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Heat Waves/cold Waves Trends and Agricultural Impact in Mid Hills of Himachal Pradesh

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ABSTRACT

The analysis was carried out from 1984–2023 at Dr. Y. S. Parmar UHF, Nauni, using secondary data to examine heat-wave and cold-wave trends and their agricultural impact in the mid-hills of Himachal Pradesh. The variability of Heat waves and cold waves depends on local climatic and geographical conditions. Daily maximum and minimum temperature and relative humidity data were obtained from the Agrometeorological Observatory at Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan, while crop yield data were collected from the Department of Horticulture. Events of heat wave, severe heat wave, cold wave, severe cold wave, and the heat index were identified and analyzed for monthly, annual, and decadal variability. The annual mean maximum and minimum temperatures were 25.4°C and 11.6°C, with relative humidity averaging 60%. The maximum and minimum temperatures and relative humidity increased by 2.5°C, 0.55°C, and 1.07% year^{-1}, respectively. In total, 669 heat waves, 161 severe heat waves, 260 cold waves, and 37 severe cold waves were recorded. Heat waves increased by 1.11 events year^{-1}, while cold waves decreased by 2.86 events year^{-1}. Both rising and declining extremes adversely affected crop yields. The heat index showed a rising trend, indicating regional warming. These findings emphasize the need for adaptive strategies and a better understanding of extreme temperature events to safeguard agricultural production under climate change.

KEYWORDS: Heat wave, cold wave, heat index, agriculture, tomato, capsicum, extremes

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1. INTRODUCTION

Extreme temperature events have intensified globally over the past few decades, making them a critical component of contemporary climate research. Heat waves and cold waves are inconsistent extreme temperature phenomena that have received considerable scientific attention because of their severe adverse impacts on human health, agriculture, ecosystems, and industrial productivity (Fu et al., 2018; Piticar et al., 2017; Cheng et al., 2019; Ray et al., 2021). These extremes disrupt normal environmental functioning and pose substantial risks to climate-sensitive sectors, particularly agriculture and horticulture in mountainous regions, where climatic variability directly influences livelihood security. Rising global temperatures, primarily driven by anthropogenic greenhouse gas emissions, have intensified interest in climate-related extremes (Skytt et al., 2020; Anonymous, 2014; Sharma and Goyal, 2020), and the damage caused by weather-related natural disasters has escalated significantly in recent years, reflecting the growing consequences of climatic instability.

According to Anonymous (2012), warm days and nights have become more frequent and prolonged since the 1950s, and this trend is projected to continue, leading to more hot weather extremes and fewer cold weather events across Asia. Several studies, including Orlowsky and Seneviratne (2011), Clark et al. (2011), and Rajendran and Kitoh (2008), report a significant rise in the frequency of extremely hot days across East and South Asia, while Indian analyses by Kumar et al. (2013) indicate that cold days and nights are decreasing by 2.82 and 2.93 days per decade, respectively, at a 99.9% confidence level. Similar global declines in cold wave frequency have been attributed to anthropogenic warming (Lu et al., 2015; Unkasevic and Tosic, 2015; Piticar et al., 2018; Bitencourt et al., 2020; Namroodi et al., 2021). Heat waves, often referred to as "silent killers," exert direct and sometimes fatal effects on human health (Patz et al., 2005; Houndula et al., 2014; Heo et al., 2019), and numerous studies across India have documented their rising frequency, duration, intensity, and socioeconomic consequences (Rohini et al., 2016; Mazdiyasni et al., 2017; Ray et al., 2021). Variations in heat waves and cold waves pose significant risks to crop performance, food security, and economic stability. Reliable trend assessments using historical climatic records are essential for identifying emerging patterns, evaluating the magnitude of change, and anticipating future risks.

Extended high-temperature periods also reduce agricultural productivity by altering crop physiology, accelerating evapotranspiration, and lowering yield potential. To better quantify thermal stress, the Heat Index (HI), also known as apparent temperature, developed by Steadman (1979, 1984), is widely used because it combines air temperature and relative humidity to estimate perceived temperature (Zahid and Rasul, 2009; Rajb et al., 2011; Rakib, 2013; Jaswal et al., 2017), offering a more representative measure of heat-related stress than air temperature alone. Understanding such extreme events is therefore crucial for assessing their frequency, severity, and broad implications for human well-being, agricultural productivity, and environmental sustainability under changing climatic conditions.

This underlines the urgent need for long-term investigations in climate-sensitive regions such as the mid-hills of Himachal Pradesh, where agriculture and horticulture form the primary livelihood base. Such data-driven insights support the strengthening of climate resilience through early-warning systems, climate-smart agricultural practices, and responsive policy frameworks. By analysing multi-decadal secondary data spanning 1984 to 2023, the present study aims to elucidate the temporal behaviour of heat waves and cold waves and highlight their implications for agriculture in the mid-hill region of Himachal Pradesh, thus providing a scientific foundation for informed decision-making and adaptive strategies under changing climatic conditions.

2. MATERIALS AND METHODS

2.1. Study area

The study was carried out in the mid-hill region of Himachal Pradesh (Figure 1), represented by Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (33°12' N; 79°04' E; 1250 m amsl). The altitude of the region ranges between 600 and 1250 m above mean sea

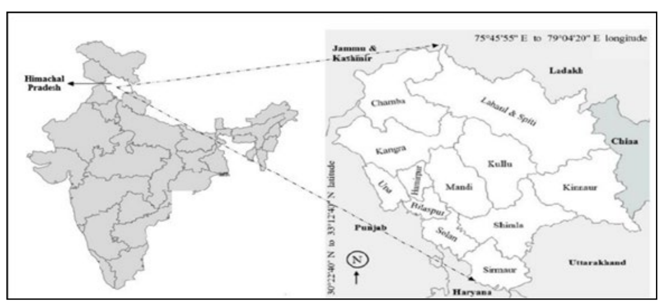

Figure 1: Study area

level, covering an approximate area of 1,936 km². The region has an annual average maximum temperature of 25.4°C, a minimum temperature of 11.4°C, and receives about 1115.1 mm of annual rainfall. The climate varies from subtropical to temperate, characterized by mild summers, cold winters, and moderate rainfall. This agro-climatic zone is highly suitable for cultivating tomatoes, capsicum, and temperate fruits such as stone and pome crops.

2.2. Data source

2.2.1. Climatic data

Daily records of maximum temperature (1984–2023), minimum temperature (1984–2023), dry bulb temperature (2004–2023), and relative humidity (2004–2023) were obtained from the Agro-Meteorological Observatory located at the experimental farm of Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan.

