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Investigation of the Indian summer in the state's popular capital and correlation between IMD and ERA5 dataset during the past five decades (1973–2022)

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Abstract

In this comprehensive study, spanning five decades from 1973 to 2022, the increasing prevalence and duration of heat waves in India, particularly in central and northwest regions, are examined. These heat waves are found to be associated with elevated pressures, anticyclonic flow patterns, clear skies, and diminishing soil moisture. Furthermore, variations in sea surface temperatures (SST) in the tropical Indian Ocean and the central Pacific significantly influence the occurrence of heat waves in India. The study predicts longer and more frequent heat waves as a consequence of the warming tropical Indian Ocean and an increase in El Nino occ-urrences, highlighting the growing heat-related challenges facing the country. Analyses of the present climate using climate models agree with the highest temperature zones that have been observed, emphasizing the importance of radiative heating. This study determines the areas that are most vulnerable to heat waves and regions with the highest temperatures, and it pinpoints the cause as wind flow from these areas, which is induced by favourable atmospheric circulations. The findings of this investigation would have broad applications in both vulnerability and risk evaluation as well as prediction.

This study focused on the ERA-Interim and IMD gri-dded data sets in order to evaluate the validity of heatwave detection across several datasets. It looked at particular heatwave dates from March to June in several places and years, included Lucknow in 2016, Delhi in 2019, Jaipur in 2016, and Bhubaneswar in 1988. Among the two datasets, the research showed a statistically substantial agreement, especially during Lucknow's 2016 summer heatwave. However, Bhubaneswar had the lowest correlation, suggesting that the temperature profile in both datasets was identical. With a larger concentration of matched pixels at the mean temperature, Jaipur in 2019 had the best fit. The study's findings were summarized by pointing out the significance of the mid-temperature range from 30°C to 40°C in heatwave identification.

Keywords: Heat weave; IMD Indian Meteorological Department); ERA5; Temperature Deta; EHF (Excess Heat Factor); NDMA (The National Disaster Management Authority).

1. Introduction

Heat waves, which are defined by abnormally high temperatures and lasting a long time, are known to have an adverse effect on farming when combined with a lack of humidity and to have a fatal effect on human health when mixed with excessive humidity.[1] As a result of the observed rise in heat wave frequency during the 1970s, which corresponds to the current trend of global warming, the occurrences are anticipated to worsen. Since 2000, heat waves have been a cause for concern around the world due to the 166,000 deaths they contributed to between 1998 and 2017.[2] Since 2016, India has recognized heat waves as natural disasters due to the 2500 deaths they contributed to in 2015.[3] The effects of heat waves on the environment are one of the main worries on Human Health. [4,5,6,7,8]

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As defined by the Indian Meteorological Department (IMD), a heatwave happens when the highest temperature on any given day of a region is equal to or greater than 40°C. Temperature deviations from the mean of 4-5°C are regarded as heatwaves, and deviations of 6°C or more are regarded as severe heatwaves. [9,10] Multiple industries, including health, agriculture, ecology, and the national economy are severely harmed by heatwaves. Extreme heat waves in India pose a serious threat to people's lives and increase the risk of deaths from heat stroke and heat stress. India regularly sees heatwaves in summertime (March–June), which contributes to an increase in the number of deaths from sunstroke, dehydration, and other medical conditions. Compared to other extreme weather events, heatwaves cause more fatalities each year. In recent decades, they have become more frequent, severe, long-lasting, and widespread globally and regionally. Tens of thousands of people have died in certain notorious heatwaves, including those in Chicago (1995), Europe (2003), and Russia (2010). [11,12,13,14]. In recent years, heatwaves have emerged as a major natural health hazard, with thousands of heat-related deaths occurring in India between 1973 and 2022. In May 2015, India experienced a mega heatwave, resulting in thousands of deaths, particularly in Andhra Pradesh. India's vulnerability to weather and climate variability is well-documented, with heatwaves causing substantial damage to human health, agriculture, and the national economy. Various studies have examined the climatological characteristics of heatwaves in different regions of India.

Heatwaves not only lead to loss of human lives but also have severe con-sequences for agriculture and animal husbandry, both of which are vital to India's economy. Heatwaves damage Rabi crops and reduce milk yield in cattle. Various parameters and indices have been used to characterize heatwave events, with the Excess Heat Factor (EHF) index gaining prominence due to its ability to assess local community adaptation and quantify temperature anomalies regionally. India is one of the nations that have made the EHF index their preferred metric for measuring heatwaves. [15,16] While in situ observations have been the main source of data for studies on heatwaves in India, reanalysis databases provide continuous geographical and temporal data for studying heatwave phenomena. utilizing the ERA-Interim reanalysis datasets from ECMWF, this study analyzes heatwaves and their severity in India, notably in state capitals, from 1973 to 2022 during the summer. It does this by utilizing the EHF index and the Sev-erity Index (HSI). The purpose of this study is to determine whether reanalysis datasets are appropriate for identifying heatwave events and assessing the effectiveness of the EHF index in India.

