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Relationship Between Urban Land Use Dynamics and Land Surface Temperature: Current and Future Scenario Modeling

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Abstract

Anthropogenic activities have ominously transformed landscape (unplanned urbanization) over past few decades affecting the atmospheric processes and the most perilous amongst it is heat stress and thermal discomfort. Mitigation techniques for plummeting the surface temperature as suggested by the scientific community across the world include dedicating a part of land in every locality for plantation, construction of green roof, terrace gardens, etc. This study analyses the effect of Land use changes on Land Surface Temperature and its variability with features on the surface contribute to the absorption and reflection of heat influx for Indian city of Kolkata. The historical city of Kolkata has experienced extravagant development residentially, commercially, industrially and culturally that has led to modification in its microclimate. The study examined temporal land use changes for Kolkata Metropolitan Area using supervised classification algorithm to understand the urban footprint and it was observed that the study area has experienced a growth of 203% in urban area over three decades. Also, quantification of land surface temperature using single window method was performed to assess thermal comfortability and a rise of 7˚C was observed in the mean land surface temperature. A buffer was considered to understand the sprawl, and urban heat island. The study also tries to relate various land cover types with LST, estimates the urban heat island and further includes modeling future land use changes. Result of the developed model based on business as usual scenario shows an increasing trend of concretization that would lead to a rise in surface temperatures. The outcome of the study will assist the decision makers, government officials, higher authorities, etc. in developing a sustainable plan and modify policies that would help in creating a balance between environment and hominids.

***Keywords**: Urban growth, Land use analysis, SLEUTH, Land Surface Temperature, Climate Change, Spatial Indices, Urban Heat Island*

1. Introduction

Since the emergence of history, hominids have had the ability to be superior than all other living forms and to abuse the resources for their immediate advantages. Previously, this was altering the climate only at local level that increased to regional, but over past few decades, due to the increased demographic pressure as a result of migration for better living standards, medical facilities and job opportunities, humans have significantly altered climate globally (Keeling, 1997; Karoly et al., 2003; Scott et al., 2006). Urbanization can be defined as a comprehensive phenomenon that can be inferred as an increment in paved surface in a town or a city due to increased population influx or unification of sub-urban areas into nearby urban area (Ramachandra et al., 2012). As per various scientific literature, unplanned urbanization is the one that creates glitches (Chandan et al., 2017). Over few decades, urban growth is not only horizontal but vertical as well and the tall structures modify the wind turbulence causing reduced displacement of pollutants. This rise in concentration of GHGs and PMs changes the atmospheric reactions causing global warming (Ramachandra et al., 2015). As per scientific agencies such as NASA and NOAA, 10 warmest year have all occurred since 1998, 2016 being the warmest.

Studies have found that this rapid change in urbanization can be understood by LULC alterations and is referred as a vital cause of changing climate. It involves conversion of vegetation, agricultural fields, shrubby areas and barren areas into urban pockets (Ramachandra et al., 2016) that affects the rate of evaporation, surface albedo, storage of heat and moisture content of the soil, increased pollution levels, solar radiation and surface temperature LULC, LST and climate change are closely related and the relationship has been developed in numerous ways across the globe. One of the several primary parameters to comprehend climate change is Land Surface Temperature (LST) as it is responsible for upward thermal radiation of surface and defines the thermal comfortability of the region (Bento et al., 2017). LST is the radiative skin temperature of surface of landmass on earth (Ministry of Statistic and Programme Implementation, 2015). LST is the main parameter that affects earth's natural cycles (biogeochemical cycle, water cycle, Nitrogen cycle, Carbon cycle, Phosphorous cycle, etc.), rainfall pattern, regional biodiversity and contributes to climate change at micro-meso-macro level (Bharath et al., 2013; Nimish et al., 2018). LST serves as a vital parameter for diverse applications such as vegetation health monitoring, hydrological modeling, urban climatic studies, environmental parameter changes, Greenhouse gases estimation, Urban Heat Islands (UHI), etc. (Anderson et al., 2008; Li et al., 2013; Ramachandra et al., 2017).

Increase in LST causes heat waves that are considered a serious threat to all the living beings globally. Urban areas are more vulnerable to these heat waves due to UHI effect and high demographic pressure. As a result of increased cases of UHI, heat waves in current scenario has become a common phenomenon and is getting stronger for longer time durations, thus, exacerbating the problem of thermal risk for the local residents (Founda & Santamouris, 2017). Paved surfaces in cities have higher albedo when compared to any naturally occurring surface (vegetation, water body, wet soil) and construction materials used in rural areas. Paved surfaces in cities also is impervious in nature and increases surface runoff when compared to rural areas, thus, decreased vegetation and water reduces the rate of evapotranspiration causing increased heat entering the air in urban area.