2.2.2. Crop data

Tomato and capsicum are the major vegetable crops of the study region. The annual tomato production is about 232,000 t from an area of approximately 4,640 ha, with an average yield of 50 t ha^{-1}. Similarly, capsicum production is about 34,510 t, with an average productivity of 28.64 t ha^{-1} (Kumar et al., 2022). Given their economic and agricultural importance, these two crops were selected to assess the impact of heat waves (HW) and cold waves (CW). Crop production and yield data for tomato and capsicum were collected from the Department of Horticulture for the period 1996–2021.

2.3. Data analysis

Temperature and crop data were analyzed on a daily, monthly, seasonal (summer, southwest monsoon, post-monsoon, and winter), annual, and decadal basis:

• Decade 1 (1984–1993)

• Decade 2 (1994–2003)

• Decade 3 (2004–2013)

• Decade 4 (2014–2023)

Heat wave (HW) and cold wave (CW) events were identified using the criteria prescribed by the India Meteorological Department (IMD).

• Heat Wave (HW): Considered when the maximum temperature reaches at least 40°C in plains or 30°C in hilly regions. Based on the positive departure from the long-term normal (≥30 years), the classification is:

o Heat Wave: +4.5°C to +6.4°C departure from normal.

o Severe Heat Wave: >+6.4°C departure from normal.

• Cold Wave (CW): Considered when the minimum temperature is ≤10°C in plains, accompanied by a significant negative departure from the long-term normal (≥30 years). The classification is:

o Cold Wave: −4.5°C to −6.4°C departure from normal.

o Severe Cold Wave: ≤−6.5°C departure from normal.

2.3.1. Variability analysis

Variability analysis was done using the following statistical tools: mean standard deviation (SD), coefficient of variation (CV), and the % contribution of annual temperature using an Excel spreadsheet.

23.2. Trend analysis

2.3.2.1. Man-kendall test

The trend in maximum, minimum temperature, heat wave (HW), severe heat wave (SHW), cold wave (CW), severe cold wave (SCW),and heat index (HI) wasworked out by using Mann-Kendall (MK) and Sen's slope estimator. The Mann-Kendall trend test is a non-parametric method widely used to identify monotonic trends in meteorological data. This test evaluates whether there are statistically significant increasing or decreasing trends of the parameter. MAKESENS software employs two types of statistics depending on the data set size. S-statistics for fewer than 10 data points and Z-statistics for 10 or more data points (Kendall, 1975).

The statistics S is calculated as shown in equation (i)

$$S=\sum_{i=1}^{n-1}\sum_{j=ith+1}\text{sgn}(xj-xi) \quad \text{.............................. (i)}$$

Where xj and xi and are annual values (in years) j and I, if j>i respectively, n is the number of data points and sgn(xj-xi) is calculated using equation (ii)

$$\text{sgn}(xj-xi)=\begin{cases} 1 \text{ if } (xj-xi>0) \\ 0 \text{ if } (xj-xi=0) \\ -1 \text{ if } (xj-xi<0) \end{cases} \quad \text{.............................. (ii)}$$

A positive or negative value of S indicates upward or downward trends, respectively.

If the number of data values is10 or more, the S-statistic approximately behavesas normally distributed and the test is performed with a normal distribution with the mean and variation as given below equations (iii) and (iv)

$$E(s)=0 \quad \text{.. (iii)}$$

$$\text{var}(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{n} ti(ti-1)(2ti+5)}{18} \quad \text{............. (iv)}$$

Where n is the number of tied (zero difference between compared values) groups,and is the number of data points in the i th tied group. The standard normal distribution (Z-statistics) is computed using equation (v).

$$z=\begin{cases} \frac{s-1}{\sqrt{\text{var}(s)}} \text{ if } s>0 \\ 0 \text{ if } s=0 \\ \frac{s+1}{\sqrt{\text{var}(s)}} \text{ if } s<0 \end{cases} \quad \text{.. (v)}$$

Statistically, the significance of the trend is assessed using the z-value. A positive value of Z shows upward (increasing) trend while a negative value indicates the downward (decreasing) trend.

2.3.2.2. Sen's estimator method

Sen's non-parametric estimator method was used for predicting the magnitude of weather data series, which uses a linear model for trend analysis. The slope Ti is calculated as:

Ti=(xj-xk)/(j-k) For i=1, 2, 3…n

Where, and are data values at time j and k (j>k) separately.

The median of these n values of Ti is represented by Sen's slope estimation, which is estimated by using the following equation

$$Qi=\begin{cases} T\frac{n+1}{2} & \text{for n is odd} \\ \frac{1}{2}\left(T\frac{n}{2}+T\frac{n+2}{2}\right) & \text{for n is even} \end{cases}$$

Sen's estimator (Qi) is calculated by using above equation depending upon value of n is either odd or even then (Qi) is computed using 100(1-*a*)%, confidence interval. A positive value of Qi indicatesan increasing trend, while a negative value represents a decreasing trend of time series data. Where *a* is a different significance level (0.05 and 0.01, etc.)

3.3.2.3. Heat index analysis

Heat index is a combination of air temperature and relative humidity; it measures how hot it really feels when relative humidity is factored in with the actual air temperature (Table 1). It is calculated using the formula:

$$HI=-42.379+2.04901523*T+10.14333127*R-0.22475541*T*R-6.83783\times10^{-3}*T^2-5.481717\times10^{-2}*R^2+1.22874\times10^{-3}*T^2*R+8.5282\times10^{-4}*T*R^2-1.99\times10^{-6}*T^2*R^2$$

Table 1: Categories of HI and its possible heat disorders for people in the high-risk group.

Category	Heat index	Possible heat caused disorders in humans
Extreme danger	(54°C or higher)	Heat stroke or sunstroke is likely.
Danger	(41–54°C)	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme caution	(32–41°C)	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	(27–32°C)	Fatigue is possible with prolonged exposure and/or physical activity.

