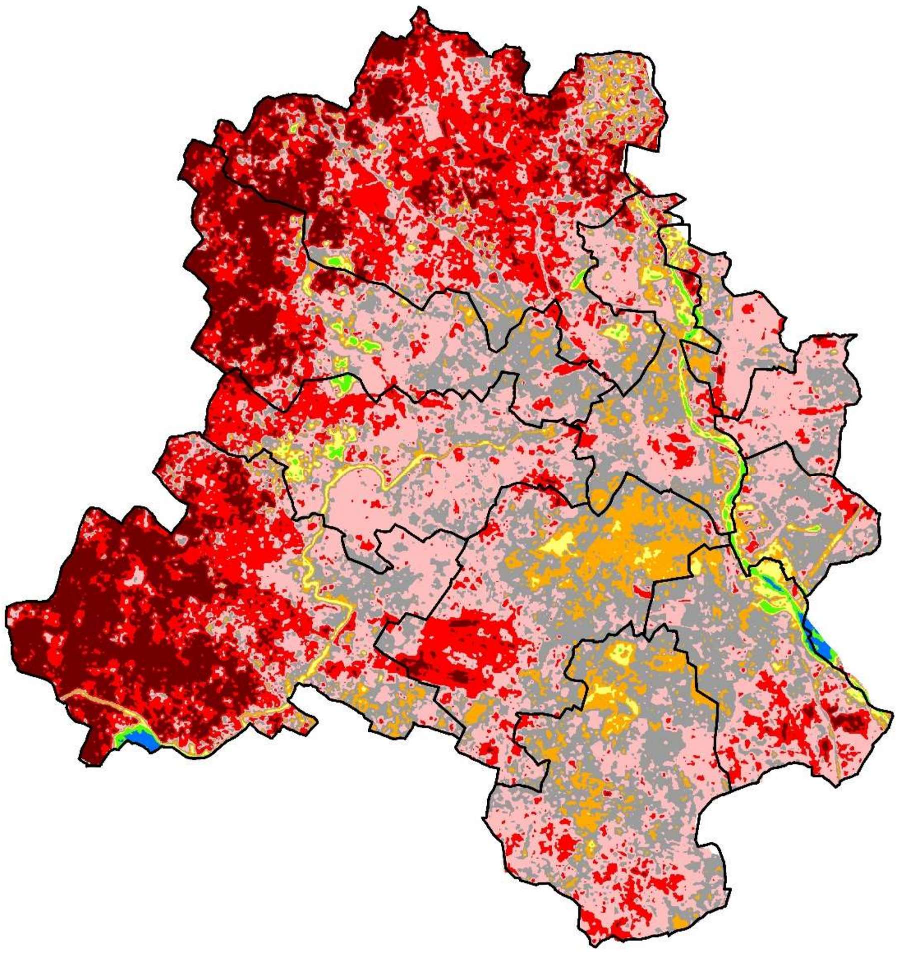
Urban Heat Stress Tracker



Delhi

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Overview

Heatwaves have become a staple of Indian summer due to the climate change. No region of the country is immune to this worsening phenomenon. States and cities are publishing their heat action plans to safeguard their populations from the dangerous heat exposures during heatwaves. These plans, while outlining the measures for emergency response and preparedness, also define the responsibilities of stakeholder departments in the event of a heatwave. These policy interventions assume significance at a time when heat and temperature trends are expected to worsen due to climate change and growing urbanization.

The relevance of these policy actions need to be understood against the rapidly changing global climate. The technical summary of the Intergovernmental Panel on Climate Change (IPCC), Working Group-I, Sixth Assessment Report (AR6 WG-I) notes that it is almost certain that the frequency and intensity of heat extremes and duration of heat waves have increased since 1950 and this will keep increasing even if global warming is stabilized at 1.5°C.[1] Combining climate change projections with urban growth scenarios, it can be said with very high confidence that future urbanization will amplify the projected increase in local air temperature.

With reference to urban centres, the IPCC Working Group-II, in its assessment (AR6 WG-II), also notes with confidence that hot extremes, including heat waves, have intensified in cities. It further notes that urban areas experience air temperatures that are several degrees warmer than surrounding areas, especially during the night. The urban heat island effect can add 2°C to local warming, reducing the adaptive capacity of cities and increasing the aforementioned risks.[2] This is due to reduced ventilation, heat trapping by closely-spaced tall buildings, heat generated directly from human activities, heat-absorbing properties of concrete and urban building materials, and limited vegetation. Infrastructure related to transportation, water, sanitation, energy and others has been compromised by extreme and slow-onset events, resulting in economic losses and disruption of services, impacting the well-being of people.

This emerging scientific evidence of the adverse impact of rising heat on urban populations builds the case for a city-specific heat management regime and the urgent implementation of heat action plans in cities. Such planning approaches also need to go much deeper than the immediate emergency response to help cope with specific heat events during summer and prevent heat lock-in. This is not only about summer action for public health protection but more sustained action throughout the year to heat proof the city and undertake heat mitigation, along with monitoring, to improve the overall adaptive thermal comfort of built structures and reduce energy and carbon intensity of built environment.

Such planning and intervention are possible if cities develop a tracking mechanism for annual and diurnal trends in temperature, humidity and the overall heat index to inform planning and implementation. Understanding the trend in heat and humidity patterns over time as well as during the day and night is necessary.

It is often noted that health emergency action considers the high daytime temperatures and not the nighttime temperatures and relative humidity. This overall trend poses risks to both public health and the energy security of the city, underlying the need tointegrate this consideration into informing the heat action plan. The heat problem is not just about focusing on daily maximum temperatures crossing the 45°C benchmark—the standard focus during summer—but involves a much more complex set of indices.

Urban heat mitigation also requires more robust scientific tracking of key indicators—not just ambient heat and temperature, but also surface heat absorption and land surface temperatures, changing land-use, including vegetative cover and water bodies that are determinants to the heat island effect. This requires effective leveraging of the available satellite technology. Given advancements in technology, such data is available but needs policy integration.

It is equally important to track the various impacts of rising heat in the cities. The increasing heat is known to compromise the adaptive thermal comfort of people in cities and increase the demand for active cooling and use of mechanical cooling systems, including air conditioning which is an energy guzzler. This impacts the overall energy demand and energy security of the city and the region. Yet, this dilapidating aspect of heat on a city's natural cooling abilities, including the rising trend in electricity demand to keep cool, is never tracked and considered for the active thermal management of cities.

This deeper conversation has to begin now because Delhi and several other states and cities have started developing their respective heat action plans.

In view of this, the Centre for Science and Environment has carried out this case study of select metro cities of India to analyse the trends in heat, humidity, land surface temperature and change in land use patterns to bring out the complex nature of heat management in cities. This detailed analysis of the heat scape of Delhi considers the time frame from 2001 to 2023.

This analysis has focused on the trends in day and night time temperature, humidity levels, seasonal variations, heat trends during day and night, trend in land surface temperature and trend in built-up area in the six megacities. Analysing these trends have provided deep insight into what is needed to inform the heat management practice in the city.