Advancement in remote sensing data and with the launch of various satellites, sensor based analysis for investigating the climatic parameters, urbanization, surface temperature measurement has become easier for the policy makers and stakeholders (Jasim et al., 2016; Bharath et al., 2017). Assessment of LULC and prediction of likely changes, its relationship with LST will help the policy makers to improve the existing policies and formulating the newer ones for sustainable development of future in terms of infrastructure, basic amenities, food, availability of fresh water, decorous solid waste management and health (Nimish et al., 2018). In this regard, one of the well-established urban growth models SLEUTH has been adopted in this study to foresee changes in urban land use by the year 2025 and therefore relate increase in growth to surface temperature variations. This communication explores the detailed linkage between Land Use, LST, future urban growth through modelling and spatial indices for Kolkata Metropolitan Area (KMA).

2. Study Area

Kolkata Metropolitan Area (KMA) also known as Greater Kolkata with 10 km buffer was considered, covers an area of 1850 km^2. As per census, 2011, it serves as a home for 14.11 million people, making it third most populous city in India and eighth largest urban agglomeration globally. Figure 1 depicts the study area and the basic geographic details is as shown in table 1.

Table 1: Geographic profile of Kolkata Metropolitan Area

Area	1886.67km^2
Latitude	22˚ 34' 21" N
Longitude	88˚ 21' 31" E
Altitude	1.5 – 9m above mean sea level (1% drainage gradient)

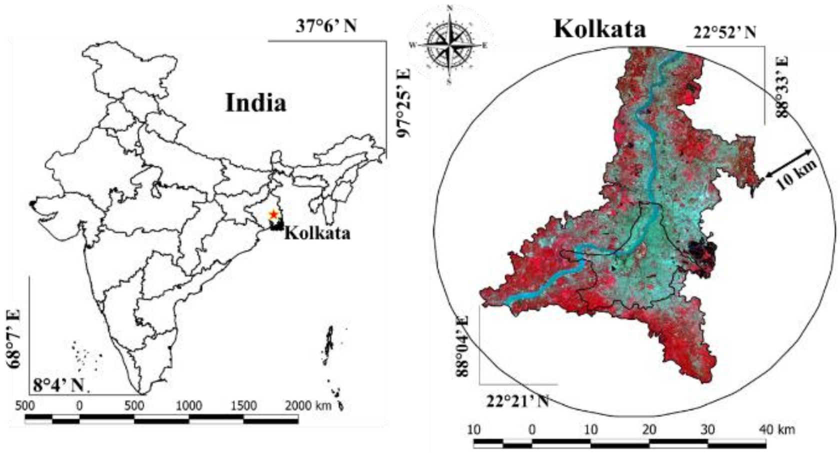

Figure 1: Study area depicting India and Kolkata Metropolitan Area with 10 km buffer and location details

3. Data and Method

A six phase process was involved in the communication as exemplified in figure 2. It includes – a) Data acquisition, b) Extraction and pre-processing, c) Landuse analysis, d) Quantification of Land Surface Temperature and NUHII (Normalized Urban Heat Island Index), e) Relationship between various Land cover and LST, and f) Landscape modeling and prediction

a) Data acquisition: Landsat and ASTER data was obtained from USGS earth explorer and were used for performing landuse classification, calculating LST and generating DEM. City development plan was downloaded from Government of Kolkata website and toposheets were acquired from Survey of India website. Road network was obtained by open street maps (OSM). Google earth, CDP and SOI toposheets were used as ancillary data.

b) Extraction and pre-processing: CDP was geo-registered using Ground Control Points (GCPs) and Google earth. Toposheets, CDP and other auxiliary datasets were used to identify Kolkata metropolitan boundary and was digitized. A 10 km buffer ring was considered around the city for understanding sprawl and urban heat islands. Road network downloaded from OSM had few missing roads in the study area, they were identified using Google earth and were manually digitized. Slope and hillshade map was generated using DEM and exclusion layer were derived from CDP that includes water bodies and protected areas. Remotely sensed data was then preprocessed for geometric errors (if any) and was resampled using ancillary data. All the maps were then cropped pertaining to study area.

