Spatiotemporal Analysis of LST and UHI Dynamics of Delhi NCR over 25 years (2000-2024) using GEE

Abhishek Malik[1], Shubham Mor[2], Ranbir Singh[3], Prof. Gaurav Kalotra[4]

Abstract

Urbanization in the National Capital Region (NCR) of India over the past 25 years (2000 – 2024) has drastically changed the energy balance of the surface of the land. This report presents a comprehensive longitudinal study of land surface temperature, diurnal temperature range, and urban heat island for all 35 districts in the NCR and utilizes MODIS thermal data (MOD11A2) and MODIS land cover data (MCD12Q1) that have been processed using Google Earth Engine and a dynamic rural masking method to quantify the real intensity of urban heat islands. Spatial analysis of the thresholds shows a significant growth in impervious surfaces caused by anthropogenic activity to be the main contributor to thermal anomalies in NCR. A major diurnal inversion exists between the urban cores (which exhibit the Urban Cool Island [UCI] effect) on summer days, resulting from rapid thermal heating of surrounding semi-arid barren land. The true environmental issue is found after sunset, when the high thermal inertia and summer heat retained within the urban matrix create extreme Nighttime Urban Heat Island (NUHI) impacts and a significant reduction in the diurnal temperature range (DTR) due to inhibited nocturnal cooling (overnight). Finally, the use of Pearson correlation analysis using 2011 Census demographic information has identified a significant positive correlation (r = 0.76) between population density and NUHI intensities and identified anthropogenic clustering as the primary cause of thermal stress caused by population density.

[1]Research Scholar, Department of Geography, Panjab University, Chandigarh, malikabhishek83@gmail.com
[2]Assistant Professor (Geography), Rajiv Gandhi Government College, Saha, Ambala (Haryana), shubhammor1996@gmail.com
[3]Assistant Professor (Geography), Government. PG college, Barwala, Panchkula, email ranbir009@gmail.com
[4]Professor (Geography), Department of Geography, Panjab University, Chandigarh, gauravkalotra@gmail.com
*Corresponding author
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Introduction:

In the 21st Century, an accelerated rate of urbanization has occurred resulting in a complete transformation of the Earth's energy balance. The increasing tendency of replacing natural vegetation with impervious urban surfaces like roads, buildings, and pavements has led to a modification of the local environment's climate. One of such anthropogenic phenomena is the urban heat island effect characterized by higher temperatures within the urban centres in comparison to those of rural locations. The continuous heat entrapment caused by the urban infrastructure contributes to an increased Land Surface Temperature (LST) and a narrower Diurnal Temperature Range (DTR).

Despite its negative impact on the environment, the intensity of the UHI effect significantly varies depending on climatic zones. For instance, in arid areas, there is the phenomenon of diurnal inversion when high-speed warming of surrounding barren soil and cultivated crops may lead to their temperatures becoming higher compared to the urban centres where building shadows mitigate overheating, resulting in "Urban Cool Islands". However, nighttime temperatures are usually much higher owing to the thermal properties of urban soils which cause heat retention and slow release at night. Therefore, it results in the appearance of powerful night-time urban heat islands.

The Indian National Capital Region (NCR) serves as an important example that allows for a detailed investigation of urban heat islands nature. Being one of the fastest-growing urban clusters in the world, it incorporates 35 districts from several states. Intensive industrial activity and large migration flows have led to significant Land Use and Land Cover (LULC) changes over the last 20 years. As evidenced by the statistics for 2011, some districts within the NCR have extreme population densities surpassing 20,000 people/sq.km. Consequently, it resulted in urbanization of vast agricultural lands, thus creating the conditions for extreme urban heat island effect formation. Despite the critical nature of this issue, the majority of existing literature on the Delhi NCR focuses either exclusively on the core NCT region or relies on short-term, episodic satellite data. There is a glaring lack of comprehensive, long-term spatiotemporal studies that quantify the transition of LST (Land Surface Temperature), DTR (Diurnal Temperature Range), and UHI (Urban Heat Island) intensity across the entire 35-district expanse of the NCR. Furthermore, the statistical correlation between these microclimatic shifts and core demographic indicators remains under-explored.

Review of Literature

Research on the spatiotemporal dynamics of Urban Heat Islands (UHI) and Land Surface Temperature (LST) has evolved significantly with the advent of advanced geospatial technologies. The relevant literature can be broadly categorized into four thematic areas: (1) global UHI dynamics, (2) spatiotemporal monitoring using remote sensing, (3) the Urban Cool Island (UCI) effect in semi-arid regions, and (4) microclimatic studies specific to the Delhi NCR.

Perspectives of Global Urbanization and Thermal Anomalies: The basic science behind urban microclimates has been well-developed by Oke (1982), who explained the energetics underlying the concept of the Urban Heat Island (UHI). Following up, Voogt and Oke (2003) made pioneering use of thermal remote sensing techniques in measuring the SUHI, replacing standard ground meteorological stations' data by spatially continuous thermal imaging of the landscape. At the global level, it was shown by Imhoff et al. (2010) that ISA and population density account for two key explanatory factors of UHI intensity in different ecological biomes. Similar arguments are provided by Estoque et al. (2017) when asserting that the composition of the landscape, namely the relative balance between concrete and green cover, is the key factor explaining extreme heat exposure in fast-expanding Asian megacities.

Urbanization and Spatiotemporal Analysis Using MODIS Satellite Remote Sensing: When looking at long time series data for sustained analysis, one may use satellite high-frequency sensors like MODIS. Using MODIS, Tran et al. (2006) have analysed the extent of the UHI in Asian megacities, proving that there is always a consistent increase in city core temperatures compared to the rural background. Peng et al. (2012) conducted a large-scale analysis involving 419 global cities based on MODIS LST, showing that nighttime UHI occurs globally and that it is correlated significantly with spatial growth. Finally, Clinton and Gong (2013) emphasized the utility of using MODIS land cover maps alongside LST in order to effectively exclude rural backgrounds, which is necessary for estimating UHI intensities for several decades in a row.

Diurnal Temperature Range and the Effect of the Urban Cool Island (UCI): A change in the Diurnal Temperature Range (DTR) as a result of increased urban concretization is a key indicator of climate alteration. As proved by Karl et al. (1993), the process of urbanization creates an asymmetry in the temperature trends; minimum temperatures increase faster than maximums. Interestingly, in semi-arid and arid environments, such an asymmetry reverses during daytime hours. In line with that Haashemi et al. (2016), after analyzing Tehran, a semi-arid environment in the wider NCR ecosystem, observed an urban cool island effect in summer days. Similar findings were obtained by Lazzarini et al. (2013) studying desert environments where LST of barren soils was found to be greater than in built-up areas before sunset time.