In order to understand the differences between the dataset's abilities to detect heatwaves, correlation between the ERA-Interim and IMD gridded data sets were examined for certain selected heatwaves across a number of years and at a specific location in the summertime (March, April, May, and June). According to the analysis, the correlation between the ERA-Interim & IMD datasets is highly significant for heatwave analysis, which is in line with the findings of the research by [17,18,19]

The dataset's estimated temperature pixels for the designated heatwave dates were used to validate this; all analysed correlations show linear spreading of the pixels with sati-sfactory agreement research revealed that the mid-temperature interval (30–40 °C) is where the cor-relation among two datasets is most significant. Overall, the ERA-Interim statistical analysis shows strong agreement with the IMD dataset.

2. Dataset

IMD everyday surface-level maximum temperature data with a grid precision of 1^0*1^0 for the Indian region from 1972 to 2022.[20] Summer time (March, April, May, June) data are taken into consi-deration for analysis. For the summer month, the 50-year study period for each of the particular location points was taken into consideration for calculating the monthly climatological averages of surface air maximum temperatures. In order to determine the zones of highest temperature, the total number of days in summer time with maximum temperatures > 42 °C is calculated for each grid point using data from 1972 to 2022. Following the IMD standards, which are utilized in many research, the number of heat wave dates is determined. [21,22,23,24,25,26] that appears below.

- A normal heat wave is verified when the highest recorded temperature at a station reaches 40 °C for fields and 30 °C for hilly areas, and the temperature departing from normal is 4-6 °C; (ii) a severe heat wave is declared when the average highest temperature is 40 °C and the temperature departure about normal exceeds 6 °C, or when the actual highest temperature is 47 °C or 6.5°C over normal. The highest temperature must be above 37 °C and the deviation must be 4 °C to qualify as a heat wave over coastal stations. Furthermore, if the heat wave criterion continues without interruption for at least three days, the happening of a heat wave is confirmed. Daily data from the ERA-Interim global atmospheric reanalysis with a resolution of 0.5*0.625 degrees, accessible from 1 March 1980 to 30 June 2022 at 0900UTC (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc). The present analysis uses data from 1973 to 2022 for 2-m level air temperature, surface (10-m level), and higherlevel wind. For the summer month from 1973 to 2022, the mean 2-m level temp and

10-m level air are calculated and utilized to create regional patterns over the region of famous capitals of Indian states. For the chosen heat wave occurrences, composites containing wind deviations at 10-m, 925 hPa, and 850 hPa levels are created. Utilizing the daily wind data, time-sections of the lower troposphere's wind are created for the periods before, during, and after the chosen heat wave occurrences.

3. Methodology

Nairn and Fawcett's (2013) and Nairn et. All (2018) techniques were used to evaluate the degree of severity and intensity of heatwaves. The investigation includes the creation of a without dimensions Heatwave Severity Index (HSI), using the long-term (30+ days) and short-term (3 days) daily average temperatures to calculate the Excess Heat Significance Index (EHIsig) and the Excess Heat Accli-matization Index (EHIaccl), respectively. The variances in EHIsig and EHIaccl for a particular period of time were combined to form the Excess Heat Factor (EHF). The EHF values for the time period were then standardised to provide a without dimensions HSI.

The Excess Heat Index is denoted by

EHIsig on day 'i' is defined by [15,16] as

$EHI_{sig} = TDP_i - T_{95}$.

where T 95 represents the climate reference period (1972–2022)'s 95th percentile of DMT (T_i). According to definitions by, daily median temperature is the mean of the highest and lowest temperatures.

$T_m = \frac{T_{max} + T_{\min}}{2}$

TDPi and the 95th percentile of the DMT are directly compared in the EHIsig index (°C). The EHIsig index must be positive (EHIsig > 0) for TDPi to be characterized as considerably hot [15,16]. TDP is classified as an uncommon heat event, on the other hand, if EHIsig is negative (EHIsig 0). You can think of EHIsig as a TDP anomaly over a protracted climatological timeframe.

$$TDP = \frac{T_{m_i} + T_{m_{i+1}} + T_{m_{i+2}}}{3}$$

the heat stress that develops when temperatures are generally higher than they have been recently. To define the heat stress, average highest and subsequent lowest temperatures over the previous 30 days and a three-day period are compared. A short-term (accli-matization) temperature anomaly is used to describe this.

The definition of heat stress is

$$EHI_{accl} = TDP_i - \sum_{k=3}^{32} \frac{T_{m_{i-k}}}{30}$$

Ti is the DMT on day i in this case. EHIaccl is, in fact, a three-day DMT anomaly with respect to the previous 30 days. °C are the units of measure used for EHIaccl.

Excess Heat Factor (EHF) is a metric that compares the occurrence rate, duration, and spatial distributions of heat wave events by combining the effects of excess heat and stress from heat. Positive EHF values indicate the presence of a heat wave.