Methodology and data

The study is based on comparative statistical analysis of temperature and the humidity condition observed in Delhi since 2001. The study's definition of summer is the period from March to August. It is further divided into pre-monsoon (March-May) and monsoon (June-August) as per IMD classification. This is based on publicly available datasets from various national and global agencies. Ambient temperature and humidity data have been sourced from Indian Meteorological Department (IMD) weather stations at Palam and Safdarjung. An average of the findings from these two weather stations is used to represent Delhi in this study. Heat Index computation has been done using the U.S. National Oceanic and Atmospheric Administration's (NOAA) formula. Complex geospatial calculations have been done in python and ArcGIS.

Moreover, freely accessible MODIS Land Science data from NASA Earth Observations has been used for seasonal and long term analysis of land surface temperature. For more granular analysis of heat and land use conditions on extremely hot days, satellite imagery data from the United States Geological Survey (USGS) Earth Explorer website has been used. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 operational land imager/thermal infrared sensor (OLI/TIRS) satellite imagery were downloaded and used to analyse the land surface temperature, land use, land cover and Normalized Difference Vegetation Index (Green cover).

This city-level assessment focuses on changes in heat patterns over the years for the summer season, urban expansion over the years, and land surface temperature variation during the summer of 2003, 2013, and 2022. For Delhi, the later analysis is based on 10 May 2003, 29 May 2013, 14 May 2022, and 9 May 2023.

Highlights

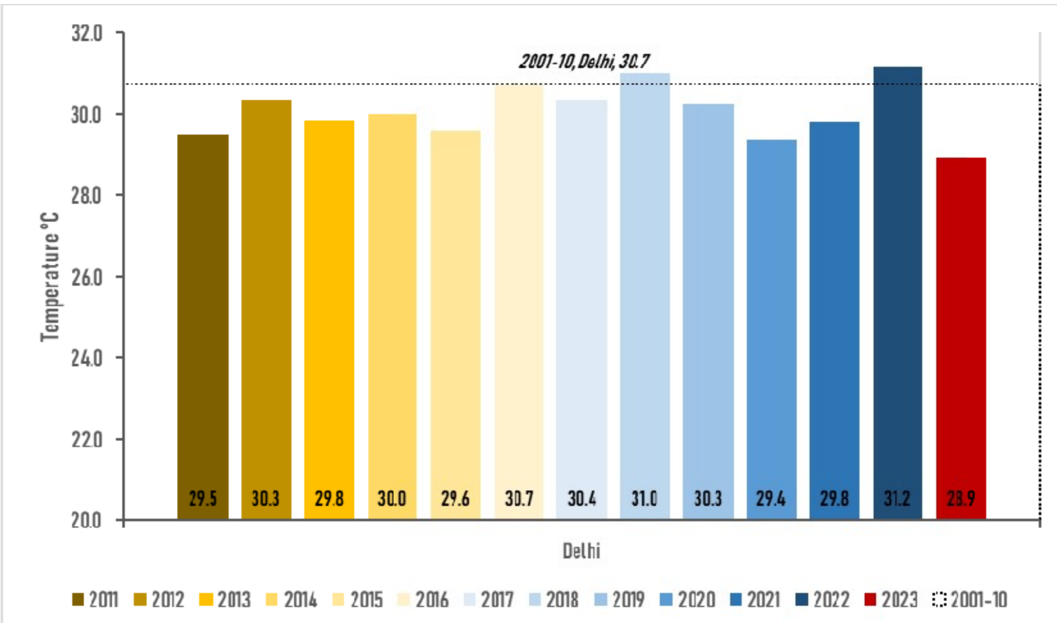
- **2024 March-April so far has been 3°C cooler than the average of 2014-23.**
- **Delhi's summertime has registered 0.6°C lower decadal average ambient air temperature but the relative humidity has increased by 8 per cent between 2001-10 and 2014-23.**
- **High humidity is responsible for adding on average 3.3°C of heat stress to the city.**
- **Monsoon are getting more thermally more unconformable than pre-monsoon. Average heat index during monsoon is 9.4°C more than pre-monsoon.**
- **City is not cooling down at night. The diurnal cooling down of land surface temperature between daytime and nighttime is down by 9 per cent.**
- **Urban heat island phenomena is stronger at night than daytime in Delhi. At night the peri-urban area cools down 12.2°C while the city core cools down only 8.5°C. So the city core is cooling down 3.8°C less than its peri-urban.**
- **There is direct co-relation between increase in built-up area and increase in urban heat stress. Increase in green cover shows impact on daytime temperatures but has no impact on nighttime temperature and increasing heat index in the city.**

Key findings

Decadal trend in summertime heat

Ambient air temperature in Delhi during summertime shows little change: 2023 summer (March-August) was not as hot as thesummer before for Delhi but if last ten summers (2014-23) is compared to the first decade of the 21st century (2001-10) there are clear trends. Decadal summertime average for Delhi is down by 0.6°C compared to 2001-10 (see *Graph 1: Trend in summertime seasonal average ambient temperature in Delhi 2011-2023*).

Graph 1: Trend in summertime seasonal average ambient temperature in Delhi 2011-2023



Note: Summer is defined as the period from March to August. A city's weather profile is based on average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

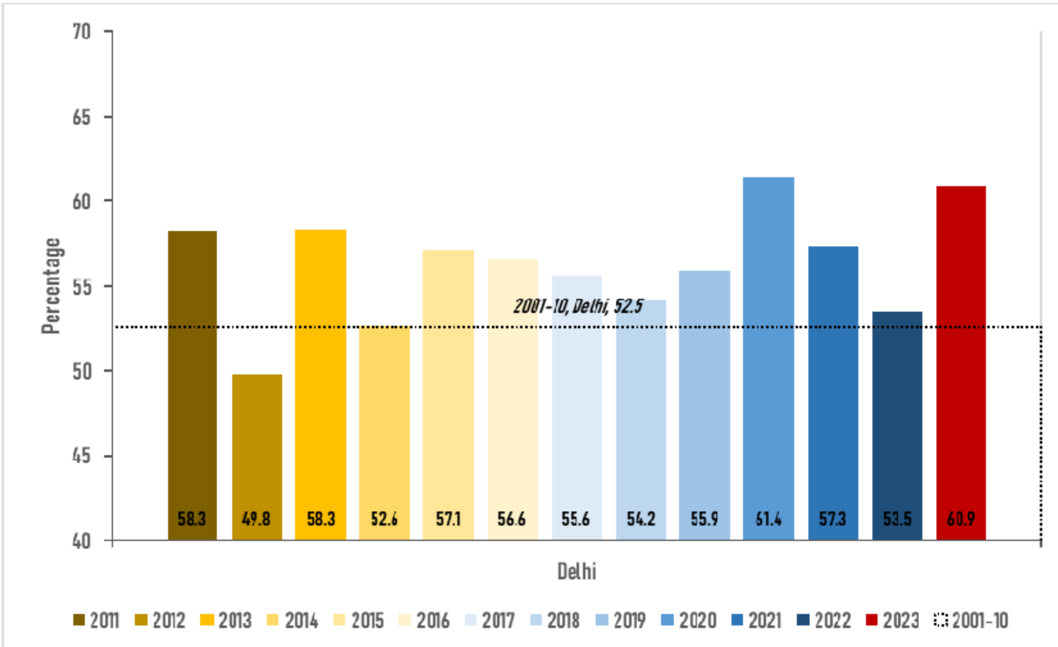
Nature of heat is changing in Delhiwith significant increase in relative humidity during summer even though ambient air temperature is stable: Average Relative Humidity (RH) has significantly increased in the last 10 summers compared to 2001-10 average. Delhi's last ten summers have been 8 per cent more humid on average compared to its 2001-10 average (see *Graph 2: Trend in summertime seasonal relative humidity in Delhi 2011-2023*).