Microclimate Studies in the National Capital Region (NCR) of Delhi: The NCR, considering its significant demographic changes and rapid growth in industry, has been subjected to many microclimatic studies. Mohan et al. (2011) have shown how there have been several LULC changes in the area of Delhi, and these have been correlated with the reduction in vegetation cover and water bodies leading to increases in thermal changes. Pandey et al. (2014) conducted a study on urbanization's influence on the land surface temperature (LST) of Delhi and found a strong inverse relationship between the NDVI and the UHI effects. Grover & Singh (2015) made a comparison between Delhi and Mumbai and found that since Delhi has a semiarid local climate, it is more prone to large variations in temperatures than coastal cities. In terms of studying the influence of the demographics, Yuan & Bauer (2007) (globally) and Mallick et al. (2008) (locally) have established through statistical analyses that highly populous regions tend to show sharp and unmuffled thermal spikes.

Despite these extensive studies, there remains a substantial research gap. Most localized studies focus merely on the core NCT region or analyse episodic, short-term data using Landsat. Comprehensive, long-term (25-year) statistical assessments mapping the DTR, Day-Night UHI inversion, and exact demographic correlations across all 35 expanding districts of the NCR are notably absent. This research addresses this precise spatial and temporal void.

- To address this important research gap, this study uses 25 years (2000 to 2024) of continuous MODIS thermal and LULC data to meet the following aims:

1. Evaluate the changes in Land Surface Temperature (LST) over time and identify trends over decades using the Google Earth Engine.
2. Assess the seasonal differences in temperature patterns, particularly comparing the extremes of peak summer and winter.
3. Quantify the Diurnal Temperature Range (DTR) to understand how much heat is retained at night.
4. Measure the intensity and spread of the Urban Heat Island (UHI) effect.
5. Identify key thermal hotspots to find areas facing severe and ongoing environmental heat stress.

Materials and Methods

Study Area: The National Capital Region (NCR), India

The study takes place in the National Capital Region (NCR) of India, one of the largest and fastest-growing urban areas in the world. Covering about 55,083 sq. km, the NCR includes the entire

National Capital Territory (NCT) of Delhi and nearby districts from the states of Haryana, Uttar Pradesh, and Rajasthan. This region has a semi-arid climate, known for its extreme temperature swings—very hot summers from April to June, and cold winters from November to January. The rapid growth in industry and infrastructure has led to significant population growth in the NCR. According to the 2011 Census of India, the region shows a wide variation in how people are distributed. Some core districts have extremely high population densities, exceeding 20,000 persons per sq. km. This makes it an excellent location to study how rapid urbanization affects microclimates.

Data Acquisition

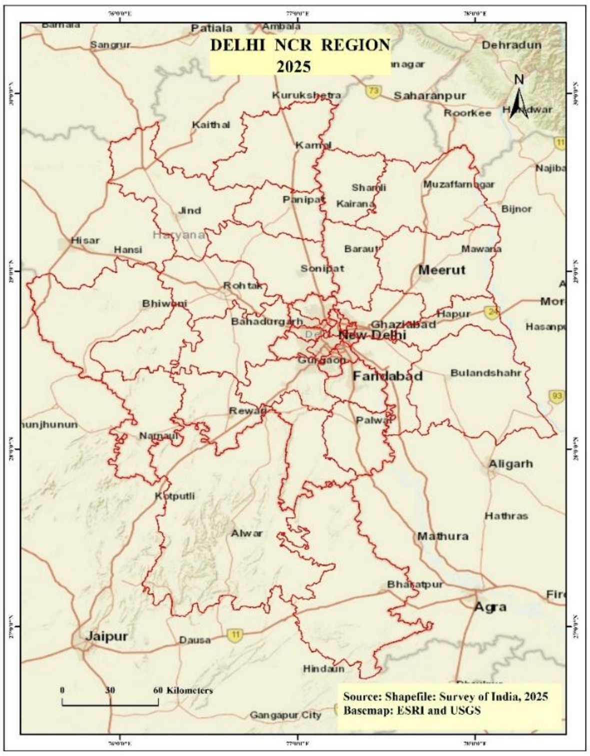
To conduct a detailed 25-year (2000-2024) study, we used multiple high-resolution spatial and demographic datasets and all of the dataset has been computed using the Google Earth Engine java script-based codes. The following data has been computed for the study:

Thermal Data: We obtained Land Surface Temperature (LST) data from the MODIS Terra MOD11A2 Version 6.1 product. This dataset offers an 8-day composite of LST with a spatial resolution of 1 km, providing reliable daytime and nighttime thermal bands.

Land Use/Land Cover (LULC) Data: We received annual land cover classification from the MODIS Terra/Aqua MCD12Q1 Version 6.1 product with a 500m spatial resolution. This used the International Geosphere-Biosphere Programme (IGBP) classification scheme.

Vector Boundary and Demographics: We mapped the administrative boundaries of the 35 NCR districts using a Survey of India 2025 shapefile. Demographic indicators, such as Total Population, Population Density, and Urban Population Percentage, came from the 2011 Census of India.

Figure 1: Delhi NCR region Map



Source: Shapefile from Survey of India, 2025 and Basemap from ESRI and USGS

Software and Technicalities used in Study:

Extensive use of Google Earth Engine (GEE) for all the analysis and calculation part apart from this ArcGIS 10.4 for producing map layouts

Methodological Framework

All spatial data processing, including cloud masking and image compositing, was done using the Google Earth Engine (GEE) cloud computing platform. The methodology was divided into four steps:

Spatiotemporal LST and DTR Extraction

The MOD11A2 daytime and nighttime LST bands were first converted from raw digital numbers (DN) to Celsius using the standard radiometric scale factor (0.02) and an adjustment for absolute zero (-273.15):

$$\mathbf{LST(°C) = (DN \times 0.02) - 273.15}$$

To remove extreme anomalies and cloud cover interference, seasonal median composites were created for Summer (April 1 to June 30) and Winter (November 1 to January 31) for each year from 2000 to 2024. In addition, the Diurnal Temperature Range (DTR) was calculated for each pixel as the absolute difference between daytime and nighttime median LST.

Quantification of Urban Expansion

To measure the physical footprint of urbanization, the MCD12Q1 dataset was analysed. Pixels marked as 'Urban and Built-up' (IGBP Class 13) were collected for each consecutive year from 2001 to 2024. The total area of these pixels within the NCR boundary was calculated in square kilometres, giving a continuous timeline of urban sprawl.

Dynamic Urban Heat Island (UHI) Intensity Calculation

A strong dynamic rural masking technique was used to calculate UHI intensity. Instead of a static rural baseline, which does not consider continuous urban growth over 25 years, the reference rural area was updated each year. For any given year i, the corresponding LULC map was used to mask out Urban (Class 13) and Water (Class 17) pixels. The mean LST of the remaining natural and agricultural areas was used as the rural baseline (LST{rural_mean}). The UHI intensity for each pixel was then calculated as:

$$\mathbf{UHI_{\{intensity\}} = LST_{\{pixel\}} - LST_{\{rural\_mean\}}}$$

Positive values indicate the standard UHI effect, while negative values show the Urban Cool Island (UCI) effect. For the year 2000, the 2001 LULC data was used as the closest proxy baseline.

Statistical and Zonal Analysis

After geospatial computation, the raster arrays underwent zonal statistical analysis to extract district-wise median values for LST, DTR, and UHI intensity. Finally, a Pearson correlation analysis was conducted to determine the statistical significance and relationship between the 25-year mean UHI intensities and key demographic variables (Population Density and Urbanization Percentage) across the 35 districts.

