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Analyzing dynamics of extreme weather events (EWE) in India: unfolding trends through statistical assessment of 50 years data (1970–2019)

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Abstract

Objective Over the last five decades, extreme weather events (EWEs) have made a substantial contribution to the overall climate change impacts in India. Intergovernmental Panel on Climate Change (IPCC) has predicted that India will experience an increase in extreme weather events in the future. The primary aim of the study was to gain insights into India's overall occurrence of EWEs between 1970 and 2019 across different states.

Methods In the present study, data from the Indian Meteorological Department (IMD) spanning the last five decades (1970–2019) was examined to understand how specific EWEs have changed in India over varying regions and time spans. The analysis involved descriptive statistics using heatmaps, and trend analysis using the Mann- Kendall test.

Findings In the past 50 years (1970–2019), around 11,158 EWEs occurred in India. EM-DAT data shows a rise from 4+events in the 1950s to 20+in 2018, while IMD data indicates an increase from 50+events in the 1970s to 400+in 2019. The event-wise trend analysis of 50 years of data on EWEs in India revealed a consistent increase in the incidence of each EWE. The Mann–Kendall test, conducted to detect trends in EWEs over 50 years revealed a significant upward trend at 1% level for total EWEs, including heat waves, floods, heavy rains, and thunderstorms. Heat map and spatial analysis revealed that significant regions for heat waves include Maharashtra, Odisha, West Bengal, Uttar Pradesh, Rajasthan, and Uttarakhand. Cold waves have increased in Uttar Pradesh, Uttarakhand, Rajasthan, Bihar, and Jharkhand. Floods, heavy rains, thunderstorms, and lightning are common in Maharashtra, West Bengal, Kerala, Assam, and Karnataka.

Conclusion The findings of the study have critical implications for climate resilience strategies and disaster management in India. The increasing frequency and geographical concentration of EWEs call for region-specific preparedness and mitigation plans. By knowing the trends of EWEs and hotspot states through retrospective data records, the Government can proactively plan for future adverse events to prioritize high-risk areas, implementing targeted preparedness and mitigation strategies to prevent significant mortality and morbidity.

Keywords Climate change, IMD, Extreme weather events, Statistical analysis

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Introduction

Intergovernmental Panel on Climate Change (IPCC) defines an extreme weather event (EWE) as 'an event that is rare at a particular place and time of year', and an extreme climate event as 'a pattern of extreme weather that persists for some time, such as a season [1]. EWEs have occurred throughout the history of our planet. Due to the sustained increase in Green House Gas (GHG) production (mainly carbon dioxide (CO_2) an alarming trend of persistent increase in global surface and ocean temperatures has been observed, leading to global warming [2]. The National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) reports Earth's average global temperature has increased by at least 1.1° Celsius (1.9° Fahrenheit) since 1880. Notably, most of this warming has taken place since 1975, with temperatures increasing at a rate of approximately 0.15 to 0.2 °C per decade. Since the preindustrial period of 1850–1900, global land-surface air temperatures have increased by 1.53 °C, with significant regional differences in warming. This rise is notably higher than the combined temperature increase over both land and oceans, which stands at 0.87 °C [3]. This in turn has led to a drastic change in the earth's climate and in the overall character of the EWEs. An increase in the frequency and intensity of cyclones, extreme rainfall events which includes floods, flash floods, and landslides, dust, hail and thunderstorm with lightning, disruption of the monsoon leading to cycles of floods and drought, heat waves, cold waves and cold days with ground frost, heavy snowfall leading to avalanche are some of the changes that have been observed recently [2, 4].

The overall growth in the global human population, coupled with the rapid expansion in residential and commercial land usage and a continual decline in forest cover have contributed to changes in the frequency and intensity of many EWEs, with some regions experiencing increase heat waves, floods, and droughts than they witnessed in the past [5]. The number of EWEs has been increasing for every continent. For every year since 1970, the number of extreme events in Asia has been greater than in any other continent [6]. In Asia, both temperature and rainfall have been, on average, higher, more variable, and more extreme. The year 2021 witnessed more than 100 natural hazard events in Asia, of which 80 percent were flood and storm events [7]. While floods caused the highest fatalities and economic damage, drought in the region affected the highest number of people [7]. The "State of the Climate in Asia 2021" report highlights how climate change is accelerating water-related extreme weather conditions, which have become the most significant hazards in the Asian region. Furthermore, rainfall patterns have become more variable and extreme, exacerbating the impact of these weather events [7].