Delhi might have registered a significant increase in relative humidity level but it is located in one of the driest climatic zones of India. This significant jump in decadal relative humidity still doesn't bring its overall humidity levels to coastal cities which are located in more humid climates. But this increased humidity in part nullifies the marginal drop in ambient air temperatures in Delhi.

This combination of high heat and humidity can compromise the human body's main cooling mechanism: sweating. The evaporation of sweat from skin cools our bodies, but higher humidity levels limit this natural cooling. As a result, people can suffer heat stress and illness, and the consequences can even be fatal even at much lower ambient temperatures. Impact of this increasing humidity can be measured on human thermal comfort via means of Heat Index (HI). According to the U.S. National

Weather Service, the heat index is a measure of how hot it really feels when humidity is factored in with the actual temperature. It is considered that a heat index of 41°C is dangerous to human health.

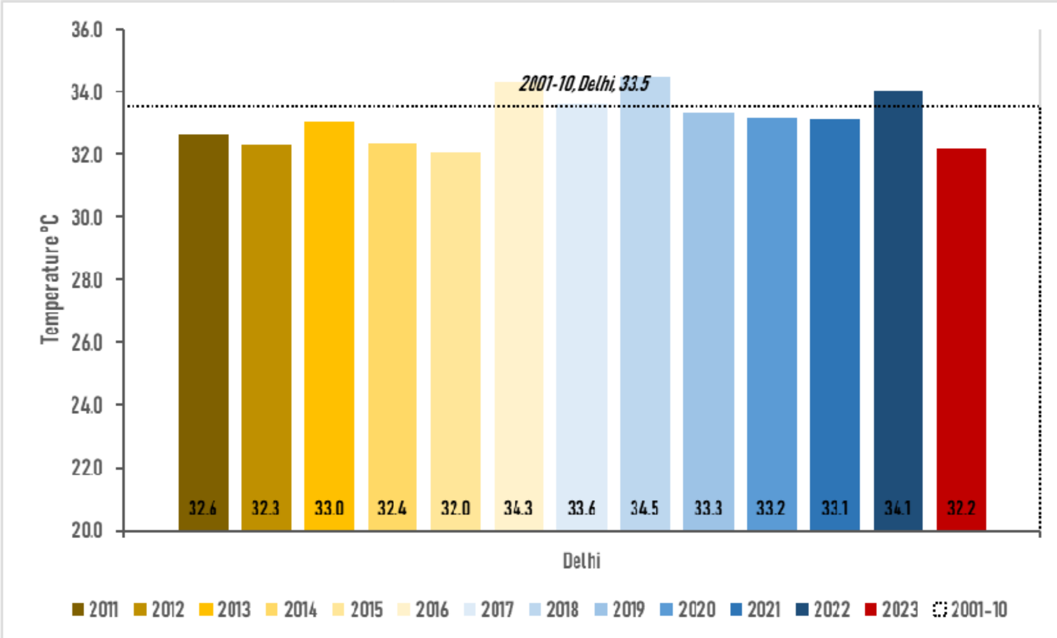
Graph 2: Trend in summertime seasonal relative humidity in Delhi 2011-2023



Note: Summer is defined as the period from March to August. A city's weather profile is based on the average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Heat Index rising faster than ambient temperature in Delhi: Given the rise of relative humidity during summer, the heat index (HI) has risen which is a better measure of human thermal discomfort. Delhi's summer HI average stood at 32.2°C (impact of humidity: 3.3°C) making the feel like temperature much hotter (see *Graph 3: Trend in summertime seasonal average Heat Index in Delhi 2011-2023*).

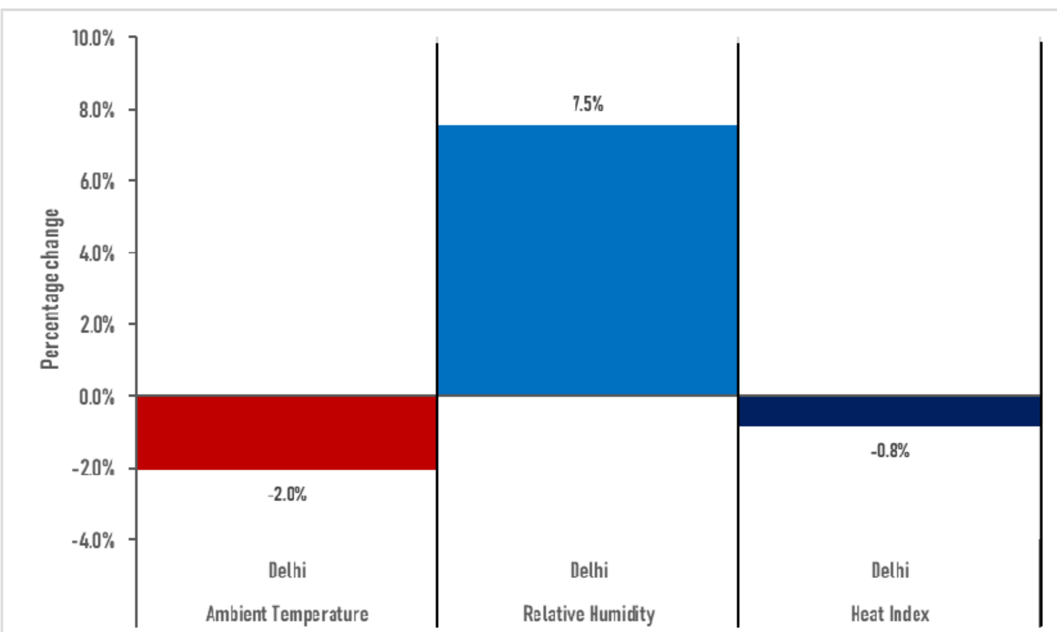
Graph 3: Trend in summertime seasonal average Heat Index in Delhi 2011-2023



Note:Note: Summer is defined as the period from March to August. A city's weather profile is based on average of all IMD weather stations located in the city. Heat index has been calculated using the U.S. National Oceanic and Atmospheric Administration formula. * Data uptill 30 August 2023.
Source: CSE analysis of climatological data from IMD

Delhi summer on average is marginally less hotter than it was in the first decade of the century: Decadal RH average (2014-23) rose by 7.5 per cent in Delhi compared to 2001-10 average. This has nullified the 2 per cent drop in the decadal ambient air temperature. Delhi's decadal average HI is down by 0.8 per cent (see *Graph 4: Trend in decadal summertime heat in Delhi 2014-23 vs 2001-2010*).