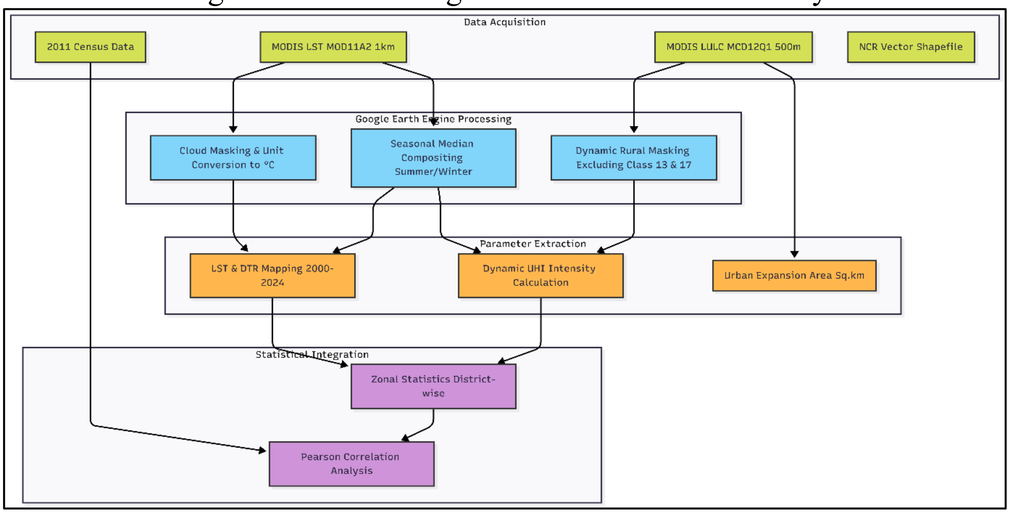
Table 1: Demographic profile of the Delhi NCR

Sr.No.	District	Total Population 2011	Population Density sq.km	Urban Population Percent	Literacy Rate Percent	Sex Ratio
1	Alwar	3674179	438	17.8	70.72	895
2	Baghpat	1303048	986	21.1	72.01	861
3	Bharatpur	2548462	503	19.5	70.11	880
4	Bhiwani	1634445	342	19.3	75.21	886
5	Bulandshahr	3499171	776	24.8	68.88	892
6	Central	582320	23000	100	85.14	892
7	Charkhi Dadri	502276	370	11.5	74	880

8	East	1709346	27000	99.7	89.31	884
9	Faridabad	1809733	2442	79.5	81.7	873
10	Gautam Buddha Nagar	1648115	1161	59.1	80.12	851
11	Ghaziabad	4681645	3971	67.6	78.07	881
12	Gurugram	1514432	1204	68.8	84.7	854
13	Hapur	1338311	2000	28.7	71.59	898
14	Jhajjar	958405	523	25.4	80.65	862
15	Jind	1334152	494	22.9	71.44	871
16	Karnal	1505324	597	30.2	74.73	896
17	Mahendragarh	922088	486	14.4	77.72	895
18	Meerut	3443689	1346	51.1	72.84	886
19	Muzaffarnagar	4143512	1034	28.8	69.12	889
20	New Delhi	142004	4057	100	88.34	822
21	North	887978	14557	99.7	86.85	869
22	North East	2241624	36155	97.4	83.09	886
23	North West	3656539	8254	94.1	84.45	865
24	Nuh	1089263	723	11.4	54.08	907
25	Palwal	1042708	767	22.7	69.32	880
26	Panipat	1205437	951	46.1	75.94	864
27	Rewari	900332	565	25.9	80.99	898
28	Rohtak	1061204	608	42	80.22	867
29	Shahdara	322931	27000	99	88	885
30	Shamli	1274815	1200	29	69	890
31	Sonipat	1450001	683	31.3	79.12	856
32	South	2731929	11060	99.6	86.57	862
33	South East	1500000	12000	99	86	865
34	South West	2292958	5446	93.7	88.28	840
35	West	2543243	19563	99.7	86.98	875

Source: Census of India, 2011

Figure 2: Methodological Framework of the Study



Source: created by author

Results and Discussion

Rapid Urban Expansion in the NCR (2001–2024)

Prior to analysing the complex thermal anomalies across the study area, it is imperative to quantify the physical transformation of the landscape as land cover modification is the primary physical driver of microclimatic shifts. The longitudinal analysis of MODIS MCD12Q1 LULC data revealed a massive, continuous and relentless urban sprawl across the 35 districts of the National Capital Region (NCR). The category 'Urban and Built-up' (IGBP Class 13) experienced an exponential spatial growth during the 24-year observation period. This aggressive concretisation has been largely driven by decentralised industrial setups, the creation of special economic zones (SEZs) and huge residential demands driven by inward migration.

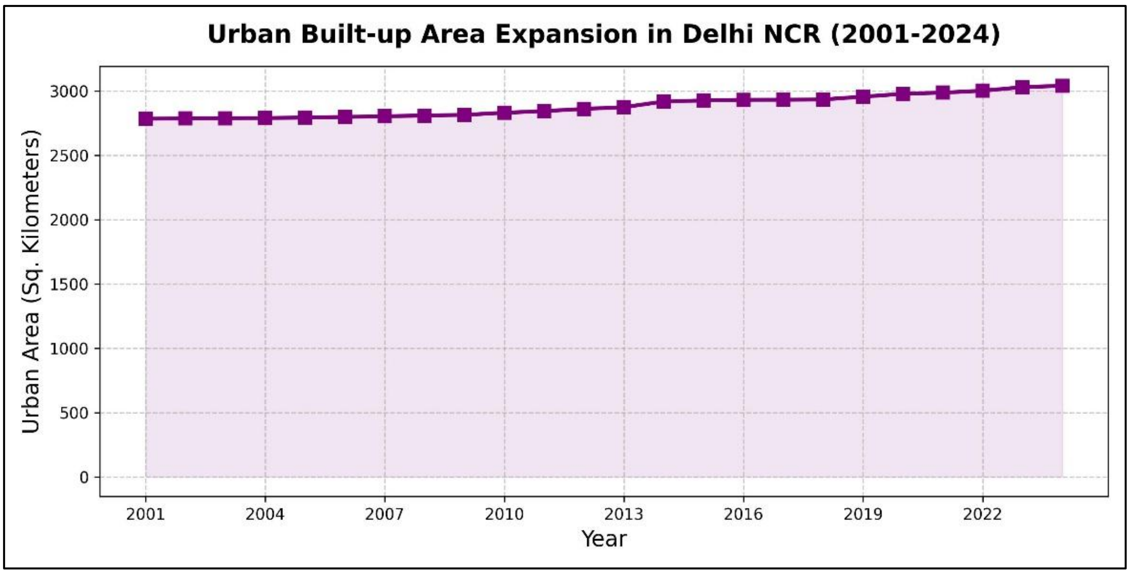
Large parts of the agricultural land, natural peri-urban surfaces and sparse vegetation have been irrevocably replaced by impervious materials such as concrete and asphalt. The transformation is particularly brutal in industrial nodes like Faridabad, Gurugram and Gautam Buddha Nagar which have turned into dense concrete jungles. The physical reorganisation has a profound impact on the surface albedo and a significant increase in the thermal inertia of the landscape, providing the physical basis for the extreme thermal trapping observed in the following LST and UHI analyses.