The following is a definition of the Excess Heat Factor (EHF):

$EHF = EHI_{sig(i)} \times \max |1, EHI_{accl(i)}|$

4. Overview of Heatwaves in India (1973–2022)

The summertime of 2018 had much more intense heatwaves in India. across average, May and June are the warmest months across the Indian subcontinent.[10] The National Disaster Management Authority (NDMA) reports that 2018 saw more heatwaves than prior years. India saw the largest heatwave anomalies over the central states of the country, making this year the sixth warmest since 1950. The monsoon's later arrival and less regular rains made the situation worse. Andhra Pradesh, Telangana, Punjab, Odisha, and Bihar are among the eastern coast states with the highest mortality rates (NDMA, 2017) [28]. The extension of heatwaves eastward was considered to be caused by the advection of drier hot air, which enhanced EHF and intensified heatwave events. From 2010 to 2019, a sizable number of deaths in Andhra Pradesh were caused by the state's high daily temperatures.

In recent years, Indian cities have been strongly exposed to heatwaves, especially in the summer months from 2005 to 2019. At this time, several states, including Andhra Pradesh, Telangana, Odisha, Rajasthan, and surrounding regions, saw exceptionally high temperatures between 43 and 47°C (Singh et al., 2021). The Indian Meteorological Department (IMD) reports that multiple heatwaves have occurred in states including Maharashtra, Punjab, Haryana, and Uttar Pradesh. These heatwaves, which persisted in eastern coastal regions through June, posed a grave risk to thousands of lives (Andhra Pradesh State Disaster Management Authority (APSDMA), 2019).

5. The seasonal patterns and occurrence of heatwaves in India

Warm air advection over summertime typically causes the sensible heat flux to be amplified, which leads to the accumulation of heat with little heat transmission. Due to meridional advection during the summer, India's geographic circumstances cause the heat to be carried northward from the equator. The recurrence of cyclones in the Bay of Bengal can further worsen heatwave conditions at a synoptic scale by strengthening the pressure system across the Indian peninsula and escalating the heat wave (Indian Meteorological Department (IMD) 2018.

In especially in April, the northwest regions of India become the epicentre for the genesis of heatwaves. The emergence of an anticyclonic circulation pattern, which is the result of a quasi-stationary anomalies Rossby wave train starting in North Africa, is directly related to the occurrence of heatwaves in this northwest region. These waves are created by divergent winds stretching the vorticity, and they spread over northwestern India with westerly jet streams. This sinking motion causes an increase in outgoing long-wave radiation (OLR), which causes heat waves [26,13]).

The pre-monsoon season, which lasts from April to June, brings unusually scorching temperatures along with periodic heatwaves to India. Throughout this season, the Indian mainland often experiences 20 to 30 heatwave episodes [30]; India Meteorological Department (IMD) 2018; [29]). Indian cities are currently experiencing one of the longest annual heatwave stages; this pattern has persisted since 2016. This phenomenon is illustrated by time series data of the summertime maximum temperature average (Tmax) over a 50-year climatology spanning 1973 to 2022.

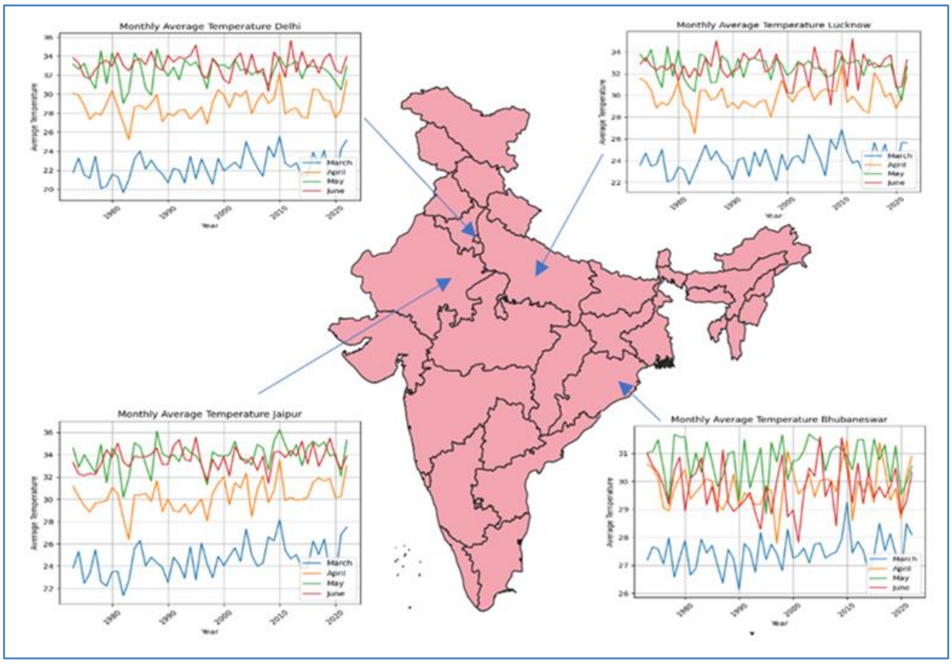

Figure 1 (Time series of the mean temperature for the summer months (March: blue, April: Orange, May: Green, and June: Red) for the four populous cities. The panel values have corresponded to the location specified pixel**.**

In this fig.1 show The time series shows the climatological average temperature throughout the summertime months in India's most populated cities (March: blue, April: orange, may: green, and June: red). The values on the panel match the pixel at the specified place.