Graph 4: Trend in decadal summertime heat in Delhi 2014-23 vs 2001-2010



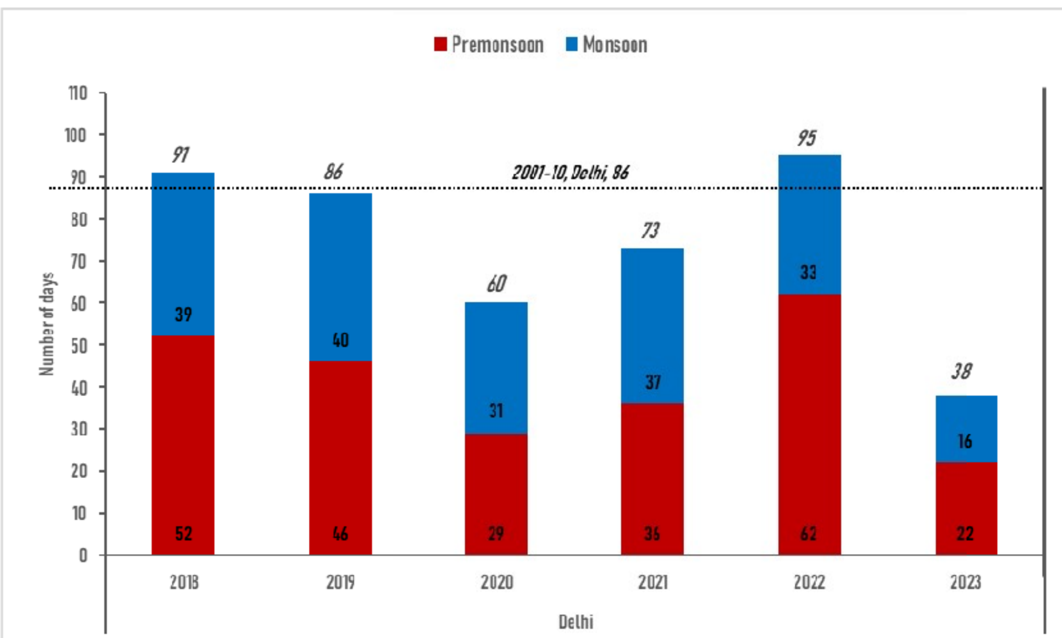
Note: Summer is defined as the period from March to August. A city's weather profile is based on the average of all IMD weather stations located in the city. Heat index has been calculated using the U.S. National Oceanic and Atmospheric Administration formula. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Number of days with high ambient temperatures are stable over the last two decades but days with dangerously high heat index are on a rise: Delhi on average used to have 86 days in a summer with high ambient temperature (37°C+)during 2001-10 but it registered just 38 days with such high temperatures in 2023 summer (see *Graph 5: Trend in days with 37°C+ daily maximum temperature in Delhi 2018-2023*).

But just looking at the daily maximum temperature figure is not a good measure of thermal discomfort and heat stress on the population as daily average temperature and humidity are critical to parameters as well.Human body is worse at handling humid heat than dry heat. If the heat index crosses the 41°C mark it is considered dangerous to human beings. In 2023 summer, Delhi registered 14 days when the daily average heat index crossed the danger threshold of 41°C (see *Graph 6: Trend in days with 41°C+ daily heat index in Delhi 2018-2023*). This is similar to its 2001-10 average of 15 days but the summers of 2020 and 2021registered 32 days and 23 days of danger HI respectively.

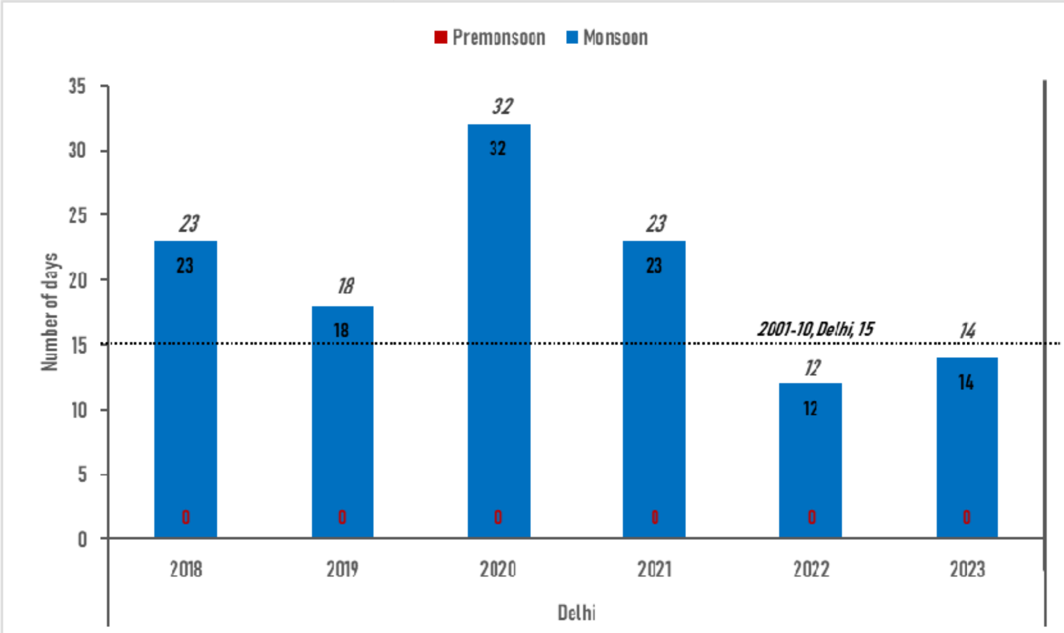
Additionally, it must be noted that in Delhi the majority of days with 37°C+ ambient temperature occur during pre-monsoon period (March-May) compared to monsoon period (June-August). Meanwhile, when looking at days with 41°C+ HI the situation reverses, all days with danger HI levels happen during monsoon period (June-August).

Graph 5: Trend in days with 37°C+ daily maximum temperature in Delhi 2018-2023



Note: Summer is defined as the period from March to August. A city's weather profile is based on the average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Graph 6: Trend in days with 41°C+ daily heat index in Delhi 2018-2023



Note: Summer is defined as the period from March to August. A city's weather profile is based on the average of all IMD weather stations located in the city. Heat index has been calculated using the U.S. National Oceanic and Atmospheric Administration formula. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