India being home to around one-sixth of humanity is the 3rd highest emitter of GHGs and is among the top ten emitting countries with the highest gross domestic production (GDP) worldwide [8]. Further, according to the Climate change report published by the Ministry of Earth Sciences (MoES), the surface air temperature over India has risen by about 0.7 °C during 1901–2018 which is accompanied by an increase in atmospheric moisture content. The sea surface temperatures in the tropical Indian Ocean have also increased by about 1 °C during 1951– 2015 [9]. This increase in GHG emissions coupled with increase in temperature have led to a consistent pattern of warming and climate change [10, 11]. Human-induced climatic have contributed to the intensification of EWEs, including more frequent high-intensity rainfall, rising maximum temperatures, warmer winters, and increased uncertainty in the timing of the monsoon which is crucial for India's agricultural-driven economy [10].

Exposure to intense or prolonged heat can lead to heat stress, which, if not addressed, can result in various heat-related illnesses. These illnesses range from mild and manageable conditions like prickly heat, heat-related swelling, cramps, and exhaustion, to a severe medical emergency known as heat stroke. Heat stroke, the most serious of these illnesses, is characterized by impaired brain function caused by uncontrolled body overheating, akin to a stroke. It's a critical condition that often proves fatal if body temperature isn't rapidly and actively cooled down without delay. In addition to neurological impairment, other symptoms of heat stroke include a significantly elevated core body temperature (at least 40 degrees Celsius) and hot, dry skin.

EWEs have a direct impact on attaining the targets for SDG 6 which focuses on water and sanitation. These events also have broader implications for the attainment of various other Sustainable Development Goals (SDGs) 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health & Wellbeing), 4 (Quality Education), and 11 (Sustainable Cities & Communities). Additionally, EWEs can exacerbate existing health issues and increase the risk of disease outbreaks. Severe heatwaves can lead to heat related illnesses and deaths, particularly affecting vulnerable populations such as the elderly and those with pre-existing health conditions. Floods can lead to drowning and waterborne diseases, while droughts can contribute to food and water shortages, impacting overall nutrition and health. Furthermore, after a severe weather event, access to healthcare facilities and services may be compromised, leading to delays in medical treatment and reduced healthcare capacity to handle other health emergencies.

IPCC has predicted that in the future, India would experience more weather extremities, such as heat waves, floods, cyclones, drought, etc. [12]. Thus, there is a need to explore the occurrence of EWEs in India.

EWEs are critical natural hazards with severe direct impacts, including loss of life and property. Their indirect effects are equally concerning, manifesting as disruptions to power and water supplies, increased incidence of food- and water-borne diseases, and the overburdening of healthcare systems. Earlier studies, such as those by Goyal and Surampalli [13], have highlighted significant shifts in precipitation and temperature patterns over recent decades in comparison to the last 100 years, reflecting broader climate change impacts [13]. Similarly, research by Keim [14] have documented an upward trend in global EWEs, with India exhibiting similar patterns [14]. These studies have provided a broad overview of the increasing frequency and intensity of EWEs, including heat waves, floods, and cyclones. Study by [15] assessed the impact of EWEs on mortality, thereby highlighting maximum mortality rates due to EWE in the last two decades [15].

The present study delivers a comprehensive analysis of extreme weather trends across India over a 50-year period (1970–2019). This extended timeframe allows for a more nuanced understanding of long-term trends and variations. The study employs detailed heat map analysis to identify regional hotspots for various EWEs, offering granular insights into the trends and intensity of specific events across different states. The study focuses on five types of EWEs: floods and heavy rains, heat waves, cold waves, lightning and thunderstorms, and tropical cyclones. By examining the temporal and spatial distribution patterns of these climatological events and testing for existing trends, the study aims to quantify the magnitude of change in individual events. The analysis is expected to enhance vulnerability assessments of geographical regions, thereby informing better planning and the development of region-specific mitigation and adaptation strategies.

Methods

Data used

Data on the occurrence of EWEs have been extracted from India Meteorological Department (IMD) which is the official weather monitoring agency of India and has been observing EWEs since 1967. The data from 1970 to 2019, covering 50 years, was used. The original data was captured from annual IMD published reports [16]. The published reports available at IMD website gives a summary of occurrences of all EWEs and natural hazards, i.e., Floods and Heavy Rains, Snowfall, Cold and Heatwave, Dust storm, Lightning, Thunderstorm, Cyclonic Storm, Drought, etc. supplemented with counts for mortality corresponding to each event for districts across India.

Data from 1970 to 2019, covering a span of 50 years, was used. The original data, initially published in print, was converted into an Excel file. This dataset included date-specific and location-specific events. The EWEs considered were heat waves, cold waves, lightning, tropical cyclones, and floods caused by heavy rains.

