Anomalous heat!

Understanding the heat conditions of North India in the context of national and regional heat stress

Avikal Somvanshi (with inputs from Sharanjeet Kaur)

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The Urban Lab of Centre for Science and Environment (CSE) has analyzed the temperature trends for India from Jan 2015 till May 2022. This is an effort to understand the warming tread in a comprehensive way by covering all three dimensions of heat stress–Surface air temperature, Land surface temperature, and relative humidity (heat index). The study has analyzed heat stress trends at global, national, regional, and local level. The city level analysis of this study covers metropolises of Delhi, Mumbai, Kolkata and Hyderabad (each located in different Indian Meteorological Department or IMD's four homogenous region). Objective of the city analysis is to understand the combined effect of climate change induced unseasonal heatwaves and urbanisation induced heat Island effect on the thermal comfort and heat stress among these topographically and climatically diverse in cites.

For city reports go to the following links:

- Delhi *(https://www.cseindia.org/urban-heat-stress-Delhi.pdf)*
- Mumbai *(https://www.cseindia.org/urban-heat-stress-Mumbai.pdf)*
- Kolkata *(https://www.cseindia.org/urban-heat-stress-Kolkata.pdf)*
- Hyderabad *(https://www.cseindia.org/Urban-Heat-Stress-Hyderabad.pdf)*

Study methodology and data

Method: The study is based on comparative statistical analysis of temperature anomalies and observed heat related impact in Indian cities and regions. This is done using various publically available datasets from various national and global agencies. Complex geospatial calculations are done in python and Arc-GIS. Heat Index computation is done using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula. The study is limited to temperature anomalies and observed actual temperatures. It does not include computation or assessment of heat in terms of heatwave spells as data needed for that is not available in public domain.

Temperature anomaly: The term temperature anomaly means a departure from a reference value or long-term average or baseline. A positive anomaly indicates that the observed temperature was warmer than the baseline, while a negative anomaly indicates that the observed temperature was cooler than the baseline. It is generally used to report monthly, seasonal, annual, or decadal temperature changes. Heatwaves are also anomalous temperature events but of much shorter duration and are defined in comparison to an absolute temperature threshold in addition to departure from normal. Therefore, the term temperature anomaly is generally not used to identify a heatwave.

Baselines: Various temperature anomaly data sets have varying baselines that make comparative analysis complicated. To reduce this complication, efforts have been made to have same baseline. For instance, global temperature anomaly data is available only with baseline of 1951-80, therefore to compare India's anomaly has been computed vis-à-vis 1951-80 baseline using Indian Meteorological Department (IMD) annual temperature data. Otherwise, anomaly published by IMD are based on 1981-2010 baseline. Similarly, land surface temperature anomaly data is only available with baseline of 1971-2000, therefore same baseline is used for India and Northwest India as well. Fire and humidity data were not available for dates before 2010, therefore for their anomaly analysis average of oldest 10 year data is used. These variation in baselines are mentioned with each comparative analysis and corresponding graphs.

Air Temperature data: Surface air temperature data for India of varying resolutions has been sourced from various IMD publications, namely Annual Climate Summary reports, Annual Statement on Climate of India, Monthly Weather and Climate Summery reports, and Climate Data Service Portal- All India Mean Seasonal Temperature. For intra-city temperature variation data from the Continuous Ambient Air Quality Monitoring Stations is used. Global surface air anomaly data is sourced from NASA's Goddard Institute for Space Studies (GISS).

Land Surface Temperature data: Land surface temperature anomaly analysis is based on the NOAA Global Surface Temperature (NOAAGlobalTemp) data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/. For city level spatial analysis Landsat 8 satellite image from USGS Earth Explorer website has been used. For city level land surface temperature anomaly data from NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published June 2022, retrieved on June 17, 2022 from https://www.ncei.noaa.gov/cag/ has been used.

Fire data: NASA's Fire Information for Resource Management System (FIRMS) data is used. The study employs satellite observation from both NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS). This is done to minimize known biases of the two products. Further, analysis is based on the product of observed fire counts and average Fire Radiative Power (FRP) of the observed fires. This matrix provides a better measure of total fire activities accounting not just the number of fires but also the relative strength of it (quantum of energy released).

Fatality data: National Crime Record Bureau (NCRB) data as published in annual Accidental Deaths & Suicides in India is used in the analysis of report human fatalities due to heat stress. Additionally, IMD's annual Disastrous Weather Events reports have been consulted for crossing checking and verification of annual fatality figures.

Land use data: Google earth data is used for land use analysis.

IMD's four homogeneous regions:

- Northwest India – Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh and Uttrakhand.
- Central India – Chhattisgarh, Dadar & Nagar Haveli, Daman & Diu, Goa, Gujarat, Madhya Pradesh, Maharashtra and Odisha.
- East and Northeast India – Anurachal Pradesh, Assam, Bihar, Jharkhand, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, and West Bengal.
- South Peninsula India – Andaman & Nicobar, Andhra Pradesh, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu and Telangana.

IMD's four season classification:

- Winter – January and February
- Pre-monsoon – March, April, and May
- Monsoon – June, July, August, and September
- Post-monsoon – October, November, and December

Important terminologies

Heatwave conditions: When the temperature, spatial spread and duration criteria for heatwave as defined by IMD are met at the Met Subdivision or higher level.

Heatwave spell: A heatwave episode is referred as heatwave spell. It is a period of consecutive days when heatwave conditions prevailed uninterrupted over one or multiple Meteorological Sub-divisions. A heatwave spell is generally multiple days long and spread across many adjoining Meteorological Sub-divisions i.e. geographically continuous landmass. If heatwave conditions form concurrently in two regions or subdivisions that are not geographically continuous then they can be counted as two distinct heatwave spells.

Heatwave days: IMD's Climate and Vulnerability Hazard Atlas has developed a special term "heatwave days" to define days with heatwave conditions that reported a human casualty due to heat stress. It is a count of days that reported human casualty but is agnostic to number of casualties on any particular day. It is also location specific; IMD currently only computes "heatwave days" at district level.

Heat stress: Heat stress occurs when the human body cannot get rid of excess heat generated routinely due to natural metabolic activities. When this happens, the body's core temperature rises and the heart rate increases. As the body continues to store heat, the person begins to lose concentration and has difficulty focusing on a task, may become irritable or sick, and often loses the desire to drink. The next stage is most often fainting and even death if the person is not cooled down. Factors that contribute to heat stress are high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, and strenuous physical activities.

Heat Index: The heat index is the combination of air temperature and relative humidity, it measure of how hot it really feels when relative humidity is factored in with the actual air temperature.