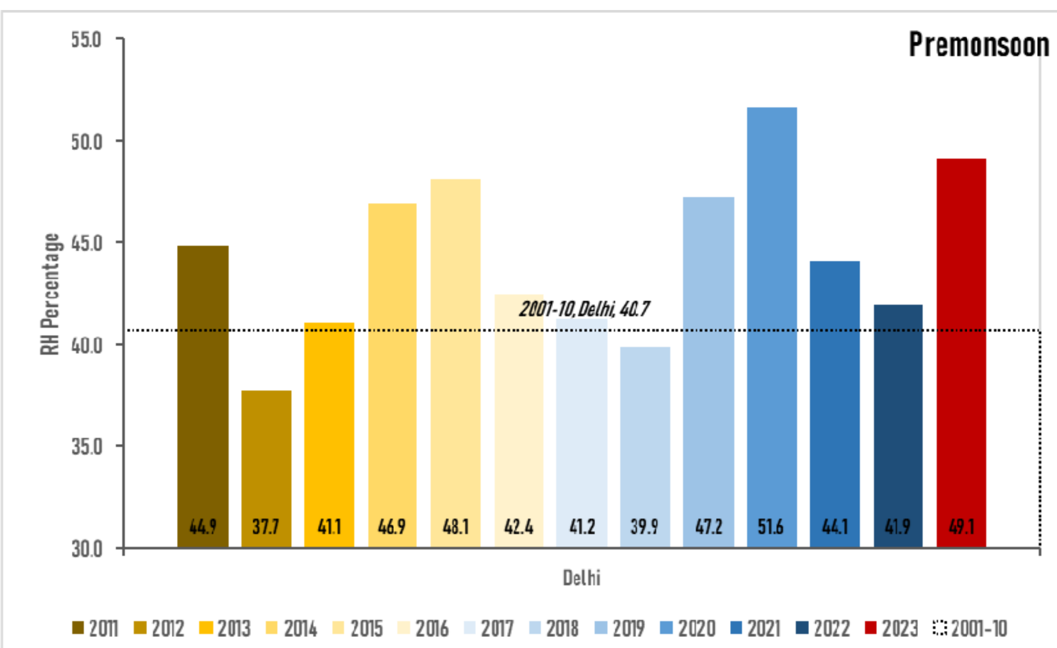
Pre-monsoon vs monsoon heat

Dry pre-monsoon period is getting muggier but the heat impact of humidity is most pronounced during monsoon: Summer can be divided into two distinct periods, i.e. pre-monsoon or dry heat period and monsoon or humid heat period.IMD defines pre-monsoon as March to May, while monsoon is considered from June to August. Naturally relative humidity is much lower during pre-monsoon compared to monsoon period. The study has found that average Relative Humidity (RH) has significantly increased for both pre-monsoon and monsoon period compared to 2001-10 average for Delhi. Last ten pre-monsoons have been on average 11 per cent more humid compared to 2001-10 average. Meanwhile monsoon humidity levels have risen by 5 per cent (see *Graph 7: Trend in relative humidity in Delhi 2011-2023 a. Pre-monsoon; b. Monsoon*).

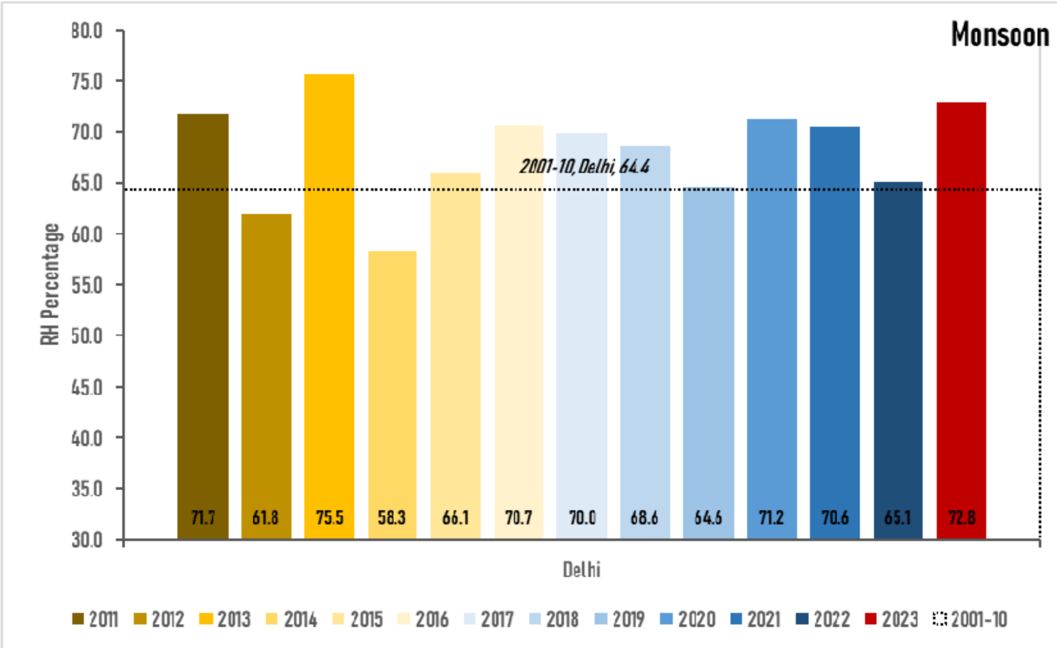
Humidity has little impact on the pre-monsoon heat conditions of Delhi it has added on average (2014-23) less than 1°C in terms of heat index (see *Graph 8: Trend in impact of relative humidity on the ambient air temperature in Delhi 2011-2023 a. Pre-monsoon; b. Monsoon*).

During monsoon, humidity are much elevated compared to pre-monsoon which has a significant impact on the heat conditions. Any additional increase in RH levels can absolutely exacerbated the heat stress. This impact is severe in Delhi with its last ten monsoons with HR adding4.9-7.4°C in the heat index over the ambient heat. This is an increase of 12 per cent compared to the average impact of RH during 2001-10 (see *Graph 8: Impact of relative humidity on the ambient air temperature in Delhi 2011-2023 a. Pre-monsoon; b. Monsoon*).