The EWE definitions used in this paper are summarized in the Supplementary file.

In addition to the IMD data on EWEs, data from EM-DAT, the International Disaster Database of the Centre for Research on the Epidemiology of the Disasters (CRED), was also analyzed to compare the trend of EWEs over the last 50 years [6].

The number of events in the IMD and EM-DAT databases differs because IMD considers events involving one or more deaths, while EM-DAT includes events involving ten or more deaths. The occurrences of EWEs through IMD were visualized through geospatial maps.

Statistical methods

The statistical analysis was carried out in three steps:

(1) Standardized occurrences of individual EWEs visualized through heatmaps. (2) Trend analysis performed on EWEs using Mann–Kendall test to quantify the trend with significance. Looking at the volume and nature of IMD data on EWEs and the objectives stated it was customary to visualize the change in intensity of EWEs through heatmaps for understanding shift in patterns of individual EWEs both spatially and temporally.

Heatmaps

By summarizing massive data sets, the data visualization approach known as the heatmap was utilized in the study to enhance the descriptive analysis and visualization, specifically when there is a wealth of data available for many time periods, locations, or qualities. Each data point received after standardization was given a relative score, and each score was then further assigned to a color based on our preference built under “ggplot2” package in R [17]. The heatmap normalizes each feature being analyzed through standardization across a time period (in years) or a set of locations, depending on the data [18].

Trend analysis

Mann–Kendall (MK) Test is the preferred test for detecting trend in time series data [19, 20]. More specifically it detects whether data has any monotonic trend or not. MK test quantifies the trend and provides statistical evidence. An impartial estimator of trend magnitude is the Kendall slope, which is the median over all combinations of record pairings for the whole data set. MK test is a

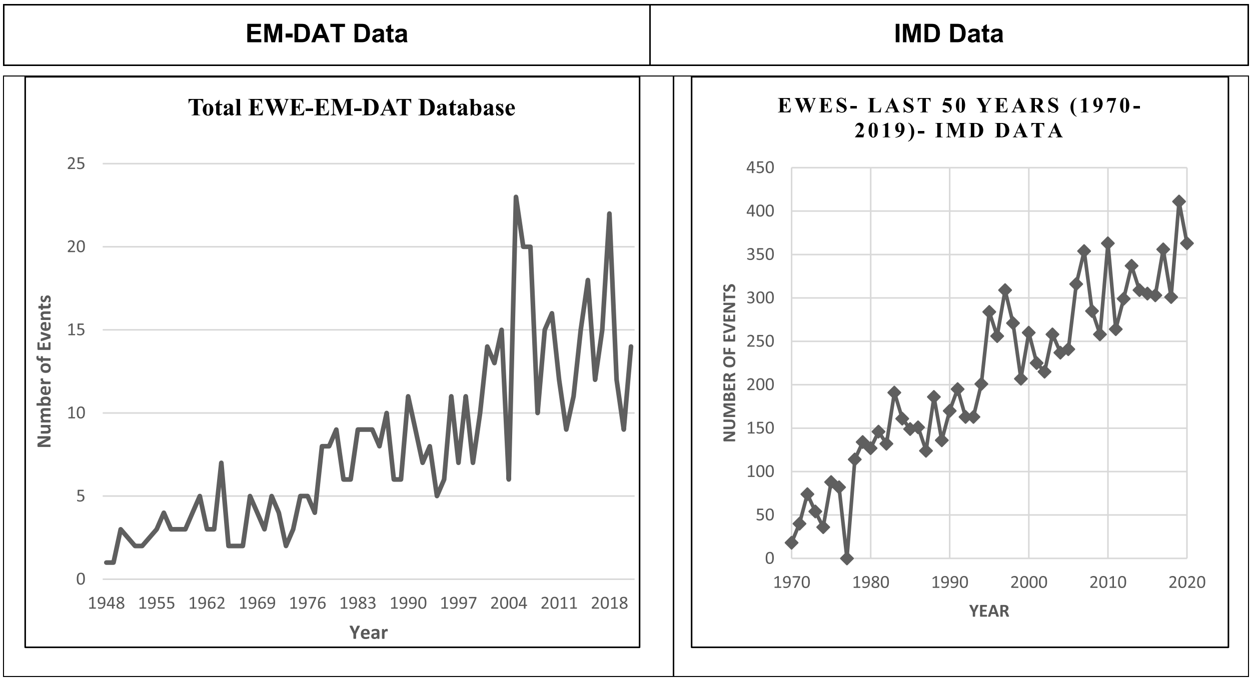

Fig. 1 Time series of EWEs in India from 1950–2019

non-parametric test and henceforth data need not be justified for normality, linearity and independence encountered in climatological datasets. The trend test is further analyzed by Sen's Slope to validate MK test results [21].