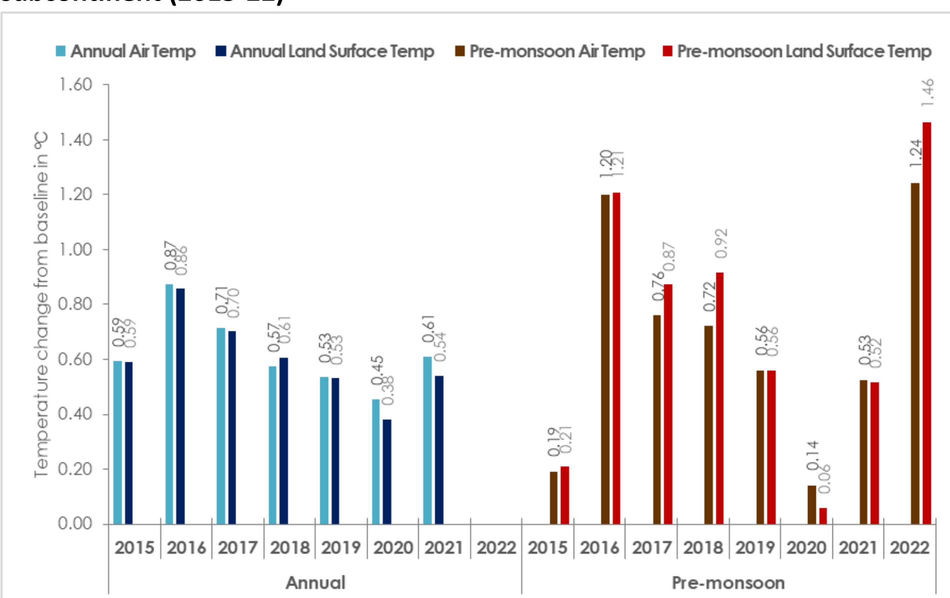
Urban Heat Island: Urban or metropolitan area are observed to be significantly warmer than their surrounding rural areas and this phenomenon is referred as Urban Heat Island (UHI) effect. The temperature difference is usually larger at night than during the day, and is most apparent when winds are weak. The main cause of the UHI effect is the modification of land surfaces that leads to higher heat absorption and retention. Waste heat generated by energy usage in cities is a secondary contributor. It is a direct effect of human activities and can get exacerbated by heatwaves but is independent of the larger climate systems that cause heatwaves.

Additional information regarding heatwaves and their classifications around the world can be found in the annexure at the end of this report.

Findings

This year's summer/pre-monsoon season overtakes 2016 as the second hottest pre-monsoon season on record for India: The seasonal average air temperature for 2022 pre-monsoon or summer (March, April, and May as per IMD classification) is 1.24°C warmer than the baseline trends that relate to 1971-2000 climatology (baselines are defined based on historical timelines and may vary for different metrics - anomaly is generally computed from 1951-80, 1971-2000, or 1981-2010 climatology baseline). This is warmer than 1.20°C anomaly noted in 2016 pre-monsoon but lower than 1.45°C anomaly recorded in 2010 pre-monsoon season (See *Graph 1: Anomaly in annual and pre-monsoon air and land surface temperature over Indian subcontinent (2015-22)*). Similarly, land surface temperature anomaly has been extreme this pre-monsoon season with 1.46°C departure from baseline (1971-2000). It must be noted that pre-monsoon seasonal trend in both land and air temperature is identical to annual trend but with more pronounced high and lows.

Graph 1: Anomaly in annual and pre-monsoon air and land surface temperature over Indian subcontinent (2015-22)



Note: Based on the observed spatial air temperature anomaly pattern of monthly and seasonal average temperature over India and Global. Temperature anomalies are based on the climatology from 1971 to 2000.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data

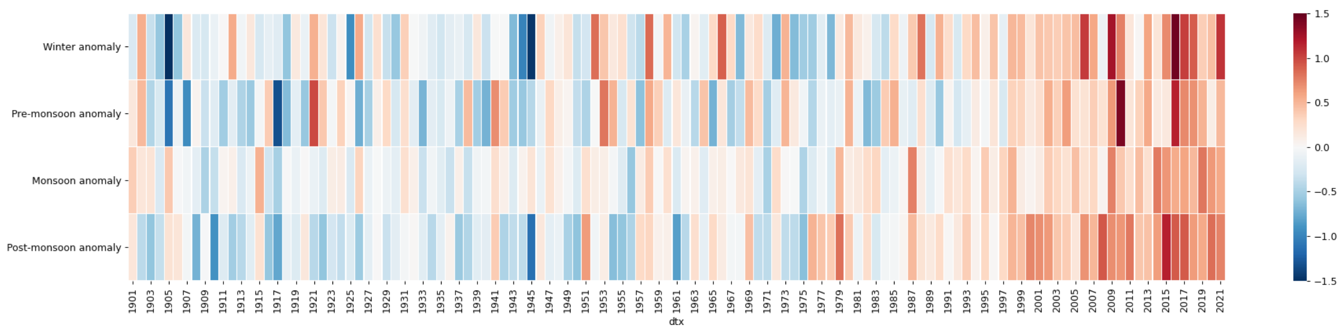
Monsoon is hotter than pre-monsoon on average while winter and post-monsoon seasons are warming up faster: At all India level the monsoon season has been 0.3-0.4°C hotter than pre-monsoon (summer) and with time monsoon is getting even hotter. In fact, pre-monsoon is exhibiting slowest rise among seasonal average temperature. Last decade post-monsoon got hotter by 0.73°C compared to normal (1951-80 baseline). Similarly, winter got hotter by 0.68°C and monsoon by 0.58°C. Pre-monsoon registered only 0.49°C rise in decadal seasonal average (See *Table 1: Change in seasonal averages at all India level* & *Graph 2: Heatmap of trend in Indian seasonal surface air temperature anomalies 1901-2021*).

Table 1: Change in seasonal averages at all India level

	Normal (1951-80)	Last decade (2012-21)	Change
Winter	20.34°C	21.02°C	0.68°C
Pre-monsoon	27.47°C	27.97°C	0.49°C
Monsoon	27.79°C	28.38°C	0.58°C
Post-monsoon	22.92°C	23.64°C	0.73°C
Annual	25.25°C	25.86°C	0.61°C

Source: CSE analysis of IMD ground observation data

Graph 2: Heatmap of trend in Indian seasonal surface air temperature anomalies 1901-2021



Note: Based on the observed spatial air temperature anomaly pattern of monthly and seasonal average temperature over India. Surface air temperature anomalies are based on the climatology from 1951 to 1980.
Source: CSE analysis of IMD ground observation data

High heat stress and heat waves in northwest states: This year, the observed average daily maximum for March and April for Northwest states (Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh and Uttrakhand – as per IMD classification) has been almost 4°C above the normal (compared to its baseline of 1981-2010). This is almost twice as much as the anomaly observed at all India level, and it holds true for even average daily minimum, daily average and land surface temperatures. Temperatures become relatively closer to normal during the month of May (See *Graph 3: All India and Northwest India monthly temperature anomaly comparison (March-May, 2022)*).

Other regions were even hotter in absolute terms: In absolute terms most of India outside Northwest states was even hotter even if extreme heat wave days were lesser. Average daily maximum for Northwest states for month of March was 30.7°C when the all India average was 33.1°C, i.e. 2.4°C hotter. Average daily minimum shows even larger (4.9°C) difference. Average daily maximum of Northwest states crossed all India average in the months of April and May but only by 1-1.5°C. But daily minimum and average temperature continues to be higher in other regions of India (See *Graph 4: All India and Northwest India monthly absolute temperature comparison (March-May, 2022)*).

