Research paper

Climatological understanding of heat and cold wave variability in Eastern Uttar Pradesh

R. BHATLA[1,2*], HARI SHANKAR PATEL[1], RICHA SINGH[1], RISHABH SHARMA[3], and B. MANDAL[1]

[1]Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India.
[2]DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India.
[3]Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India.
*Corresponding Author Email- rbhatla@bhu.ac.in

ABSTRACT

This study examines the trends and impacts of heat waves (HWs) and cold waves (CWs) in Eastern Uttar Pradesh, India, from 1961 to 2020, utilizing gridded daily maximum and minimum temperature data from the Indian Meteorological Department. This study analyzes the decadal totals of days, maximum continuous duration days, and mean maximum and minimum temperatures of HWs and CWs across nine meteorological stations. The findings reveal a significant increase in HW occurrences, particularly in stations like Fatehpur and Varanasi, while a decline in CW events is noted across the region. The Excess Heat Factor (EHF) index indicates a rising trend in heat stress events, and this study suggests that the intensity of HWs is increasing due to changes in temperature variability rather than mean warming alone. The findings are based on descriptive climatological analysis of observed heat and cold wave patterns.

Keywords: Heat wave, Cold wave, Eastern Uttar Pradesh, Excess heat factor, Kernel Density Estimation (KDE)

Global and localized changes in intensity and frequency of extreme weather events have a significant impact on both humans and their environment (Shi *et al.,* 2015). Extreme weather conditions have been extensively studied and show substantial financial losses (Bouwer, 2018). Among extreme events, heat waves (HWs) and cold waves (CWs) are the most prevalent temperature extremes, and they have a significant impact on agriculture, human health, and industrial production (Ray *et al.,* 2021). Both phenomena have undergone important studies over different regions in recent decades, due to their harmful socio-economic impacts. A study showed that from 1970 to 2019, India had 0.4 fewer cold waves per decade and 0.6 more heat waves per decade (Bhattacharya *et al*., 2023). In southern and coastal India, a decline in cold nights and a rise in warm days, notably indicating a clear warming trend have been reported by Dash & Mamgain, (2011). Temperatures increase in March, often reaching over 40°C by April, with steep rises to over 45°C by the end of May and early June, especially in the southwest UP (Chand & Ray, 2014). Long-term IMD station data (1961-2010) observed a sharp rise in HW and severe HW days over a wide region of northern, northwestern, and central India. The decade 2001-2010 had the highest frequency of HW, especially during El Niño years (Mahdi *et al.,* 2020). The Indian Ocean warming and repeated El Niño episodes are also very important factors that potentially impacted (Rohini *et al.,* 2016). SHWs are linked to the 1998 El Niño event in a study, which is one of the strongest of the 20th century (Mohamed *et al.* 2023).

Cold waves (CWs) in India are marked by an unusual drop in temperature, which is usually caused by dry, cold winds from the north (Ratnam *et al*., 2016). Those waves are dangerous to crops, human health, and agricultural productivity, and usually come between November and February. Severe cold waves (SCWs) and CWs are common over the Indo Gangetic Plain (IGP), particularly in January and December (Bhatla *et al*., 2020a). Researches indicate that on average, the number of CWs in India is on the decline (Dash & Mamgain, 2011; Mahdi *et al.,* 2020). Nonetheless, there has been an increase in CW/SCW occurrences in some areas, including Bihar, Jharkhand, and Odisha (Singh *et al.,* 2025). ENSO plays a crucial

Table 1: Coordinates of nine meteorological stations

Station	Latitude (°N)	Longitude (°E)
Bahraich	27.57	81.58
Ballia	25.76	84.15
Fatehpur	25.92	80.82
Fursatganj	26.35	82.20
Gorakhpur	26.75	83.37
Mau	25.95	83.56
Prayagraj	25.43	81.84
Sant Kabir Nagar	26.77	82.83
Varanasi	25.31	82.97

role in which CWs with extremely low temperatures in northwest India are frequently linked to the warming phase (El Niño), whereas CWs across the majority of India are linked to the cooling phase (La Niña) (Bhatla *et al.,* 2020b; Ratnam *et al.,* 2016). A steady increase in minimum temperatures (~0.027 °C/decade since the 1980s), particularly in northwestern India, coincided with a decrease in CW days (- 0.29 days/decade) and SCW days (-0.02 days/decade) in India between 1951 and 2021 (Singh *et al.,* 2025).