Table 2: Temporal expansion of the urban built-up area in the NCR (2001-2024)

Year	Urban Built-up Area Sq.km	Year	Urban Built-up Area Sq.km
2001	2784.52	2013	2874.52
2002	2787.01	2014	2918.38
2003	2788.4	2015	2926.84
2004	2790.15	2016	2931.4
2005	2793.4	2017	2931.9
2006	2798.39	2018	2934.37
2007	2804.08	2019	2956.13
2008	2809.07	2020	2978.04
2009	2814.81	2021	2987.51
2010	2830.99	2022	3002.19
2011	2844.13	2023	3029.99
2012	2861.35	2024	3041.22

Source: Based on the MODIS Land Use and Land Cover data (2001 – 2025), extracted using GEE

Figure 3: Spatiotemporal expansion of the urban built-up area in the NCR (2001-2024)



Source: Based on the MODIS Land Use and Land Cover Data (2001 – 2025)

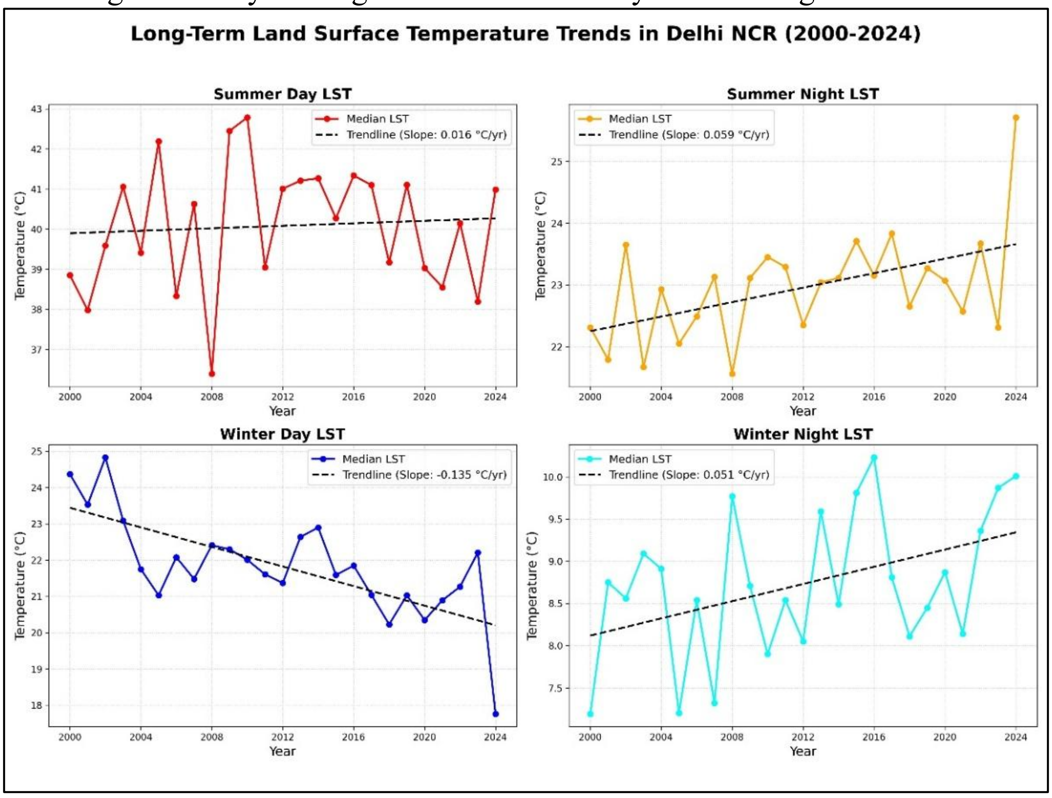
Spatiotemporal Trends of Land Surface Temperature (LST) and DTR

The 25-year longitudinal assessment (2000–2024) of the MOD11A2 thermal dataset indicates a statistically significant and pervasive warmer temperature pattern across the NCR. However, different places exhibit differing levels of warming. Central urban and heavily industrialized areas—

such as Central Delhi, East Delhi, Faridabad and Ghaziabad—show consistently higher maximum daytime and minimum nighttime temperature than other parts of the NCR. Moreover, the decadal trendlines suggest these urban areas are warming more rapidly than the larger regional average, owing largely to the ever-increasing amounts of anthropogenic heat being produced by vehicles and other industrial activities.

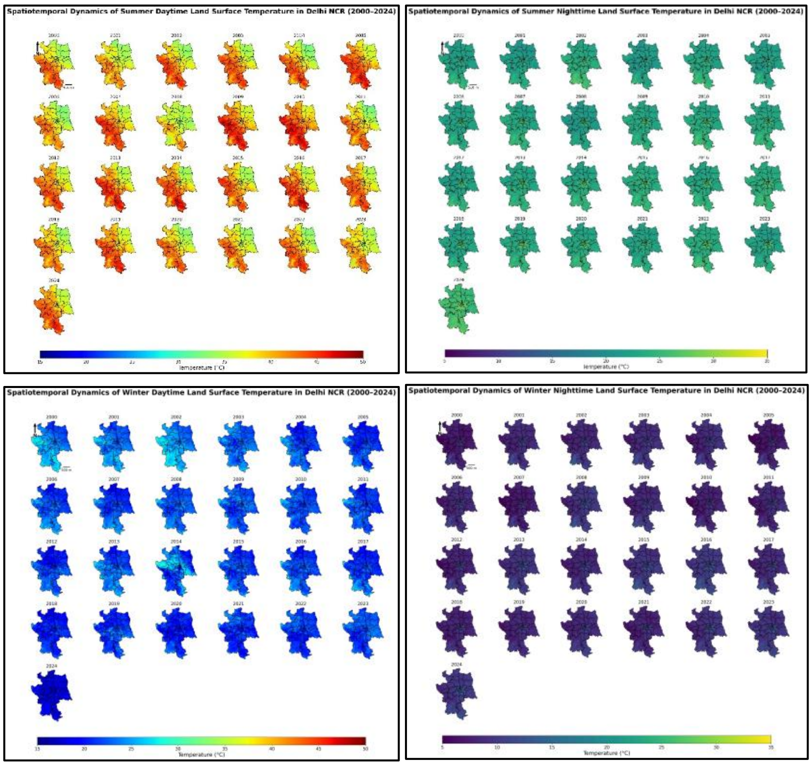
In addition; the spatial mapping of the diurnal temperature ranges (DTRS) illustrates another key climatic signature of urbanization—namely; that the period between maximum daytime temperatures and minimum nighttime temperatures is shrinking. The range between maximum daytime temperatures and minimum nighttime temperatures is much smaller in heavily urbanized areas as compared to the rural outskirts. The geometric configurations of impervious urban surfaces have the ability to absorb large quantities of shortwave solar radiation during the day, with a correspondingly high thermal admittance and therefore slowly release longwave radiation after the sun goes down. As a result; the natural cooling cycle that occurs overnight is seriously impeded, producing disproportionately high minimum nighttime temperatures and leading to a tight DTR; thus, placing an increased thermal burden on the population.