However, the Central India (Chhattisgarh, Dadar & Nagar Haveli, Daman & Diu, Goa, Gujarat, Madhya Pradesh, Maharashtra and Odisha as per IMD classification) and South Peninsular regions (Andaman & Nicobar, Andhra Pradesh, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu and Telangana as per IMD classification) have higher normal temperatures compared to Northwest region for the pre-monsoon or summer season. Central India's normal maximum is 2-7°C higher than Northwest states while South

Peninsular India's normal minimum is 4-10°C higher than Northwest India (See *Table 2: Normal temperatures for IMDs homogenous regions (March, April, and May)*).

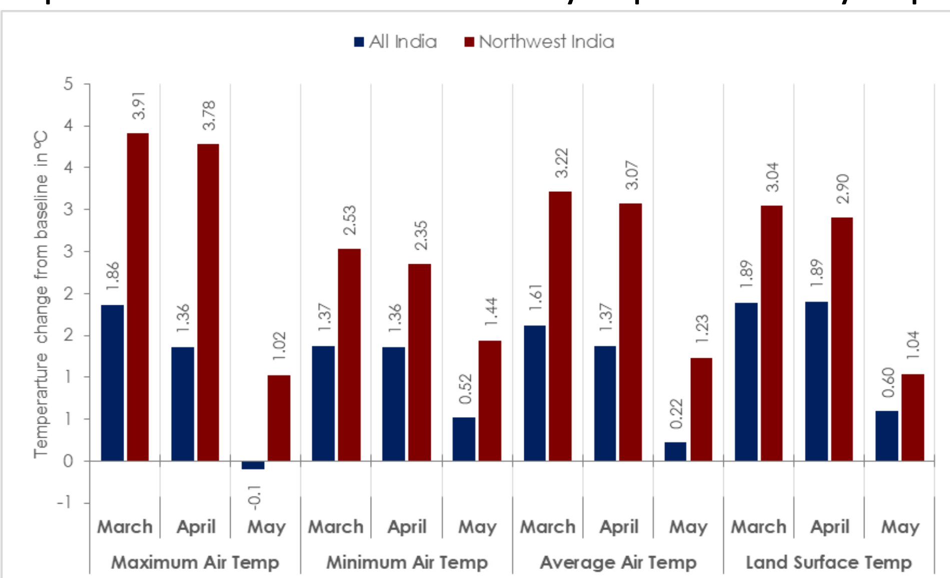
Table 2: Normal temperatures for IMDs homogenous regions (March, April, and May)

	Mean Maximum Temperature			Mean Minimum Temperature			Mean Average Temperature		
	March	April	May	March	April	May	March	April	May
Northwest India	26.82°C	32.54°C	35.58°C	12.73°C	17.69°C	21.46°C	19.77°C	25.11°C	28.52°C
East & Northeast India	30.21°C	31.99°C	33.03°C	16.58°C	20.13°C	22.64°C	23.39°C	26.06°C	27.84°C
Central India	33.58°C	36.29°C	37.43°C	19.62°C	23.32°C	25.94°C	26.60°C	29.81°C	31.68°C
South Peninsular India	33.08°C	34.26°C	34.46°C	23.34°C	25.18°C	25.88°C	28.21°C	29.72°C	30.17°C
All India	31.24°C	33.94°C	35.17°C	18.87°C	22.15°C	24.32°C	25.06°C	28.04°C	29.74°C

Note: Normal is based on the climatology from 1981 to 2010. Cells highlighted in yellow indicate warmest region for that category and month.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data

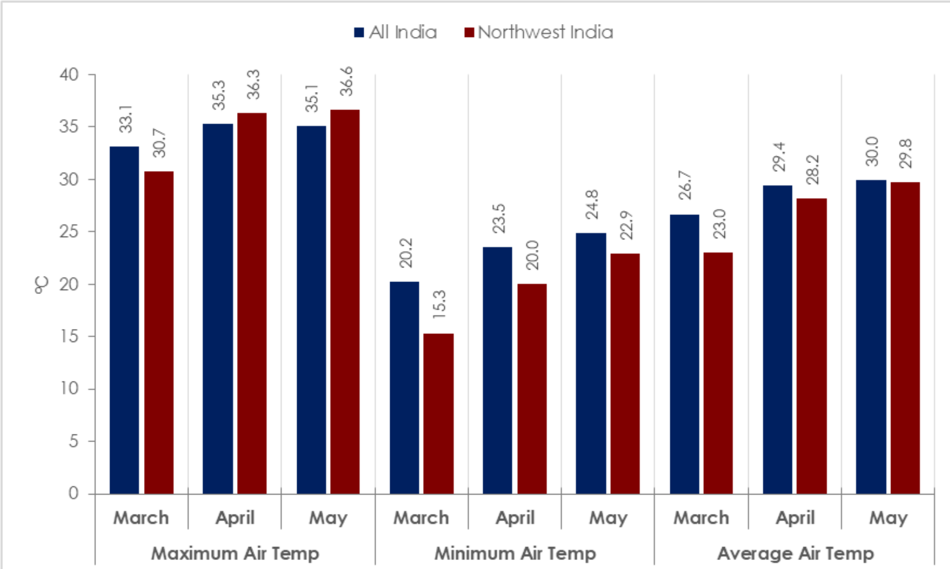
It is necessary that both extreme heat conditions as well as overall anomalous heat conditions draw equal attention to reduce the overall heat stress in the region and protect public health. It may be noted that the IMD criteria for heat waves are defined when the daily maximum temperature exceeds the normal for the season by at least 4.5°C in at least two sub division stations on two consecutive days and in absolute terms when temperature exceed 45°C. The normal temperature for the season is defined based on a particular day at a particular station and in relation to the baseline of 1981-2010 average. Much of the heatwave conditions in March has been due to departure from the normal.

Graph 3: All India and Northwest India monthly temperature anomaly comparison (March-May, 2022)



Note: Based on the observed spatial air and land surface temperature anomaly pattern of monthly average temperature over India. Surface Air Temperature anomalies are based on the climatology from 1981 to 2010. Land Surface Temperature anomalies are based on the climatology from 1971 to 2000. Northwest India consists of Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh and Uttrakhand.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data

Graph 4: All India and Northwest India monthly absolute temperature comparison (March-May, 2022)

