MAUSAM, **76**, 1 (January 2025), 303-316

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i1.6457
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No.551.524:551.509(540)

Evolution of heat wave monitoring and forecasting in India

M. MOHAPATRA, AKHIL SRIVASTAVA, RAGHU NADIMPALLI
and NARESH KUMAR

India Meteorological Department, Ministry of Earth Sciences, New Delhi-110 003

e mail :akhils.imd@gmail.com

सार– अध्ययन में ऊष्ण लहर पूर्वानुमान और चेतावनी सेवाओं के माध्यम से मौसम संबंधी पहलुओं के संबंध में नोडल एजेंसी के रूप में भारत मौसम विज्ञान विभाग की यात्रा का वर्णन किया गया। यह पिछले 150 वर्षों के दौरान ऊष्ण लहर की परिभाषाओं, वैज्ञानिक समझ, शोध और प्रचालनात्मक पूर्वानुमान पद्धतियों के संदर्भ में भारत के लिए विशिष्ट विकास से संबंधित है। अध्ययन ऊष्ण लहर प्रभाव पर आधारित प्रारंभिक चेतावनी और पूर्वानुमान सेवाओं के संबंध में आईएमडी द्वारा अपनाई गई निगरानी और पूर्वानुमान रणनीतियों, उपकरणों और तकनीकों की वर्तमान स्थिति पर भी प्रकाश डालता है।

ABSTRACT. The article describes the journey of India Meteorological Department as a nodal agency with respect to weather related aspects since its inception through the lens of Heat Wave forecasting and warning services. It deals with the evolution specific to India in terms of heat waves definitions, scientific understanding, researches and operational forecasting methodologies during the past 150 years. The article also touches upon the current situation of the monitoring and forecasting strategies, tools and techniques followed by IMD with respect to Heat Wave impact based early warning and forecasting services.

Key words – India, Heat waves, Impact based forecasting, IMD, History.

1. Introduction

Heat Waves have garnered a lot of interest in India and around the globe during recent decades due to underlying sustained average rate of increase of surface temperatures during past decades and their subsequent impact on all walks of life including agriculture, hydrological cycles, transport sector, physiological imbalances, Aviation and so on (Chaudhuri *et al*., 2000; Attri and Rathore 2003; Chakraborty *et al*., 2019, Dash and Mamgain, 2011; Siebert *et al*., 2014; Steffen *et al*. (2014), Kjellstrom and McMichael (2013); Patz *et al*. (2005); Hondula *et al*. (2014), Heo *et al*., 2019, Ray *et al*., 2021, Oldenborgh *et al*. (2018), Nitschke *et al*. (2007); Hansen *et al*. (2008); Wilker *et al*. (2012); Srivastava *et al*., 2022).Asia had witnessed year 2022, as its second-warmest year on record at +1.80 °C above average temperatures during 20th century and was also 35th consecutive year when temperatures were above average (NOAA, 2022). These trends supplemented with enhanced interest in global warming and visible impacts of heat waves have propelled many new studies on heat waves and its vagaries in recent years.

The current enthusiasm over heat waves particularly from 21st century is linked largely to its enhanced negative implications for the society and ecology but there had been significant and consistent interest in the monitoring and forecasting of Heat Waves over India from past several decades and can be traced up to the formative years of India Meteorological Department (IMD) in 1875. There are many publications from late 19th century and 20th century pointing to the efforts and strategies followed in the monitoring and forecasting of heat waves over India. India Meteorological Department (IMD), the nodal agency of Government of India for all meteorological aspects, has been in the forefront with respect to the monitoring, forecasting and understanding of Heat wave over the country during all these decades. A paper published in 1889 based on *Indian Meteorological Memoirs* mentions about the importance given to the evaluation of incident solar heat and manned mission were planned under auspices of IMD to Leh, Shimla and Mussoorie to take physical observations of solar heat around 1882. Due to constraint in the instrument design and technology these didn’t generate fruitful conclusions but were very important steps to study the solar heating (B. H., 1892). Apart from solar heat, this process also brought out the increased temperature of the earth-surface as compared to the air aloft and also discussed the increase in temperature with depth (B.H., 1892). The paper published in 1905 based on *Indian Meteorological Memoirs* discusses about the temperature variation s during 1892 to 1905 and brings about the fact that the temperatures were above average during 1894 to 1905 and below average during 1892-94 (M.W., 1905). The first of its kind climatological atlas was published in 1905 considering the 30 years data since the establishment of India Meteorological Department in 1875 (Hann, 1907). This gave details about the mean temperatures, annual maximum and minimum temperatures, diurnal ranges with the help of isotherms (Hann, 1907).

The increased importance given to heat wave events could be understood by the fact that first ever published Mausam Journal (Formerly Indian Journal of Meteorology and Geophysics Vol. 1. No. 1) in January 1950 contained an editor piece describing the intense and sweltering heat waves over United Province that occurred in 1949 and caused heat strokes on human, loss of fauna and impact on agriculture (E. Mausam, 1950). There had been regular publication by IMD with respect to disastrous weather events which also included Heat Wave events. For instance, the climatological aspect of heat waves over India during 1911 to 1961 and 1962 to 1967 were studied by Raghavan (Raghavan, 1966) and Bedekar (Bedekar *et al.*, 1974) respectively. The Disastrous heat weather events of 1967 published details regarding the moderate to severe heat wave events over Bihar, Orissa and parts of Andhra Pradesh in the first week of June (IMD, 1979). The first comprehensive forecasting manual with respect to heat waves origin, climatology and forecasting aspects was published in 1974 (Bedekar *et al.*, 1974).

2. Evolution of heat waves monitoring and forecasting in Indian context: unified seamless forecasting system

IMD is the nodal agency regarding all meteorological aspects in India. In this respect since its inception in 1875 IMD has been involved in the day-to-day monitoring and forecasting of Heat waves, its intensity, spatial and temporal extensions. In the beginning the surface temperature were observed in different observatories which became the initialization of monitoring of temperature and its variation & tendency in India. These temperatures along with their climatological information became the basis of classification and criteria of Heat Waves. The departures of observed temperatures with respect to the normal temperatures of a region.

Initially, the practice at IMD was to declare a region (or a station) under the grip of "Moderate Heat Wave", if recorded temperatures were 6 ºC to 7 ºC above normal and it was called a "Severe Heat Wave" if maximum temperatures were 8 ºC or more above normal (IMD 1958, Raghavan 1966). It was also seen that the Heat Wave was generally recommended to be used when maximum temperatures were 8 ºC or more above normal and to cover moderate heat wave activities with the nomenclature of markedly above normal temperatures (Bedekar *et al.*, 1974). These criteria didn't take into account the actual temperatures but uses departures considering the acclimatization and physiological responses of human being (Bedekar *et al.*, 1974). This nomenclature associated with temperatures and heat waves was modified in 1978 (DDGM (WF) UOI NO. W-33808/ dated November 1978) by replacing the terminology of "Nearly Normal" to "Normal" as depicted in Fig. 1.

These nomenclatures were further modified in 1989 (DDGM (WF) UOI No. W-969/ 6015 to 6024 dated 23 December 1988) by providing separate nomenclature for departures of maximum temperatures to regions when normal maximum temperature is 40 ºC or below and for regions where normal maximum temperatures are more than 40 ºC (Fig. 2.).

Extracts from DDGF's Technical Circular Forecasting No. 23*

TEMPERATURES

Magnitude of change or departure in 0°C	Description of change	Description of departure
1 to -1	Little change	Nearly normal
2 to 3	Rise	Above normal
4 to 5	Appreciable rise	Appreciably above normal
6 to 7	Marked rise	Markedly above normal (Moderate heat wave)
8 or more	Large rise	Severe heat wave
-2 to -3	Fall	Below normal
-4 to -5	Appreciable fall	Appreciably below normal
-6 to -7	Marked fall	Markedly below normal (Moderate cold wave)
-8 or more	Large fall	Severe cold wave

Fig. 1 Sourced from IMD Forecasting Manual Part IV issued by The Deputy Director General of Observatories (Forecasting) (October 1974)

DDGM (WF) UOI No.W-969/ 6015 to 6024 dated 23 December 1988

Ref.: DDGM (WF) UOI No.W-969/ 4037 to 4065 dated 18 October 1988.

As per Rec. No. 13 of the Xth F.O.'s conference a set of new criteria for declaring heat wave/ cold wave conditions have been circulated vide letter under reference. Some offices pointed out anomalies in description of the 24 hrs temperature changes and the new criteria for heat wave/ cold wave conditions. Those anomalies are inevitable because of the existence of old set of limits for describing 24 hrs temperature changes and a new set for describing heat wave / cold wave conditions. All these aspects have been critically examined. To remove these anomalies the following revised criteria for describing the 24 hrs temperature changes shall be effective w.e.f. 1-1-1989.

A) Maximum temperature

(a) When the normal maximum temperature of a station is 40° C or below.

Nomenclature	Past 24hrs change
Little change	-1° C to 1° C
Rise	2° C
Appreciable rise	3° C to 4° C
Marked rise	5° C to 6° C
Large rise	7° C or more

(b) When the normal maximum temperature of a station is more than 40° C.