Graph 7: Trend in relative humidity in Delhi 2011-2023
a. Pre-monsoon

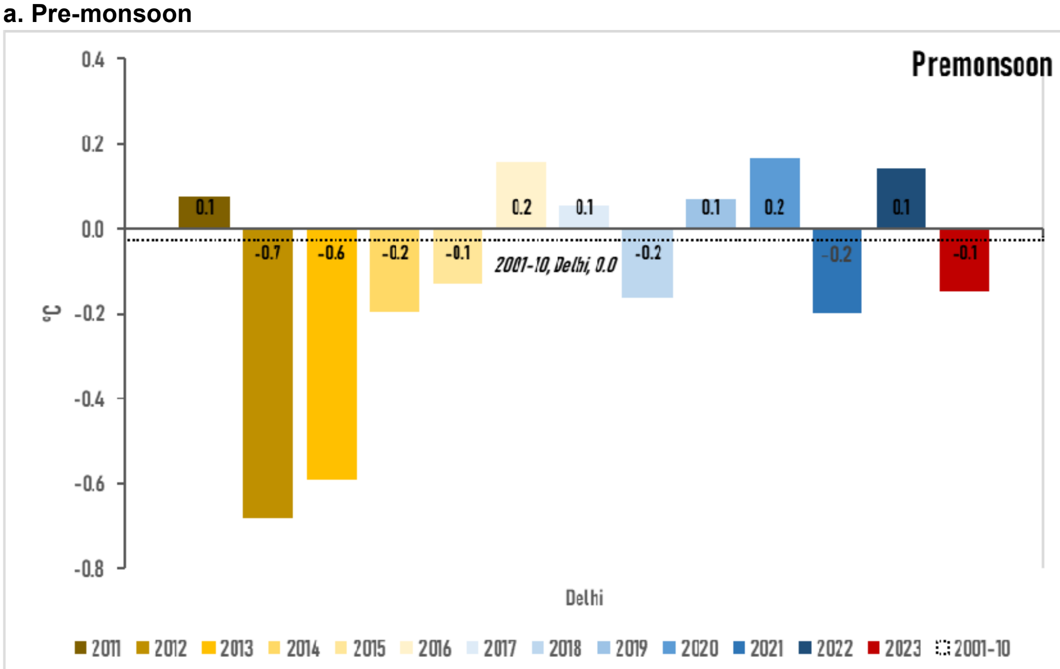


b. Monsoon

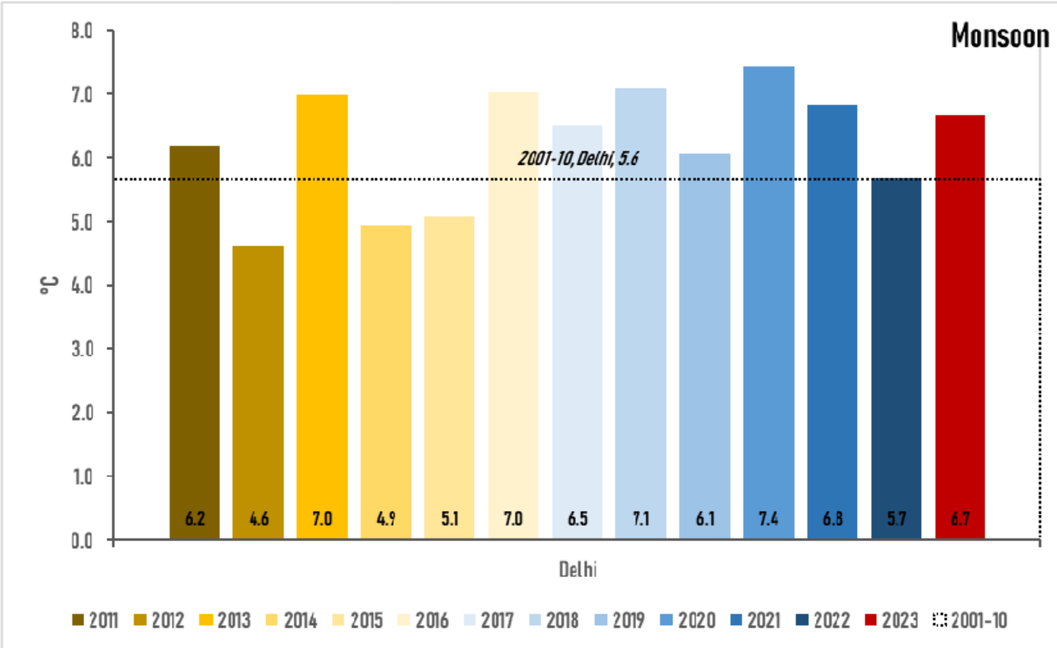


Note: Pre-monsoon refers to the months of March, April and June. Monsoon falls within June, July and August. A city's weather profile is based on the average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Graph 8: Impact of relative humidity on the ambient air temperature in Delhi 2011-2023
a. Pre-monsoon



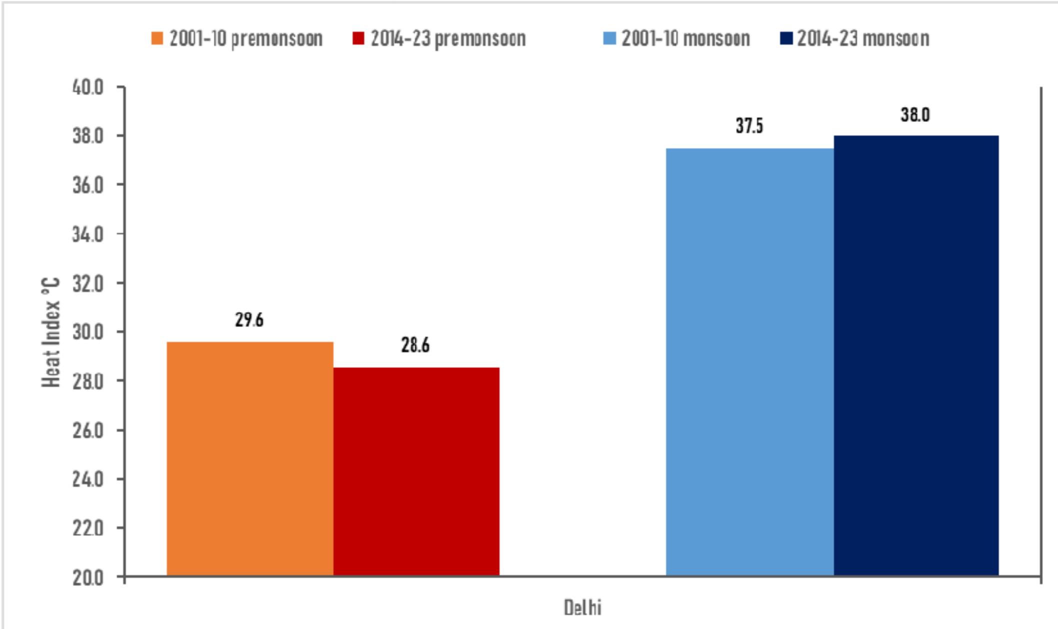
b. Monsoon



Note: Pre-monsoon refers to the months of March, April and June. Monsoon falls within June, July and August. Heat index has been calculated using the U.S. National Oceanic and Atmospheric Administration formula.A city's weather profile is based on the average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Monsoons are getting more thermally discomfortable; monsoon in Delhi hotter than pre-monsoon: During 2001-10, the Heat Index used to rise between pre-monsoon and monsoon in Delhi by 7.9°C on average. This has increased to 9.4°C during 2014-23. Basically, the pre-monsoon has on average got lesser heat index while monsoon has become more uncomfortable(see *Graph 9: Decadal change in heat index in Delhi pre-monsoon vs monsoon*).

Graph 9: Decadal change in heat indexin Delhi pre-monsoon vs monsoon



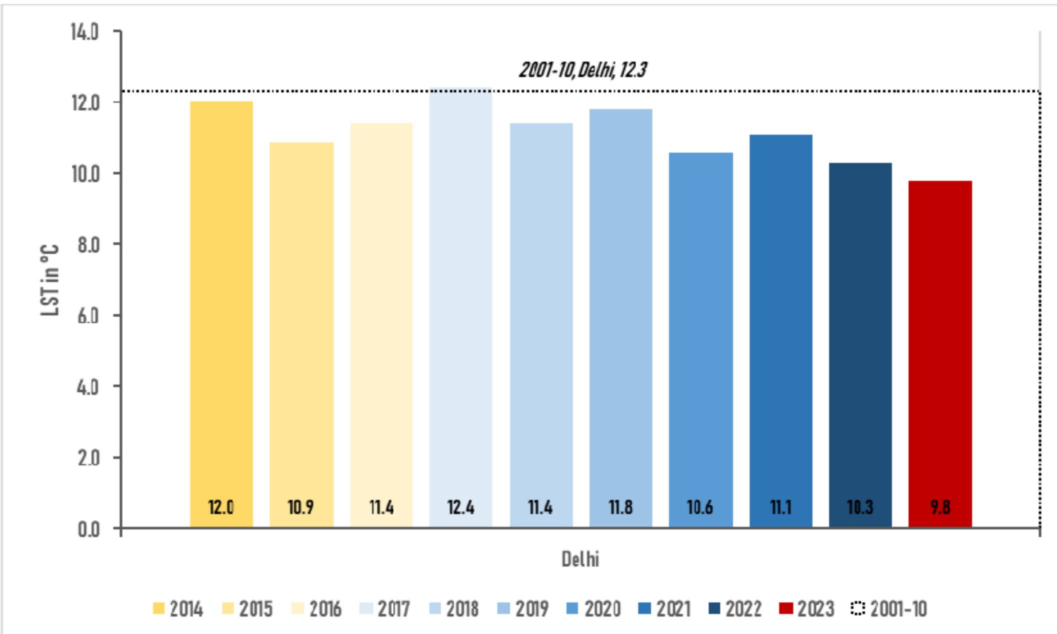
Note: Pre-monsoon refers to the months of March, April and June. Monsoon falls within June, July and August. Heat index has been calculated using the U.S. National Oceanic and Atmospheric Administration formula.A city's weather profile is based on the average of all IMD weather stations located in the city. * Data until 30 August 2023.
Source: CSE analysis of climatological data from IMD