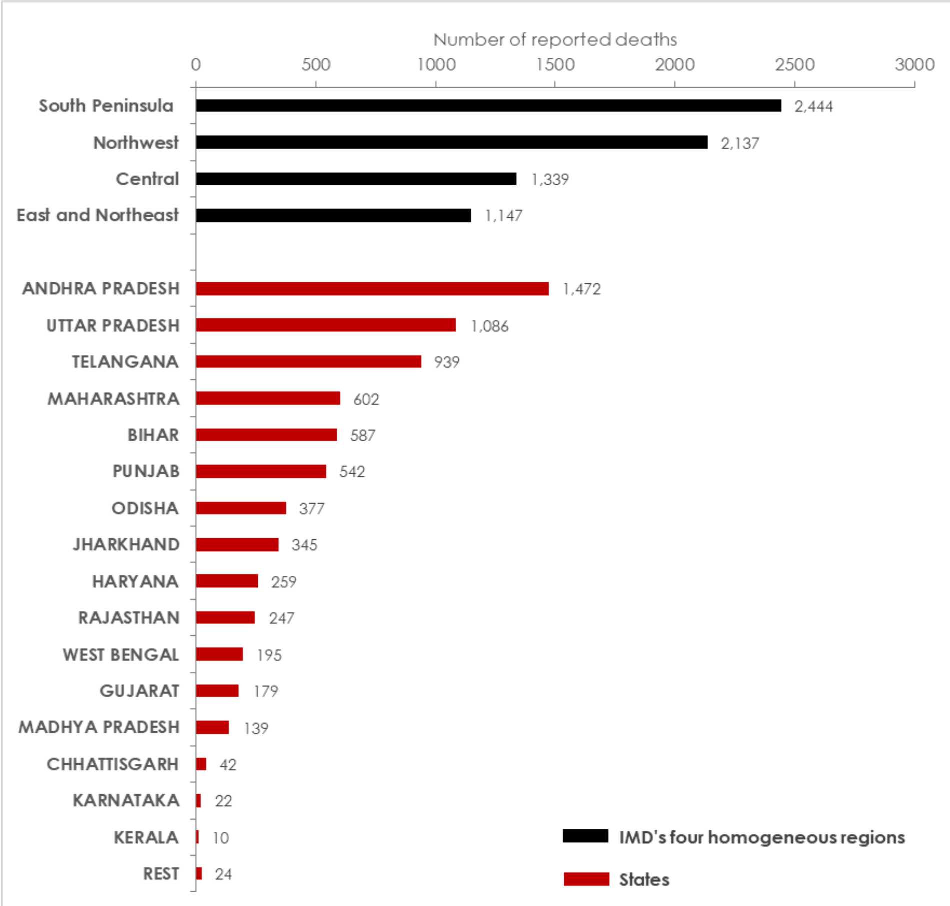


Note: Based on the observed spatial air temperature over India and Northwest India. Temperature is monthly average temperature as reported by IMD. Northwest India consists of Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh and Uttrakhand.
Source: CSE analysis of IMD ground observation data

Most deaths due to heat-stroke reported from states outside Northwest states: The data from the National Crime Record Bureau (NCRB) that also captures accidental deaths including those from climatic stress show that between 2015 and 2020, 2,137 people had reportedly died due to heat stroke in the Northwest states. But the South Peninsula region had reported 2,444 deaths due to excess environmental heat (See *Graph 5: State-wise heat-stroke deaths reported (2015-2020)*). Within the South Peninsula region Andhra Pradesh alone accounts for over half of the reported human casualties. Delhi has reported only one death for the same period. Most deaths are reported among working age men (30-60 year olds), considered highly vulnerable to temperature anomalies. The understanding of public health impact of meteorological conditions like heat wave is still weak in India.

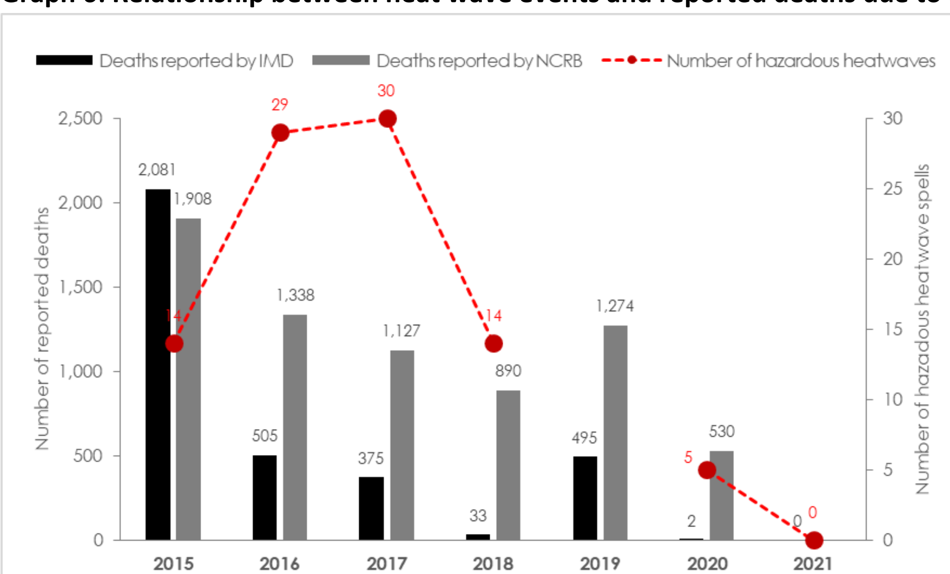
Death due to heatwaves are on a decline as per official reports: Heatwave are the second most deadly natural force in India. It has killed over 20,615 people during 2000-20. Lightning with 49,679 deaths was the top killer. There has been a decline in number of reported deaths since 2015 when IMD reported 2,081 deaths and NCRB reported 1,908 deaths. There were no deaths reported by IMD in 2021 and NCRB is yet to publish 2021 edition of their annual Accidental Deaths & Suicides in India (ADSI). 2016 and 2017 reported twice the number of heatwave events compared to 2015 but reported deaths caused were less than a quarter of 2015 toll(See *Graph 6: Relationship between heat wave events and reported deaths due to heat-stroke (2015-2022)*). This year media reports suggest about 90 deaths due to heatwaves in India, but there is no official verification for the number. It is quite possible that most of the deaths due to heat stress goes unreported as death may be attributed to other comorbidities or not get reported at all. Mostly, deaths occur among rural, low income and marginalized populations. However, these estimates need to be improved and ensure that there is no undercount in the data reported by NCRB and IMD.

Graph 5: Region and state wise heat-stroke deaths reported (2015-2020)



Source: CSE analysis of National Crime Record Bureau data as reported in annual Accidental Deaths & Suicides in India (2015-2020)

Graph 6: Relationship between heat wave events and reported deaths due to heat-stroke (2015-2022)

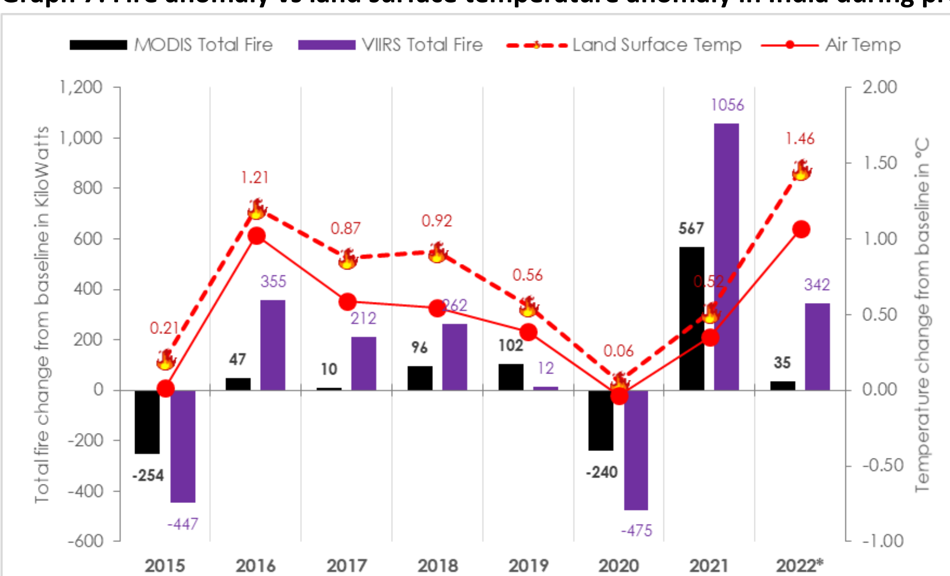


Note: Number of hazardous heatwaves for 2019 have not been reported by IMD in publically available documents.
Source: CSE analysis of National Crime Record Bureau data as reported in annual Accidental Deaths & Suicides in India, IMD data as reported in annual Disastrous Weather Events reports.