Nomenclature	Past 24hrs change
Little change	-1° C to 1° C
Rise	2° C
Marked rise	3° C to 4° C
Large rise	5° C or more

B) Minimum temperature

(a) When the normal minimum temperature of a station is 10° C or more.

Nomenclature	Past 24hrs change
Little change	1° C to -1° C
Fall	-2° C
Appreciable fall	-3° C to -4° C
Marked fall	-5° C to -6° C
Large fall	-7° C or less

(b) When the normal minimum temperature of a station is less than 10° C.

Nomenclature	Past 24hrs change
Little change	1° C to -1° C
Fall	-2° C
Marked fall	-3° C to -4° C
Large fall	-5° C or less

These instructions supercede the earlier instructions on the matter.

Sd/
(D. S. Desai)
For D.D.G.F.

Fig. 2. sourced from IMD Forecasters' Guide (2008)

A) **Heat Wave**

Heat wave is considered if maximum temperature of a station reaches at least 40^{0}C or more for Plains and at least 30^{0}C or more for Hilly regions.

a) **Based on Departure from Normal**

Heat Wave: Departure from normal is 4.5^{0}C to 6.4^{0}C
Severe Heat Wave: Departure from normal is >6.4^{0}C

b) **Based on Actual Maximum Temperature**

Heat Wave: When actual maximum temperature ≥ 45^{0}C
Severe Heat Wave: When actual maximum temperature ≥47^{0}C

c) **Warm Night**

It should be considered only when maximum temperature remains 40^{0}C or more. It may be defined based on departures or actual minimum temperatures as follows:

Warm night: minimum temperature departure is 4.5^{0}C to 6.4^{0}C
Very warm night: minimum temperature departure is >6.4^{0}C

d) **Criteria for describing *Heat Wave* for coastal stations**

When maximum temperature departure is 4.5^{0}C or more from normal, *Heat Wave* may be described provided actual maximum temperature is 37^{0}C or more.

Fig. 3. Sourced from India Meteorological Department Forecasting Circular No. 5/2015 (3.7)

Finally, in 2002 the criteria were again revised to declare Heat Waves in the Annual Monsoon Review (AMR-2002) meeting of 2002. Also, role of minimum temperature departures in declaring warm night situations was clearly demarcated. This revision saw the major changes in the criteria of Heat Wave definition used by IMD and introduced separate threshold maximum temperatures for Plains, Hilly and Coastal regions along with the declaration of heat waves once actual maximum temperatures crosses 45 ºC criteria irrespective of the normal maximum temperatures of a place. The objective criteria for warm night declaration were provided along with the condition that, either Heat Wave (based on maximum temperature criteria) or warm night (based on minimum temperature criteria) was declared prioritizing heat wave warnings over warm nights. The further development came in 2008 when the maximum temperature forecast for 5 days lead time was introduced at district level. Further refinements in the declaration of heat waves monitoring and forecast were introduced with forecasting circular (Forecasting Circular No. 5/2015 (3.7)) issued in 2015 which brought out the fact that the Heat Wave and warm night warnings based on maximum temperature, minimum temperature and their departures can co-exist and required to be provided simultaneously in warnings. The criteria of 2 stations in a met-subdivision with persistency of conditions for 2 days before declaring heat waves was also introduced with this circular. The finalized objective criteria defined in 2015 is shown in Fig. 3. These definitions are currently been used in IMD along with some further refinement considering the shift towards Impact based forecasting (details provided in subsequent sections).

There were also significant developments and transitions towards seamless unified forecasting system of IMD with respect to heat waves and temperatures during the past decade. With Forecasting circular No.1/2014,

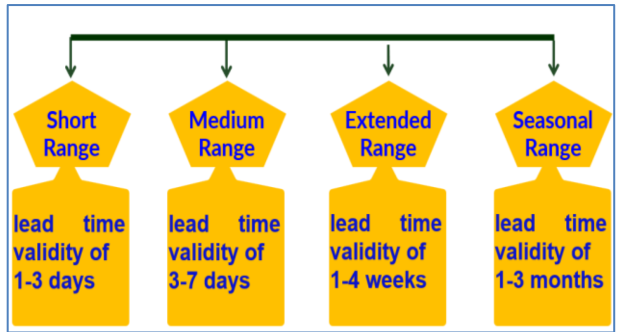


Fig. 4. Unified & Seamless Temperature forecast and Warning system of IMD

nearly one week forecast issuance in IMD consisting of 3 days forecast & warning and subsequent 4 days of outlook was started. These issuances were further improved with Forecasting Circular No. 1/2015 where forecast and warning validity was increased from 3 days to 5 days and subsequent outlook was reduced to 2 days from 4 days making more actionable 5 one week forecast. Year 2016 saw another development with the introduction of seasonal outlook of temperatures for heat waves over the country at sub-division scales and in 2017 the Extended range heat wave guidance (2 weeks lead time) was initiated. This marked the transition of IMD's temperature and heat wave warning towards seamless unified forecast system covering seasonal (1-3 months lead time/validity), extended range (1-4 weeks lead time/validity), medium range (4-7 days lead time /validity) and short range (1-3 days lead time/validity) forecasting (Fig. 4).

3. Recent research efforts for heat wave monitoring and predictions.

There have been lot of efforts to improve heat waves understanding, their climatological perspective, monitoring and forecasting aspects. The following section provides a brief review of some of the recent studies pertaining to modelling, climatological and other aspects related to heat waves.

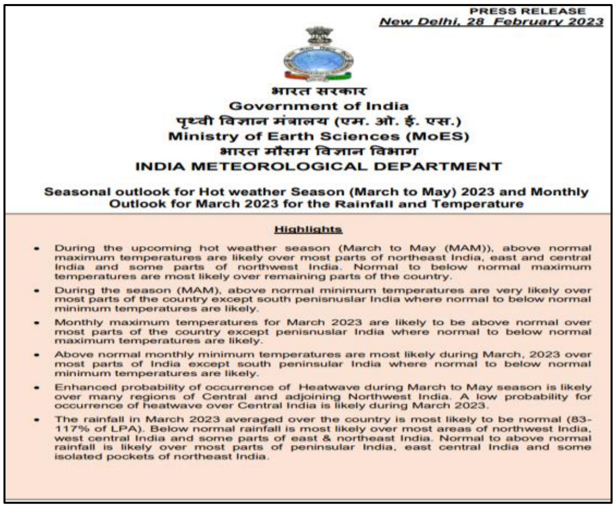
Regional climate models (RCMs) are utilized globally to extract detailed climate data from global climate models (GCMs) [Beniston *et al.*, 2007]. RCMs have the ability to accurately represent local climate features such as temperature and precipitation systems at a finer scale due to improved surface physics and higher resolution [Giorgi *et al.*, 1989 and Li *et al.*, 2020]. Numerical weather prediction (NWP) models have been employed to investigate the mechanisms behind heat waves and explore interactions between land and atmosphere [Fischer (2007) and Patel *et al.*, 2022]. Recent advancements in computational power and the availability of frequent input data have allowed NWP models to forecast heat wave events with greater precision over large areas [Patel *et al*., 2022]. In recent years, there have been significant improvements in the forecasting capabilities of NWP models, prompting researchers to simulate weather parameters at high spatial and temporal resolutions for both research and operational purposes [Srivastava *et al*. 2022; Nadimpalli *et al*. (2023); Mohanty *et al*. (2022)]. The ability of mesoscale models, like the Weather Research and Forecasting (WRF) model (Skamarock *et al*. 2008), to replicate urban processes relies on accurately representing the land surface and effectively simulating processes at scales that reflect urban heterogeneities (Talbot *et al*., 2012; Nadimpalli *et al*., 2023). The WRF model is a cutting-edge RCM for dynamic downscaling [Ren *et al*., 2022; Boyaj *et al*., 2023]. However, accurately applying NWP models to forecast heat wave events and other climatology requires careful selection of model parameterization schemes [Kharin *et al*., 2023]. In the NWP model, diverse physical parameterization schemes are used to predict weather forecasts [Shrivastava *et al*., 2014]. Thus, choosing an appropriate combination of physical parameterization schemes is of utmost importance as it significantly influences the simulation [Fischer *et al*., 2007].

Land surface processes have a substantial impact on elevated temperatures [Patel *et al*., 2022]. The land surface encompasses various intricate surfaces that play a crucial role in the Earth's atmospheric boundary. The exchange of energy, water vapor, momentum, and radiative transfer between the land and atmosphere is governed by land surface processes. Consequently, there exists a close correlation between the land surface and high temperatures, influencing local, regional, and global atmospheric circulation, as well as climate change [Sellers *et al*., 1997]. To further investigate this relationship, Jin, Miller *et al*. (2010) examined the sensitivity of four land surface schemes (LSS) in the WRF: the simple soil thermal diffusion (STD) scheme, Noah scheme, RUC scheme, and community land model. The study conducted by Lhotka *et al*. (2018) demonstrates that land surface activities have a significant impact on temperature simulations in the western United States. The researchers examined how well the model represented land-atmosphere interactions and large-scale circulation during heat waves using RCMs. They discovered that the RCMs both overestimated and underestimated these events in central Europe, while the ensemble mean of EURO-CORDEX accurately captured the extremity of heat waves [Lhotka *et al*. 2018]. Additionally, the introduction of the new classification system known as Local Climate Zones (LCZs) by Stewart and Oke (2012), along with the global standardization provided by the World Urban Database Access Portal Tool (WUDAPT; http://www.wudapt.org/), presents an opportunity to enhance the representation of land use and land cover (LULC) in mesoscale models [Bechtel *et al*., 2015; Mills *et al*., 2015; Ching *et al*., 2018; Nadimpalli *et al*.., 2022; Patel *et al*. 2022]. Furthermore, the development of the Building Effect Parameterization and Building Energy Model (BEP) by Salamanca *et al*. (2010) has allowed for the parameterization of atmospheric processes on a grid-scale resolution within the Weather Research and Forecasting (WRF) model.