3. RESULTS AND DISCUSSION

3.1. Monthly and seasonal variability analysis of weather parameters

The monthly and seasonal variability of maximum temperature, minimum temperature, and relative humidity was analyzed using Z-statistics and Q-statistics (Tables 2 and 3). The mean annual maximum and minimum temperatures were 25.4°C and 11.6°C, with standard deviations (SD) of 0.9°C and 0.7°C, and coefficients of variation (CV) of 3.7% and 6.5%, respectively. The highest monthly maximum temperature was recorded in May (31.2°C), followed by June (30.9°C), with SD values of 1.7°C and 1.9°C and CVs of 5.4% and 6.2%, respectively. Among the seasons, summer registered the highest average maximum temperature (29.6°C), with an SD of 1.6°C and the lowest CV (5.2%) (Table 2). Similar findings were reported by Asseng et al. (2011) in Australia, where maximum temperature showed an increasing trend except during January and June. Rising temperatures influence crop growth, nutrient uptake, pollen development, and grain formation by modifying water requirements. Prolonged exposure to temperatures above 34°C accelerates leaf senescence, potentially reducing crop yields by up to 50% (Asseng et al., 2011).The highest monthly minimum temperature was observed in July (20.0°C), followed by August (19.5°C), with SDs of 0.9°C and 1.2°C and CVs of 4.8% and 6.3%, respectively. On a seasonal scale, the southwest monsoon recorded the highest average minimum temperature (18.7°C), with an SD of 1.0°C and the lowest CV (5.3%). The mean annual relative humidity (RH) was 60%, with an SD of 2.3% and a CV of 3.8%. The highest RH occurred in August (80%), followed by July (78%), with corresponding SDs of 3.4% and 3.6% and CVs of 4.3% and 4.6%. According to Bhutiyani et al. (2007), minimum temperatures in the northwestern Himalayan region increased significantly during the 20th century. Similarly, Sharma et al. (2017) reported a non-significant rise in average minimum temperatures, which aligns with the present findings.

Long-term trend analysis of weather parameters (Table 3) revealed that both annual maximum and minimum temperatures exhibited increasing trends as per the Mann–Kendall (MK) test. The monthly mean maximum temperature showed an upward trend in all months except May and June. Minimum temperature exhibited a non-significant rise in most months, except April, May, June, and December, where a slight decline was observed. Annual mean RH also showed an increasing trend, while monthly RH increased in most months except January, February, March, and August. At the seasonal scale, RH indicated an increasing trend across all seasons. The simultaneous decrease in RH and increase in maximum temperature imply a higher rate of evapotranspiration, thereby escalating the irrigation demand for crops.

3.2. Monthly, seasonal, and annual heat and cold wave events

Descriptive statistics of the monthly, seasonal, and annual

Table 2: Monthly and seasonal mean and variation of different weather parameters

Months/Seasons	Maximum temperature (°C)			Minimum temperature (°C)			Relative humidity (%)		
	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV(%)
January	17.6	2.0	11.3	2.2	1.0	46.1	58	6.6	11.4
February	19.5	2.4	12.3	4.3	1.5	35.6	57	6.3	11.1
March	23.5	2.3	9.7	8.1	1.3	15.9	52	9.1	17.3
April	28.1	2.1	7.5	12.3	1.5	12.5	46	5.4	11.7
May	31.2	1.7	5.4	15.9	1.3	8.3	49	5.5	11.4
June	30.9	1.9	6.2	18.5	1.1	5.8	59	9.2	15.6
July	28.4	1.3	4.5	20.0	0.9	4.8	78	3.6	4.6
August	28.0	1.1	3.8	19.5	1.2	6.3	80	3.4	4.3
September	28.0	1.2	4.2	16.8	1.5	8.8	73	3.5	4.8
October	26.5	1.3	5.0	10.5	1.4	13.3	59	6.6	11.1
November	23.2	1.3	5.5	5.8	1.3	22.1	55	6.7	12.1
December	20.0	2.1	10.3	2.8	1.0	35.5	54	5.0	9.2
Annual	25.4	0.9	3.7	11.4	0.7	6.5	60	2.3	3.8
Summer	29.6	1.6	5.2	14.1	1.2	8.8	48	3.9	8.3
Southwest monsoon	28.8	1.0	3.5	18.7	1.0	5.3	72	3.1	4.2
Post monsoon	23.3	1.4	5.8	6.4	1.0	14.9	56	4.8	8.6
Winter	20.2	1.7	8.5	4.9	0.8	17.2	56	5.6	10.0

Table 3: Man, Kendall and sens's slope trend analysis of different weather parameter

Time series	Maximum temperature (°C)			Minimum temperature (°C)			Relative humidity (%)		
	Z-statistics	Q-statistics	Trends	Z-statistics	Q-statistics	Trends	Z- statistics	Q-statistics	Trends
January	2.1*	0.07	↑	0.97	0.02	↑	-0.03	-0.037	↓
February	2.7**	0.09	↑	1.41	0.03	↑	-0.49	-0.167	↓
March	1.6	0.06	↑	0.52	0.01	↑	-0.29	-0.155	↓
April	1.4	0.03	↑	-0.06	-0.001	↓	0.88	0.244	↑
May	-1.7+	-0.04	↓	-1.40	-0.03	↓	1.91	0.510	↑
June	-0.2	-0.01	↓	-1.33	-0.018	↓	1.27	0.575	↑
July	0.1	0.00	↑	0.87	0.006	↑	1.20	0.128	↑
August	2.2*	0.03	↑	1.57	0.017	↑	-0.75	-0.142	↓
September	2.2*	0.03	↑	1.06	0.025	↑	1.43	0.252	↑
October	1.5	0.02	↑	1.43	0.029	↑	0.68	0.253	↑
November	3.1**	0.06	↑	1.04	0.018	↑	0.75	0.180	↑
December	1.6	0.05	↑	-1.03	-0.015	↓	0.88	0.161	↑
Annual	2.5*	0.04	↑	0.55	0.004	↑	1.07	0.133	↑
Summer	-0.1	0.00	↓	-0.80	-0.012	↓	1.85	0.359	↑
Monsoon	0.9	0.01	↑	0.87	0.007	↑	1.27	0.178	↑
Post monsoon	2.5*	0.05	↑	0.24	0.003	↑	1.07	0.222	↑
Winter	3.1**	0.07	↑	1.39	0.015	↑	0.36	0.087	↑

distribution of heat waves, severe heat waves, cold waves and severe cold waves of the study area from the period 1984-2023 (Table 4). The total annual heat wave and severe heat wave were 669 and 161, with the corresponding standard deviation of 11.5 and 0.1, and the lowest coefficient of variation of 1.7% and 0.1% respectively and the monthly number of heat waves and severe heat waves were highest during February (110, 46 events respectively), with a CV of 2.8% and 6%. The total number of heat waves and severe heat waves was high during the winter season (266 events) and summer season (61 events). Similar results were obtained by Singh et al. (2020),who noticed a change in the incidence of HW events, with an increasing trend in three heat-wave-prone regions: northwestern, central, and south-central India, with West Madhya Pradesh having the highest rate (0.80 occurrences per year). This growing trend in HW and SHW incidents might represent a serious threat to human health and crop production, disproportionately affecting the most vulnerable segments of society.

The total annual cold wave and severe cold wave were 260 and 37, with the corresponding standard deviation of 11.9 and 3.0, and had a coefficient of variation of 4.6% and 8.2% respectively (Table 4). The number of cold waves and severe cold waves was highest during March (33 events) and August (12 events). The cold waves and severe cold waves were also high, especially in the summer season (95 events) and monsoon season (22 events), respectively. The shifting pattern of severe temperature occurrences suggests that conventional seasonal boundaries are becoming blurred as a result of climate change and atmospheric instability. Rising climate unpredictability poses a hazard to agriculture by altering crop cycles and increasing ecosystem and community vulnerability.