Any direct correlation between heatwaves and intensity or frequency of fire instances in India is not evident: Most instances of fire as recorded by NASA satellites was recorded in 2021 pre-monsoon season at all India level. Despite massive temperature anomaly this year (over 3-times higher in anomaly compared to 2021), fire anomaly this season is just 6 per cent of 2021 for MODIS and 32 per cent of 2021 for VIIRS (See *Graph 7: Fire anomaly vs land surface temperature anomaly in India during pre-monsoon (2015-22)*). Further, this analysis is based on the product of observed fire counts and average Fire Radiative Power (FRP) of the observed fires. This matrix provides a better measure of total fire activities accounting not just the number of fires but also the relative strength of it (quantum of energy released). The anomaly in fire instances is based on 2012-19 baseline.

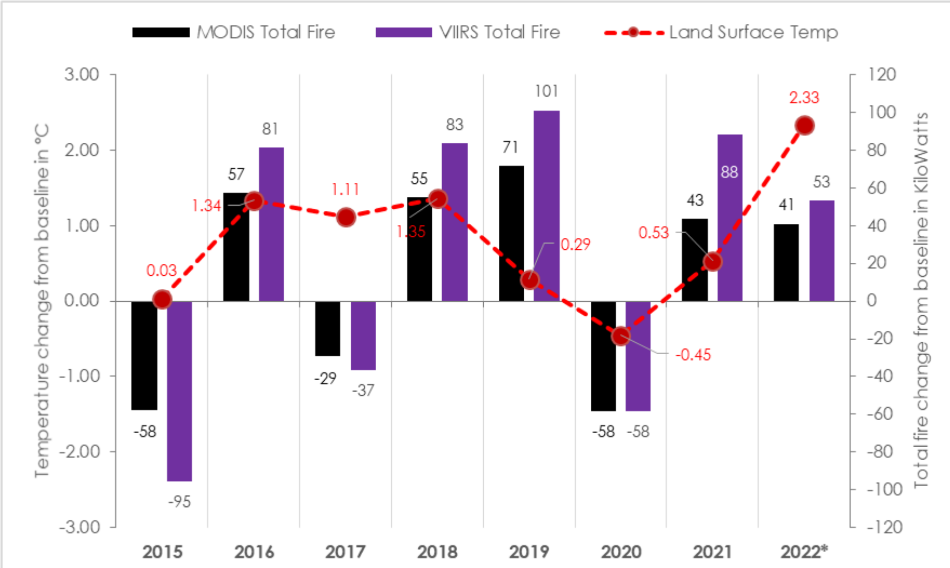
It must be noted that most of the pre-monsoon fire instances in India are reported from the forests of Central India and Eastern Himalayas. Northwest region which has been worst affected by heatwaves is not a hotspot for natural fire as the region doesn't have much forest cover outside the Western Himalayas. Fires instances reported from the region are mostly farm stubble fires and these are not generally governed by weather events. The region accounts for only 13-14 per cent of all fires in India recorded during pre-monsoon season while it constitutes about 28 per cent of India's landmass. This pre-monsoon season anomaly is less than half of what was observed in 2019 despite over 2°C hotter land surface temperature (See *Graph 8: Fire anomaly vs land surface temperature anomaly in Northwest India during pre-monsoon (2015-22)*). (Seasonal air temperature averages for Northwest region is only available for 2022, therefore assessing deviation in air temperature over years for Northwest could not be undertaken. Given the close relationship noted between air and land temperature anomaly this year, it can be assumed air temperatures will show similar behavior as land in the previous years as well)

Graph 7: Fire anomaly vs land surface temperature anomaly in India during pre-monsoon (2015-22)



Note: Based on the observed spatial air temperature anomaly pattern of monthly and seasonal average temperature over India and Global. Temperature anomalies are based on the climatology from 1971 to 2000. Total fire is based on the product of average seasonal Fire Radiation Power and total number of fire counts. It is computed for both MODIS and VIIRS. Total fire anomaly is based on departure from average of 2012-19.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data including products from its Fire Information for Resource Management System (FIRMS)

Graph 8: Fire anomaly vs land surface temperature anomaly in Northwest India during pre-monsoon (2015-22)

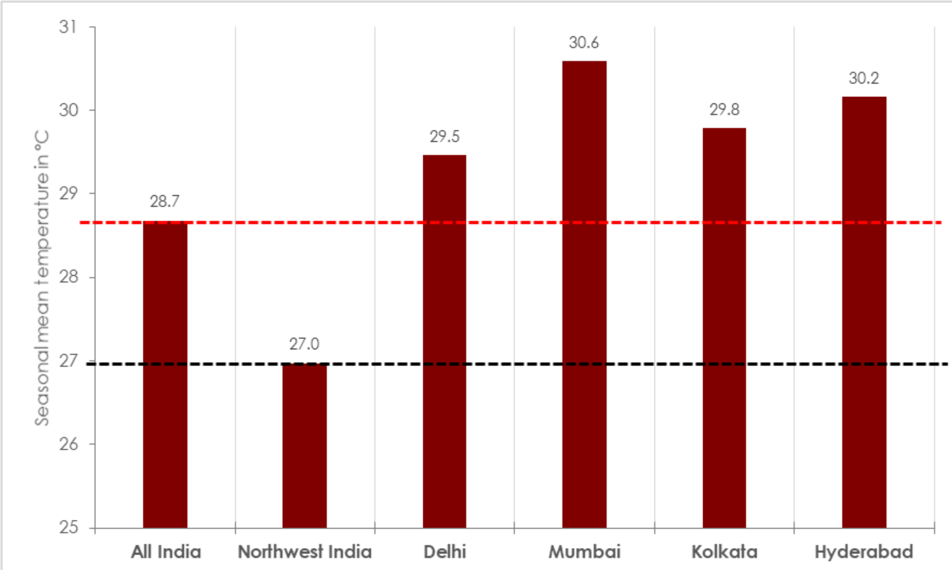


Note: Based on the observed spatial air temperature anomaly pattern of monthly and seasonal average temperature over India and Global. Temperature anomalies are based on the climatology from 1971 to 2000. Volume of fire instances is computed as product of average seasonal FRP and total number of fire counts. It is computed for both MODIS and VIIRS. Fire anomaly is based on departure from average of 2012-19. Northwest India consists of Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Ladakh, Punjab, Rajasthan, Uttar Pradesh and Uttrakhand.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data including products from its Fire Information for Resource Management System (FIRMS)

Mega cities are much hotter than the larger region around them: Seasonal average of Delhi, Mumbai, Kolkata and Hyderabad was 1-2°C higher than the all India average and 2.5-3.8°C higher than northwest India that is often the reference point in public mind (See *Graph 9: Seasonal average temperature comparison: National, regional and city level (March-May, 2022)*). This is due to the urban heat island phenomenon. Due to excessive hard and dark surfaces cities tend to absorb the heat coming from the sun during the day, further city also generates lot of waste heat due to human activities which adds to the natural heat. This extra heat should dissipate after sunset but due to pollution and continuing generation of waste heat the city fails to cool down leading warmer condition compared to rural areas.