Land surface heat and land use pattern

Delhi is not cooling down at night: During summers of 2001-10, the land surface temperature (LST) used to come down on average by 12.3°C from the daytime peak to nighttime low in Delhi. In the last ten summers (2014-23) the nighttime cooling has reduced to11.2°C. This translates to roughly 9 per cent reduction indiurnal cooling down (see *Graph 10: Trend in summertime diurnal land surface* *temperature changes in Delhi 2014-2023*). It must be noted that the nighttime cooling is getting even lesser in the last few years.

Hot nights are as dangerous as midday peak temperatures. People get little chance to recover from daytime heat slaughter if temperatures remain high overnight, exerting prolonged stress on the body. A study published in the Lancet Planetary Health by a group of scientists from China, South Korea, Japan, Germany and the U.S. noted that the risk of death from excessively hot nights would increase nearly six-fold.[1] This prediction is much higher than the mortality risk from daily average warming suggested by climate change models.

Graph 10: Trend in summertime diurnal land surface temperature changes in Delhi 2014-2023



Note: Summer is defined as the period from March to August. * Data uptill 30 August 2023.
Source: CSE analysis of monthly MODIS Land Science data from NASA Earth Observations.

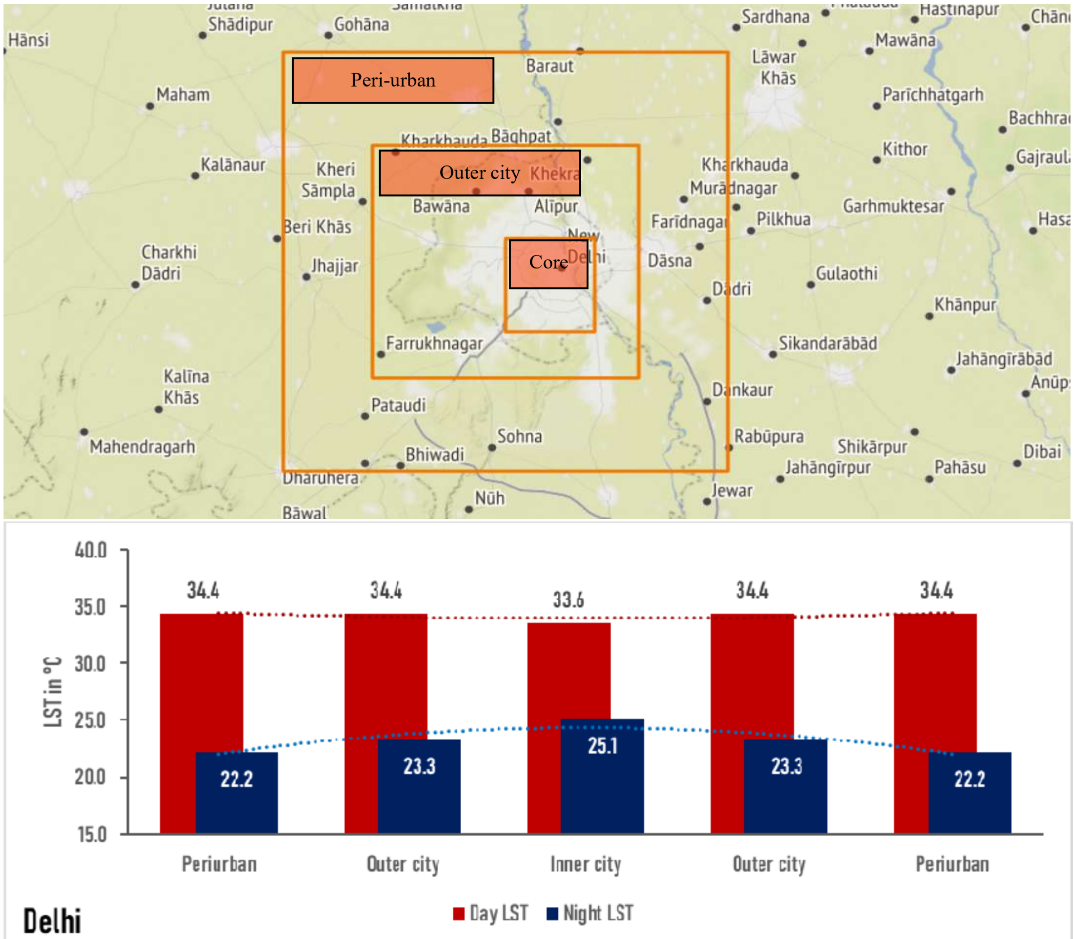
Analysis of Delhi's spatial heat-scape shows that its core is not cooling down at night at the same rate as its peri-urban region: City cores are usually hotter than their surrounding peri-urban and rural areas as high population and built-up density traps and retains heat for longer duration.It is called the urban heat island phenomenon. Analysis of NASA satellite images shows that Delhi's nighttime land surface temperature exhibit urban heat island formation. But Delhi's daytime land surface temperature exhibits inverse of an urban heat island, i.e. the core of the city is cooler than its peri-urban during the daytime.

During the daytime, the core of Delhi is 0.8°C cooler than its peripheries and peri-urban areas during the summer. But at night the core of Delhi is 2.9°C hotter than its peripheries and peri-urban areas (see *Graph 11: Spatial variation in land surface temperature among the core city, outer city and peri-urban region of Delhi*). At night the peri-urban area cools down 12.2°C while the city core cools down only 8.5°C. So the city core is cooling down 3.8°C less than its peri-urban.

This abnormality in the daytime heat-scape of Delhi can be attributed to presence of more green spaces in the city core but a detailed investigation into its causation is beyond the scope of this study.