Table 4: Descriptive statistics of heat waves, severe heat waves, cold waves, and severe cold waves from 1984 to 2023

	Heat waves			Severe heat waves			Cold waves			Severe cold waves		
	Total	SD	CV (%)	Total	SD	CV (%)	Total	SD	CV (%)	Total	SD	CV (%)
January	106	3.0	2.8	27	0.0	0.0	16	1.0	6.1	0	0.0	0.0
February	110	3.5	3.1	46	2.7	6.0	26	1.5	5.9	1	0.2	15.8
March	105	3.2	3.1	36	2.7	7.6	33	1.8	5.5	7	0.5	7.8
April	94	4.3	4.5	12	1.1	8.9	31	1.4	4.5	1	0.2	15.8
May	53	2.1	3.9	13	0.9	6.6	31	1.2	3.9	6	0.6	9.7
June	87	3.2	3.6	15	0.9	6.0	23	1.0	4.4	4	0.4	9.5
July	26	1.6	6.1	1	0.2	15.8	17	2.0	11.7	1	0.2	15.8
August	11	1.2	10.5	0	0.0	0.0	12	1.9	15.8	12	1.9	15.8
September	5	0.6	11.3	0	0.0	0.0	30	2.6	8.8	5	0.8	15.8
October	12	1.0	8.1	0	0.0	0.0	17	2.2	13.0	0	0.0	0.0
November	10	0.8	7.8	0	0.0	0.0	17	2.1	12.3	0	0.0	0.0
December	50	2.0	4.0	11	0.8	6.8	7	0.5	7.2	0	0.0	0.0
Annual	669	11.5	1.7	161	0.1	0.1	260	11.9	4.6	37	3.0	8.2
Summer	252	7.8	3.1	61	3.6	5.9	95	2.7	2.9	14	0.8	5.7
Monsoon	129	4.4	3.4	16	0.9	5.8	82	7.0	8.6	22	3.0	13.7
Post monsoon	22	1.2	5.3	0	0.0	0.0	34	4.3	12.6	0	0.0	0.0
Winter	266	5.4	2.0	27	0.0	0.0	49	1.8	3.8	1	0.2	15.8

3.3. Trend in heat waves, severe heat waves, cold waves, and severe cold waves:

The Mann-Kendall test and Sen's slope estimator were applied to the time series data from 1984 to 2023 for different weather parameters (Table 2). The annual heat waves showed a non-significant increasing trend (1.11 HWyear^{-1}) while there was no trend observed in severe heat waves. The HW indicated a decreasing trend in February, May, August, October and December, while an increasing trend was observed in March, January, April, June, September, and November. Similarly, in severe heat waves, there was an increasing trend observed in January, March, April, and June. The seasonal trend also indicates an increasing trend of HW in the summer and monsoon season. This analysis indicates a clear warning signal and increasing climate variability in the study area.

The annual cold waves showed a decreasing trend (-2.86 CW year^{-1}), while there was no trend observed in severe cold waves. Also, there was an increasing trend observed during January and a decreasing trend in March, April, May, June, and no trend during the remaining months, while severe cold waves showed a decreasing trend in May and no trend was observed during the remaining months (Table 2). Rising heat waves and declining cold waves due to climate change and rapid urbanization are causing significant crop stress, reduced yields, and increased water and pest pressure in agricultural systems. The present study similarly observed decreasing tendencies in cold nights and increasing trends in warm nights, indicating a clear shift toward warmer minimum temperatures. These patterns align with earlier findings by Klein Tank et al. (2006), New et al. (2006), and You et al. (2011), who also reported a consistent rise in warm nights and a decline in cold nights across various regions of Asia. More recent studies reinforce this trajectory: for example, Perkins-Kirkpatrick and Lewis (2020) documented intensified heat wave characteristics globally, while Li et al. (2021) showed a substantial reduction in cold extremes in South and East Asia due to anthropogenic warming (Table 5).

Table 5: Monthly, seasonal, and annual trend analysis of heat wave, severe heat wave, cold wave and severe cold wave from 1983-2023

Months and seasons	Heat waves (statistics)			Severe heat waves(statistics)			Cold waves (statistics)			Severe cold waves (statistics)		
Time series	Z	Q	Trend	Z	Q	Trend	Z	Q	Trend	Z	Q	Trend
January	0.07	0.000	↑	1.40	0.061	↑		0.037	↑			
February	-0.51	0.000	↓	-0.29	0.000		0.00	0.000				
March	2.21*	0.071	↑		0.056	↑	-0.47	0.000			0.000	
April	0.36	0.000	↑		0.119	↑	-0.74	0.000				
May	-1.05	-0.047	↓		0.000		-1.42	0.000			-0.333	↓
June	0.92	0.065	↑		0.029	↑	-1.08	0.000			0.000	
July	0.00	0.000						-1.000	↓			
August	0.00	-0.255	↓									
September	0.00	0.030	↑					-0.154	↓			
October	0.00	-0.030	↓					0.000				
November	0.00+	0.155	↑					0.000				
December	-0.76	-0.030	↓					-0.027	↓			
Average	1.11	0.167	↑				-2.86**	-0.151	↓			
Summer	0.44	0.010	↑				-3.02**	-0.013	↓			
Monsoon	0.61	0.032	↑				-2.90**	-0.125	↓			
Post monsoon	0.23	0.000					-1.63	-0.069	↓			
Winter	0.47	0.000										

3.4. Monthly and seasonal highest number of heat waves, severe heat waves, cold waves and severe cold waves

The monthly, seasonal, and annual highest number extremes heat waves, severe heat waves, cold waves and severe cold waves were calculated for the study area from 1984-2023 (Table 6). The highest number of heat wave and severe heat was recorded in April (16 HW in 1999) and March (12 SHW in 2004 and 2022) respectively and the lowest in September (3 HW in 2020) and July (1 SHW in 1987) and no severe heat wave were observed during August, September, October and November whereas, highest number of cold wave and severe cold wave was observed during September (15 CW in 1985) and August (12 SCW in 1985) and lowest during December (2 CW in 1985) and February, April, July (16 SCW in 1985, 2011 and 2013). The highest number of annual heat waves, severe heat waves, cold waves and severe cold waves(1984-2023) were 49 (2004), 20 (2006), 75 (1985) and 19 (1985), respectively. This reflects early-season extreme heat events; in contrast, cold extremes were more prominent in earlier years, and recent decades have seen a shift toward more frequent and intense heat extremes, indicating changing climate patterns in the region.