Results

Globally, all types of events, whether floods, storms, or droughts, have increased in frequency from an average of 50-plus events during the 1950s to 350 events in 2014 [6]. The number of EWEs has been increasing for every continent across the globe. For every year since 1970, the number of EWEs in Asia has been greater than in any other continent in the world [6].

EWEs in India from 1970–2019

Over the past 50 years (1970- 2019), India has experienced about 11,158 EWEs. EM- DAT statistics reveals a significant rise in these events, increasing from an average of over 4 events in the 1950s to more than 20 events in 2018 (Fig. 1). Additionally, data from the IMD database shows that the frequency of EWEs has surged, climbing from an average of over 50 events in the 1970s to more than 400 events in 2019, as depicted in Fig. 1.

An event-wise trend analysis of 50 years of EWEs data from 1970 to 2019 in India revealed a notable pattern: the incidence of each EWE, with the exception of tropical cyclones, has consistently increased over this period (Table 1).

Table 1 Mann Kendall Test for total EWEs and individual EWE

EWEs	Kendall's rank correlation coefficient (τ)	*P*-value	Sen's slope
Total EWEs	0.783	< 0.01	6.1531
Heat Wave	0.509	< 0.01	0.6062
Floods and Heavy Rains	0.55	< 0.01	2.2323
Thunderstorm and Lightening	0.821	< 0.01	4.5
Cold Wave	0.169	0.09	0.1363
Snowfall	-0.0105	0.9	0
Cyclone	-0.2	0.06	0

The Mann–Kendall test, applied to 50 years of data on EWEs, revealed significant trends. A pronounced upward trend was observed at the 1% significance level for total EWEs, including heat waves, floods, heavy rains, and thunderstorms. Cold wave events also showed an increasing trend, significant at the 10% level. Conversely, snowfall events exhibited a slight but statistically insignificant decline, while cyclone events demonstrated a discernible decline, significant at the 10% level. These findings highlight the dynamic nature of weather phenomena over the studied period.

Figure 2 presents a Heatmap illustrating the evolving patterns of individual EWEs in India from 1970 to