High humidity is the real killer but is not accounted for in the heatwave cacophony: Heatwaves that lashed Northwest India this summer were predominantly dry in nature, i.e. relative humidity was low. Dry heatwaves are relatively less hazardous compared to humid heatwaves, the kind that occur in coastal regions. High humidity can exponentially increase the public health risk posed by hot air temperatures. In fact, high humidity can make even below 40°C temperature deadly. The abnormally high fatalities reported from Andhra Pradesh is due to the humid nature of the heatwaves that are frequent in the region. IMD doesn't account for the impact of relative humidity which computing heatwave conditions. IMD does have a lower temperature threshold for declaring heatwave in coastal areas but that is based on "normal" temperature observed in the region. Globally, heat index is used to access combined impact of air temperature and relative humidity. IMD doesn't use this matrix. It doesn't even share daily relative humidity data as part of its public communication which make computing national heat index average near impossible. To get some understanding of this problem, CSE sourced and analyzed relative humidity data from IMD weather stations at Delhi, Mumbai, Kolkata and Hyderabad. Daily heat index was computed using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula.

Graph 9: Seasonal average temperature comparison: National, regional and city level (Mar-May, 2022)



Source: CSE analysis of IMD ground observation data

Urban heat islands with massive temperature variations were found in all four metro cities: The study looked into the temperature and humidity data collected by the real-time air quality monitoring network and found massive variation in temperatures within the cities. In terms of absolute air temperature Hyderabad with 7.1°C variation has most pronounced heat islands while Kolkata with just 1.3°C has the least pronounced ones. Delhi has 6.2°C variation and Mumbai 5.5°C variation. Form heat index perspective Mumbai leads the group with 17.3°C variations. From land surface temperature perspective Delhi leads the group with 24.6°C variation (See *Graph 10: Intra-city variation in seasonal temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)*). The difference among the cities can be explained by environmental difference in the nature of the heat in their region and also difference in their topography and land use patterns. But given all four cities show significant variation in their intra-city temperatures (in all three forms) is a strong evidence urban heat island problem within the cities.

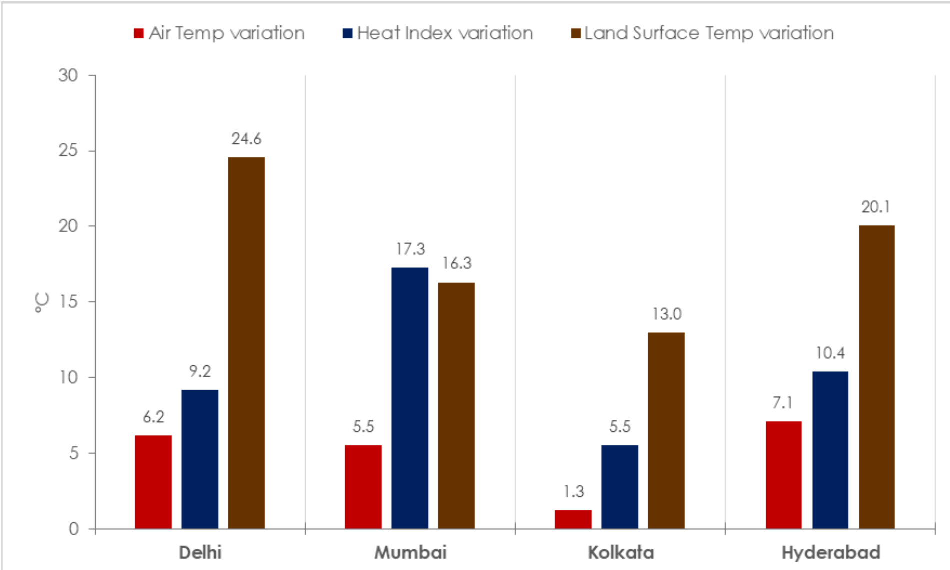
Hotspots in the cities: Given limited spatial distribution of air temperature official monitors, the study uses the land surface temperature to identify the heat hotspots within the city. In Delhi, maximum surface temperature was recorded in the south-west part of the city, Najafgarh is the persistent area with the highest temperature across all the time periods. Badarpur and Jaitpur are the other neighborhoods that have constant maximum temperatures above 40 °C. Minimum was observed for Yamuna River and Okhla bird sanctuary (See *Graph 11: Land surface temperature variation among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)*).

In Mumbai maximum surface temperature were recorded around Deonar dumping ground followed by Chhatrapati Shivaji International Airport and its surrounding areas. Minimum surface temperature were recorded in areas around water bodies such as Tulsi Lake, Vihar Lake and Powai Lake and regions in the vicinity of the sea.

In Hyderabad, hotspot areas were observed in south western region around the Rajiv Gandhi International Airport, Nadergul, and Turkayamjal. Jawahar Nagar and Bollaram Industrial area are the other hotspots. Areas around the lakes in the city had the lowest temperature.

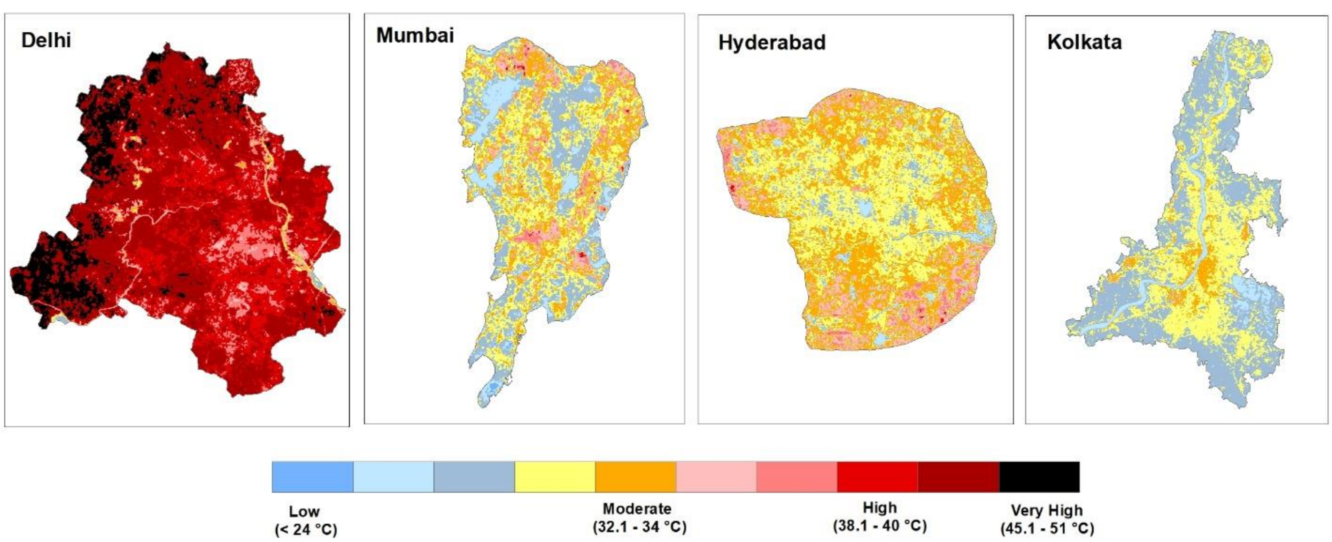
In Kolkata, there is not much variation in the land surface temperature within the city. Still the surface temperature were found to be relatively high around the city center and Netaji Shubash Chandra Bose International Airport. The area around the wetlands was the coolest.