The analysis of extreme temperature events-specifically heat waves and cold waves-during the critical phenological

Table 6: Number of heat waves, severe heat waves, cold waves, and severe cold waves from 1983 to 2023

Months/ seasons	Highest no. of heat waves	Highest no. of severe heat waves	Highest no. of coldwaves	Highest no. of severe cold waves
January	10 (2003)	4 (2001, 2004)	4.0 (2008)	-
February	12 (1999)	15 (2006)	8.0 (2011)	1 (2011)
March	14 (2021)	12 (2004, 2022)	10.0 (1988)	3 (1988)
April	16 (1999)	6 (2022)	7.0 (1995)	1 (2013)
May	8 (1999)	4 (1988)	4.0 (1987)	3 (1989)
June	13 (1995)	4 (2005)	4.0 (1985)	2 (1995)
July	7 (1991)	1 (1987)	12.0 (1985)	1 (1985)
August	7 (1986)	-	12.0 (1985)	12 (1985)
September	3 (2020)	-	15.0 (1985)	5 (1985)
October	5 (1987)	-	14.0 (1985)	-
November	4 (2016)	-	13.0 (1985)	-
December	6 (1998)	4 (2007)	2.0 (1985)	-
Annual	49 (2004)	20 (2006)	75.0 (1985)	19 (1985)
Summer	29 (1999, 2004)	18 (2022)	12.0 (1988)	3 (1988, 1999)
Monsoon	19 (1986)	4 (2005)	43.0 (1985)	19 (1985)
Post monsoon	5 (1987)	-	27.0 (1985)	-
Winter	21 (2006)	-	8.0 (2011)	1 (2011)

stages of tomato and capsicum crops revealed a negative correlation between temperature extremes and crop yield. For tomato, which undergoes its vegetative growth and fruit development stages during June and July, data from 1996 to 2021 showed that even low-intensity heat wave events significantly impacted yield. For instance, in 2020, when there were no heat waves and the yield was 500 qha^{-1}, whereas in 2021, with 5 heat wave days, the yield dropped slightly to 495 qha^{-1}. Similarly, in 1996, the absence of cold waves corresponded with a yield of 337.2 qha^{-1}, while a single cold wave in 1997 reduced yield to 323.9 qha^{-1}. Similar results were obtained by Steven et al. 2001 in who observed that Tomato was sensitive to high as well as low temperatures in their maturation stage and growth rate. There was a tendency at both high and low temperature regimes, which, combined with low flower numbers and poor fruit set, resulted in low fruit yields. Temperature also affected the shoot dry matter content and partitioning.

In the case of capsicum, which shares similar critical stages during June and July, revealed that rising heat wave events also negatively affected yield. In 2004, with 4 heat wave days, the yield was 90 qha^{-1}, whereas in 2005, with 7 heat wave days, the yield dropped to 78 qha^{-1}. Conversely, in 2020, with no heat wave days, the yield peaked at 268.9 qha^{-1} and in 2021, with 5 heat wave days, the yield dropped slightly to 258.5 qha^{-1}. Moreover, cold wave events during winter and early growing periods of capsicum also demonstrated a yield-reducing effect, as seen in 2019, where the absence of cold waves resulted in a yield of 301.7 qha^{-1}, whereas in 2020, with 2 cold waves, the yield sharply declined to 268.9 qha^{-1}. These patterns underscore the sensitivity of both crops to thermal extremes, which can disrupt physiological processes such as photosynthesis, pollen viability, nutrient uptake and fruit development. The findings highlight the urgent need for climate-resilient cultivars and adaptive agronomic strategies to sustain vegetable productivity under increasing climate variability. This decline can be attributed to the adverse effects of low temperatures on yield, nutrient uptake and overall plant metabolism, which ultimately limit plant vigor and fruit development. Similar results were obtained by Saha et al. (2010) at the Asian Vegetable Research and Development Centre (AVRDC), Taiwan,whofound that high temperature reducesthe fruit set as well as the size of fruits, and also performed poorlyin respect of per plant yield at higher temperature compared to the lower temperature in capsicum.

3.5. Decadal variation: Trend and variability in temperature extremes over the decades

The variability analysis of temperature extremes on a decadal basis is shown in Tables 7, 8, 9, and 10. The annual heat wave, severe heat wave, cold wave and severe cold wave in the study area were 669, 161, 260 and 37, with corresponding standard deviations of 11.5, 0.1, 11.9 and 3.0, respectively.

Table 7: Descriptive decadal statistics of heat waves from 1984-2023

	1984–1993				1994–2003			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	14	2.5	17.9	-1.3	28	3.4	12.2	0.2
February	15	2.6	17.3	-1.3	30	4.3	14.5	0.3
March	13	2.1	16.2	-1.3	12	1.5	12.3	-1.4
April	9	1.7	19.2	-1.5	27	4.9	18.0	0.4
May	14	2.0	14.0	0.1	17	2.6	15.2	0.4
June	20	2.7	13.7	-0.2	24	4.0	16.8	0.2
July	14	2.5	17.6	0.8	2	0.6	31.6	-0.5
August	8	2.2	27.5	0.5	0	0.0	0.0	-0.3
September	2	0.6	31.6	0.1	0	0.0	0.0	-0.1
October	5	1.6	31.6	0.2	1	0.3	31.6	-0.2
November	0	0.0	0.0	-0.3	2	0.4	21.1	-0.1
December	6	1.9	31.6	-0.7	11	2.0	17.9	-0.2
Annual	120	1.9	19.9	-0.4	154	11.4	74.2	-0.1
Summer	36	3.6	9.9	-2.7	56	8.6	15.3	-0.7
Monsoon	44	6.3	14.4	1.2	26	4.0	15.4	-0.6
Post monsoon	5	1.6	31.6	-0.1	3	0.5	16.1	-0.3
Winter	35	3.2	9.2	-3.2	69	5.0	7.3	0.3

Table 7: Continue...