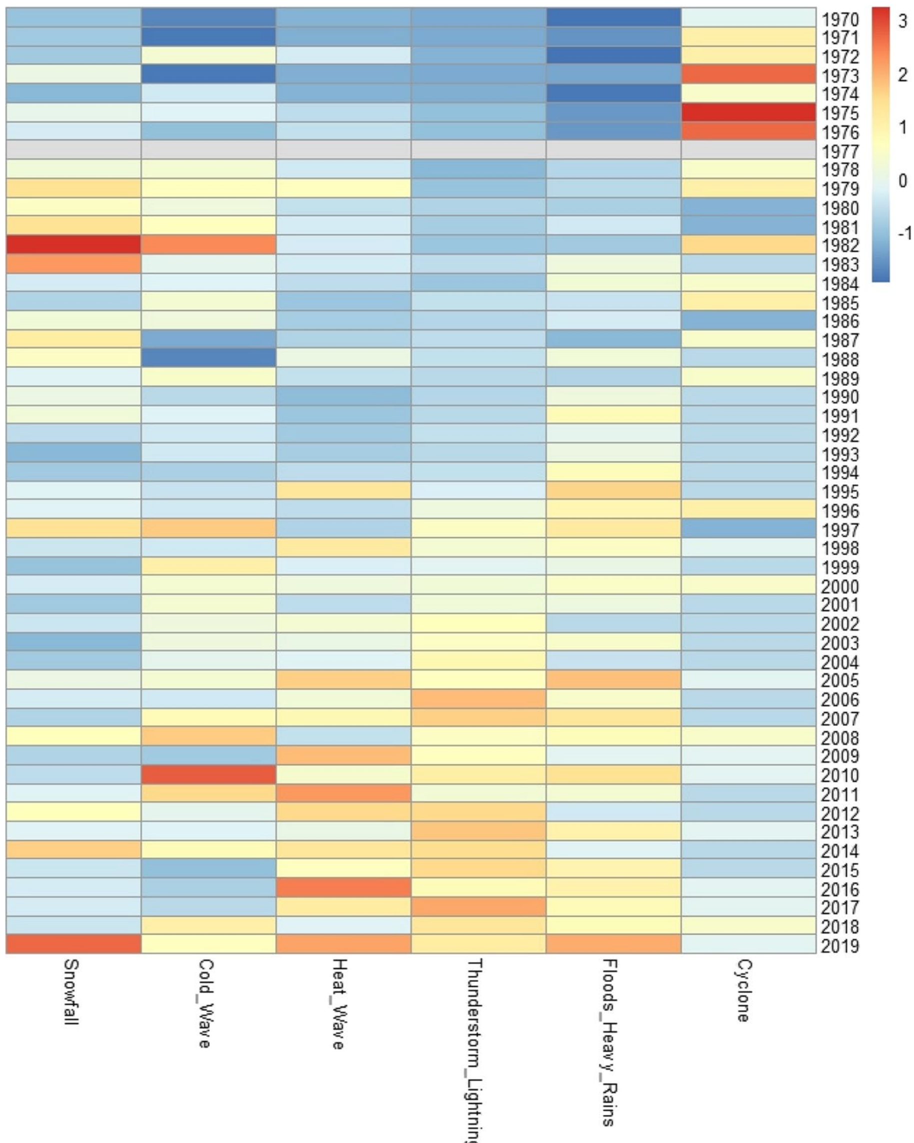

Fig. 2 EWEs in India from 1970–2019

2019. Over the past five decades, heat waves, thunderstorms, and floods have emerged as the predominant EWEs in the region, with all three event types experiencing a substantial increase in occurrence since the 1990s. Heat wave events show sporadic jumps in frequency from 2005 to 2019, while thunderstorms and lightning display a consistent upward trend, mirroring the patterns observed in flood and heavy rain events during the same period. Closer examination of the heatmap reveals that cyclones were predominant during the 1970s, with minor peaks in 1996, 2008, and 2018. Snowfall events are concentrated in the late 1970s and early 1980s, indicating a higher frequency of significant occurrences during that period. Cold wave events generally declined from the 1970s to the 1980s, with intermittent spikes between 2000 and 2010, and again after 2015.

In our exploration of India's diverse climates, we examined the pattern of EWEs across different states from 1970 to 2019, as depicted in Fig. 3. The intensity is visually represented by colors, with red indicating high frequency and blue representing low frequency of EWEs. Our analysis highlights certain states as focal points for specific EWEs.

Due to India's varied topography and terrain, different states are impacted in distinct ways. For instance, the states of Maharashtra, Orissa, West Bengal, Uttar