Graph 10: Intra-city variation in seasonal temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)



Note: Daily heat index was computed using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula.
Source: CSE analysis of temperature and humidity data from CAAQMS network of CPCB and NASA satellite based remote sensing data

Graph 11: Land surface temperature variation among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)

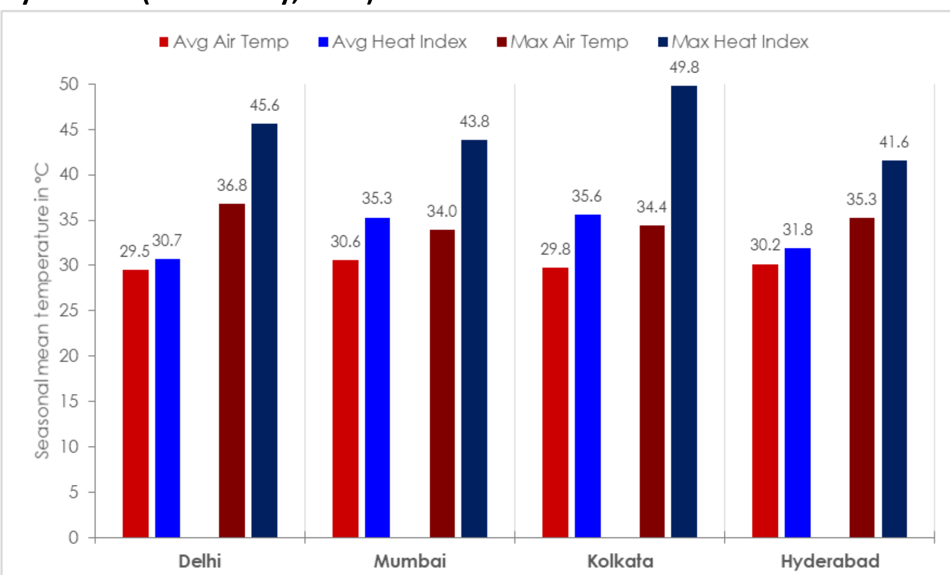


Source: CSE analysis of Landsat 8 satellite image from USGS Earth Explorer website

Heat index that accounts for both temperature and humidity show that Mumbai, Kolkata and Hyderabad, were more stressed than Delhi this summer: The daily average Heat Index for Kolkata has been almost 5°C higher than that of Delhi this summer. Mumbai's summer heat index has been 4.6°C and Hyderabad 1.1°C higher than Delhi (See *Graph 12: Comparison of seasonal temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)*). Even though seasonal average daily maximum air temperature in Delhi has been 1.5-2.8°C higher than the other three metros but in terms of heat index Kolkata with almost 50°C as seasonal maximum heat index was significantly hotter. Delhi's seasonal average daily maximum heat index was 45.6°C.

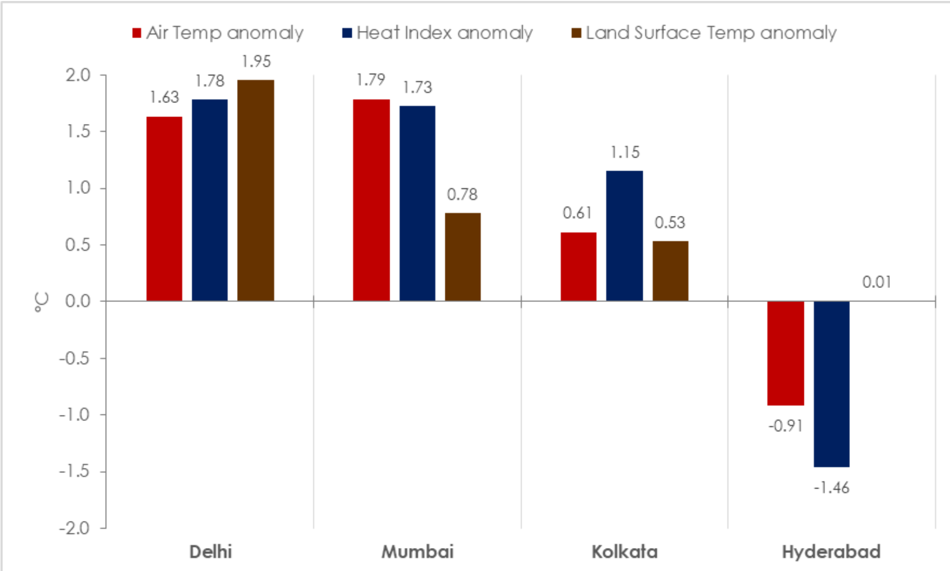
Hyderabad is experiencing an unusually cooler than normal summer this year: The seasonal average air temperature of Hyderabad was about 1°C lower than the normal, even the heat index was down by almost 1.5°C (See *Graph 13: Comparison of seasonal anomaly in temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)*). The land surface temperature has been normal as well. This is a complete contrast from other three metros, all of which recorded higher than normal temperatures. Delhi had most extreme anomalies of the four metros.

Graph 12: Comparison of seasonal temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)



Note: Daily heat index was computed using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula.
Source: CSE analysis of IMD data.

Graph 13: Comparison of seasonal anomaly in temperature and heat index among Delhi, Mumbai, Kolkata and Hyderabad (March-May, 2022)



Note: Daily heat index was computed using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula. Air temperature and land surface temperature anomalies are computed with respect to 1981-2010 baseline.
Source: CSE analysis of IMD ground observation data and NASA satellite based remote sensing data

Annexure

What is a heatwave?

There are no universal definition of heatwave. IPCC defines it as “a period of abnormally hot weather.” The U.S. National Oceanic and Atmospheric Administration (NOAA) defines a heatwave as "a period of abnormally and uncomfortably hot and unusually humid weather…typically, a heatwave lasts two or more days".

According to IMD “qualitatively, heatwave is a condition of air temperature which becomes fatal to human body when exposed. Quantitatively, it is defined based on the temperature thresholds over a region in terms of actual temperature or its departure from normal.”

Hot day or a heatwave or just the summer season?

Ambient temperatures can get warmer seasonally and some days can be much hotter than others due to a multitude of reasons that can be local, global or both. But high daily temperature on itself doesn’t qualify as a heatwave. High temperatures have to last for multiples days without a break to qualify as heatwave. A generic reading of this without any qualifiers runs the risk of qualifying the entire summer season as heatwave, therefore a certain threshold is always set to distingue heatwave from an isolated hot day or the whole summer season in general.

Meteorological agencies across the world have defined heatwaves based on local summer conditions and set criteria for minimum duration and minimum temperature threshold for differentiating heatwaves from summer season. Minimum temperature threshold can be defined as absolute air temperature or departure from local normal or both.