Numerous studies have been conducted in different regions of the world, but there is a scarcity of literature based on NWP specifically focused on the Indian subcontinent. Mohan and Gupta (2018), Gunwani and Mohan (2017), and Sathyanadh, *et al*. (2017) utilized various physical WRF schemes to enhance the accuracy of meteorological variables in different parts of India. In the Iran region, Zeyaeyan*et al*. (2017) investigated the impact of 26 different PBL, cumulus, and microphysical schemes on summer rainfall. The sensitivity of the WRF model's schemes was assessed across northwest India, and it was found that a combination of physical parameterization schemes, including Kain-Fritsch cumulus, YSU PBL, Dudhia shortwave, RRTM longwave radiation, and one-moment microphysics, yielded improved results (Patil and Kumar, 2016). In India, there have been limited studies on predicting heat waves in real-time. These studies utilize real-time extended-range forecasts (Mandal *et al*., 2019; Pattanaik *et al*., 2017). The real-time extended-range forecast for heat waves in India in 2015 indicated an upcoming extreme temperature in different parts of the country with a lead time of 2 weeks (Pattanaik *et al*., 2017). Another study by Mandal *et al*. (2019) found that the real-time extended-range forecast system (IITM-IMD) is effective in predicting heat waves in India with a 2-week lead time.

A recent study (Singh *et al*., 2017) demonstrates that ensemble forecasts are better than deterministic forecasts in detecting extreme temperature events. In this regard, IMD has also developed a Multi-Model Ensemble tool to provide the numerical guidance with respect to rainfall distribution, intensity, temperatures, relative humidity *etc*. The MME for this purpose employs different global models from Indian as well as other global modeling center to generate the numerical guidance to support forecasting activities with respect to Heat waves & warm nights (maximum & minimum temperatures) at district level in IMD (Bushair *et al*., 2023).

Since the beginning of the establishment of IMD, there has been a lot of focus on the observations and monitoring aspects of temperatures as well as associated features. The same is continuing till date and is also one of the prime mandates of the organization. These observational data and network of IMD has been utilized in number of observational studies to improve the



PRESS RELEASE
New Delhi, 28 February 2023

भारत सरकार
Government of India
पृथ्वी विज्ञान मंत्रालय (एम. ओ. ई. एस.)
Ministry of Earth Sciences (MoES)
भारत मौसम विज्ञान विभाग
INDIA METEOROLOGICAL DEPARTMENT

Seasonal outlook for Hot weather Season (March to May) 2023 and Monthly Outlook for March 2023 for the Rainfall and Temperature

Highlights

- During the upcoming hot weather season (March to May (MAM)), above normal maximum temperatures are likely over most parts of northeast India, east and central India and some parts of northwest India. Normal to below normal maximum temperatures are most likely over remaining parts of the country.
- During the season (MAM), above normal minimum temperatures are very likely over most parts of the country except south penisnuslar India where normal to below normal minimum temperatures are likely.
- Monthly maximum temperatures for March 2023 are likely to be above normal over most parts of the country except penisnuslar India where normal to below normal maximum temperatures are likely.
- Above normal monthly minimum temperatures are most likely during March, 2023 over most parts of India except south peninsular India where normal to below normal minimum temperatures are likely.
- Enhanced probability of occurrence of Heatwave during March to May season is likely over many regions of Central and adjoining Northwest India. A low probability for occurrence of heatwave over Central India is likely during March 2023.
- The rainfall in March 2023 averaged over the country is most likely to be normal (83-117% of LPA). Below normal rainfall is most likely over most areas of northwest India, west central India and some parts of east & northeast India. Normal to above normal rainfall is likely over most parts of peninsular India, east central India and some isolated pockets of northeast India.

Fig. 5. Seasonal Outlook release for Hot Weather Season of 2023 and Month of March 2023

Colour code	Alert	Warning	Impact	Suggested Actions
Green (No action)	Normal Day	Maximum temperatures are near normal.	Comfortable temperature. No cautionary action required.	No cautionary action required
Yellow Alert (Be updated)	Heat Alert	Heat wave conditions at isolated pockets persists on 2 days	Moderate temperature. Heat is tolerable for general public but moderate health concern for vulnerable people e.g. infants, elderly, people with chronic diseases	(a) Avoid heat exposure. (b) Wear lightweight, light coloured, loose, cotton clothes. (c) Cover your head: Use a cloth, hat or umbrella
Orange Alert (Be prepared)	Severe Heat Alert for the day	i. Severe heat wave conditions likely to persist for 2 days. ii. With varied severity, heat wave is likely to persist for 4 days or more.	High temperature. Increased likelihood of heat illness symptoms in people who are either exposed to sun for a prolonged period or doing heavy work. High health concern for vulnerable people e.g. infants, elderly, people with chronic diseases.	a) Avoid heat exposure– keep cool. Avoid dehydration. (b) Drink sufficient water- even if not thirsty. (c) Use ORS, homemade drinks like lassi, torani (rice water), lemon water, buttermilk, etc. to keep yourself hydrated
Red Alert (Take Action)	Extreme Heat Alert for the day	i. Severe heat wave likely to persist for more than 2 days. ii. Total number of heat/severe heat wave days likely to exceed 6 days.	Very high likelihood of developing heat illness and heat stroke in all ages.	Extreme care needed for vulnerable people.

Fig. 6 Impact based forecast matrix with action suggested used by IMD

understanding of heat waves leading to their better forecasting. These recent studies have by and large indicated an increasing trend in heat waves, temperatures in India and some of them also studied their relationship with EL Nino. (Pai *et al*., 2013; Jaswal *et al*., 2015;Ratnam et al., 2016; Jaswal *et al*., 2017; Pai *et al*., 2017;Rohini *et al*., 2016; Pai and Smitha 2022; Devi *et al*., 2023). The phenology of heat waves was also studied over India using data from 1951-2015 (Satyanarayan & Bhaskara Rao, 2020). A number of heat wave studies are studying their impact on humans (Debnath *et al*., 2023). Dodla *et al*. (2017) analyzed the 2015 catastrophic heat wave over the east coast of India, which claimed about 2500 lives. Many studies are exploring the utilization of different indices to convey the impact information of heat waves to reduce loss of life and property. Mazdiyasni *et al*. (2017) showed that even a moderate increase in average temperatures can lead to a sharp rise in heat-related mortality and supports the efforts of governments and international organizations. Jaswal *et al*. (2017) studied heat index evolution in scenario of climate change. There are also efforts going on to indicate the relative and cumulative effect of different meteorological parameters such as Maximum temperatures, minimum temperatures, wind, relative humidity and persistence of heat waves in aggravating the impact of heat waves (Srivastava *et al*., 2022). Sharma and Mujumdar (2017) addressed the question of impact of concurrent occurrence of droughts and heat waves. Recently lot of interest is also seen on Artificial Intelligence and Machine Learning based tools in monitoring and forecasting of these extreme temperature events (Narkhede *et al*., 2022; Suthar *et al*. 2023; Shah *et al*., 2023, Ratnam *et al*., 2023).

4. Current status of heat wave monitoring and forecasting in India: impact based forecasting & multi-agency coordination

With the introduction of seasonal outlook in 2016 (Fig. 5) and extended range guidance in 2017 IMD has been providing seamless forecast of Heat Waves which is continuing till present. 2017 was one of the defining moments in forecasting in IMD, where by Impact based forecasts of weather events along with general weather information was started. This saw the bulletins with information not only about the occurrence and severity of heat waves but also contained the impact of heatwaves / warm nights over different sectors and walks of life.

IMD has been providing the colour coded warning messages based on the severity of the events (considering different meteorological parameters) and their persistence to convey the impact-based heat wave warnings (Fig 6). These impact parameters have evolved based on consultation with different stakeholder and National Disaster Management Authority (NDMA). The impact associated with the heat wave events get aggravated by different meteorological and socio-economic consideration. In this regard IMD has been transitioning from subjective assessment of meteorological and socio-economic conditions towards objective assessment of meteorological and socio-economic consideration to provide specific impact-based forecast and warning services (Fig. 7).