	2004–2013				2014–2023			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	39	3.5	9.0	1.3	25	2.4	9.5	-0.2
February	41	3.7	9.0	1.4	24	3.0	12.3	-0.4
March	44	3.1	7.0	1.8	36	4.5	12.4	1.0
April	30	5.4	17.8	0.7	28	4.5	16.0	0.5
May	16	2.2	13.9	0.3	6	1.6	26.3	-0.7
June	23	3.2	13.8	0.1	20	3.1	15.3	-0.2
July	6	1.3	22.5	-0.1	4	1.3	31.6	-0.3
August	3	0.7	22.5	0	0	0.0	0.0	-0.3
September	0	0.0	0.0	-0.1	3	0.9	31.6	0.2
October	0	0.0	0.0	-0.3	6	1.1	17.9	0.3
November	4	0.8	21.1	0.2	4	1.3	31.6	0.2
December	16	2.2	13.9	0.4	17	2.0	11.8	0.5
Annual	222	13.2	59.6	0.5	173	11.5	66.2	0.0
Summer	90	9.2	10.2	2.7	70	8.8	12.6	0.7
Monsoon	32	3.8	11.9	0.0	27	3.1	11.3	-0.5
Post monsoon	4	0.8	21.1	-0.2	10	1.5	14.9	0.5
Winter	96	7.2	7.5	3.0	66	4.2	6.3	-0.1

Table 8: Descriptive decadal statistics of severe heat wave from 1984–2023

	1984–1993				1994–2003			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	2	0.4	21.1	-0.5	4	1.3	31.6	-0.3
February	6	1.3	22.5	-0.6	3	0.7	22.5	-0.9
March	1	0.3	31.6	-0.8	0	0.0	0.0	-0.9
April	1	0.3	31.6	-0.2	0	0.0	0.0	-0.3
May	6	1.3	21.1	0.3	6	1.1	17.9	0.3
June	3	0.5	16.1	-0.1	2	0.6	31.6	-0.2
July	1	0.3	31.6	0.1	0	0.0	0.0	0.0
August	0	0.0	0.0	0.0	0	0.0	0.0	0.0
September	0	0.0	0.0	0.0	0	0.0	0.0	0.0
October	0	0.0	0.0	0.0	0	0.0	0.0	0.0
November	0	0.0	0.0	0.0	0	0.0	0.0	0.0
December	0	0.0	0.0	-0.3	2	0.4	21.1	-0.1
Annual	20	2.2	10.8	1.3	17	1.9	11.5	1.0
Summer	8	1.5	19.4	-0.7	6	1.1	17.9	-0.9
Monsoon	4	0.7	17.5	0.0	2	0.6	31.6	-0.2
Post monsoon	0	0.0	0.0	0.0	0	0.0	0.0	0.0
Winter	8	1.3	16.5	0.1	9	1.7	19.2	0.2

Table 8: Continue...

	2004–2013				2014–2023			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	14	1.5	10.8	0.7	6	1.3	21.1	-0.1
February	20	4.7	23.7	0.9	17	2.4	13.9	0.6
March	19	3.8	20.2	1.0	16	3.8	23.6	0.7
April	4	1.0	24.2	0.1	7	1.9	27.0	0.4
May	1	0.3	31.6	-0.2	0	0.0	0.0	-0.3
June	8	1.5	18.4	0.4	2	0.6	31.6	-0.2
July	0	0.0	0.0	0.0	0	0.0	0.0	0.0
August	0	0.0	0.0	0.0	0	0.0	0.0	0.0
September	0	0.0	0.0	0.0	0	0.0	0.0	0.0
October	0	0.0	0.0	0.0	0	0.0	0.0	0.0
November	0	0.0	0.0	0.0	0	0.0	0.0	0.0
December	7	1.3	19.1	0.4	2	0.4	21.1	-0.1
Annual	73	7.1	9.7	6.6	50	6.4	12.7	4.3
Summer	24	4.4	18.1	0.9	23	5.6	24.3	0.8
Monsoon	8	1.5	18.4	0.4	2	0.6	31.6	-0.2
Post monsoon	0	0.0	0.0	0.0	0	0.0	0.0	0.0
Winter	41	6.2	15.1	3.4	25	3.5	14.0	1.8

Table 9: Descriptive decadal statistics of cold wave from 1984-2023

	1984–1993				1994–2003			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	1	0.3	31.6	-0.3	0	0.0	0.0	-0.4
February	9	1.5	16.9	0.3	4	1.0	24.2	-0.3
March	21	3.2	15.1	1.3	5	0.7	14.1	-0.3
April	11	1.4	12.5	0.3	14	2.2	15.5	0.6
May	10	1.4	14.1	0.2	10	1.5	14.9	0.2
June	11	1.4	13.2	0.5	5	1.0	19.4	-0.1
July	17	3.8	22.5	1.3	0	0.0	0.0	-0.4
August	12	3.8	31.6	0.9	0	0.0	0.0	-0.3
September	26	4.9	18.9	1.9	1	0.3	31.6	-0.7
October	16	4.4	27.4	1.2	0	0.0	0.0	-0.4
November	17	4.1	23.9	1.3	0	0.0	0.0	-0.4
December	2	0.6	31.6	0.0	2	0.6	31.6	0.0
Annual	153	21.9	14.3	0.7	41.0	2.5	6.0	-0.2
Summer	42	3.9	9.2	1.8	29.0	2.6	9.1	0.5
Monsoon	66	13.4	20.3	4.6	6.0	1.0	16.1	-1.5
Post monsoon	33	8.4	25.4	2.5	0.0	0.0	0.0	-0.9
Winter	12	1.6	13.5	0.0	6.0	1.1	17.9	-0.6

Table 9: Continue...

	2004–2013				2014–2023			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	8	1.4	17.5	0.4	7	1.3	17.9	0.3
February	11	2.5	22.9	0.5	2	0.4	21.1	-0.5
March	5	1.0	19.4	-0.3	2	0.4	21.1	-0.6
April	4	0.7	17.5	-0.4	2	0.6	31.6	-0.6
May	6	1.1	17.9	-0.2	5	0.8	17.0	-0.3
June	3	0.7	22.5	-0.3	4	0.7	17.5	-0.2
July	0	0.0	0.0	-0.4	0	0.0	0.0	-0.4
August	0	0.0	0.0	-0.3	0	0.0	0.0	-0.3
September	3	0.9	31.6	-0.5	0	0.0	0.0	-0.8
October	1	0.3	31.6	-0.3	0	0.0	0.0	-0.4
November	0	0.0	0.0	-0.4	0	0.0	0.0	-0.4
December	1	0.3	31.6	-0.1	2	0.4	21.1	0.0
Annual	42.0	2.9	6.8	-0.2	24.0	1.8	7.7	-0.3
Summer	15.0	1.4	9.0	-0.9	9.0	1.3	14.3	-1.5
Monsoon	6.0	1.3	22.5	-1.5	4.0	0.7	17.5	-1.7
Post monsoon	1.0	0.3	31.6	-0.8	0.0	0.0	0.0	-0.9
Winter	20.0	2.6	13.1	0.8	11.0	1.7	15.7	-0.1