Figure 4: 25-year longitudinal trends of Daytime and Nighttime LST.



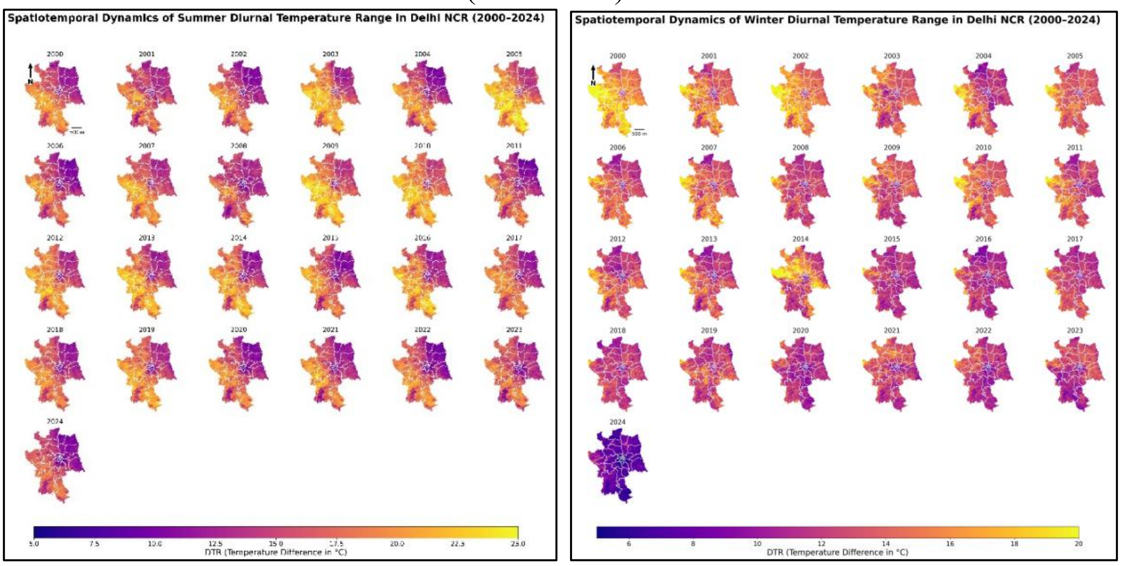
Source: Computed using the MODIS LST dataset (2000 – 2025) using Google colab and GEE

Figure 5: 25-year longitudinal trends of Daytime and Nighttime LST



Source: extracted and visualized MODIS LST dataset (2000 – 2025)

Figure 6: Spatiotemporal dynamics of Summer and Winter Diurnal Temperature Range in Delhi NCR (2000-2024)



Source: extracted and visualize using the MODIS LST dataset (2000 – 2025)

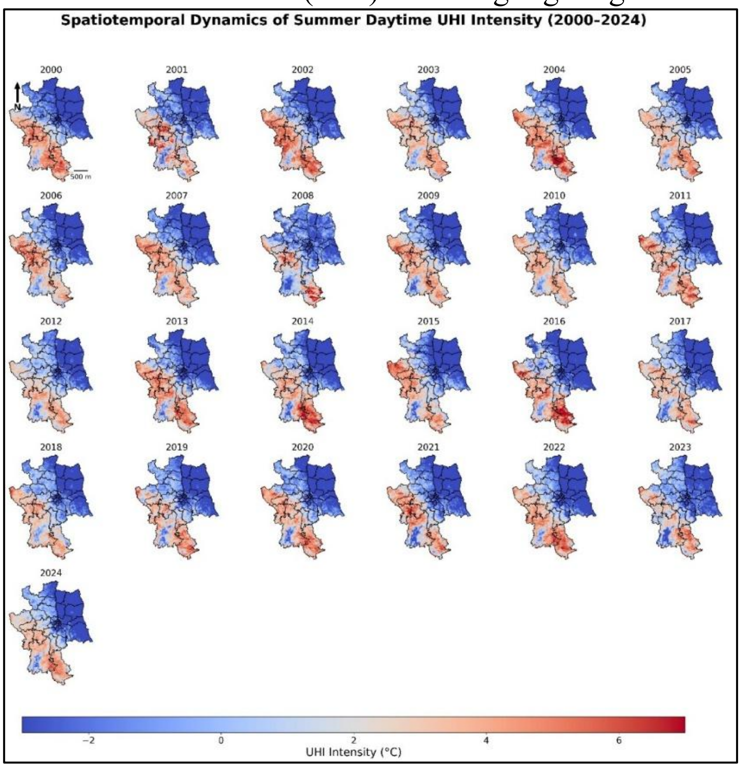
Spatial Heterogeneity and Decadal Acceleration: The increase in LST or land surface temperature has been observed to continue consistently across the NCR as well as on a regional basis, but the difference between each district shows a significant amount of variability which can lead to different levels of thermal increases within the 2.5 by 10 km band of each district. Analyses of the highest levels of thermal increase demonstrated that the largest levels of thermal increase occur primarily within the central and south-eastern corridors of the NCR which encompasses the NCT of Delhi, Faridabad and Gurugram due to their contiguous patterns of impervious surface and significant industrial developments. In comparison, peripheral areas such as Alwar, Nuh and Baghpat have a much larger amount of agriculture land and fewer people which has resulted in much more gradual thermal increases. Additional analysis demonstrates that the rate at which land surface temperatures have increased over a decade is not uniform. The warming rates between 2012 and 2024 are significantly steeper than the warming rates that were measured from 2000-2011. These warmer temperatures between 2012 and 2024 are closely associated with the rapid pace of development within both the transportation and residential sectors of the NCR.

The Diurnal Inversion: Daytime Cool Island vs. Nighttime Heat Island

The finding that diurnal variation (daytime cool vs. nighttime hot islands) is one of the most complex and compelling findings from this research, illustrates that both daytime and night time thermal retrievals have been conducted through the use of the dynamic annual rural-masking methodology, as well as through longitudinal analysis of LST data. Both techniques have produced two very different yet strong thermal behaviours (UHI) resulting from the semi-arid ecology of the NCR.

The Daytime Urban Cool Island (UCI) Effect: Several core urban areas had prominent negative values for UHI intensity. This shows a daytime Urban Cold Island (UCI) effect occurring within the NCR due to extremely high temperatures. The adjacent rural areas consist mainly of semi-arid land and harvested agricultural fields such as Alwar, Bhiwani and Rewari. Intense solar irradiation creates very high surface temperatures on dry soils during the day because of their low moisture levels and poor thermal capacity, whereas the dense urban cores receive a large degree of shading through building geometry, aerosol scattering and a concentration of trees within the urban core area. Thus, the rural peripheries of cities have a higher surface temperature than the urban core areas during the day.

