fig.8 District-wise annual extreme-heavy rainfall trend

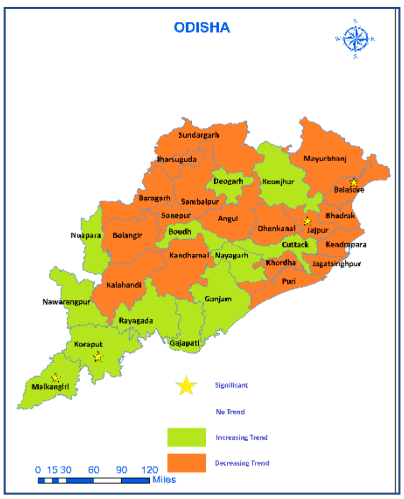

Fig.9 District-wise heavy rainfall trend in monsoon period

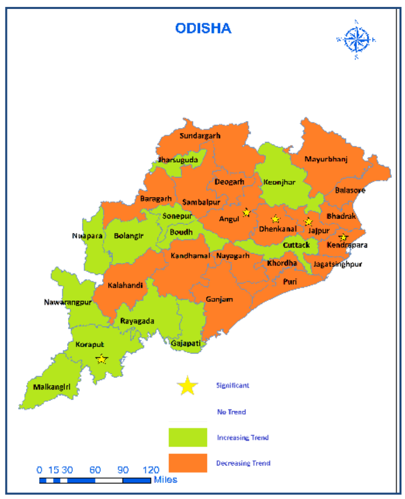

Fig.10 District-wise very-heavy rainfall trend in monsoon period

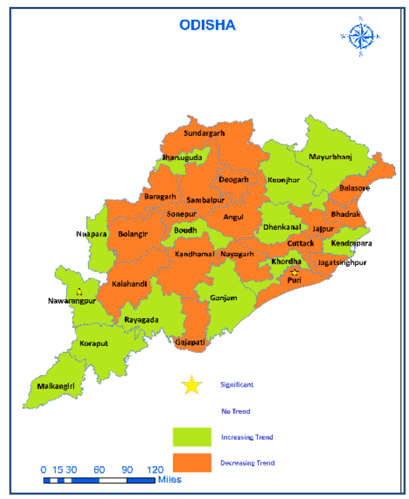

Fig.11 District-wise extreme-heavy rainfall trend in monsoon period

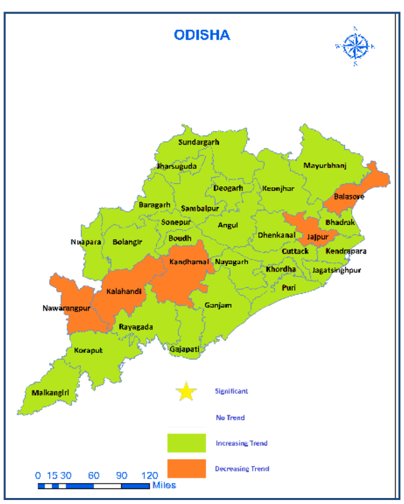

Fig.12 District-wise heavy rainfall trend in non-monsoon period

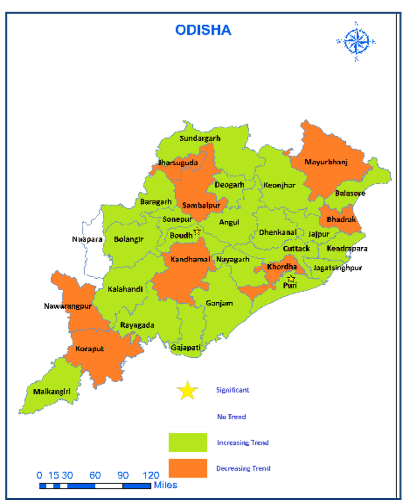

Fig.13 District-wise very-heavy rainfall trend in non-monsoon period

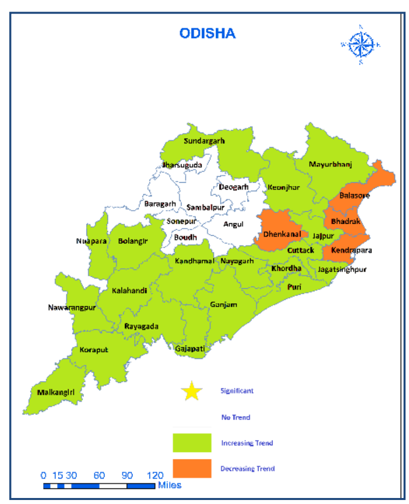

Fig.14 District-wise extreme-heavy rainfall trend in non-monsoon period

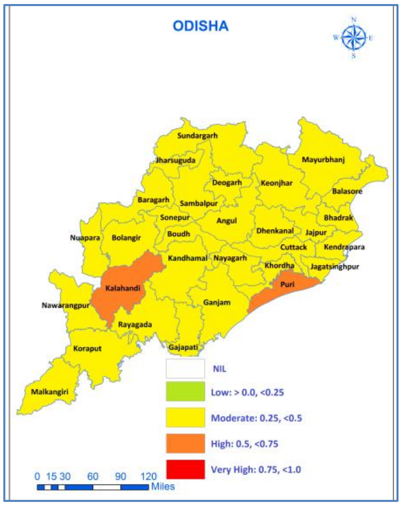

Fig.15 District-wise NVI w.r.t. Annual Rainfall Extremes

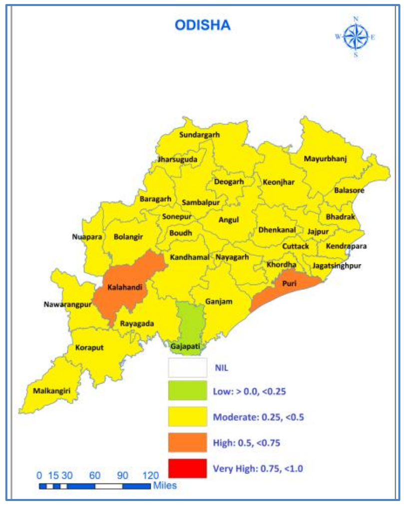

Fig.16 District-wise NVI w.r.t. Monsoon Rainfall Extremes

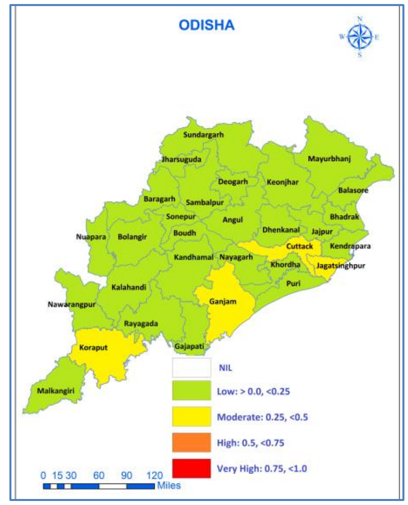

Fig.17 District-wise NVI w.r.t. Non-monsoon Rainfall Extremes

(37.4) and Kendrapara (34.9). The districts namely, Keonjhar and Mayurbhanj receive only 23.2% and 23.7% of their annual rainfall from the top seven rainfall events, respectively (Table 4). The other districts