To further improve the Impact based forecasting with respect to Heat Wave services, Hot weather hazard analysis was conducted over India considering the differential and cumulative localized impacts of different meteorological parameters (Maximum Temperatures, Minimum Temperatures, Relative Humidity, Wind Speed and Persistence of Heat Waves) in aggravating the situation of Heat Wave over the country

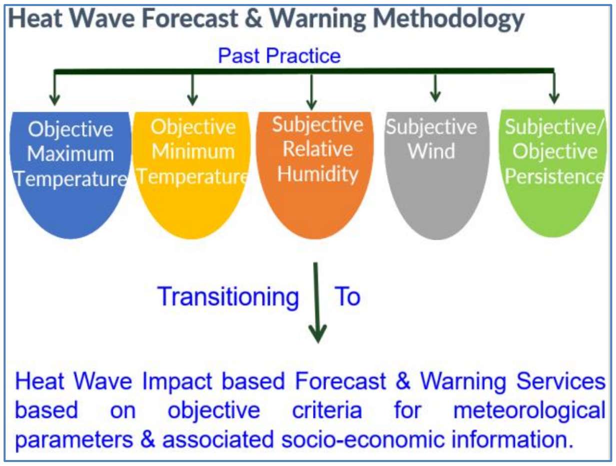


Fig. 7. Meteorological & Socio-Economic criteria for Impact based forecast & warnings

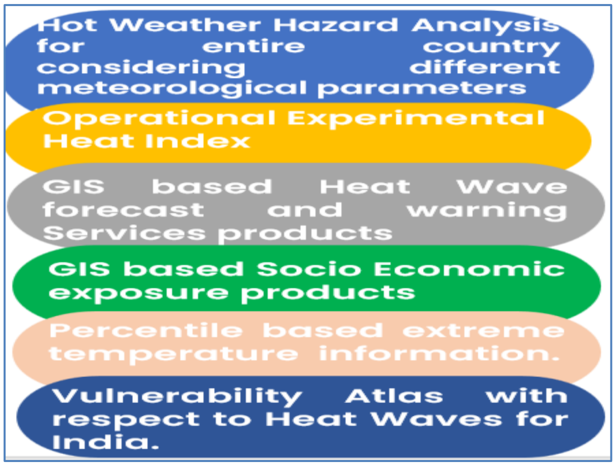


Fig. 8 List of products currently utilized for Heat Wave Warning Services in IMD

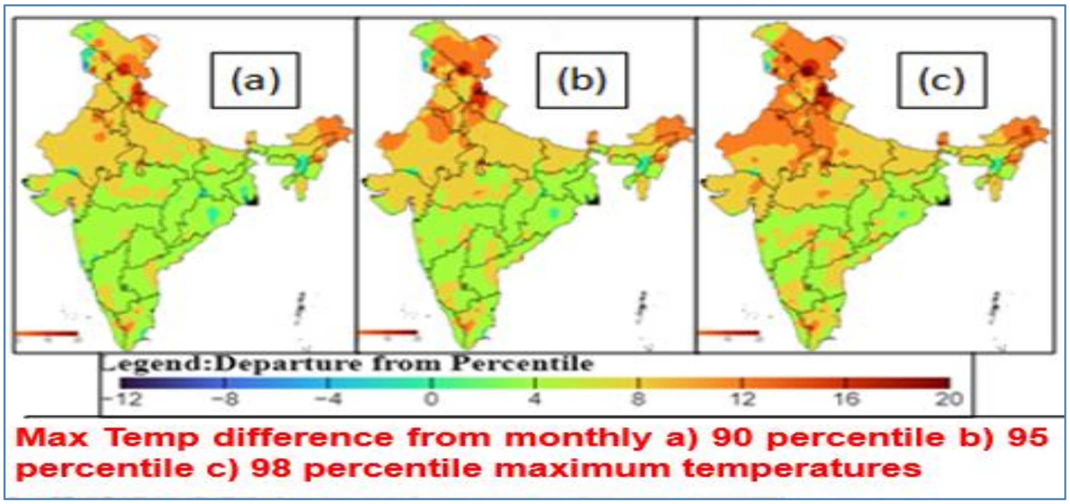


Fig. 9. Percentile based products with respect to Maximum Temperatures

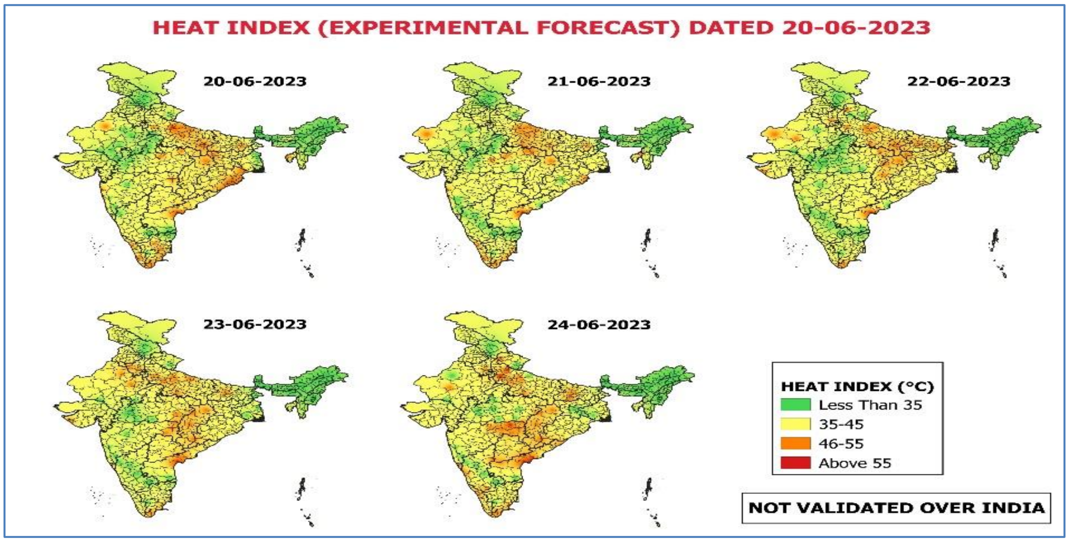


Fig. 10. Experimental Heat Index forecast operationalized in 2023 by IMD

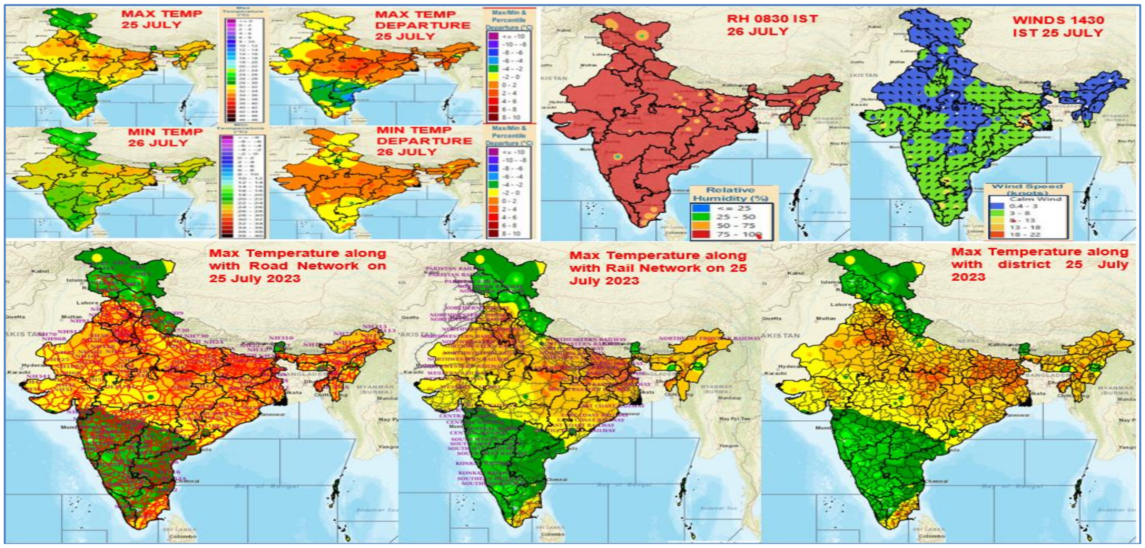


Fig. 11. GIS based products (Max Temperature & Minimum Temperature with their departures, Relative Humidity, Wind Speed and Exposure layers of Road & Rail network) provided to support Heat Wave forecast and warning dissemination by IMD

(Srivastava *et al*., 2022). This study is a step towards transition from currently practiced subjective to objective utilization of meteorological parameters in providing the impact-based warnings related to Heat Waves. IMD has evolved and improved the forecast and warning services during past few years by introduction of new techniques and products dedicated for heat wave services including on GIS platform (Fig. 8). IMD also introduced percentile based maximum and minimum temperature categorization to convey the extremeness of the events. It also provides the observed and forecast information with respect to top 90, 95 & 98 percentile crossing regions of the country for mitigation and precautionary actions (Fig. 9). IMD also experimentally introduced the operational Heat Index forecast for next 5 days in 2023 to convey the feel like temperature considering the temperature and relative humidity and their physiological impact-based color-coded warnings (Fig. 10). For this purpose, IMD utilizes the station level value added maximum temperature forecast provided by the field offices along with the Relative Humidity forecast generated at IMD using MME technique. Substantive efforts are invested by IMD in research and study of new tools, techniques and indices for Heat Wave forecasting such as Excess Heat Factor Index, Wet bulb globe temperatures *etc*.