6. Results and discussion

6.1. Average count of heat wave days monthly 0.5*0.625 deg. (1980-2022)

All of the images in the figures were retrieved from the NASA GIOVANNI platform, adjusted to include meteorological data, and then all of the photographs were retrieved.The average number of days each month with extremely high and prolonged temperatures is referred to as the "monthly count of heat wave days." This metric aids in studying heat wave seasonal trends and effects on society by tracking the frequency and length of heat waves.

The summer months of March, April, May, and June each have 50-year heat wave days, as shown in Figs. 2(a), 2(b), 2(c), and 2(d).

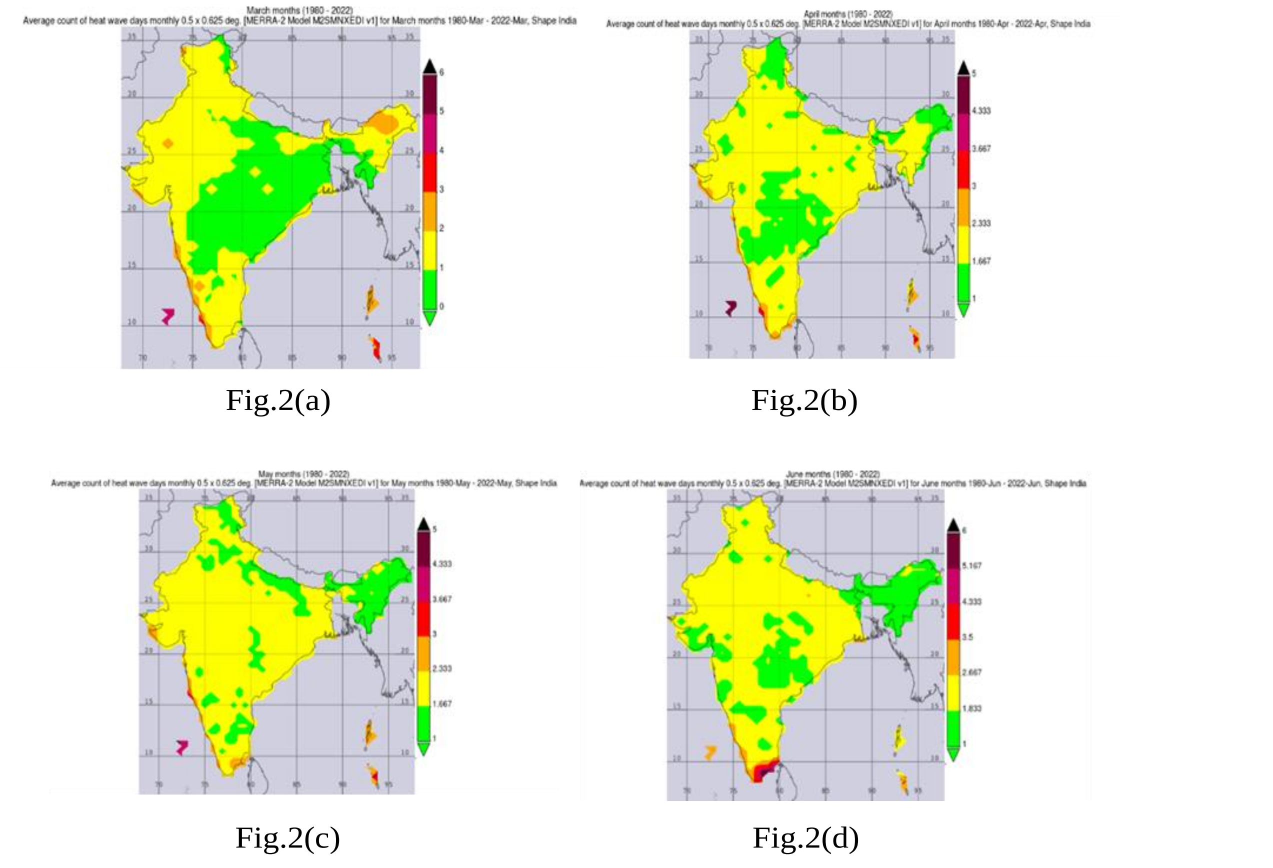

Fig.2(a) Fig.2(b) Fig.2(c) Fig.2(d)

Figure 2 Average count of heat wave days monthly 0.5*0.625 deg. (1980-2022).

6.2. Average Count of Heat wave events monthly 0.5*0.625 deg. (1980-2022)

In all the figures, we obtained the images from NASA's GIOVANNI platform, made adjustments to incorporate meteorological information, and subsequently retrieved all the images. The Average Count of Heat wave events monthly" is a statistical measure that calculates the typical number of heat wave events observed within each calendar month over a last five decades. Heat wave events are characterized by prolonged periods of unusually high temperatures.