Heat waves (HWs) and cold waves (CWs) have posed significant challenges to human health, agriculture, and economic stability, especially in regions like Eastern Uttar Pradesh (EUP). Climate change has been linked to an increase in the frequency and intensity of HWs. However, CWs are less frequent but can be more severe. These changes threaten food security and public health that highlighting the urgent need for a comprehensive analysis and understanding of these phenomena. The purpose of this analysis is to investigate the long-term trends of HWs and CWs in Eastern Uttar Pradesh to assess changes in the frequency, duration, and intensity of these extreme weather events, which is crucial for public health preparedness and improving agricultural resilience in the face of ongoing climate variability.

MATERIAL AND METHODS

Uttar Pradesh is one of the most populous and fourth-largest states of India and is located in the Indo-Gangetic plain, with the Himalayas in the north, the Chota Nagpur Plateau and the Vindhya Mountain range in the south, and the Ganga River flowing through it. The summers are very hot, and the winters are bitterly cold (Chand & Ray, 2014). The eastern Uttar Pradesh (EUP) comprises 18 districts. The present study focuses on nine meteorological stations of EUP, namely Bahraich, Ballia, Fatehpur, Fursatganj, Gorakhpur, Mau, Prayagraj, Sant Kabir Nagar, and Varanasi (Table 1).

The gridded daily maximum (T_{max}) and minimum (T_{min}) temperature data of IMD at a special resolution of 1º×1º were used over 9 stations of EUP from 1961 to 2020. For the sake of accuracy of the data, nine regions have been considered in this study because gridded datasets provide relatively higher accuracy in areas closer to meteorological stations, as the interpolation relies directly on observed measurements. In this study for cold waves, colder months (November to March) and heat waves, the warmer months (April to July) have been considered.

Heat wave (HW) and cold wave (CW)

Based on IMD criteria (Table 2), the long-term climatology and long-term trends of HW and CW waves over Eastern Uttar Pradesh are examined. Daily maximum temperatures were used to analyze HW occurrences, while daily minimum temperatures were utilized for CW occurrences. The IMD's criteria are particularly relevant for India, where regional climatic conditions significantly influence the occurrence and impact of extreme temperature events.

Excess heat factor (EHF)

The excess heat factor (EHF) is based on two excessive heat indices namely. Significant excess heat index (EHI_sig) and acclimatization excess heat index (EHI_accl). The daily mean temperature (Tmean), is used as the basis for both components. 95th-percentile climatology is calculated for each day of the month. Heatwave days were identified when EHF was positive, and the climatological Tmax exceeded 35°C. A heatwave event was defined as a minimum of three consecutive heatwave days (Rohini *et al.,* 2016; Narkhede *et al.,* 2022).

The excess heat factor (EHF) was computed using the equation

$$EHF = EHI_{sig} \times \max(1, EHI_{Accl})$$

Where, EHI_{Accl} is acclimatization excess heat index and EHI_{Sig} is

Table 2: IMD standards for heat/cold wave for operational purposes (Rajeevan *et al.,* 2023)

S. No.	Heat wave conditions		Cold wave conditions	
1.	Heat wave condition is considered when maximum temperature (Tmax) of a station in the plains reaches at least 40°C; in hilly region it's 30°C		The actual minimum temperature (Tmin) of station should be reduced to wind chill effective minimum temperature (WCTn); cold wave condition is WCTn ≤ 10°C	
2.	Departure from normal, when normal Tmax of station is 40°C or less		Departure from normal, when normal Tmin of station is 10°C or more	
	Heat wave	Severe heat wave	Cold wave	Severe cold wave
	5 to 6 °C	≥7 °C	-5 to -6 °C	≥ -7 °C
3.	Departure from normal, when normal Tmax of station is 40°C or more		Departure from normal, when normal Tmin of station is 10°C or less	
	Heat wave	Severe heat wave	Cold wave	Severe cold wave
	4 to 5 °C	≥6 °C	-4 to -5 °C	≥ -6 °C
4.	When actual T_{max} remains ≥45°C, heat wave condition is declared irrespective of normal T_{max}		When WCTn is ≤0°C, cold wave condition is declared	

Table 3: Trends in maximum temperature (Tmax), excess heat factor (EHF), and heatwave in Eastern Uttar Pradesh