Figure 7: Daytime Urban Cool Island (UCI) effect highlighting hotter rural peripheries

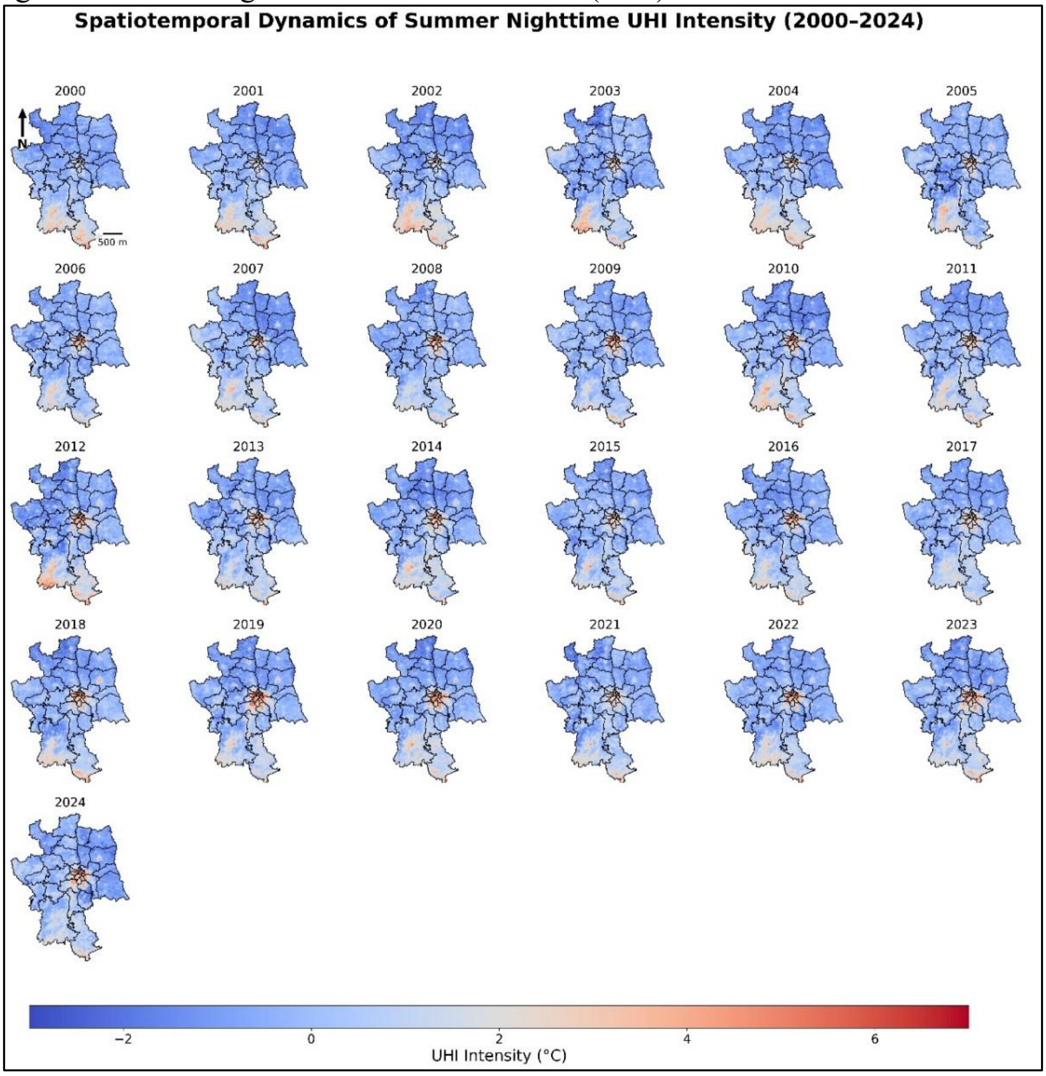


Source: Analysis result of UHI (2000 – 2025)

The Nighttime Urban Heat Island (SUHI) Effect: The Nighttime Urban Heat Island (SUHI)

Effect is harshly demonstrated after sunset. The phenomenon occurs as a result of an immediately obvious characteristic of urbanization in the NCR, which is that once solar insolation begins to cease, all barren rural land will cool very rapidly due to their low thermal inertia and thus rapidly lose heat. Conversely, the densely packed concrete and asphalt matrix of the urban and industrial centre will begin to release the vast amounts of heat that were stored during the day. This results in a very high and positive Urban Heat Island intensity during nighttime hours. The spatial maps provide consistent evidence of very large areas of high thermal retention (deep reds) over the entire NCT Delhi, Faridabad and Gurugram area, clearly indicating that as a result of an urban canopy, there is an ongoing and continuous nighttime heat trap effect taking place.

Figure 8: Severe Nighttime Urban Heat Island (UHI) intensities across urban cores.



Source: Analysis result of UHI (2000 – 2025)