In all the summer months March show in Fig.3(a), April show in fig.3(b), May show in fig.3(c), June show in fig.3(d) show 50 year heat wave events.

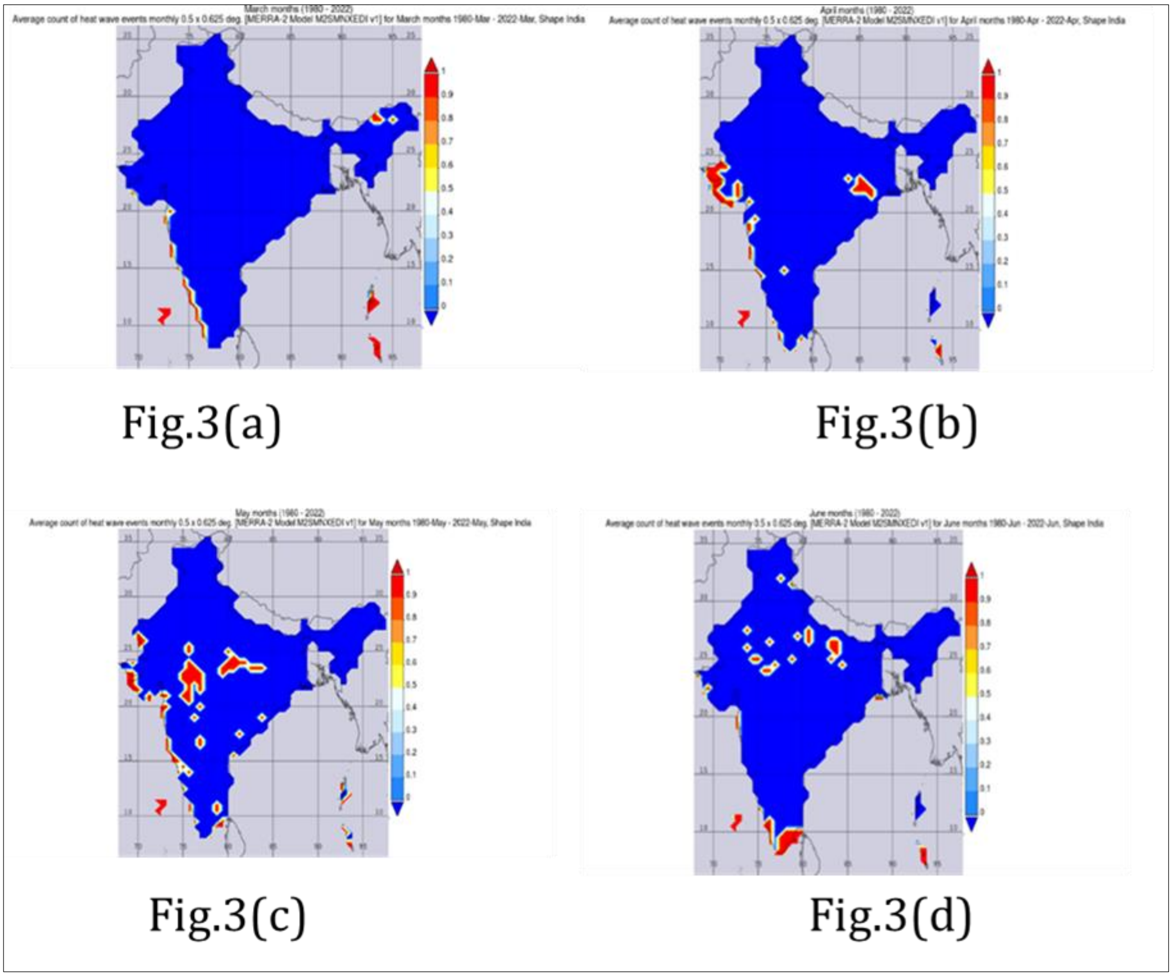

Figure 3 Average Count of Heat wave events monthly 0.5*0.625 deg. (1980-2022).

6.3. Average length of longest of Heat wave events monthly 0.5*0.625 deg. (1980-2022)

The average duration of the longest heat wave occurrences that occurred within a given time period or geographic area is described by the statistical metric "The Average length of the longest Heat wave events." Events known as heat waves are characterized by protracted stretches of extremely high temperatures. This particular statistic is useful since it provides information on the length of the longest periods of increased temperatures that take place during heat waves.

More specifically, this statistic enables scientists, meteorologists, and decision-makers to comprehend both the frequency of heat wave events and the duration of their persistence. By analysing the average length of the longest heat wave events, one can gain a deeper appreciation of the potential challenges posed by these extended periods of extreme heat. This information is critical for various purposes, including assessing their impact on public health, agriculture, energy demand, and infrastructure resilience. It also aids in the development of effective strategies for mitigating and adapting to heat wave-related risks.