namely, Bargarh, Bhadrak, Balangir, Cuttack, Ganjam, Jagatsinghpur, Jajpur, Jharsuguda, Kandhamal, Kendrapara, Khordha, Nawrangpur and Nayagarh also receive 30% or more of their annual rainfall from top seven rainfall events.

3.6. *District-wise Vulnerability to high-intensity rainfall events*

The analysis of NVI values for the contribution of the top seven rainfall events to annual normal rainfall revealed that five districts viz. Boudh, Cuttack, Jajpur, Jharsuguda and Khordha come under the highly vulnerable category while rest 25 districts of the state come under the moderately vulnerable category. (Fig 18)

3.7. *Extreme Temperature Occurrence& Trend*

Balangir in western Odisha recorded the maximum number of extreme temperature events for both the temperature thresholds of ≥40 ºC and ≥45 ºC followed by Sambalpur and Hirakud located in the same region of the state (Table 5).

The analysis of the trend of extreme temperature events revealed that the stations *viz*. Balasore, Bhadrak, Dhenkanal and Goplapur showed a decreasing trend of temperature extremes of ≥40 ºC over the study period (2000-2022). Similarly, the stations, Angul, Cuttack, Jharsuguda, Malkangiri, Sonepur, Talcher and Titlagarh showed significant negative trends of temperature extremes of ≥45 ºC.