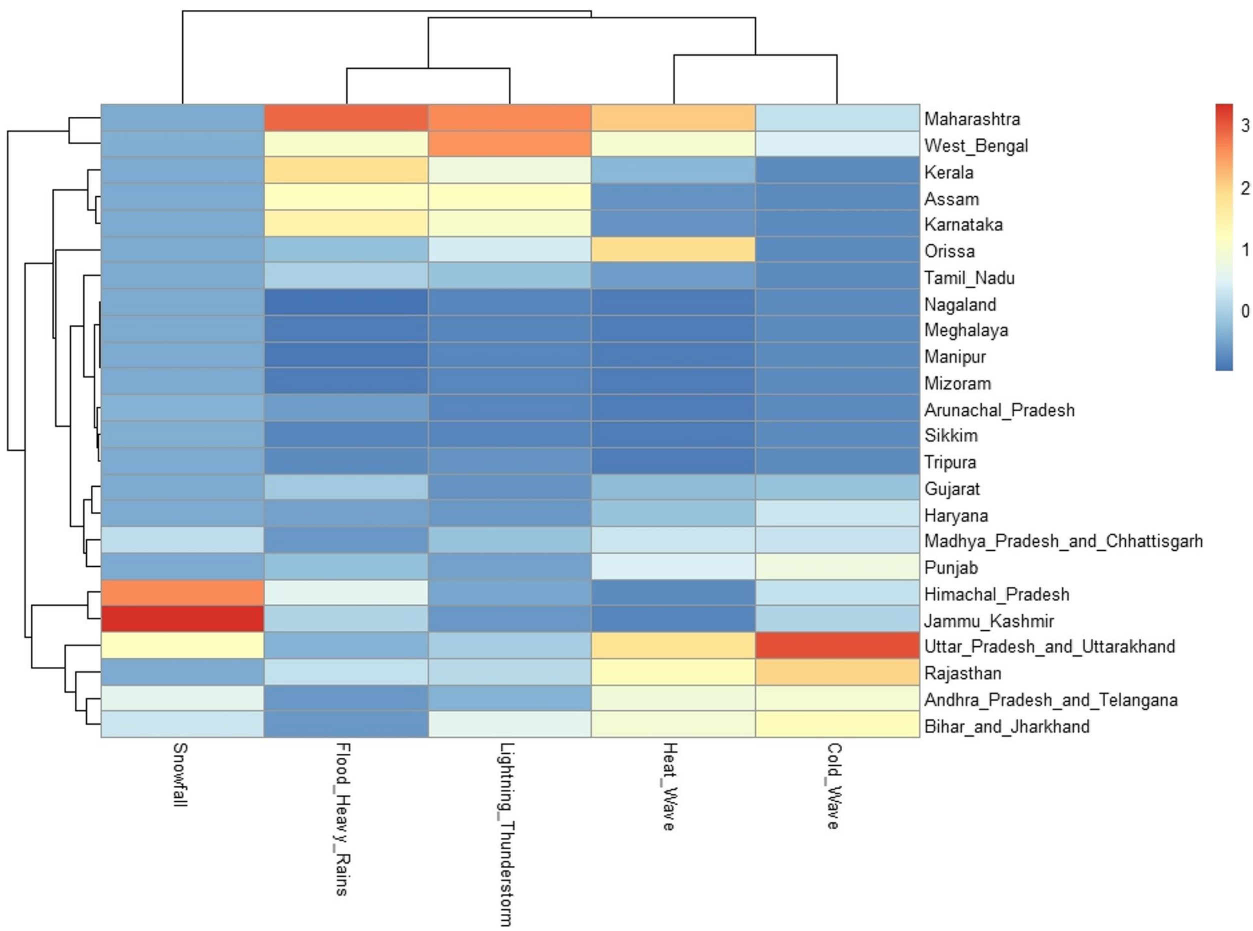

Fig. 3 EWEs across different States of India (1970 to 2019)

Pradesh, Rajasthan, and Uttarakhand emerge as significant regions for Heat Wave events, suggesting an upward trend in their frequency. The geospatial analysis of heatwave occurrences over the past 50 years reveals that the states of Maharashtra, Orissa, West Bengal, Rajasthan, Bihar, and Jharkhand have experienced the highest number of heatwave events (Fig. 4). Moreover, the states of Maharashtra, West Bengal, Kerela, Assam, and Karnataka are identified as hotspot regions for flood and heavy rains, as shown through heat maps and geospatial analysis (Figs. 3 and 4). Regions most prone to lightning and thunderstorms are concentrated in the states of Maharashtra, Karnataka, Bihar, Jharkhand, Assam, and West Bengal (Figs. 3 and 4). On the other hand, the states of Uttar Pradesh, Uttarakhand, Rajasthan, Bihar, and Jharkhand show an increasing trend in Cold Wave occurrences.

The dendrogram lines in Fig. 3 reveal clusters of similar events occurring in specific states, providing further insight into the spatial distribution of EWEs across India.

Discussion

The present study based on reported EWEs reveals a notable surge across India over the past 50 years. EWEs exhibit varying frequencies, with floods, heavy rains, lightning, and thunderstorms demonstrating the highest occurrence rates among the observed phenomena. Heat waves and cold waves follow suit, albeit with comparatively lower frequencies along with cyclones.

To comprehend these changes, study by Kulkarni et al. [22] indicates significant variations in precipitation patterns across different regions. Compared to the period from 1901 to 1975, rainfall reduced by 1–5 mm/day during 1975–2015 over central India (the core monsoon zone), Kerela, and extreme northeastern regions [22]. In contrast, rainfall increased over the Jammu and Kashmir and parts of western India. Human-induced factors at the regional level, including aerosols and changes in land use driven by urbanization and agricultural expansion, may play a significant role in the recent variations in spatial precipitation patterns [23].