In all the summer months March show in Fig.4(a), April show in fig.4(b), May show in fig.4(c), June show in fig.4(d) show 50 year length of longest of Heat wave events in monthely.

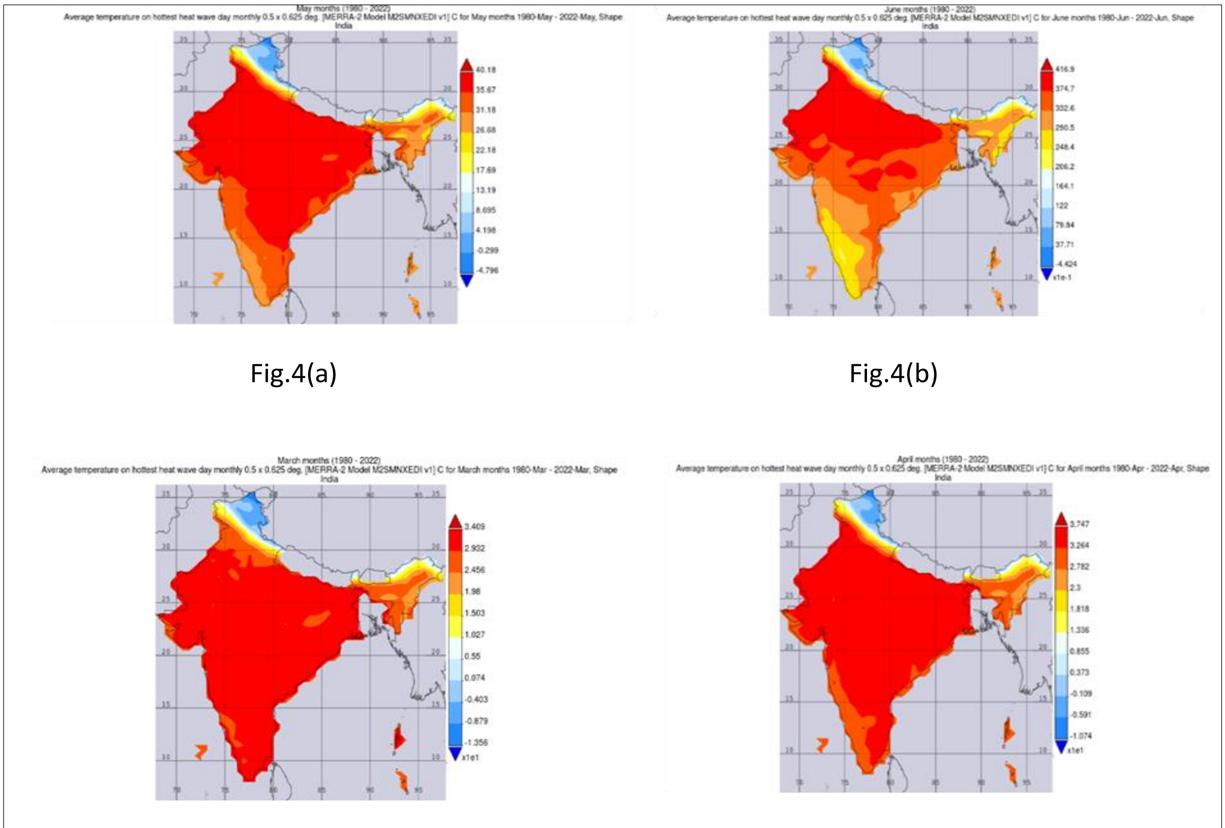

Fig.4(a) Fig.4(b) Fig.4(c) Fig.4(d)

Figure 4 Average length of longest of Heat wave events monthly 0.5*0.625 deg. (1980-2022).

6.4. Dataset statistical evaluation: IMD Gridded Data Validation of ERA-Interim

The study examined the correlation among ERA-Interim and IMD gridded data sets to identify specific heatwave dates, those are specific location and particular year in summer (March–June) time including Lucknow March-June 2016, Delhi March-June 2019, Jaipur 2016, March–June in Bhubaneswar, 1988, March–June. The aim was to evaluate the consistency of heatwave detection across datasets. The analysis showed statistically considerable agreement between the ERA-Interim and IMD datasets for heatwave analysis, which is in line with studies by [17,18,19]. Based on the selected heatwave dates' interpolated temperature data, which showed a linear distribution of pixels with high concordance.

The data sets showed a favourable correlation on the days of the 2016 summer heatwave in Lucknow. Contrarily, the summer season in Bhubaneswar showed the lowest correlation, indicating that both datasets showed a similar pattern of pixel layout with greater temperatures falling between 20°C and 40°C. However, among the selected heatwave dates, the scenario in Jaipur during the summer of 2019 showed the best linear fit of heat pixels, which was consistent with a higher concentration of matching pixels at Average temperatures. The research revealed that the mid-temperature range of 30°C to 40°C was where the agreement between the two datasets was most significant.

Correlation between IMD and ERA 5 dataset in various city and specific date in summer month.