Stations	Maximum temp. (Tmax)		Excess heat factor (EHF)		Heat wave (HW)		Severe heat wave (SHW)	
	Mean (^{0}C)	Trend (^{0}C/ decade)	Mean	Trend	Mean (Days)	Trend (Day/decade)	Mean	Trend (Day/decade)
Bahraich	35.98	-0.075	1.73	+0.032	23	-0.55	0.33	+0.02
Ballia	35.53	+0.002	1.41	+0.037	19	+0.16	0	0
Fatehpur	37.31	0.017	1.2	+0.056	25	-1.80	0.50	-0.03
Fursatganj	36.45	-0.060	1.67	+0.058	24	-1.44	0.66	+0.04
Gorakhpur	35.65	-0.020	1.64	+0.029	20	-0.69	0	0
Mau	36.19	+0.008	1.5	+0.017	16	-0.71	0	0
Prayagraj	37.04	+0.016	1.41	+0.023	21	-1.83	0.83	+0.03
Sant Kabir Nagar	36.31	-0.010	1.64	+0.021	19	-1.12	0.33	+0.02
Varanasi	36.19	+0.008	1.525	+0.017	16	-1.12	0.33	-0.02

Table 4: Trends in minimum temperature (Tmin), and cold wave in Eastern Uttar Pradesh.

Stations	Minimum temperature (Tmin)		Cold wave (CW)		Severe cold wave (SCW)	
	Mean (^{0}C)	Trend (^{0}C/ decade)	Mean (Days)	Trend (Day/decade)	Mean	Trend (Day/decade)
Bahraich	11.57	+0.181	10	-0.45	0.8	0.00
Ballia	12.26	+0.110	6	-0.15	0.0	0.00
Fatehpur	11.63	+0.200	22	-0.73	0.8	-0.05
Fursatganj	11.75	+0.209	11	-0.50	0.8	0.00
Gorakhpur	12.02	+0.124	7	-0.24	0.0	0.00
Mau	12.05	+0.133	8	-0.25	0.0	0.00
Prayagraj	11.71	+0.168	16	-0.51	0.7	-0.04
Sant Kabir Nagar	11.78	+0.161	7	-0.28	0.3	0.00
Varanasi	12.05	+0.133	8	-0.25	0.0	0.00

significant excess heat index, given by

EHI_{Sig} = (3-day mean Tmean) − (95th percentile climatological Tmean)

EHI_{Accl} = (3-day mean Tmean) − (30-day mean Tmean)

and,

$$Tmean = \frac{(Tmax + Tmin)}{2}$$

Kernel density estimation (KDE)

This method employs a probabilistic framework to examine how variations in the mean and variance of the temperature distribution impact the frequency of extreme heat and cold events. The probability distributions of HW and CW are estimated using Gaussian kernel density estimation (KDE) to obtain smooth and continuous probability density functions (PDFs) that accurately represent extreme temperature behavior (Gawai *et al.*, 2024).