[1] Cheng He et al 2022. "The effects of night-time warming on mortality burden under future climate change scenarios: a modelling study", The Lancet Planetary Health, Volume 6, Issue 8. https://doi.org/10.1016/S2542-5196(22)00139-5

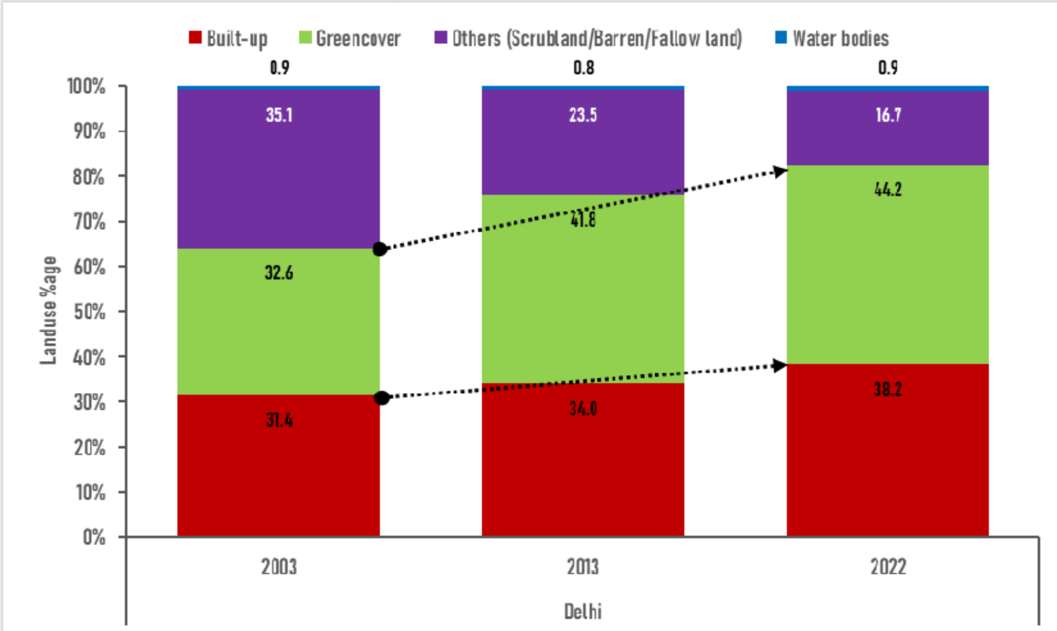
Graph 11: Spatial variation in LST among the core city, outer city and peri-urban region of Delhi



Note: Based on average of 2018, 2019, 2020, 2021, 2022 and 2023 data. Summer is defined as March to August. * Data uptill 30 August 2023.
Source: CSE analysis of monthly MODIS Land Science data from NASA Earth Observations.

Delhi have become more concertize in last two decades which has contributed to rise in urban heat stress: Delhi'sbuilt up area has increased from 31.4 per cent in 2003 to 38.2 per cent in 2022. Green cover has increased from 32.6 per cent in 2003 to 44.2 per cent in 2022 (See *Graph 12: Change in land use pattern in Delhi in last two decades*).

Graph 12: Change in land use pattern among megacities in last two decades

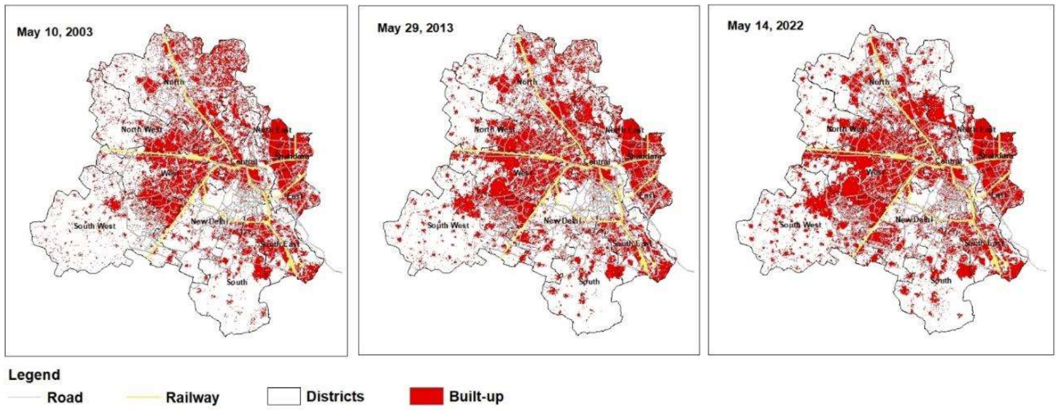


Note: Summer heat wave months (May-June) are chosen to analyse the Normalized Difference Vegetation Index (NDVI) and urban expansion for each year.
Source: CSE analysis of Landsat 7 and Landsat 8 satellite images from United States Geological Survey (USGS) Earth Explorer.

Land Use pattern change analysis: Delhi saw a significant increase in its built-up area, with an expansion from 467.8 sq. km in 2003 to 568.9 sq. km in 2022, which depicts a gradual rise in the percentage share of the state's geographical area from 31.4 per cent in 2003 to 38.2 per cent in 2022. Significant and rapid urban expansion is observed in the East, South, Southwest, and South East zone (See *Map 1: Growth in Urban Built-up in Delhi during 2003, 2013 and 2022*).

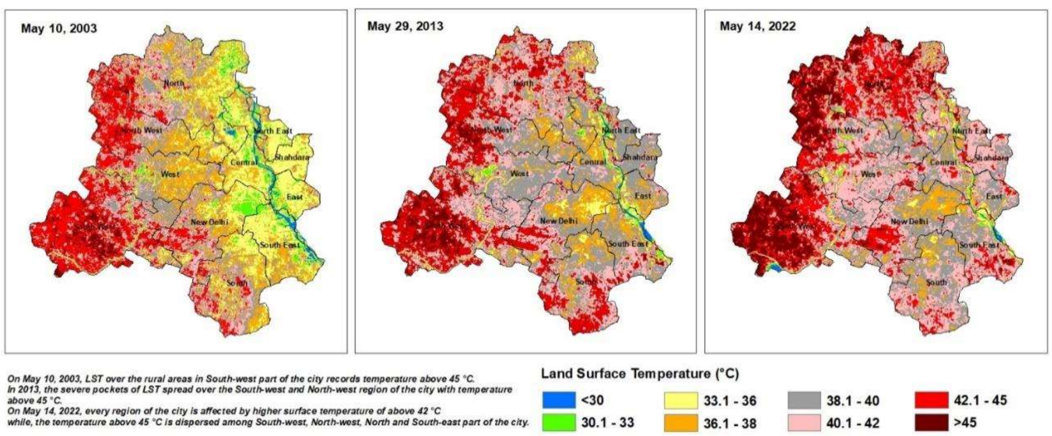
Impact of land surface changes on the distribution of land surface temperature: In 2003, the central part of Delhi had a low temperature ranging from 30.1°C to 36 °C, while the northern and southwest suburban areas, covered by rock and new growth settlements, recorded temperatures above 36°C. The middle part of Delhi, which was covered by enough density of vegetation and tree cover, showed moderately lower temperature values. Conversely, densely populated built-up areas in the Southwest, Northwest, North, New Delhi, and Southern parts of Delhi recorded temperatures above 40°C. However, in 2022, there was a dramatic rise in land surface temperature inside the city, exceeding 40°C and covering almost all regions, except the vegetation or green cover area was observed, with temperatures that ranged from 38°C to 40°C—a significant increase from the earlier 30–33°C (See *Map 2: Variation in Land Surface Temperature over Delhi for 2003, 2013 and 2022*).

Map 1: Growth in Urban Built-up in Delhi during 2003, 2013, and 2022



Note: Urban expansion for each year – 2003, 2013, and 2022.
Source: CSE analysis of Landsat 7 and Landsat 8 satellite images from United States Geological Survey (USGS) Earth Explorer.

Map 2: Variation in land surface temperature in Delhi over 2003, 2013 and 2022



Note: Summer heat wave months (May-June) are chosen to analyse the Land Surface Temperature (LST). The respective date of acquisition of the images are May 10, 2003, May 29, 2013, and May 14, 2022.
Source: CSE analysis of Landsat 7 and Landsat 8 satellite images from United States Geological Survey (USGS) Earth Explorer.