As indicated earlier, IMD has also started to provide the heat wave and temperature information (observed & forecast) in geographic information system (GIS) platform in addition to routinely available dissemination methods. This has helped the stake holders and disaster managers to have localized impact-based warnings for further mitigation actions at different spatial scales. The same is hosted on IMD website at https://dss.imd.gov.in/dwr_img/GIS/heatwave.html. Utilising the GIS based framework all products including maximum temperatures, minimum temperatures, wind, RH, Heat Index, Exposure layers (Hospitals, Sports stadiums, Airport, Oil refineries, Roadways, Railways *etc.*) with heat wave warnings are provided to stakeholders and general public which can be utilised to extract localized heat wave information (Fig. 11).

Till hot weather season of 2023 (March-June), IMD has been issuing the All-India Weather Forecast & All India Weather Warning Bulletins updated 4 times in a day based on 0530 hours IST, 0830 hours IST, 1430 hours IST and 1730 hours IST consisting of the updated observed and forecast information (5 days forecast & subsequent 2 days outlook) with respect to temperatures, heat waves and warm nights. IMD also issues dedicated Heat Wave Bulletins on daily basis covering all aspects of Heat Waves with 5 days forecast and subsequent 2 days outlook. Apart from this IMD has also started providing sectoral bulletins with respect to Heat Wave forecasting for *e.g*., Climate information for health bulletin providing guidance with respect to evolution of transmission window for Malaria and Dengue (vector borne diseases). These bulletins are regularly been disseminated through different mediums such as through emails, print & electronic media, websites, Common Alert Protocols, Whatsapp groups, YouTube, Facebook, twitter, Instagram, X (twitter) & through different other social media platforms. Daily & Weekly audio-video information is also disseminated to the general public & stake holders.

IMD has been also playing a vital role in development of Heat Action Plans (HAP) in coordination with NDMA & local agencies. At present the HAP are being

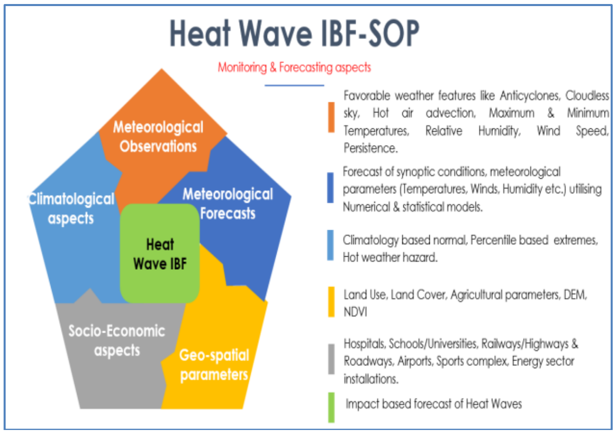


Fig. 12. Inputs used for Impact based forecasting of Heat waves in IMD

worked out in 23 states (PIB 2022). HAPs are comprehensive early warning system & preparedness plan for extreme heat events suggesting immediate as well as long-term actions to increase preparedness, information sharing and response coordination to reduce the health impacts of extreme heat on vulnerable populations. The plan intends to facilitate coordination between different government agencies, healthcare sector and other stakeholders to work with an integrated approach and implement strategies for behavior change to mitigate the ill effects of heat waves particularly on most vulnerable population. The steps suggested under HAP provides for adjustment of work hours, school hours and other arrangements necessary to tackle heat waves (Knowlton, 2014). In 2023, Jodhpur (Rajasthan) heat action plan was implemented using the early warning services of IMD.

5. Current heat wave forecasting standard operating procedure

For issuing Heat Wave monitoring and forecasting different meteorological observations, climatological aspects, meteorological forecasts in association with geo-spatial and socio-economic parameters are used as show in Fig. 12.

The brief overview with respect to main meteorological observations & forecasts utilized in the monitoring & forecasting aspects of Heat waves services in IMD is presented in Table 1.

The inputs such as surface and upper air charts, change chart, T-phi gram, Radar & Satellite products and guidance from various global & regional Numerical Weather Prediction (NWP) models (IMD Global Forecast System (GFS), NCEP GFS, NCMRWF Unified Model (NCUM), Global Ensemble Forecast System (GEFS) of MoES, NCMRWF Ensemble Prediction System (NEPS), European Centre for Medium Range Weather Forecast (ECMWF) model, Regional Weather Research & Forecasting (WRF) Model of IMD and NCMRWF regional (NCUM-R) model) are used in conjunction with the climatological information based on normal, departures, percentiles and past hazard to decide on the severity of the Heat wave events. The information with respect to geo-spatial and socio-economic parameters is then analyzed with respect to severity of heat wave events to generate and disseminate impact-based forecast of heat waves.

6. Heat wave forecasting skills of IMD during past decade.

IMD has been continuously improving the heat wave forecast and warning services. The operational setup of heat wave forecasting has evolved to provide better and actionable guidance for different stake holders. The temperatures (maximum & minimum) and their anomaly forecast for seasons and months are issued maintaining the temporal connectivity with extended range and short to medium range forecast. The Fig. 12 provides the evolution of skills of heat wave forecasting of IMD during 2016-2023. Considering data for years 2016 to 2023, there has been a gradual improvement in the heat wave forecasting skill as seen from different skill scores. Probability of detection (PoD) has consistently improved during 2016-2023 except in 2021 which was covid affected year. The Probability of Detection has improved by 20%-30% for Day 1 to Day 5 forecasts in 2023 as compared to 2016 and the POD for Day 1 forecast reached 95% in 2023 against 81% in 2016. Similarly, False alarm rate (FAR) and missing rate (MR) has been reduced during this period. The PoD close to 100% is observed for day 1 forecast and around 90% for day 2 forecast, 65% for day 3 forecast and around 50% for day 4 & day 5 forecast. The critical success index of 60% and above is seen for 2 days forecast lead time and is close to 50% for 72 hours forecast.

The following definition is used for the skill score metrics used in Fig. 13.

(*i*) The Probability of Detection (POD) quantifies the fractional success of the forecast system in predicting the particular event on the occasions when it actually occurs, with a score of 100% indicating a perfect hit score.

(*ii*) The False Alarm Rate (FAR) is the ratio of false alarms to the total amount of non-occurrence’s of the event. FAR of 0% indicates perfect score.

(*iii*) Missing Rate (MR) is the ration of missed events to the total number of events that have occurred. MR of 0% indicates perfect score.

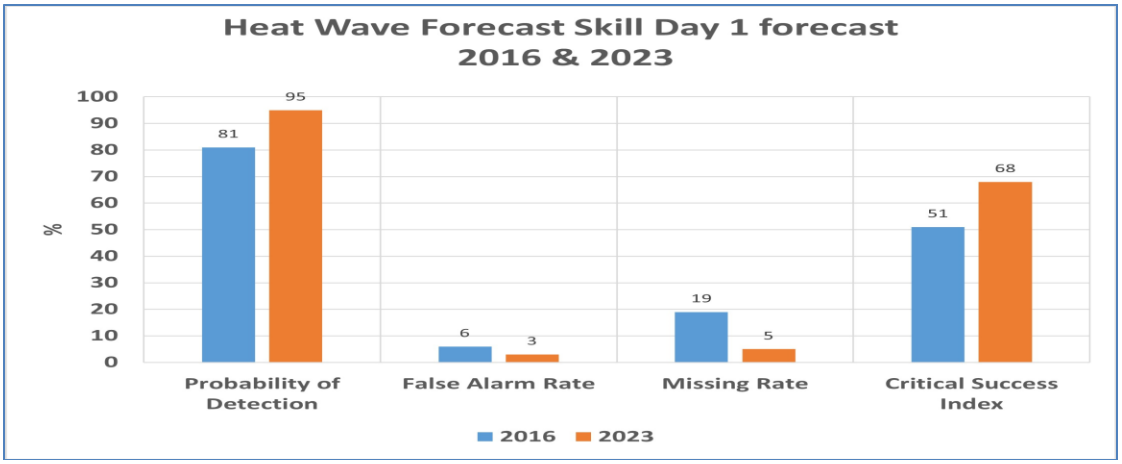
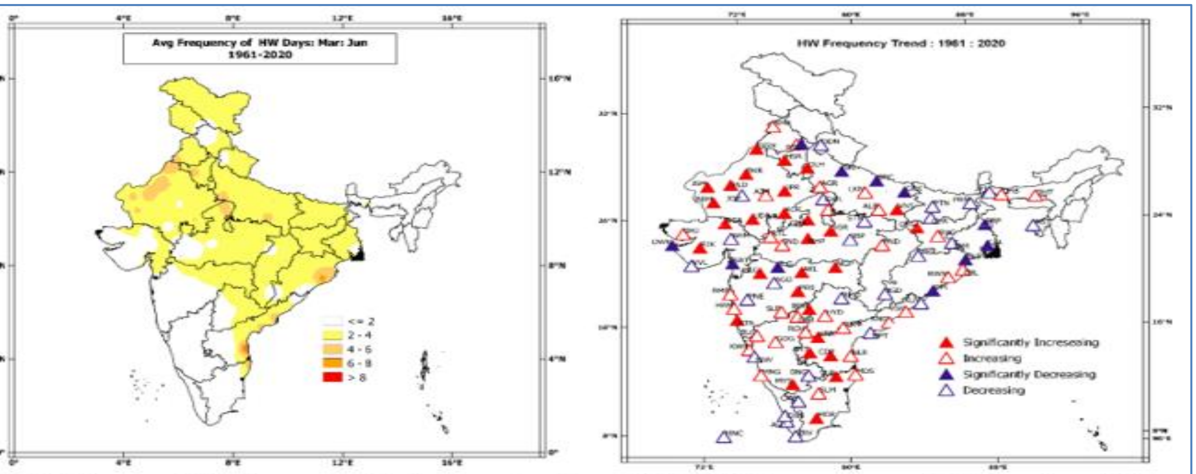