3.8. *District-wise Vulnerability to Temperature Extremes*

The stations in western Odisha *viz.* Balangir, Hirakud, Jharsuguda, Sambalpur, Sonepur and Titlagarh and one coastal station *i.e.* Cuttack were found to be moderately vulnerable to extreme temperature events of ≥ 45 ºC (Table 6). Out of 24 stations in the state, 15 stations covering 11 districts viz. Angul, Baripada, Bolangir, Cuttack, Daringibadi, Hirakud, Jharsugura, Keonjhar, Malkangiri, Phulbani, Sambalpur, Sonepur, Sundargarh, Talcher & Tiltlagarh were found to be highly vulnerable to extreme temperature events of ≥ 40 ºC. Two coastal stations *viz*. Puri & Paradip and one interior station, Koraput come under the low vulnerability category of extreme temperatures of ≥ 40 ºC. The rest of the stations in the state come under the moderately vulnerable category w.r.t. temperature extremes.

4. Results and discussions

This study found that Kalahandi district recorded the highest number of extreme rainfall events, followed by Cuttack. The highest incidence of extreme rainfall occurred during the decadal period of 2001–2010, after which it decreased. Notably, two southern districts namely, Korpaut & Malkangiri and one district Nawarangapur have been experiencing an increasing trend of heavy and extremely heavy rainfall events during annual and monsoon periods respectively, which is a cause for concern. These districts must implement adaptation measures to address the adverse impacts of such events.

In terms of non-monsoon rainfall extremes, the coastal districts of Puri (60), Balasore (54), Kendrapara

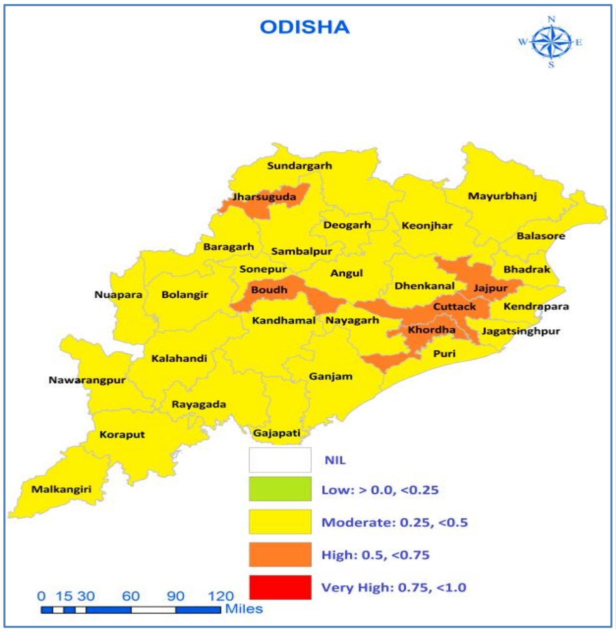

Fig.18. NVI of contribution of top seven rainfall events to district normal rainfall

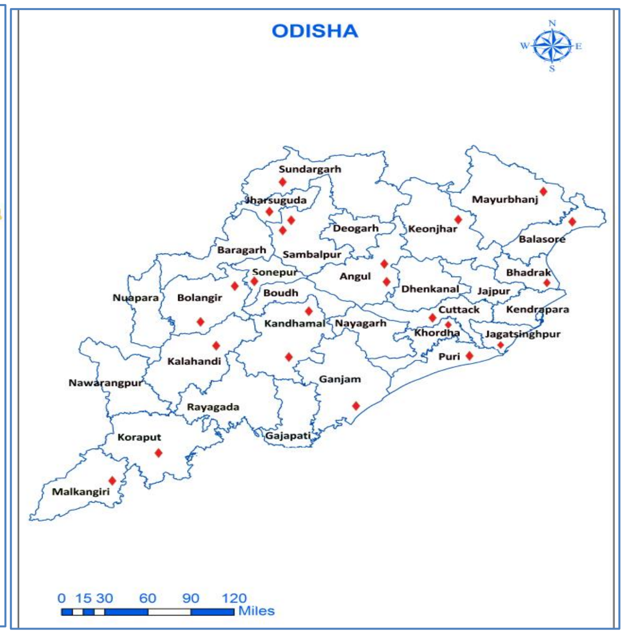

Fig.19. IMD weather stations across Odisha state, India (24)