Regional differences in heatwave criteria

The World Meteorological Organization (WMO), defines a heat wave as “five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5°C or more.”

Many countries follow WMO definition but there are a few that have custom defined it based on their local conditions and understanding of hazard to public health. Here is a selection of some of these custom definitions:

<u>Australia:</u> The Australian Bureau of Meteorology defines a heatwave as "three days or more of maximum and minimum temperatures that are unusual for the location". The federal states have their own technical definitions, for instance the federal state of South Australia defines it as “five consecutive days at or above 35°C or three consecutive days at or over 40°C.”

<u>Canada:</u> Environment Canada issues heat warnings at different temperatures depending on the region. For typically warmer climates, like southern Ontario, a heat warning will be issued after at least two days of a humidex of 42°C or higher. Whereas in the northern province of Newfoundland and Labrador, there will be a heat warning after only an hour of the humidex reaching 40°C. [The humidex is an index number used by Canadian meteorologists to describe how hot the weather feels to the average person, by combining the effect of heat and humidity.]

China: The China Meteorological Administration defines a heatwave as a period when "the maximum day temperature exceeds 35°C for at least three consecutive days."

Denmark: A national heatwave is defined as a period of "at least 3 consecutive days of which period the average maximum temperature across more than fifty percent of the country exceeds 28°C."

France: According to the French National Meteorological Service a heatwave is "a periods when the average minimum and maximum temperatures over three consecutive days exceeded predefined departmental thresholds." Each department, French equivalent of districts, has its own threshold based on local climatology.

Germany: According to the German Meteorological Service (Deutscher Wetterdienst, DWD) a heatwave is defined as "98th percentile and a temperature threshold of 28°C lasting of at least three days."

Israel: The Israel Meteorological Service defines heatwave as "a prolonged event in which the heat load is heavier than usual and lasts many hours a day."

Mexico: The definition varies based on region. For Mexico City heat wave is defined as "daily maximum of 30°C observed for three or more consecutive days and 25°C or more as mean temperature."

South Africa: According to the South African Weather Service a heatwave is "when for at least three consecutive days the maximum temperature of a certain region or grid point is five degrees or higher than the average mean maximum for the hottest month for that particular station or grid point."

Sweden: A heatwave is defined as "at least five days in a row with a daily maximum temperature exceeding 25°C."

The Netherlands: A heat wave is defined as a period of at least five consecutive days in which "the daily maximum temperature in DeBilt (headquarter of the Royal Netherlands Meteorological Institute) exceeds 25°C, provided that on at least three days in this period the maximum temperature in DeBilt exceeds 30°C." This definition of a heatwave is also used in Belgium and Luxembourg.

The United Kingdom: According to the UK Met Office "a heatwave threshold is met when a location records a period of at least three consecutive days with daily maximum temperatures meeting or exceeding the heatwave temperature threshold." The threshold is set at the UK counties level. There is no national threshold. The UK Met Office updated heatwave threshold this year. The initial heatwave thresholds were calculated based on "the 1981-2010 climatology of daily maximum temperature at the mid-point of the meteorological summer (15 July)." The revised thresholds will use the 1991-2020 averaging period introduced in January 2022.

The United States: According to US EPA a heat wave is "a period of two or more consecutive days when the daily minimum apparent temperature (the actual temperature adjusted for humidity) in a particular city exceeds the 85th percentile of historical July and August temperatures (1981–2010) for that city." Technical details varies by regions within the US. In the Northeast US, a heatwave is typically defined as three consecutive days where the heat index (combined effective of temperature and relative humidity) reaches or exceeds 32.2°C.

Indian criterion for declaring heatwave

IMD has two systems for declaring heatwave; first is based on departure from normal and second is based on actual maximum temperature. The thresholds are set according to topographical divisions.

- Based on Departure from Normal
    - Heatwave: Departure from normal is 4.50°C to 6.40°C, given the maximum temperature is at least 40°C or more for Plains, at least 37°C or more for Coastal regions and at least 30°C or more for Hilly regions
    - Severe Heatwave: Departure from normal is higher than 6.40°C, given the maximum temperature is at least 40°C or more for Plains, at least 37°C or more for Coastal regions and at least 30°C or more for Hilly regions
- Based on Actual Maximum Temperature
    - Heatwave: When actual maximum temperature is in the range of 45°C-47°C
    - Severe Heatwave: When actual maximum temperature is equal or higher than 47°C

If above criteria met at least in two stations in a Meteorological sub-division for at least two consecutive days and heatwave is declared on the second day for the whole subdivision.

Normal is based on the climatology of maximum temperature prepared for the period 1981-2010 of the day for particular station.

India has 36 metrological subdivisions and their boundaries sometimes coincides with actual state/union territory boundaries but not always. For instance Chandigarh, Delhi and Haryana are included in a single subdivision while Maharashtra has four sub-divisions and Uttar Pradesh has two subdivisions.

What causes heatwaves?

According to NOAA, "a heatwave occurs when a system of high atmospheric pressure moves into an area and lasts two or more days. In such a high-pressure system, air from upper levels of our atmosphere is pulled toward the ground, where it becomes compressed and increases in temperature."

This high concentration of pressure makes it difficult for other weather systems to move into the area, which is why a heatwave can last for several days or weeks. The longer the system stays in an area, the hotter the area becomes. The high-pressure inhibits winds, making them faint-to-nonexistent. Because the high-pressure system also prevents clouds from entering the region, sunlight can become punishing, heating up the system even more. The combination of all of these factors come together to create the exceptionally hot temperatures that is referred as a heatwave.

According to IMD, "in India heat waves generally develop over Northwest India and spread gradually eastwards & southwards but not westwards (since the prevailing winds during the season are westerly to northwesterly). But on some occasions, heat wave may also develop over any region in situ under the favorable conditions."

How does heat wave impact health?

According to WHO heatwaves can have a significant impact on society, including a rise in heat-related deaths. Heatwaves are among the most dangerous of natural hazards, but rarely receive adequate attention because their death tolls and destruction are not always immediately obvious.

Heat gain or heat stress in the human body can be caused by a combination of external heat from the environment and internal body heat generated from metabolic processes. Rapid rises in heat gain due to exposure to hotter than average conditions compromises the body's ability to regulate temperature and can result in a cascade of illnesses, including heat cramps, heat exhaustion, heatstroke, and hyperthermia.

Deaths and hospitalizations from heat can occur extremely rapidly (same day), or have a lagged effect (several days later) and result in accelerating death or illness in the already frail, particularly observed in the first days of heatwaves. Even small differences from seasonal average temperatures are associated with increased illness and death. Temperature extremes can also worsen chronic conditions, including cardiovascular, respiratory, and cerebrovascular disease and diabetes-related conditions.

Heat also has important indirect health effects. Heat conditions can alter human behavior, the transmission of diseases, health service delivery, air quality, and critical social infrastructure such as energy, transport, and water. The scale and nature of the health impacts of heat depend on the timing, intensity and duration of a heatwave, the level of acclimatization, and the adaptability of the local population, infrastructure and institutions to the prevailing climate. The precise threshold at which temperature represents a hazardous condition varies by region, other factors such as humidity and wind, local levels of human acclimatization and preparedness for heat conditions.