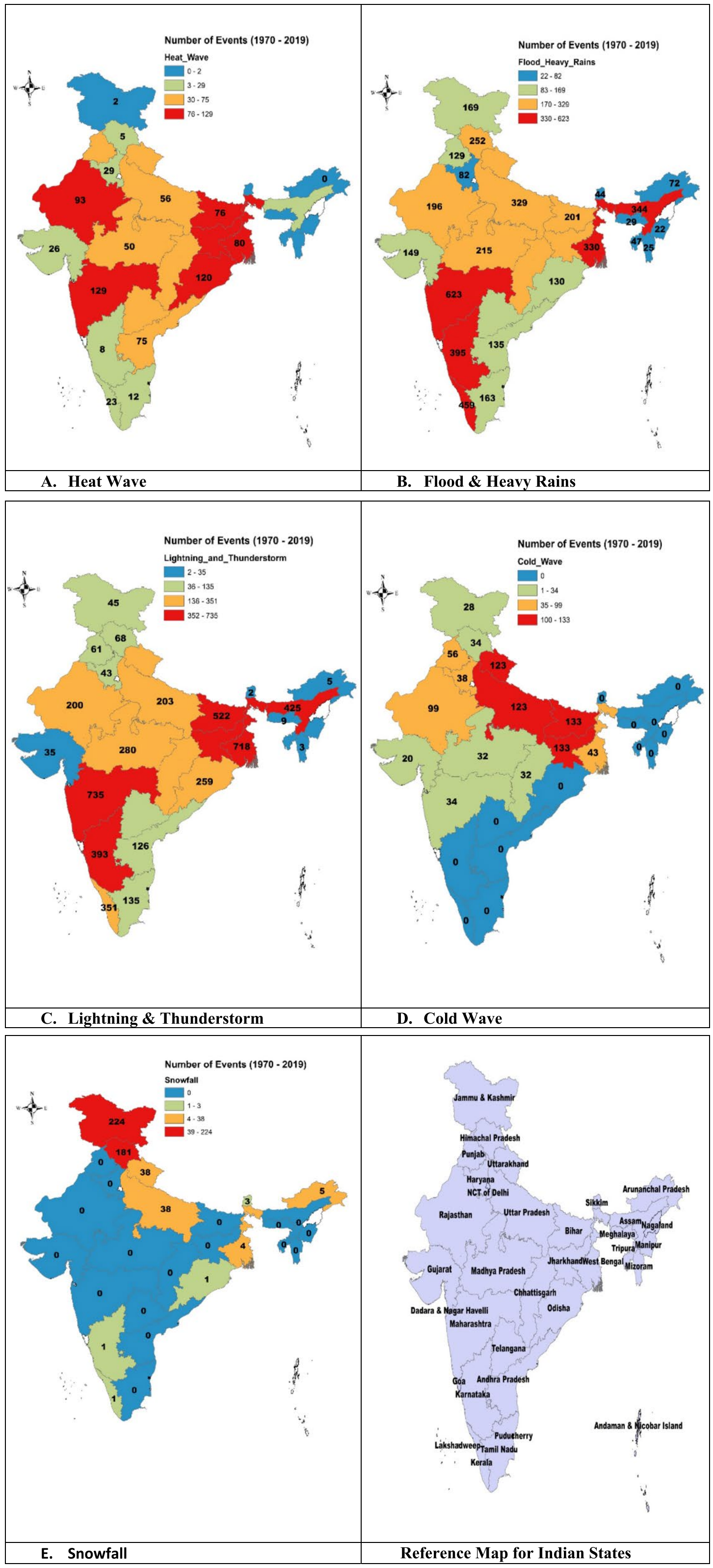

Fig. 4 Geospatial representation of extreme weather events in India

Globally, from 1969 to 2018, there has been an upward trend in the annual incidence of EWE, as reported by EM-DAT [6]. During this period, a total of 10,009 EWE disasters were recorded worldwide, resulting in 2,037,415 deaths and 3,998,466 instances of disease, as documented by Keim in 2020 [14].

The present study unveils a concerning trend in India, revealing a significant rise in heat waves, thunderstorms, and floods over the past five decades. Notably, these EWEs have shown a marked increase since the 1990s. While heat waves have exhibited irregular jumps in occurrences between 2005 and 2019, thunderstorms, lightning, floods, and heavy rain have steadily risen over the entire 50-year span. Particularly concerning is the prominence of floods, which have emerged as the leading cause of mortality, accounting for 46.1% of total deaths [15]. Global climatic shifts have contributed to this trend, with precipitation on the rise in higher latitudes of the northern hemisphere while decreasing in subtropical regions. Climatic events such as heightened heavy rainfall in areas of the northern hemisphere, warm phases of the El Niño Southern Oscillation (ENSO) in tropical regions, and a rising occurrence of droughts in specific parts of Asia and Africa have been observed and documented [12].

The heat map analysis depicted that the states of Maharashtra, Orrisa, West Bengal, Uttar Pradesh, Rajasthan, and Uttarakhand are prominent states for Heat Wave events depicting an upward trend in the frequency of heat wave occurrences. Similar finding was observed by Mazdiyasni et al., who demonstrated that the rise in average summer temperatures in India between 1960 and 2009 resulted in a 146% higher likelihood of heat-related mortality events involving more than 100 individuals [24]. Moreover, during the period from 2010 to 2019, the frequency of heat wave events rose by approximately 24% compared to the period from 2000 to 2009. Correspondingly, mortality rates associated with heat waves increased by about 27%, elevating heat waves from the third most devastating EWE in terms of fatalities to the second most disastrous event linked to mortality [15]. Srivastava et al. underscores the vulnerability of certain hilly regions in Himachal Pradesh, Jammu & Kashmir, Arunachal Pradesh, Manipur, and Mizoram in northeast India to the effects of heat-related stress, particularly during March and April, owing to elevated maximum temperatures [25]. Additionally, their study also identifies Bihar, Jharkhand, West Bengal, parts of Odisha, and Northeast India as the regions most significantly impacted by heat wave hazards. Other affected areas include parts of the Bundelkhand region, northern parts of south peninsular India, and southern parts of Madhya Maharashtra and Tamil Nadu from March to June, with heightened impacts in the Jammu region in April and May, and Gujarat and the Saurashtra region in May and June [25].