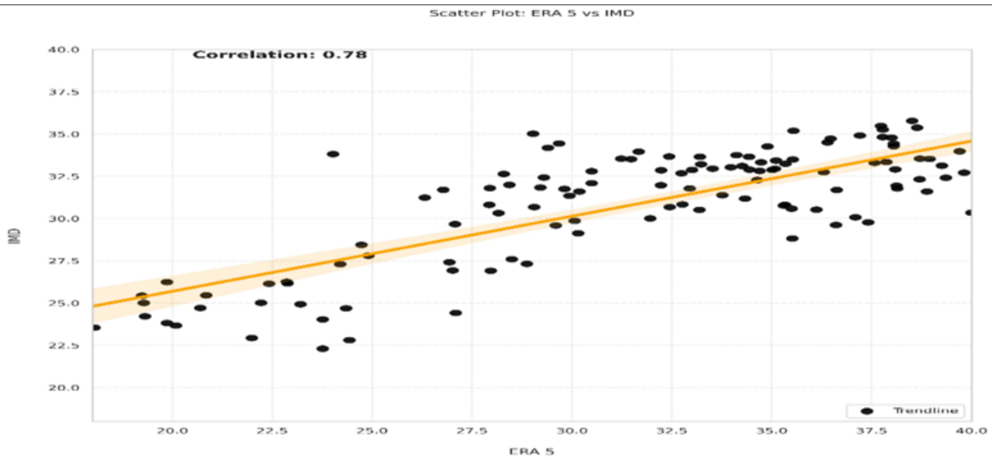

Fig.5(a)

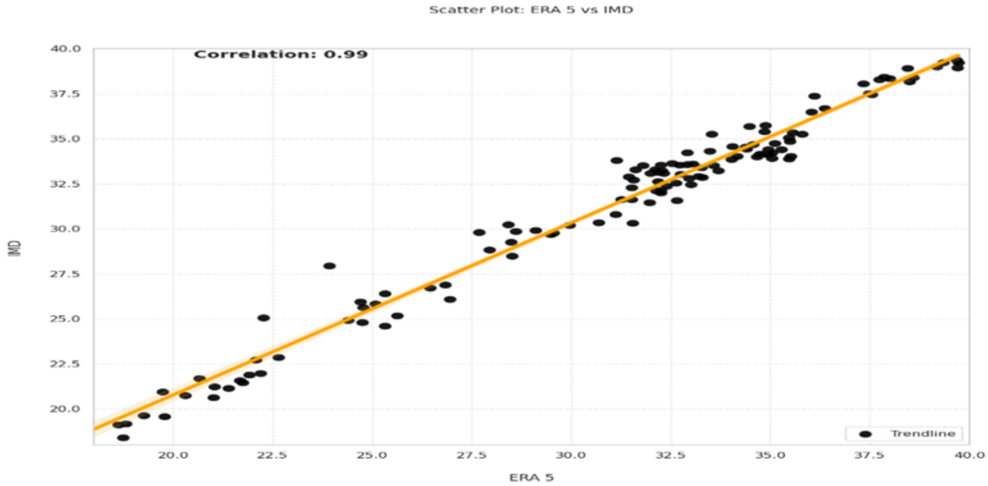

Fig.5(b)

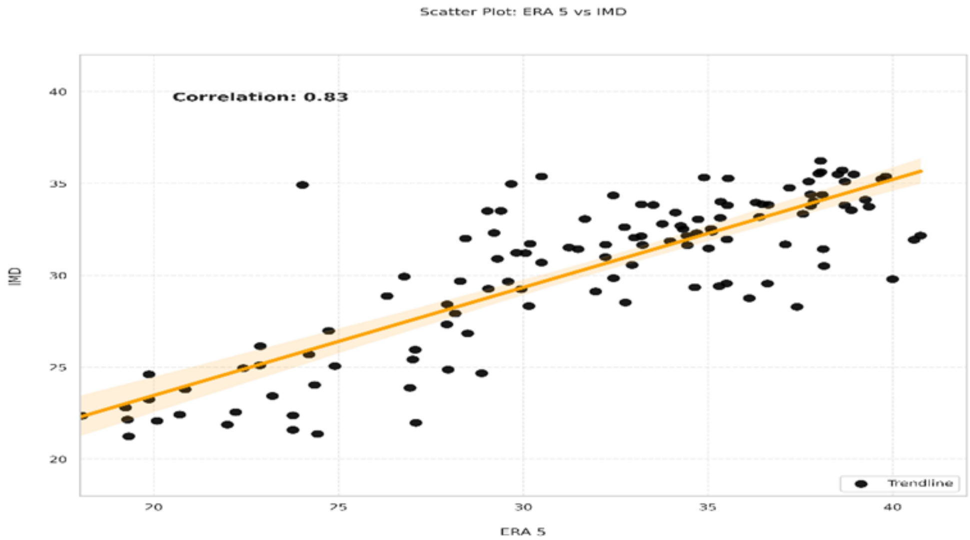

Fig.5(c)