Kernel density estimation (KDE) is given by

$$f(T) = \frac{1}{nh} \sum_{l=1}^{n} k\left(\frac{T-Ti}{h}\right)$$

Where k is the Gaussian kernel, T is temperature

RESULTS AND DISCUSSION

Variability and trends in heatwave

Table 3 shows the long-term mean along with linear trends (per decade) for Tmax, EHF, heatwave (HW) days, and severe heatwave (SHW) days. Negative trends show a decrease in occurrences over all nine stations, whereas positive trends show an increase in intensity and frequency. The long-term analysis shows a continuous increase in heat stress conditions. Fatehpur and Prayagraj continue to be the hottest stations, with mean maximum temperatures (Tmax) from 35.5°C to 37.3°C. Tmax trends are generally low, with small cooling tendencies at certain sites, including Bahraich (−0.075°C/decade) and Fursatganj (−0.06°C/decade), and slight positive changes at others, up to +0.017°C each decade. On the other hand, despite slight variations in mean temperatures, the Excess Heat Factor (EHF), which measures the intensity of extended hot periods, shows a consistent upward trend at all stations, showing that multi-day heat stress events are intensifying. Most stations show an average decrease in heatwave (HW) days, with Prayagraj (−1.83 days/decade), Fatehpur (−1.8 days/decade), and Fursatganj (−1.44 days/decade) showing major decreases, while Baliya shows a small increase. A few stations show a little increase trend, while severe heatwave (SHW) events are still uncommon throughout the region, with mean values at zero. The results point to an increasing risk of long-term heat-related hazards in the area as while maximum
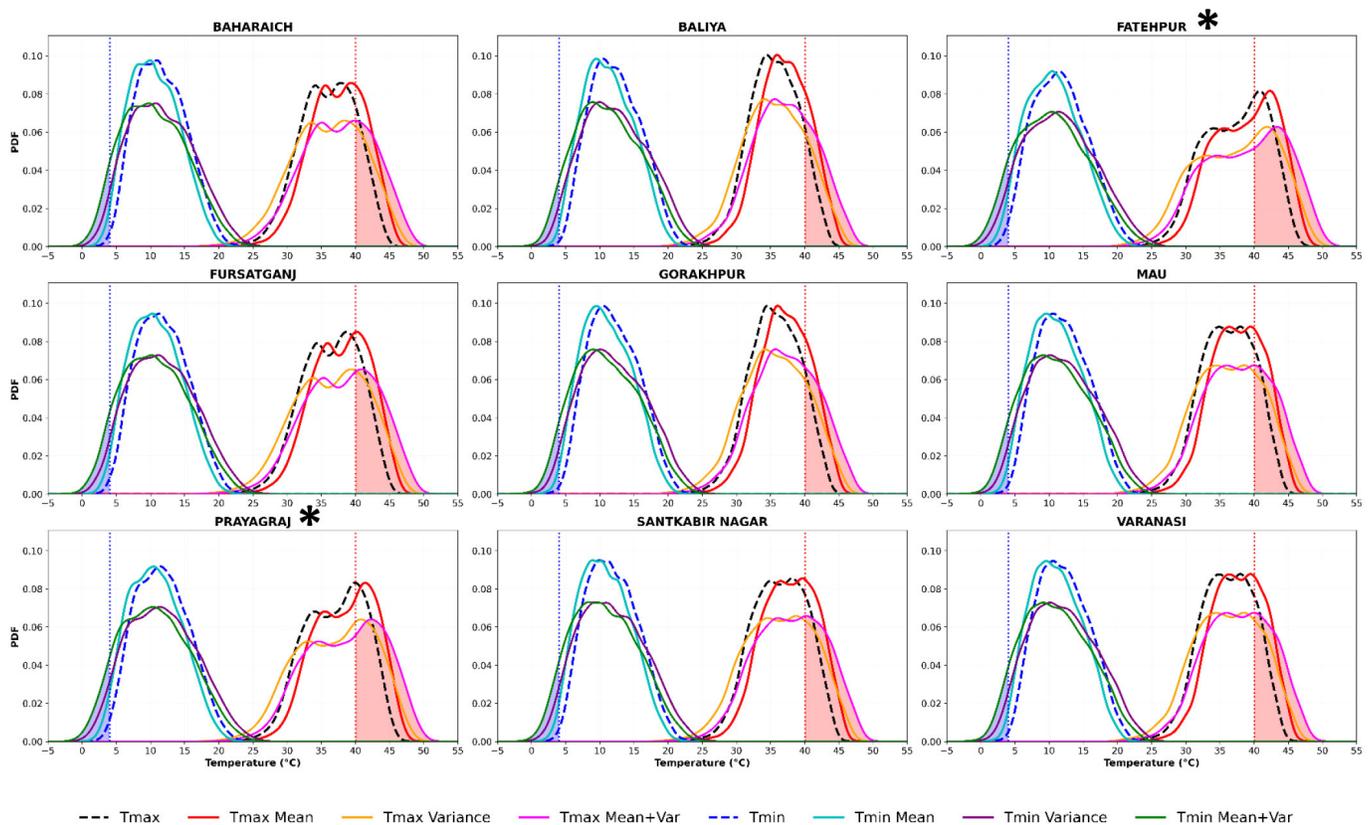
Fig. 1: The black and blue dashed curves show the observed PDFs of Tmax and Tmin, respectively. The red and cyan curves show mean-shifted warming and cooling scenarios. The orange and purple curves show variance-increased distributions, while the magenta and green curves show the combined mean-plus-variance shift. The shaded red area (Tmax ≥ 40 °C) shows the projected increase in the probability of extreme heat waves, and the shaded blue area (Tmin ≤ 4 °C) shows the increased probability of cold waves. Uniform global axis limits are used for consistent inter-station comparisons. Asterisk mark shows the stations with significant shift.

temperatures are not rising significantly, the severity and persistence of heat stress, as measured by EHF.