The heat map analysis conducted in the present study over the past 50 years has revealed that floods, heavy rains, thunderstorms, and lightning are most prevalent in Maharashtra, West Bengal, Kerala, Assam, and Karnataka. Notably, there has been a sudden increase in the intensity of these EWEs in Jammu and Kashmir, Kerala, and Maharashtra in 2019. Flood disasters are the leading cause of economic damage and loss of human lives in India. In a study by Pal et al. [26], projections based on land use and land cover (LULC), rainfall patterns, and flood susceptibility indicate that maximum monthly rainfall will increase by approximately 40–50 mm by 2100 [26]. Moreover, severe flood events are predicted to expand by up to 122%, encompassing an area of 0.15 million square kilometers from the present time onwards [26].

Cyclones, as per Singh and Patwardhan's findings in 2012, represent the least prevalent EWEs in India [27]. However, despite the declining frequency of cyclonic events over time, their impact remains significant [28]. For instance, the "Gulab" cyclonic storm originating in the Bay of Bengal on the 24th of September 2021, hit the eastern Indian coasts two days later resulting in widespread devastation and extensive flooding [29]. This event inflicted substantial damage to crop areas in four eastern Indian states, namely Andhra Pradesh, Chhattisgarh, Odisha, and Telangana [29]. Looking ahead, projections suggest that tropical cyclones will become even more intense, with a predicted 17% increase in intensity by the end of the twenty-first century [30]. Additionally, the maximum potential wind speed is anticipated to rise by 5–7% per degree Celsius of global warming [30], emphasizing the escalating threat posed by these extreme weather phenomena [31]. According to Ray et al. [15], tropical cyclones accounted for 28.6% of all deaths, while heat waves and cold waves contributed 12.3% and 6.8% to the overall mortality, respectively. Lightning had the least impact on mortality, representing only 6.3% of the total deaths [15].

Given the susceptibility of certain regions in India to EWEs, it is imperative to prioritize climate change mitigation and resilience-building efforts [32]. Specifically, states such as Maharashtra, Orrisa, West Bengal, Uttar Pradesh, Rajasthan, Uttarakhand, Bihar, Jharkhand, Kerala, Assam, and Karnataka warrant heightened attention due to their vulnerability to EWEs.

EWEs not only have direct consequences but also trigger various indirect health effects, stemming from disruptions in essential services like power, water, and transportation. These events lead to an uptick in food and water-related diseases, drowning incidents, and accidents, while also straining already overburdened healthcare systems. Globally, thousands lose their lives annually, and many face long-term consequences on their livelihoods due to EWEs. However, the complete impact of such events often becomes apparent only weeks or even months later.

Moreover, EWEs have compounding and cascading environmental repercussions, such as concurrent droughts, glacial lake outbursts resulting in flash floods, and urban or wildfires. They also contribute to increased air pollution through ground-level ozone and dust storms. Given their potential to cause widespread health and economic harm, EWEs can rightfully be classified as disasters.

To conclude**,** India faces significant challenges in developing strategies to reduce vulnerability to EWEs due to limited resources and technology access. Understanding the trends of EWEs and identifying hotspot states is crucial for effective planning and mitigation strategies. In other words, knowledge about which regions are most frequently affected by EWEs and understanding the patterns of these events will be beneficial and is crucial for effective planning and mitigation. By recognizing these areas, policymakers, urban planners, and disaster management teams can develop targeted actions to minimize impact and damage. A notable success is the zero deaths reported in Odisha due to the Very Severe Cyclonic Storm (VSCS) 'Phailin'. This highlights the exceptional preparedness of the Government of Odisha (GoO) and the coastal communities. Their commitment to ensure zero casualties led to prompt action in response to the cyclone warning through early warning systems [33]. Thus, by knowing the trends of EWEs and hotspot states through retrospective data records, the government can proactively plan for future events, implementing targeted preparedness and mitigation strategies to prevent significant morbidity and mortality.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
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Data availability
The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

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Competing interests
The authors declare no competing interests.

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