Table 10: Descriptive decadal statistics of severe cold wave from 1984–2023

	1984–1993				1994–2003			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	0	0.0	0.0	0.0	0	0.0	0.0	0.0
February	0	0.0	0.0	0.0	0	0.0	0.0	0.0
March	5	1.0	19.4	0.3	1	0.3	31.6	-0.1
April	0	0.0	0.0	0.0	0	0.0	0.0	0.0
May	6	1.1	17.9	0.5	0	0.0	0.0	-0.2
June	1	0.3	31.6	0.0	3	0.7	22.5	0.2
July	1	0.3	31.6	0.1	0	0.0	0.0	0.0
August	12	3.8	31.6	0.9	0	0.0	0.0	-0.3
September	5	1.6	31.6	0.4	0	0.0	0.0	-0.1
October	0	0.0	0.0	0.0	0	0.0	0.0	0.0
November	0	0.0	0.0	0.0	0	0.0	0.0	0.0
December	0	0.0	0.0	0.0	0	0.0	0.0	0.0
Annual	30	5.8	19.2	2.1	4.0	0.7	17.5	-0.5
Summer	11	1.3	11.7	0.8	1.0	0.3	31.6	-0.3
Monsoon	19	6.0	31.6	1.4	3.0	0.7	22.5	-0.3
Post monsoon	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Winter	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 10: Continue...

	2004–2013				2014–2023			
	Total	SD	CV (%)	DEV	Total	SD	CV (%)	DEV
January	0	0.0	0.0	0.0	0	0	0	0.0
February	1	0.3	31.6	0.1	0	0	0	0.0
March	0	0.0	0.0	-0.2	1	0.3	31.6	-0.1
April	1	0.3	31.6	0.1	0	0	0	0.0
May	0	0.0	0.0	-0.2	0	0	0	-0.2
June	0	0.0	0.0	-0.1	0	0	0	-0.1
July	0	0.0	0.0	0.0	0	0	0	0.0
August	0	0.0	0.0	-0.3	0	0	0	-0.3
September	0	0.0	0.0	-0.1	0	0	0	-0.1
October	0	0.0	0.0	0.0	0	0	0	0.0
November	0	0.0	0.0	0.0	0	0	0	0.0
December	0	0.0	0.0	0.0	0	0	0	0.0
Annual	2.0	0.4	21.1	-0.7	1	0.3	31.6	-0.8
Summer	1.0	0.3	31.6	-0.3	1	0.3	31.6	-0.3
Monsoon	0.0	0.0	0.0	-0.6	0	0	0	-0.6
Post monsoon	0.0	0.0	0.0	0.0	0	0	0	0.0
Winter	1.0	0.3	31.6	0.1	0	0	0	0.0

On a decadal basis, the total annual heat wave was recorded as 120 (1984–1993), 154 (1994–2003), 222 (2004–2013), and 173 (2014–2023). Similarly, the total annual cold wave was 11.3°C (1984–1993), 11.5°C (1994–2003), 11.3°C (2004–2013) and 11.5°C (2014–2023). The average number of HW events shows a steady increase over the decades, with a positive slope (y=1.135x+12.18) and R^2=0.473, including a warming climate. Similarly, SHWs display a gradual increase (y=0.73x+1.08) with an R^2=0.503, peaking in the most recent decades. In contrast, cold waves exhibit a significant declining trend, with the highest frequency recorded during 1984–1993 and a sharp reduction in subsequent decades. The trend line (y=−1.93x+14.22) and R^2=0.707 suggest a substantial decrease in CW events, consistent with rising temperatures where as Severe cold waves, which are the least frequent, also show a declining trend (y=−0.445x+2.705) with an R^2=0.684, becoming almost negligible in the last decade (2014–2023). The strong correlations underscore increasing vulnerabilities to heat-related extreme weather events, aligning with global patterns of climate change.

According to the results the highest number of heat wave and severe heat wave was observed in March (44 heat wave event) and February (20 severe heat wave events) during 2004-2013, On the other hand the highest number cold wave and severe cold wave was observed in September (26 heat wave event) and August (12 severe heat wave events) during 1984-1993. These values indicate that the heat wave deviation ranged between −1.5 and +1.8, severe heat wave deviation ranged from −0.9 to +1.0,whereas cold wave deviation ranged between -0.8 and +1.9, while severe cold wave deviation ranged between -0.3 and 0.9 over the observed period. It was generally observed that there were decreasing trends in the cold nights compared to increasing trends in the warm nights. These results agreed with the works of (Klein Tank et al., 2006; New et al., 2006; You et al., 2011)

3.6. Heat index trends

Heat Index is a measure that combines air temperature and relative humidity to determine the "apparent temperature" or how hot it actually feels to the human body. Heat Index was calculated on the basis of months from 2004 to 2023, and it was showing a gradual increase over time for January, February, August, September, October, and December with notable year-to-year fluctuations, suggesting a warming tendency. The variability of heat wave was explained by 7.2%, 1%, 14%, 1%, 3.2% and 1.2% where as it was showing a decreasing trend for March, April, May, June, July, November and variability was explained by 5%, 0.9%, 32.6%, 0.2%, 6.9%, 9.8% indicates a seasonal shift in perceived temperature patterns over the period 2004 to 2023 (Figure 2). There is a gradual increase in heat index,suggestinga warming trend even during non-peak summer periods, pointing to less thermal relief throughout the year. Fluctuations in humidity levels reflect possible short-term climatic variability, or adaptive land–atmosphere interactions that temporarily moderated apparent temperature, despite actual warming. This indicates greater year-to-year instability, which could influence heat stress unpredictably. Overall, the findings suggest a shifting