TABLE 4

Percentage contribution of top seven rainfall events to annual rainfall

Sl. No.	District	1991-2000 (number)	2001-2010 (number)	2011-2020 (number)	2021-2022 (number)	1991-2022 (number)
1	Angul	27.2	29.1	25.1	27.1	27.1
2	Balasore	28.7	30.9	27.5	28.8	28.8
3	Bargarh	28.8	31.8	31.7	30.4	30.4
4	Bhadrak	30.1	31.4	31.1	30.8	30.8
5	Balangir	28.8	38.6	31.0	32.4	32.4
6	Boudh	25.2	31.7	29.0	29.0	29.0
7	Cuttack	29.7	37.7	30.6	32.6	32.6
8	Deogarh	25.9	25.2	27.0	26.1	26.1
9	Dhenkanal	30.1	26.1	26.5	27.4	27.4
10	Gajapati	24.5	27.2	30.2	27.3	27.3
11	Ganjam	27.7	29.2	32.9	30.0	30.0
12	Jagatsinghpur	31.9	35.2	33.5	34.2	34.2
13	Jajpur	29.1	32.5	31.4	30.9	30.9
14	Jharsuguda	28.8	34.0	37.5	33.1	33.1
15	Kalahandi	32.6	52.4	40.6	41.1	41.1
16	Kandhamal	32.2	40.0	28.6	33.6	33.6
17	Kendrapara	34.0	37.7	33.1	34.9	34.9
18	Keonjhar	20.8	24.2	24.6	23.2	23.2
19	Khordha	29.4	33.3	30.0	30.8	30.8
20	Koraput	20.9	27.0	27.9	25.1	25.1
21	Malkanagiri	22.5	27.5	30.2	26.6	26.6
22	Mayurbhanj	21.8	24.5	24.7	23.7	23.7

Table 4 continued

Sl. No.	District	1991-2000 (number)	2001-2010 (number)	2011-2020 (number)	2021-2022 (number)	1991-2022 (number)
23	Nawarangpur	24.4	38.5	32.1	31.2	31.2
24	Nayagarh	26.4	32.6	30.5	30.0	30.0
25	Nuapada	24.2	34.5	31.2	29.7	29.7
26	Puri	38.1	39.8	34.1	37.4	37.4
27	Rayagada	23.1	31.8	29.3	27.6	27.6
28	Sambalpur	28.7	33.6	33.0	31.4	31.4
29	Subarnapur	33.1	37.3	33.5	34.5	34.5
30	Sundargarh	24.1	25.2	25.8	25.1	25.1
	Odisha	220	27.8	32.7	30.5	30.2

TABLE 5

Trend of extreme temperature events

Sl#	District	Tmax ≥ 40ºC			Tmax ≥ 45ºC		
		Total Events	**Trend**	**Result**	**Total Events**	**Trend**	**Result**
1	Angul	1069	-0.61	NS	107	-2.32	S (0.05)
2	Balasore	448	-2.27	S (0.05)	15	-1.43	NS
3	Baripada	652	-0.85	NS	14	-0.53	NS
4	Bhadrak	464	-2.19	S (0.05)	15	-1.43	NS
5	Bhawanipatna	652	0.85	NS	1	-0.40	NS
6	Bhubaneswar	122	-0.77	NS	0	NA	NA
7	Bolangir	1392	0.40	NS	226	-1.37	NS
8	Cuttack	845	-1.40	NS	75	-2.46	S (0.05)
9	Darinibadi	614	-1.43	NS	6	-0.87	NS
10	Dhenkanal	558	-1.95	S (0.1)	15	-1.11	NS
11	Gopalpur	92	-2.64	S (0.01)	0	NA	NA
12	Hirakud	1296	-0.24	NS	168	-1.08	NS
13	Jharsuguda	1256	0.34	NS	122	-1.69	S (0.1)
14	Keonjhar	967	-0.40	NS	60	-1.24	NS
15	Koraput	41	-1.27	NS	0	NA	NA
16	Malkangir	1092	-0.13	NS	45	-1.69	S (0.1)
17	Paradip	1	-0.45	NS	0	NA	NA
18	Phulbani	897	0.00	NS	20	-0.69	NS
19	Puri	3	-0.56	NS	0	NA	NA
20	Sambalpur	1329	0.24	NS	168	-1.08	NS
21	Sonepur	1209	0.85	NS	98	-2.06	S (0.05)
22	Sundargarh	1176	0.26	NS	84	-1.29	NS
23	Talcher	1076	-0.21	NS	110	-1.98	S (0.05)
24	Titlagarh	1229	0.95	NS	96	-2.30	S (0.05)