Variability and trends in cold wave

Table 4 shows that the mean minimum temperature (Tmin) ranges within a narrow range of approximately 11.5°C to 12.3°C, with Baliya, Gorakhpur, Mau, and Varanasi recorded the increasing Tmin temperatures, with its trends ranging from +0.11°C to +0.21°C per decade. All stations show a consistent increase in temperatures over time. Cold wave (CW) days based on Tmin show a decreasing trend at every station, with reductions ranging from −0.15 to −0.73 days per decade, with Fatehpur, Prayagraj, and Fursatganj experiencing the greatest reductions. This implies that the frequency of extreme cold events is not rising in line with this trend. With mean values at zero and essentially no discernible long-term trend, severe cold wave (SCW) occurrences are still infrequent across all stations, which indicate that thermal stress is gradually intensifying but not yet crossing severe thresholds.

Probability density functions (PDFs) of heat wave and cold wave

The temporal pattern (Fig. 1) indicates a significant decrease in the severity of winter cold and an increase in early-season warmth, which is consistent with the observed trend of increasing minimum temperatures across North India under ongoing climate variability and change. According to the IPCC framework (IPCC 2014), an increase in the mean or variability of temperature significantly alters the probability of extreme events. In the current analysis, all nine stations show that a positive mean shift in Tmax significantly increases the probability density beyond the heat-wave threshold (40°C), especially when combined with increased variance. This broadening of the right tail indicates a greater likelihood of severe heat-wave conditions under warming scenarios. This is particularly evident in Bahraich, Gorakhpur, and Varanasi, where the probability of exceeding 40°C increases significantly under the combined mean+variance perturbation scenario. Similarly, applying negative mean shift and variance amplification to the winter Tmin distribution increases the left-tail probability, increasing the likelihood of temperatures falling below the cold-wave threshold (≤4°C). Stations like Bahraich, Fursatganj, and Sant Kabir Nagar show the greatest sensitivity to cold, suggesting that despite a gradual warming trend, increasing changes could lead to an increase in cold-wave events (Fig. 1).

LIMITATIONS

The present study is based on descriptive climatological analysis of long-term meteorological observations for heat and cold wave events in Eastern Uttar Pradesh. While the analysis provides valuable insights into temporal variability and frequency patterns, formal statistical tests of significance were not undertaken to evaluate the inferential robustness of observed trends. Therefore, the findings should be interpreted as indicative of climatological tendencies rather than statistically validated trend estimates. Future studies incorporating time-series modeling, trend detection tests, and extreme climate indices would further strengthen the analytical rigor of such assessments.

CONCLUSION

The analysis of Eastern Uttar Pradesh (EUP) indicates a long-term shift toward increasing heat waves and declining cold wave occurrences over the past six decades, reflecting emerging climate-related challenges in the region. The rising duration and intensity of heat waves, as indicated by higher Excess Heat Factor (EHF) values, suggest potential implications for public health, agriculture, and local livelihoods, with stations such as Fatehpur, Prayagraj, Gorakhpur, and Varanasi showing comparatively higher heat stress exposure.

Conversely, cold wave events exhibit a decreasing tendency across most stations, indicating moderation in winter cold severity. Probability density function (PDF)-based sensitivity analysis suggests that even modest shifts in temperature mean or variability may influence the likelihood of exceeding extreme temperature thresholds, with implications for winter agriculture and human health.

The conclusions are derived from descriptive climatological analysis of long-term observations. As formal statistical significance testing was beyond the scope of this study, the findings should be interpreted as indicative rather than statistically validated trends. Future studies incorporating inferential statistical techniques and advanced extreme climate indices would further strengthen the robustness of these assessments.

ACKNOWLEDGEMENT

Author's contributions: **R. Bhatla**: Conceptualization, Methodology, Visualization, Supervision, and editing; **B. Mandal:** Conceptualization, Methodology, Visualization, Supervision; **R. Singh**: Methodology, Data curation, Investigation, Visualization Formal analysis Writing-review and Writing-original draft editing; **R. Sharma:** Writing 1st draft, Data curation; **H. S. Patel:** Data curation, Investigation, Visualization Formal analysis Writing-review and Writing-original draft editing

REFERENCES

Bhatla, R., Pant, M., Singh, D., Verma, S., & Mandal, B. (2020a). Evaluation of cold wave events over Indo-Gangetic Plain in India. *Journal of Agrometeorology*, *22*(2), 233-238. https://doi.org/10.54386/jam.v22i2.178

Bhatla, R., Varma, P., Verma, S., & Ghosh, S. (2020b). El Nino/ La Nina impact on crop production over different agro-climatic zones of Indo-Gangetic Plain of India: *Theoretical and Applied Climatology*, *142*(1), 151-163. https://doi.org/10.1007/s00704-020-03284-3