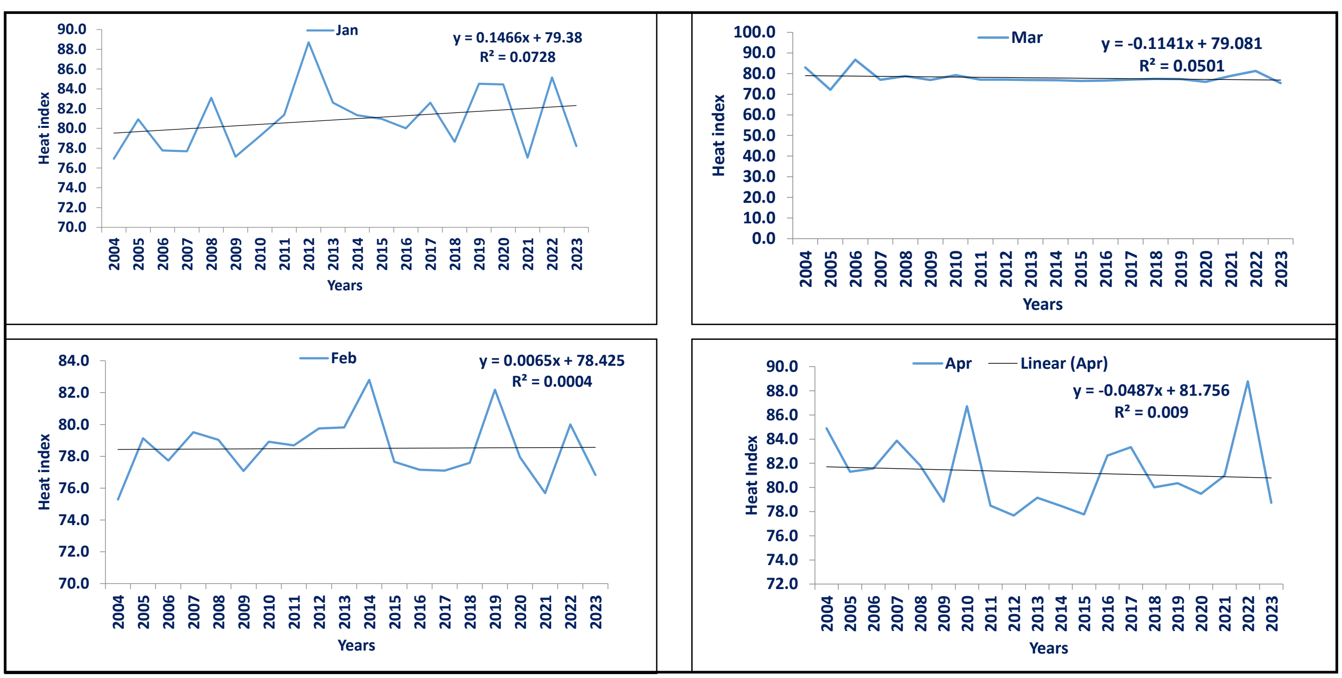

Figure 2: Continue...

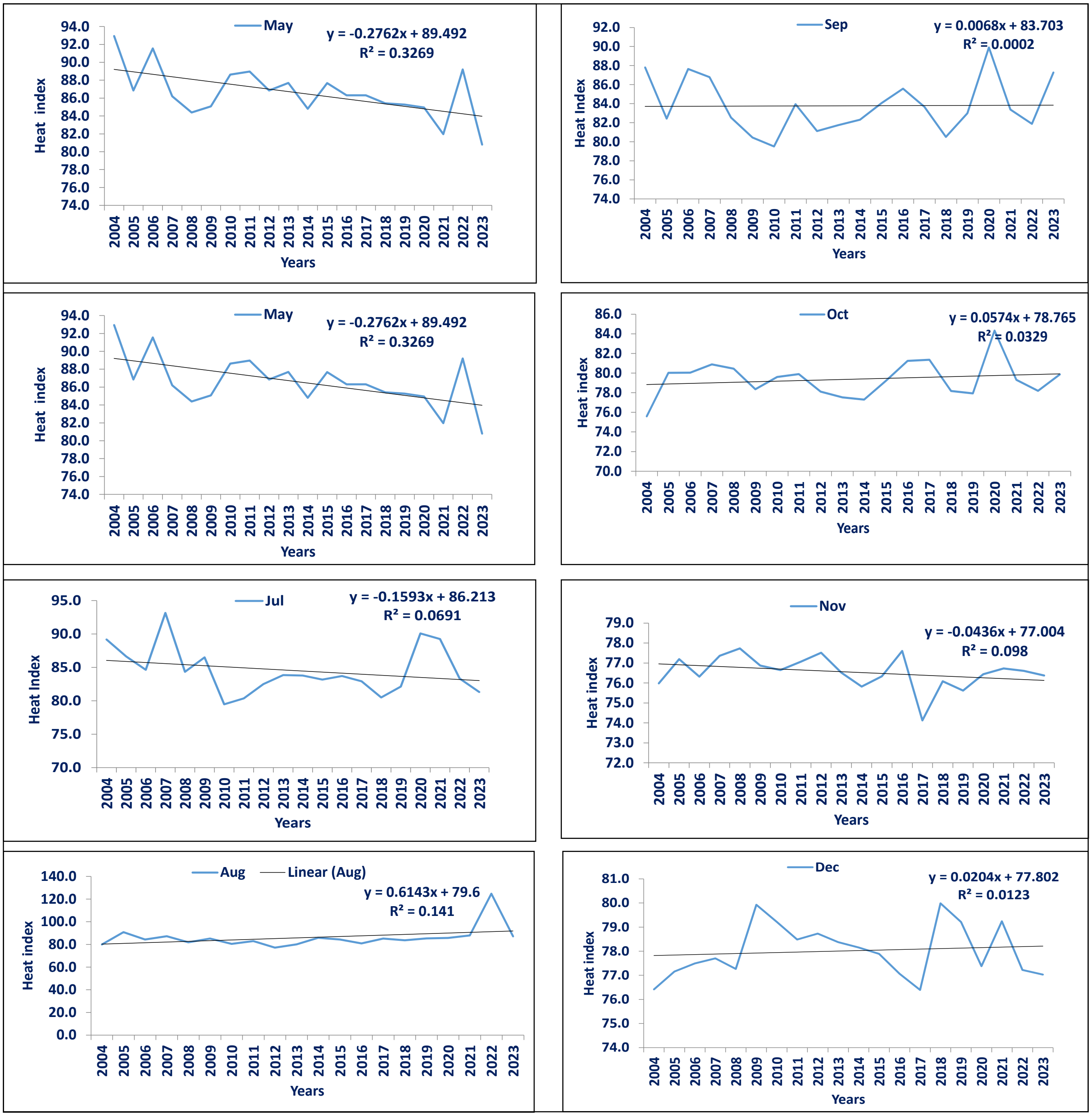

Figure 2: Trend of heat index from 2004-2023

heat stress profile, where apparent temperatures are rising in more months, possibly extending the duration of discomfort beyond the typical summer season, in line with changing climate dynamics. The IMD uses the heat index to issue heat wave warnings and assess potential impacts on human health, especially during summer months. Similar results were obtained by Alvarez et al. (2024) at the Mediterranean basin and found a positive trend of the increasing HI that indicates a clear warming at a rate of 0.43°C per decade, and agricultural production in the region is mainly based on wheat, olive, and tomato crops. Increased HI significantly influences the production of these crops, resulting in reduced crop yields (Cramer et al., 2018).

4. CONCLUSION

The study assessed temperature extremes in Solan, Himachal Pradesh, and revealed a clear rise in heat waves alongside a marked decline in cold waves. Mann–

Kendall and Sen's slope analyses indicated increasing heat wave frequency during summer and monsoon, while cold waves showed significant reductions across seasons. These shifts were associated with regional warming and growing urbanization, which intensified heat stress, reduced crop yields, and increased water and pest pressures. The findings underscored the need for climate-resilient cultivars and adaptive agronomic practices to sustain productivity.

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