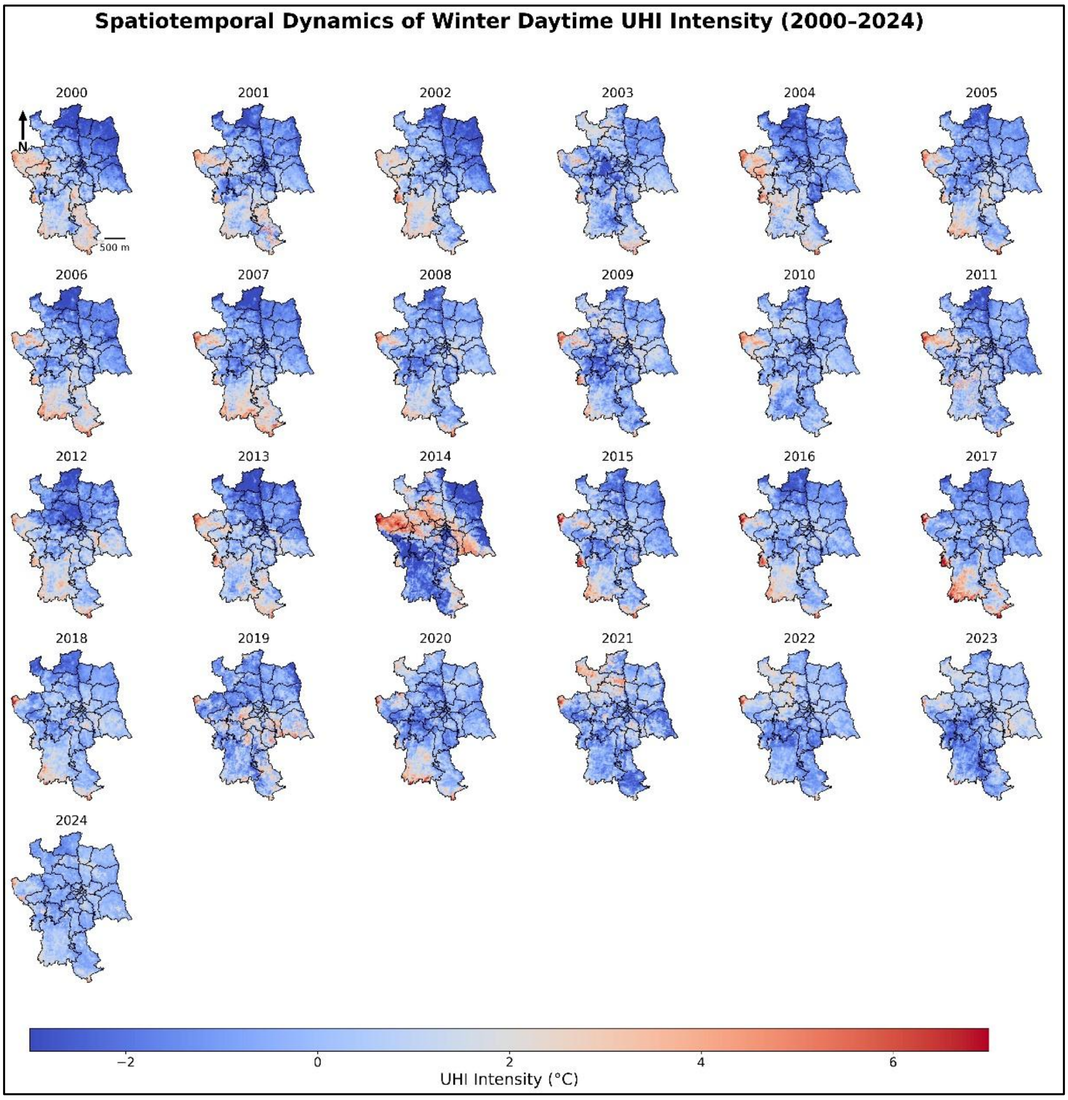
The Thermodynamics of the Cool Island Inversion: The Daytime Urban Cool Island (UCI) is a product of the differential thermal inertia of the two regions, with the NCR's rural and semi-arid fringes experiencing a drop in moisture content in their soils during pre-monsoon and summer months; conversely, very little of this moisture will be available for evaporation, causing incoming solar radiation to be changed mostly into heat. This causes the surface temperature of bare ground in outlying regions to rise rapidly. In contrast, the urban forest in the NCR takes much longer to heat up although the urban forest has a larger heat capacity than the surrounding area. Because of the physical nature of urban morphology and the amount of mutual shading caused by deep street canyons, most of the direct solar radiation from the sun will not like to reach the bottom of the canyon during the warmest parts of the day (early afternoon). This thermodynamic lag produces a temporary thermal shield over the urban centre resulting in the UCI – a phenomenon that will dissipate violently at night as a result of the complete reversal of the UCI atmospheric flow.

Seasonal Contrasts: Summer vs. Winter Thermal Dynamics

In addition to this daily cycle of atmospheric temperature change, thermal differences between different seasons in the NCR are also very high. There are clear and significant seasonal disparities in how the urban canopy of the NCR processes both ambient air temperature and solar radiation through the use of the land surface temperature (LST) as a way of comparing summer to winter.

During summer months, LST experiences maximum values because of the direct effect of solar radiation; however, when comparing the LST of the summer to that of the winter, the relative urban heat island (UHI) intensity shows a vastly different seasonality. The urban environment is often covered in dense as well as heavy layers of fog and smog during the daylight hours in winter; consequently, Urban Cool Island (UCI) effects that are readily apparent in summer noticeably decrease or disappear altogether in winter. The three factors above—existing seasonal air temperatures, high atmospheric humidity, and a very low solar zenith angle—are responsible for the reduced levels of incoming solar radiation felt at the surface of the earth during the winter.

Figure 9: Spatiotemporal mapping of Winter Daytime UHI, illustrating the diminished Cool Island effect compared to summer months.

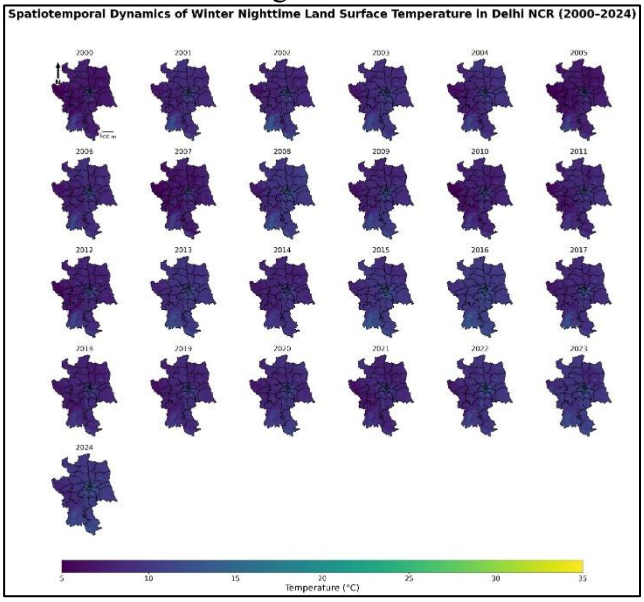


Source: Analysis result of UHI (2000 – 2025)

On the other hand, during the winter months, night temperatures can become intensified by the heating of urban areas due to the long-term influence of vehicular emissions on global climate. The NCT Delhi and adjacent areas (i.e., Ghaziabad and Gurugram) have a high-density development pattern that has been failing to provide adequate insulation against extreme winter temperatures. If the infrastructure in the NCR were designed to provide proper support to sustain normal winter temperatures and provide a barrier from extreme winter temperatures, the region's capacity for coping with high ambient temperatures would be enhanced.

In summary, while some studies indicate that average summer temperatures are lower than expected, their true extent has been emphasized by the above-discussed mechanisms that led to nighttime urban heating; in addition, as previously discussed, when summer urban heat islands occur, they can cause damage to crops and produce other impacts on food security.

Figure 10: Severe Winter Nighttime UHI intensities exacerbated by atmospheric temperature inversions and high urban thermal inertia.

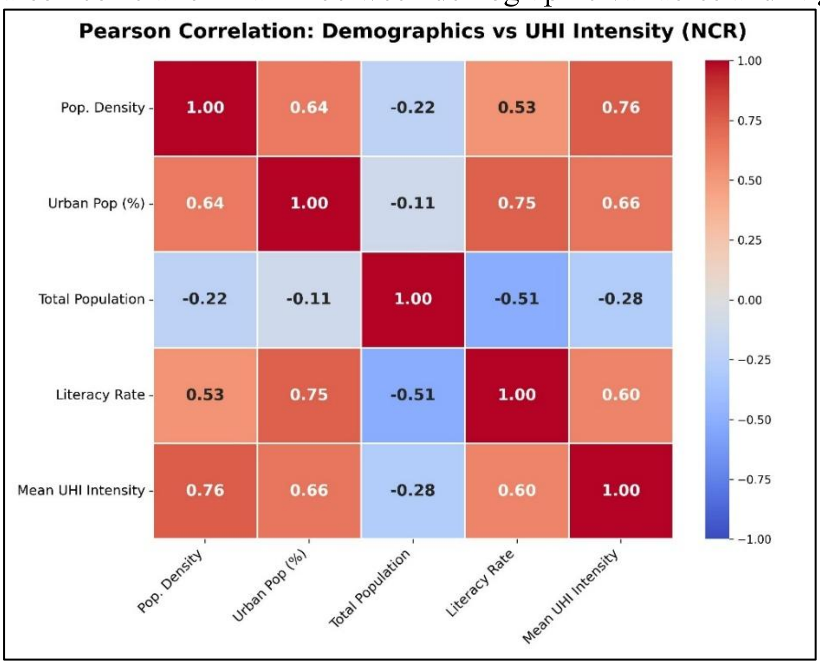


Source: Analysis result of UHI (2000 – 2025)