Fig. 12. Inputs used for Impact based forecasting of Heat waves in IMD

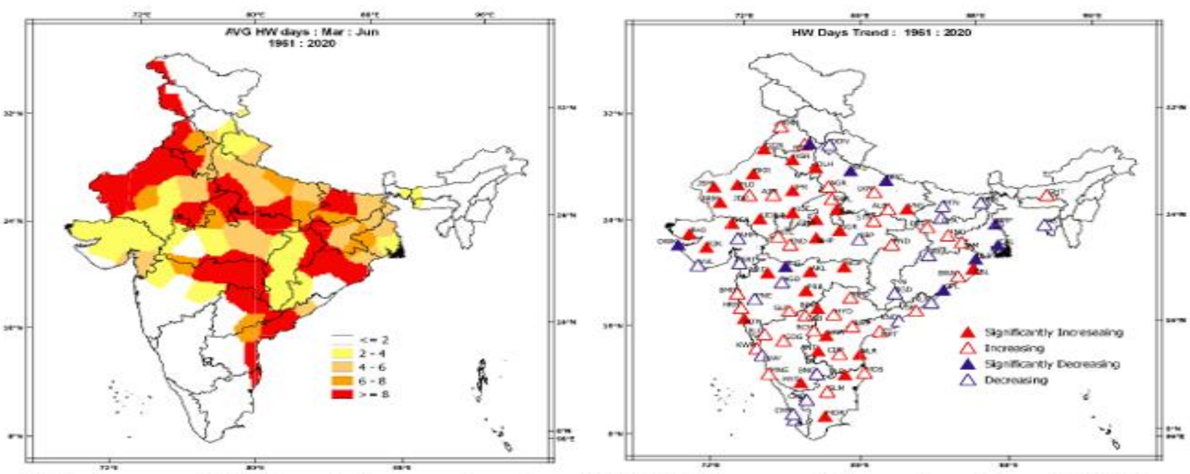
TABLE 1

Heat Wave Monitoring & Forecasting (Meteorological aspects)

Parameter	Criteria	Source	Product	Remarks
Temperature	High Maximum Temperature	Synoptic Observations Model Analysis & forecast	Max Temp. Max Temp. Departures Max Temp. tendency	High /above normal max Temperatures to be pointed out as probable region of Heat Waves.
Temperature	High Minimum Temperature	Synoptic Observations Model Analysis & forecast	Min Temp. Min Temp. Departures	High /above normal Min Temperatures to be pointed out as regions which may see more maximum temperatures the next day.
Humidity	High Relative Humidity	Synoptic Observation Model Analysis & forecast	Relative Humidity (Surface, Lower Troposphere, Middle Troposphere)	In high-pressure systems, the strong temperature inversion at the top of the boundary layer traps humidity in thin PBL and it gets very humid there.
Cloud Cover (Day Time)	Less Cloud and/or absence of low clouds	Satellite based	Visible/IR imagery RGB Products Convective Products Insolation	Cloud free sky implies more insolation and higher temperature.
Wind streamlines	Large Amplitude anticyclonic flow	Radiosonde/ Radio wind Satellite based Model Analyses & forecast	Winds streamlines at different levels (Mainly middle and upper troposphere and may intrude into lower troposphere).	Anticyclone is associated with subsidence leading to higher temperatures.
Wind streamlines	Transportation of Hot Dry Air over the region	Radiosonde/ Radio wind Satellite based Model Analyses & forecast	Winds streamlines at different levels (925,850,700,500 hPa)	The Hot Dry air advection over the region increases the temperature.
Geo Potential Height	Presence of Ridge/Anticyclone and trough/Cyclonic circulation in the region.	Model Analysis & forecast	Geopotential height at 1000 to 500 & 200 hPa and their anomaly.	Geopotential height is valuable for locating troughs and ridges which are the upper-level counterparts of surface cyclones and anticyclones.
Atmosphere Instability	Unstable atmosphere which triggers weather development	Radio Sonde/ Radio Wind Satellite based Model Analysis & forecast	CAPE, CIN & Other instability indices, T-Phi Gram.	Instability in the lower troposphere leads to cloud development.



14(a) Average HW frequency during march to June 14(b) HW frequency trend. (Reproduced from IMD Met. Monograph: MoES/IMD/Synoptic Met/01(2023)/28)



14(c) Average HW days during march to June 14(d) HW days trend (reproduced from IMD Met. Monograph: MoES/IMD/Synoptic Met/01(2023)/28)

Figs. 14 (a to d).

(*iv*) Critical Success Index (CSI) is a verification measure of categorical forecast performance equal to the total number of correct event forecasts divided by the total number of forecasts plus the number of misses and do notconsider the correct forecast of non-occurrence of the event.

7. Climatology of Heat Wave & its evolution in reference to Climate Change

A warming global climate can contribute to more intense heat waves by increasing the chances of extremely hot days and nights. The warming climate also amplifies water evaporation from land, which could exacerbate droughts and create conditions that are more susceptible to wildfires, consequently extending the wildfire season. Additionally, a warmer atmosphere is linked to more frequent occurrences of intense precipitation events, such as heavier rain and snowstorms, because the air can retain more moisture. El Niño phenomena typically trigger droughts in many tropical and subtropical regions, while La Niña events promote wetter conditions in various areas. These short-term and regional fluctuations are predicted to become more significant in a warming climate. The Earth's warmer and more humid atmosphere, in combination with warmer oceans, increases the likelihood that the most powerful cyclones will become more forceful, generate more rainfall, affect new areas, and potentially become larger and longer-lasting. This impactful weather poses a risk and hazard for direct and indirect health impacts.

The impact of climate change is evident in the increased frequency of heatwaves and hot days, with temperatures remaining above normal for extended periods (Pai *et al*., 2004; Pai *et al*., 2013). The Met. Monograph published by IMD in April 2023 analyses the data collected between 1961 and 2020 and reveals significant trends. Based on the monograph, Fig. 14(a) illustrates the average frequency of heatwaves, while Fig. 14(b) demonstrates the trend in heatwave frequency during the period 1961-2020 (IMD Met. Monograph 2023). The analysis indicates that most of the monitoring stations display an increasing trend in heatwave occurrences throughout the specified time frame. On average, the northern parts of the country, coastal Andhra Pradesh, and Odisha experience 2-4 days of heatwaves (Met. Monograph 2023). Fig. 14(c) and 14(d) sourced from Met. Monograph on Heat wave and Cold Wave services published in 2023 provides an overview of the spatial distribution of the duration (in days) of heatwaves and their respective trends spanning the period 1961-2020. Generally, the prevalence of heatwaves lasts for approximately 4-8 days across the country. However, specific regions, particularly in northwest India, Odisha, and coastal Andhra Pradesh, have experienced heatwaves lasting more than 8 days (IMD Met. Monograph 2023). Long-term data analysis further indicates an upward trend in the duration of heatwaves during the March-June season.

In some cases, heatwave-like conditions persist even beyond the summer season, meeting the criteria for heatwaves. These heatwaves are growing more intense, often breaking temperature records and lasting longer, primarily due to global warming and the combined effect of human activities and natural disasters like forest fires, war, and volcanic eruptions. The temperatures during these heatwaves regularly exceed what was once considered rare or extreme. Rapid and unplanned urbanization has led to the creation of heat islands, establishing a new norm for maximum temperatures. This exacerbates the health risks associated with prolonged exposure to such extreme weather, particularly for a significant portion of India's population that relies on outdoor work for their livelihoods. Heat-related illnesses, heat stress, and even fatalities are significant health consequences, especially among vulnerable groups such as the elderly, infants, and those with preexisting conditions.