Bhattacharya, A., Thomas, A., Soni, V. K., Roy, P. S., Sarangi, C., & Kanawade, V. P. (2023). Opposite trends in heat waves and cold waves over India. *Journal of Earth System Science*, *132*(2), 67. https://doi.org/10.1007/s12040-023-02069-2

Bouwer, L. M. (2018). Observed and projected impacts from extreme weather events: implications for loss and damage. In *Loss and damage from climate change: Concepts, methods and policy options* (pp. 63-82). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-72026-5_3

Chand, R., & Ray, K. (2014). Analysis of extreme high temperature conditions over Uttar Pradesh, India. In *High-Impact Weather Events over the SAARC Region* (pp. 383-397). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-10217-7_26

Dash, S. K., & Mamgain, A. (2011). Changes in the frequency of different categories of temperature extremes in India. *Journal of Applied Meteorology and Climatology*, *50*(9), 1842-1858. https://doi.org/10.1175/2011JAMC2687.1

Gawai, A. S., Pal, R. K., & Singh, S. (2024). Assessment of heat and cold wave incidences and their link with land surface temperature in Bathinda district of Punjab, India. *Journal of Agrometeorology*, *26*(2),204-208. https://doi.org/10.54386/jam.v26i2.2398

IPCC (2014) *Summary for policymakers In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental*

Panel on Climate Change (Cambridge Cambridge, United Kingdom and New York, NY, USA) ed C B Field *et al.* (Cambridge University Press) pp 1–32

Mahdi, S. S., Dhekale, B. S., Choudhury, S. R., Haque, M., & Gupta, S. K. (2020). Magnitude, frequency, trends of heat and cold waves in recent decades and impact assessment in wheat: the case of north Bihar, India. *Journal of Agrometeorology*, *22*(4). https://doi.org/10.54386/jam.v22i4.457

Mohamed, M. A. E. H., Hwehy, M. M., Moursy, F. I., & El-Tantawi, A. M. (2023). The synergy of ambient air quality and thermal discomfort: A case study of Greater Cairo, Egypt. *Journal of Agrometeorology*, *25*(4), 553-559. https://doi.org/10.54386/jam.v25i4.2309

Narkhede, N., Chattopadhyay, R., Lekshmi, S., Guhathakurta, P., Kumar, N., & Mohapatra, M. (2022). An empirical model-based framework for operational monitoring and prediction of heatwaves based on temperature data. *Modeling Earth Systems and Environment, 8*(4), 5665-5682. https://doi.org/10.1007/s40808-022-01450-2

Rajeevan, M., Rohini. P, Smitha Anil Nair, Snehalata Tirkey, Tanmoy Goswami, Naresh Kumar (2023). Heat and Cold Waves in India- Processes and Predictability. *Meteorological Monograph*, MoES/IMD/Synoptic Met/01(2023)/28.

https://mausam.imd.gov.in/responsive/met2.php

Ratnam, J. V., Behera, S. K., Annamalai, H., Ratna, S. B., Rajeevan, M., & Yamagata, T. (2016). ENSO's far reaching connection to Indian cold waves. *Scientific Reports*, *6*(1), 37657. https://doi.org/10.1038/srep37657

Ray, K., Giri, R. K., Ray, S. S., Dimri, A. P., & Rajeevan, M. (2021). An assessment of long-term changes in mortalities due to extreme weather events in India: A study of 50 years' data, 1970–2019. *Weather and Climate Extremes*, *32*, 100315. https://doi.org/10.1016/j.wace.2021.100315

Rohini, P., Rajeevan, M., & Srivastava, A. K. (2016). On the variability and increasing trends of heat waves over India. *Scientific Reports*, *6*(1), 1-9. https://doi.org/10.1038/srep26153

Shi, L., Kloog, I., Zanobetti, A., Liu, P., & Schwartz, J. D. (2015). Impacts of temperature and its variability on mortality in New England. *Nature Climate Change*, *5*(11), 988-991. https://doi.org/10.1038/nclimate2704

Singh, S., Mall, R. K., & Gautam, P. K. (2025). Spatio-Temporal Changes in Cold Wave Characteristics Over the Diverse Meteorological Sub-Divisions of India. *Pure and Applied Geophysics*, *182*(2), 859-875. https://doi.org/10.1007/s00024-024-03647-1