Demographic Drivers of Thermal Anomalies

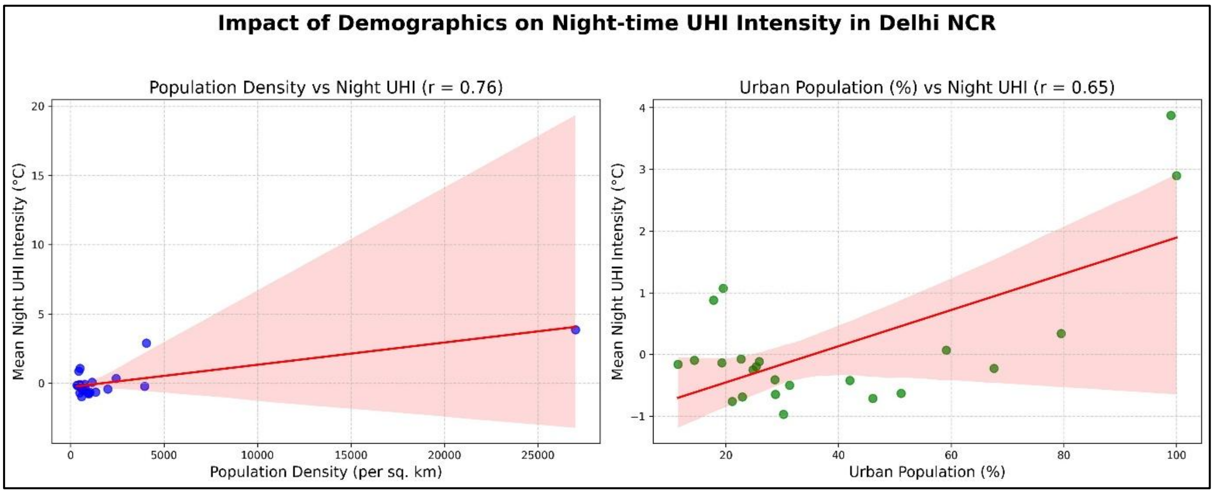
To validate that this thermal stress is directly driven by human activity, a Pearson correlation analysis was conducted between the 25-year mean Nighttime UHI intensity and 2011 Census demographic indicators. The statistical output strongly corroborates the spatial findings.

Figure 11: Pearson correlation matrix between demographic variables and Nighttime UHI.



Source: Analysis result of UHI and demographics (2000 – 2025)

Figure 12: Scatter plots showing the direct impact of Population Density and Urbanization on Thermal stress.



Source: Analysis result of UHI (2000 – 2025)

The scatterplots (refer to Figure 12) illustrate a statistically significant positive relationship between Nighttime Urban Heat Island (UHI) intensity and urban population density (r = 0.76). Likewise, there is a positive correlation (r = 0.65) between the Nighttime UHI and the percentage of an urban area's population residing there. The data points for areas with 20,000 or more people per square kilometre are grouped together at the highest end of the UHI scale (extremely high nighttime UHI). These correlate to the fact that the area with the densest, most urbanized populations are responsible for creating extreme thermal energy (heat) captures, or thermal energy entrapment, resulting from large, densely populated urban centres (demographics) located within the National Capital Region (NCR) region.

Quantifying Anthropogenic Variance: While the data shows strong positive correlations (Population Density r = 0.76; Urban Percentage r = 0.65) utilizing the coefficient of determination (R2) adds greater insight into the anthropogenic drivers. By squaring the population density correlation coefficient (R^2 ~0.58) almost 58% of the variability of Nighttime UHI intensity across the 35 districts can be attributed directly to human population density and the associated built environment. The other variability must be due to localized microclimates such as distance from water bodies (i.e., Yamuna River buffer), albedo of building materials, and wind corridor obstructions. Hence, people clustering is clearly the dominant mechanism affecting nighttime heat retention (UHI) in the NCR.

Conclusion

The objective of this extensive longitudinal analysis (2000-2024) is to contribute substantial empirical data on the significant microclimatic changes brought on by rapid, unorganized urban growth in the 35 districts comprising the National Capital Region (NCR). Unlike previous studies, this investigation worked with 25 years of MODIS thermal and land use / land cover (LULC) data to provide a continuous record of increasing Land Surface Temperatures (LSTs) and decreasing Diurnal Temperature Ranges (DTRs) within one of the most densely populated urbanized areas of the world.

The research produced four major conclusions:

Firstly, The NCR has experienced extreme and extensive physical reconfiguration, with agriculturally and environmentally vegetative cover being replaced by impermeable built-up structures. This urban development is the principal driver of the regional thermal anomalies;

Secondly, The NCR is characterized by a complex, semi-arid geographic diurnal Urban Heat Island (UHI) inversion. Urban Cool Island (UCI) effects occur during hot summer afternoons in the core cities when there is a shade from tall buildings versus rapid heating of bare areas surrounding the buildings. A significant problem is caused by the very high thermal inertia of concrete buildings. The UHI effect experienced by cities during the daytime and cool nights significantly inhibits cooling at nighttime.

Third, the statistical integration with 2011 Census data definitively proves that demographic pressure is the ultimate driver of this thermal stress. A strong positive correlation ($r = 0.76$) between population density and nighttime UHI intensity validates that districts with extreme human clustering are trapping the most heat.

Lastly, with statistical validation from the 2011 Census, it becomes undeniable that demographic pressure is the underlying cause for this thermal stress, and high positive correlation (r = 0.76) of human population density to the intensity of nighttime UHI indicates that heavily packed urban zones trap the most heat. This study, hence, becomes a crucial appeal to urban planning and policymakers, calling for the rapid implementation of green infrastructure such as cool roofs, green corridors, decentralisation of industry, among other innovative green building practices, in the planned urban areas of NCR to bring back the lost surface energy balance.

Limitations and future scope:

A temporal span of 25 years, as given by MODIS datasets for long-term trend analyses, has been achieved; nevertheless, its moderate spatial resolution (LST at 1km, LULC at 500m) is inadequate to investigate micro level, within-city level heat trapping (street scale). The 2011 Census data has been best among available, yet is cannot reflect the post 2011 micro changes. In future work, we plan to use high resolution sensors (Landsat 8/9 or Sentinel-2) to zoom down to specific neighbourhood levels and study individual micro variations. Moreover, vertical urban profiles (buildings heights) and the estimation of localised thermal emission due to transport and HVAC can add greatly to this work.

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