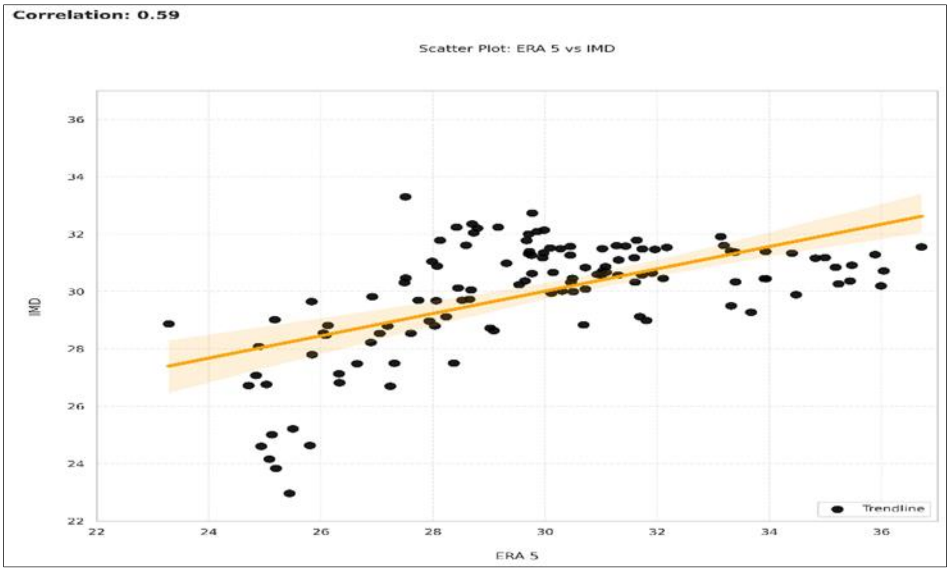

Fig 5(d)

Figure 5 Correlation between mean temperature of IMD Dataset and ERA5.

In **Figure 5(a)**, the correlation between IMD and ERA 5 datasets for Lucknow (March to June 2016) quantifies the statistical relationship between the meteorological data (specifically mean temperature) collected by the Indian Meteorological Department (IMD) and the data generated from ECMWF Reanalysis 5 (ERA 5). The correlation coefficient is 0.78, indicating a moderate degree of correlation. This coefficient is derived from the calculation of a correlation coefficient, which assesses how closely IMD measurements align with ERA 5 data.

In **Figure 5(b)**, the correlation between IMD and ERA 5 datasets for Jaipur (March to June 2019) represents the statistical relationship between meteorological data from IMD and ERA 5. The correlation coefficient is 0.99, indicating a very strong and close relationship between the datasets. This coefficient, obtained through correlation coefficient calculations, provides insights into the strength and direction of the relationship, confirming the reliability and consistency of mean temperature data in Jaipur during that period.

Figure 5(c) focuses on Delhi (March to June 2016), where the correlation between IMD and ERA 5 datasets yields a correlation coefficient of 0.83, signifying a good correlation between the two datasets. The correlation coefficient, calculated in this context, sheds light on the strength and direction of the relationship, offering valuable insights into the reliability and consistency of the meteorological data in Delhi.

Lastly, **Figure 5(d)** concerns Bhubaneswar (March to June 1988), where the correlation between IMD and ERA 5 datasets for mean temperature is 0.59. This coefficient indicates a less closely aligned relationship, as visually evident in the figure. Calculating a correlation coefficient helps determine how closely IMD measurements match with ERA 5 data during that specific time period in Bhubaneswar.

7. Conclusion

In order to describe the heat waves across India, this investigation aims to pinpoint the areas with the highest average surface temperatures as well as those that are most susceptible to them. Further research is done into the function that atmospheric wind patterns have in the development of heat waves. The most accurate temperature data set, available from the India Meteorological Department, was used by the authors. The data is generated 1 degree in- terval, taking into account all temperature evaluations that are known to be consistent with deviations in the terrain and surface, and it spans a lengthy 50-year period from 1972 to 2022.

- Three zones of greatest surface temperatures were found over West Rajasthan, East Maharashtra (Vidarbha), and North Madhya Pradesh, Southwest Uttar Pradesh, respectively.

- According to an examination of heat wave periods that took the IMD criteria into account, the northeast region of India experienced 34 (182 days) of heat waves, the North experienced 31 (165 days), & the southern region of India had 21 (111 days) of heat waves.
- ERA-Interim datasets proved reliable for detecting heatwaves in India from 1973 to 2022.
- India experienced an overall increase in Extremely Hot and Humid (EHF) days, with central and eastern states enduring more consecutive and intense heatwaves.
- Nearly all Indian states experienced summer heatwaves, with severe impacts mainly in eastern coastal and northwestern states.

In conclusion, this work presents a thorough analysis of Indian summer heatwaves, demonstrating the accuracy of ERA-Interim data in heatwave identification. Further refinement can be achieved by incorporating additional parameters such as sea surface temperatures and wind patterns, enhancing our understanding and forecasting of localized heatwaves.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no competing interests.

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