Recognizing the connection between climate change and the surge in heatwave occurrences, it becomes crucial to implement adaptation strategies. These may include public health interventions, the establishment of heatwave early warning systems, and measures aimed at reducing greenhouse gas emissions to mitigate further warming. A study conducted during the decade from 1991 to 2000 revealed a noticeable increase in the frequency, persistency, and spatial coverage of high-frequency temperature extreme events (heatwaves) (Pai *et al*., 2013). Another study in 2022 examined the impact of human activity on heatwave trends in India, indicating that anthropogenic influences have doubled the likelihood of severe heatwaves in central and central-southern India over the twentieth century (Kishore *et al*., 2022). Further research suggests that future climate warming could result in a notable surge in heat-related fatalities, particularly in lower-latitude developing nations like India, where heatwaves are expected to become more frequent, posing a higher risk to the vulnerable population (Mazdiyasni *et al*., 2017). Projections based on the analysis of CMIP data indicate that heatwaves are expected to become more severe, lasting longer, and occurring more frequently and earlier in the year (Murari *et al*., 2015). Additionally, it is predicted that southern India, currently unaffected by heat waves, will be significantly impacted by them by the end of the 21st century (Murari *et al*., 2015). An increase in the Heat Index, which considers the cumulative impact of temperature and relative humidity, has been observed across the Indian subcontinent during the summer and monsoon seasons, signaling a growing discomfort due to the effects of escalating temperature and moisture (Jaswal *et al*., 2017).

8. Future directions.

According to a report by the Indian Meteorological Department (IMD), the duration of heat waves in India has increased by about 2.5 days over the last 30 years due to climate change (Met Monograph on Heat Wave & Cold Wave 2023). The report also suggests that the number of heat wave days per season is likely to increase by about 2 days (Met Monograph on Heat Wave & Cold Wave 2023). The Intergovernmental Panel on Climate Change (IPCC) predicts that by 2060, there will be an increase of about two heat waves (12-18 days). The McKinsey Global Institute report titled “Will India get too hot to work?” warns that India could become one of the first places in the world to experience heat waves that cross the survivability limit for a healthy human being sitting in the shade. The IPCC’s Sixth Assessment Report states that heatwaves and humid heat stress will be more intense and frequent in South Asia this century. These predictions are alarming, as heat waves can have adverse effects on human health, livestock, agriculture, power, transport and the environment sector. It is essential to take necessary measures to mitigate climate change and its adverse impacts on human well-being.

In this scenario, IMD has a very important role to play as a nodal agency to provide timely and actionable early warning services specific to different sectors for different temporal and spatial scales. This would require further improvements in skills and lead times of forecast and warning of heat waves with specific information on its impact and suggestive actions. India being home to approx. 1.4 billion population with changing demography, living in diverse geographic location and belonging to different socio-economic strata makes it a daunting task for IMD to cater to specific requirement with respect to weather forecasting in general and heat wave services in particular in evolving climate change scenario. However, looking into the glorious successful journey of IMD in past many decades and the pace at which improvements and transformations have taken place we could be rest assured that IMD will be successful in its efforts leading to zero loss of life and minimal loss of property in coming years.

Acknowledgement

Authors are thankful to editorial board for bringing out this important topic's evolution on the occasion of 150th year of IMD. We are very thankful to the Mausam publication team for providing the archives of early prints of Mausam journal which greatly helped in the making of this article. We would also like to acknowledge the recently published Met Monograph on Heat Wave and Cold Wave services in 2023, the Forecaster's guide published in 2008 in addition to different volumes hosted by Climate research and Services division of IMD Pune which provided detailed insight regarding the operational and research perspective of Heat Wave services in India. Additional supporting material are taken from internet blogs (like Cloud and Sunshine *etc*.) and other internet sites in public domain.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

References

Attri, S. D., Rathore, L. S., 2003, "Simulation of impact of projected climate change on wheat in India", *Int. J. Climatol*, **23**, 693–705. doi :10.1002/joc.896.

B., H. Indian Meteorology, Nature, 45, 217–219 (1892). doi : https://doi.org/10.1038/045217a0

Bechtel, B., Alexander, P. J., Böhner, J., Ching, J., Conrad, O., Feddema, J., ... & Stewart, I., 2015, "Mapping local climate zones for a worldwide database of the form and function of cities", ISPRS International Journal of Geo-Information, **4**, 1, 199-219.

Bedekar, D. C., Dekate, M. V., A. K. Banerjee, 1974, "Forecasting Manual IV-6, Part IV, Heat and Cold Waves in India", India Meteorological Department.

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A., Frei, C., Goyette, S., ... & Woth, K., 2007, "Future extreme events in European climate: an exploration of regional climate model projections", *Climatic change*, **81**, 71-95.

Chakraborty, D., Sehgal, V. K., Dhakar, R., Ray, M. and Das, D. K., 2019, "Spatio-temporal trend in heat waves over India and its impact assessment on wheat crop", *Theoretical and Applied Climatology*, **138**, 1925-1937.

Chaudhury, S. K., Gore, J. M., Sinha Ray, K. C., 2000, "Impact of heat waves over India", *Curr Sci* **79**, 153–155.

Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., ... & Theeuwes, N., 2018, "WUDAPT: An urban weather, climate, and environmental modeling infrastructure for the Anthropocene", *Bulletin of the American Meteorological Society*, **99**, 9, 1907-1924.

Dash, S. K. and Mamgain, A., 2011, "Changes in the frequency of different categories of temperature extremes in India", *J. Appl. Meteorol. Climatol*, **50**, 1842-1858.

De, U. S., Mukhopadhyay, R. K., 1998, "Severe heat wave over Indian subcontinent in 1998 in a perspective of global Climate", *Current Science*, **75**, 12, 1308-1311.

Debnath, R, Bardhan R, Bell M. L., 2023, "Lethal heatwaves are challenging India's sustainable development", PLOS Clim 2(4): e0000156. https://doi.org/10.1371/journal.pclm.0000156.

Devi, R., Gouda, K. C. and Lenka, S., 2023, "Analysis of heat wave over different physiographical regions in India", *Theor Appl Climatol*, doi : https://doi.org/10.1007/s00704-023-04639-2.

Dodla, V. B., Satyanarayana, G. C. and Desamsetti, S., 2017, "Analysis and prediction of a catastrophic Indian coastal heat wave of 2015," *Natural Hazards*, **87**, 395-414.

E. Mausam, "Intense Heat In The United Provinces", *MAUSAM*, **1**, no. 1, 65-66, Jan. 1950.

Fischer, E. M., Seneviratne, S. I., Lüthi, D., & Schär, C., 2007, "Contribution of land-atmosphere coupling to recent European summer heat waves", *Geophysical Research Letters*, **34**, 6,

Giorgi, F., and Bates, G. T., 1989, "The climatological skill of a regional model over complex terrain", *Monthly Weather Review*, **117**, 11, 2325-2347.

HANN, J. Climatological Atlas of India, *Nature* **75**, 241–244, 1907, https://doi.org/10.1038/075241a0

Hansen, A., Bi, P., Nitschke, M., Ryan, P., Pisaniello, D., Tucker, G., 2008, "The effect of heat waves on mental health in a temperate Australian city", Environ Health Perspect 116, 1369–1375. Doi : 10.1289/ehp.11339.

Heo, S., Bell, M. L. and Lee, J. T., 2019, "Comparison of health risks by heat wave definition: Applicability of wet-bulb globe temperature for heat wave criteria", *Environmental research*, **168**, 158-170.

Hondula, D. M., Vanos, J. K., Gosling, S. N., 2014, "The SSC: a decade of climate–health research and future directions", *Int. J. Biometeorol*, **58**, 109-20.

IMD Met. Monograph: MoES/IMD/Synoptic Met/01(2023) Heat and Cold Waves in India Processes and Predictability.

IMD, DDGF Technical Circular Forecasting No. 23 dated 20th December 1958.

IMD, Disastrous Weather Events 1967-1979 https://imdpune.gov.in/library/public/dwe_1967-79.pdf.

Jaswal, A. K., Padmakumari, B., Kumar, N. & Kore, P. A. Increasing trend in temperature and moisture induced heat index and its effect on human health in climate change scenario over the

Indian sub-continent. J. Clim. Change 3, 11–25. https://doi.org/10.3233/JCC-170002 (2017).

Jaswal, A. K., Padmakumari, B., Kumar, N., Kore, P. A., 2017, "Increasing trend in temperature and moisture induced heat index and its effect on human health in climate change scenario over the Indian sub-continent", *J. Clim. Change*, **3**, 11–25.

Jin, J., Miller, N. L., and Schlegel, N., 2010, "Sensitivity study of four land surface schemes in the WRF model", *Advances in Meteorology*, 2010.

Kharin, V. V., Zwiers, F. W., Zhang, X., and Hegerl, G. C., 2007, "Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations", *Journal of Climate*, **20**, 8, 1419-1444.

Kishore P, et al. Anthropogenic influence on the changing risk of heat waves over India. Sci. Rep. 2022; 12: 3337. doi : 10.1038/s41598-022-07373-3.

Knowlton K, Kulkarni SP, Azhar GS, Mavalankar D, Jaiswal A, Connolly M, Nori-Sarma A, Rajiva A, Dutta P, Deol B, Sanchez L, Khosla R, Webster PJ, Toma VE, Sheffield P, Hess JJ; Ahmedabad Heat and Climate Study Group. Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India). Int J Environ Res Public Health. 2014 Mar 25;11(4):3473-92. doi: 10.3390/ijerph110403473. PMID: 24670386; PMCID: PMC4024996.

Lhotka, O., Kyselý, J., and Plavcová, E., 2018, "Evaluation of major heat waves' mechanisms in EURO-CORDEX RCMs over Central Europe. Climate dynamics, **50**, 4249-4262.