vulnerable category w.r.t. temperature extremes.

(49), Jagatsinghpur (43), Cuttack (43), and Ganjam (41), recorded the highest events during the study period. These extreme rainfall occurrences, especially in November and in the first fortnight of December, coincide with the ripening stage of kharif rice, leading to loss of crops. However, rainfall in October supports rainfed kharif rice during the grain-filling stage and helps establish rainfed rabi non-paddy crops. The highest mean Annual Maximum Daily Precipitation (AMDP) as well as maximum one day Probable Maximum Precipitation (PMP) was recorded in Kalahandi. The districts namely, Kalahandi and Puri were identified as the most vulnerable to extreme rainfall events.

TABLE 6

Normal Vulnerability Index (NVI) of maximum temperature extremes

Sl. No.	Station	(≥ 40ºC)		(≥ 45 ºC)	
		NVI	Category	NVI	Category
1	Angul	0.57	High	0.21	Low
2	Balasore	0.44	Moderate	0.16	Low
3	Baripada	0.51	High	0.12	Low
4	Bhadrak	0.45	Moderate	0.16	Low
5	Bhawanipatna	0.45	Moderate	0.04	Low
6	Bhubaneswar	0.33	Moderate		
7	Bolangir	0.54	High	0.41	Moderate
8	Cuttack	0.62	High	0.27	Moderate
9	Daringibadi	0.52	High	0.09	Low
10	Dhenkanal	0.49	Moderate	0.16	Low
11	Gopalpur	0.33	Moderate		
12	Hirakud	0.71	High	0.38	Moderate
13	Jharsuguda	0.66	High	0.31	Moderate
14	Keonjhar	0.66	High	0.19	Low
15	Koraput	0.16	Low		
16	Malkangir	0.67	High	0.15	Low
17	Paradip	0.04	Low		
18	Phulbani	0.57	High	0.10	Low
19	Puri	0.04	Low		
20	Sambalpur	0.68	High	0.38	Moderate
21	Sonepur	0.57	High	0.30	Moderate
22	Sundargarh	0.53	High	0.24	Low
23	Talcher	0.61	High	0.22	Low
24	Titlagarh	0.51	High	0.30	Moderate

The analysis of the Normal Vulnerability Index (NVI) based on the contribution of the top seven extreme rainfall events to annual normal rainfall showed that five districts, Boudh, Cuttack, Jajpur, Jharsuguda, and Khordha are highly vulnerable, while the other 25 districts are moderately vulnerable. These findings highlight the need for effective measures in runoff water management and soil conservation, particularly in the five highly vulnerable districts.

Bolangir in western Odisha recorded the highest number of extreme temperature events for both temperature thresholds (≥40 °C and ≥45 °C), followed by Sambalpur and Hirakud. Contrary to the global perception of increasing temperature due to global warming, four stations in the coastal region—Balasore, Bhadrak, Goplapur, and Dhenkanal—showed a decreasing trend in the frequency of ≥40 °C temperature extremes during the study period (2000–2022). The vulnerability of districts to extreme temperatures revealed that stations in western Odisha (Bolangir, Hirakud, Jharsuguda, Sambalpur, Sonepur, Titlagarh) and the coastal region (Cuttack) were moderately vulnerable to temperature extremes of ≥45 °C.

Given the frequency and severity of weather extremes, particularly rainfall and temperature, and their significant impact on the livelihoods of people in Odisha, the information compiled in this study can serve as a valuable agro-climatic resource for implementing adaptation and mitigation measures.

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