Li, Z., Li, J. J., and Shi, X. P., 2020, "A Two-Stage Multisite and Multivariate Weather Generator", *Journal of Environmental Informatics*, **35**, 2.

M. Bushair, D. Pattanaik, and M. Mohapatra, 2023, "A multi-model ensemble tool for predicting districts level monsoon rainfall and extreme rainfall events over India", *MAUSAM*, **74**, 2, 429–454.

M., W. Indian Meteorology, 1892–19021. *Nature*, **73**, 136-137 (1905). https://doi.org/10.1038/073136b0

Mandal, R., Joseph, S., Sahai, A. K., Phani, R., Dey, A., Chattopadhyay, R., &Pattanaik, D. R. (2019). Real time extended range prediction of heat waves over India. Scientific Reports, 9(1), 9008. Doi : https://doi.org/10.1038/s41598-019-45430-6.

Mazdiyasni O., Agha Kouchak A., Davis S. J., Madadgar S., Mehran A., Ragno E., Sadegh M., Sengupta A., Ghosh S., Dhanya C. T., Niknejad M. Increasing probability of mortality during Indian heat waves. *Sci Adv*. 2017 Jun 7, 3, 6, e1700066. Doi : 10.1126/sciadv.1700066. PMID: 28630921; PMCID: PMC5462497.

Mills, G., Ching, J., See, L., Bechtel, B., and Foley, M., 2015 "An introduction to the WUDAPT project. In Proceedings of the 9th International Conference on Urban Climate, Toulouse, France 20-24.

Murari, K. K., Gosh, S., Patwardhan, A., Daly, E., and Salvi, K., 2015, "Intensification of future severe heat waves in India and their effect on heat stress and mortality", *Regional* Environmental Change, **15**, 4, 569 - 579. https://doi.org/10.1007/s10113-014-0660-6.

Nadimpalli, R., Patel, P., Mohanty, U. C., Attri, S. D., and Niyogi, D., 2022, "Impact of urban parameterization and integration of WUDAPT on the severe convection", *Computational Urban Science*, **2**, 1, 41. https://doi.org/10.1007/s43762-022-00071-w.

Narkhede, N., Chattopadhyay, R., Lekshmi, S., Guhathakurta, P., Kumar, N. and 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.

Nitschke, M., Tucker, G. R. and Bi, P., 2007, "Morbidity and mortality during heatwaves in metropolitan Adelaide", *Med J Aust*, **187**, 662-665.

NOAA National Centers for Environmental Information, Monthly Global Climate Report for Annual 2022, published online January 2023, retrieved on September 22, 2023 from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213.

Oldenborgh, G. J. V., Philip, S., Kew, S., Weele, M. V., Uhe P., Otto, F., Singh, R., Pai, I., Cullen, H,. Achuta Rao, K., 2018, "Extreme heat in India and anthropogenic climate change", *Nat Hazards Earth Syst Sci*, **18**: 365–381.

Pai, D. S., Nair, S. A., Ramanathan, A. N., 2013, "Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010)", *Mausam* **64**, 585–604. doi : https://doi.org/10.54302/mausam.v64i4.742.

Pai, D. S., Thapliyal, V., Kokate, P. D., 2004, "Decadal variation in the heat and cold waves over India during 1971–2000", *Mausam* **2**, 281–92. https://doi.org/10.54302/mausam.v55i2.1083.

Pai, D. S. and Smitha A. Nair., 2022, "Impact of El-Niño-Southern Oscillation (ENSO) on extreme temperature events over India", *Mausam*, **73**, 3, 597-606.

Pai, D. S., Srivastava, A. K. and Smitha Nair, 2017, "Heat and cold waves over India", In Observed climate variability and change over the Indian Region 51-71, *Springer, Singapore*.

Patel, P., Jamshidi, S., Nadimpalli, R., Aliaga, D. G., Mills, G., Chen, F., ... & Niyogi, D., 2022, "Modeling large-scale heatwave by incorporating enhanced urban representation", *Journal of Geophysical Research: Atmospheres*, **127**, 2, e2021JD035316.

Pattanaik, D., Mohapatra, R. M., Srivastava, A. K., and Kumar, A. 2017, "Heat wave over India during summer 2015: An assessment of real time extended range forecast", *Meteorology and Atmospheric Physics*, **129**, 4, 375–393. https://doi.org/10.1007/s00703-016-0469-6.

Patz, J. A., Campbell-Lendrum, D., Holloway, T., Foley, J. A., 2005, "Impact of regional climate change on human health", *Nature*, **438**, 310-317.

Press Information Bureau (PIB) 22nd December 2022. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1885718

Shah, R., R. Pandit, and M. Gaur, 2023, "Determining the influence of meteorological parameters on outdoor thermal comfort using ANFIS and ANN", *MAUSAM*, **74**, 3, 741–760.

Raghavan, K., 1966, "A climatological study of severe Heat Waves in India", *MAUSAM*, **17**, 4 581–586. Doi: https://doi.org/10.54302/mausam.v17i4.5760.

Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M. & Yamagata, T. 2016, "Anatomy of Indian heat waves", *Sci. Rep*. **6**, 24395. https://doi. org/10.1038/srep24395 (2016).

Ratnam, J. V., Behera, S. K., Nonaka, M. et al. 2023, "Predicting maximum temperatures over India 10-days ahead using machine learning models", *Sci Rep* **13**, 17208. https://doi.org/10.1038/s41598-023-44286-1.

Ray, K., Giri, R. K., Ray, S. S., Dimri, A. P. and Rajeevan, M., 2021, "An assessment of longterm changes in mortalities due to extreme weather events in India: A study of 50 years", data, 1970–2019. *Weather and Climate Extremes*, **32**, p.100315.

Ren, J., Huang, G., Li, Y., Zhou, X., Lu, C., and Duan, R., 2022, "Stepwise-clustered heatwave downscaling and projection for Guangdong Province", *International Journal of Climatology*, **42**, 5, 2835-2860.

Rohini, P., Rajeevan, M., Srivastava, A. K., 2016, "On the variability and increasing trends of heat waves over India", *Sci Reports*, 6: 26153.

Salamanca, F., Krpo, A., Martilli, A., & Clappier, A., 2010, "A new building energy model coupled with an urban canopy parameterization for urban climate simulations-part I. formulation, verification, and sensitivity analysis of the model", *Theoretical and applied climatology*, **99**, 331-344.

Sathyanadh, A., Prabha, T. V., Balaji, B., Resmi, E. A., & Karipot, A. 2017, "Evaluation of WRF PBL parameterization schemes against direct observations during a dry event over the Ganges valley", *Atmospheric Research*, **193**, 125-141.

Satyanarayana, G. C. and Rao, D. B., 2020, "Phenology of heat waves over India", *Atmospheric research*, **245**, p.105078.

Sellers, P. J., Dickinson, R. E., Randall, D. A., Betts, A. K., Hall, F. G., Berry, J. A., ... & Henderson-Sellers, A., 1997, "Modeling the exchanges of energy, water, and carbon between continents and the atmosphere", *Science*, **275**, 5299, 502-509.

Shrivastava, R., Dash, S. K., Oza, R. B., and Sharma, D. N., 2014, "Evaluation of parameterization schemes in the WRF model for estimation of mixing height", *International Journal of Atmospheric Sciences*, 2014.

Siebert, S., Ewert, F., Rezaei, E. E., Kage, H., Graß, R., 2014, "Impact of heat stress on crop yield - on the importance of considering canopy temperature", *Env. Res. Lett*, **9**, 061002.

Singh, H., Arora, K., Ashrit, R., & Rajagopal, E. N., 2017, "Verification of pre-monsoon temperature forecasts over India during 2016 with a focus on heat wave prediction", *Natural Hazards and Earth System Sciences*, **17**, 9, 1469–1485. https://doi.org/10.5194/nhess-17-1469-2017.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., ... & Powers, J. G., 2008, "A description of the advanced research WRF version 3. NCAR technical note, 475, 113.

Srivastava, A., Mohapatra, M. and Kumar, N. Hot weather hazard analysis over India. Sci Rep 12, 19768 (2022). https://doi.org/10.1038/s41598-022-24065-0.

Steffen, W., Hughes, L., Perkins, S., 2014, "Heatwaves: Hotter, Longer, More Often. Special Report by the Climate Council of Australia, Sydney, Australia", p62. [Available online at http://www.climatecouncil.org.au/heatwaves-report].

Suthar, G., S. Singh, N. Kaul, S. Khandelwal, R. P. Singhal., 2023, "Prediction of maximum air temperature for defining heat wave in Rajasthan and Karnataka states of India using machine learning approach, Remote Sensing Applications: Society and Environment, **32**, 2023, 101048, ISSN 2352-9385, https://doi.org/10.1016/j.rsase.2023.101048.

Wilker, E. H., Yeh, G., Wellenius, G. A., Davis, R. B., Phillips, R. S., Mittleman, M. A., 2012, "Ambient temperature and biomarkers of heart failure: A repeated measures analysis", *Environ. Health Perspect*, **120**, 1083–1087.