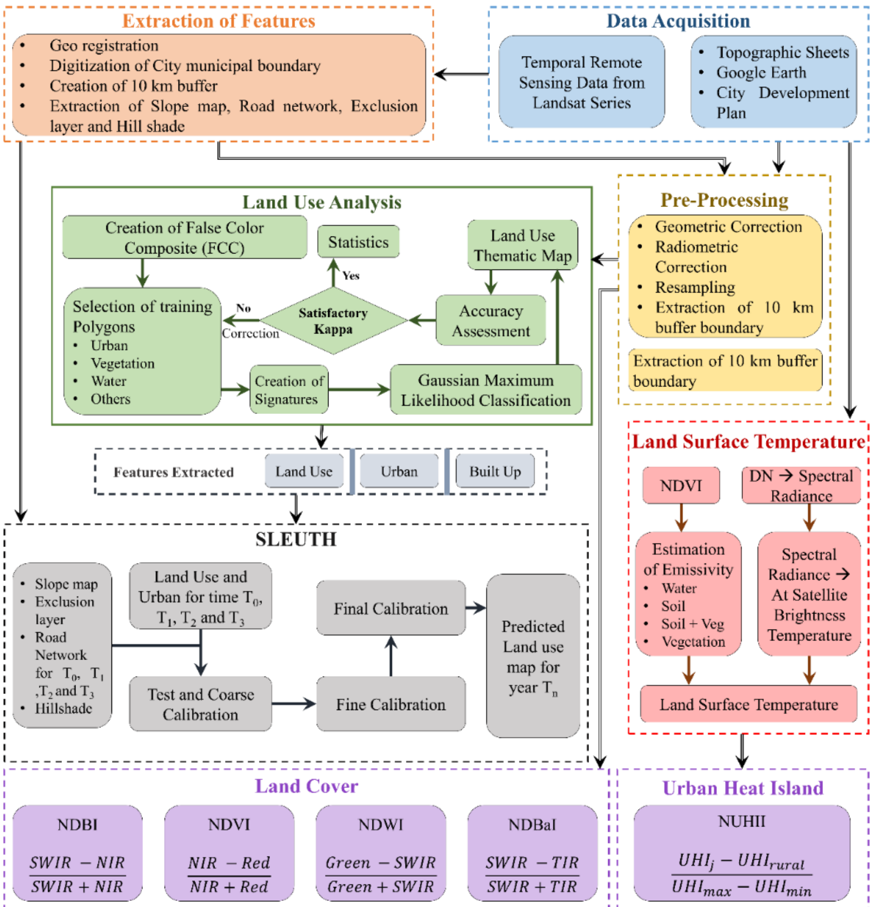

Figure 2: Method

c) ***Landuse Analysis:*** Landuse analysis is a four step process: (i) **Generation of FCC:** This involves assigning blue color to green band, green color to red band and red color to NIR band (ii) **Creation of signatures:** Training polygons are digitized based on heterogeneous and diverse features of each class from FCC. (iii) **Classification:** A supervised classification technique – Gaussian Maximum Likelihood Classification (GMLC) was performed to divide the study area into 4 classes (Urban, Vegetation, Water, Others). (iv) **Accuracy Assessment:** Google earth and ground truth data were incorporated to create a validation map. Using error matrix overall accuracy and kappa coefficient was estimated.

d) ***Quantification of LST and NUHII***

LST: In acquired remote sensing data, thermal band ranges from 10.4 to 12.5 µm and each pixel is assigned with a DN (digital number) value equivalent to the reflectance/emitted values by the feature under consideration. For obtaining information, these values are converted into spectral radiance and top-of-atmosphere temperature. Single window algorithm was used to perform calculations and obtain at-satellite brightness temperature. Due to the presence of atmosphere between the feature and sensor, few distortions occur and they can be corrected by calculating surface emissivity. At-satellite brightness temperature and surface emissivity then serves as input to estimate LST. This method was followed as established in Nimish et al., 2018. Further to understand the intra-class variability COV was estimated using eq. 1. COV is a statistical parameter that defines how distributed and deviated the observations are from mean of that particular class.

$$COV = \frac{\sigma}{\mu} X100 \tag{1}$$

here, COV = Coefficient of Variation (%), σ = Standard deviation, μ = mean

Normalized Urban Heat Island Index (NUHII): To understand the difference in temperature of urban area and rural area, UHI was estimated. This was then further divided into six categories to understand and prioritize areas facing higher UHI. Normalized UHI was estimated using eq. 2.

$$NUHII = \frac{LST_j - LST_{rural}}{LST_{max} - LST_{rural}} \tag{2}$$

here, LST_j is Land surface temperature of the pixel under analysis; LST_{Rural} is surface temperature of rural area.

e) Relationship between Land cover and LST: Land cover can be defined as the natural features present on the surface of earth. Since, the study area was divided into four classes and thus, land cover corresponding to each class: NDBI, NDVI, NDWI and NDBaI were quantified. All these ranges from -1 to +1.

i. NDBI: NDBI (Normalized Difference Builtup Index) can be used to extract paved surface as it gives higher value for feature that are impervious and lower for all other features. It plays an important role in extracting urban builtup and can be computed using eq. 3.

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \tag{3}$$

ii. NDVI: NDVI (Normalized Difference Vegetation Index) is an important index that describes the proportion of vegetation by measuring the difference between NIR band (strong reflectance for vegetation) and Red band (strong absorbance for vegetation) of electromagnetic spectrum. It can be expressed as shown in eq. 4.

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{4}$$

iii. NDWI: NDWI (Normalized Difference Water Index) is an indicator that can be used to extract water bodies in the remotely acquired data and can be equated from eq. 5.

$$NDWI = \frac{Green - SWIR}{Green + SWIR} \quad (5)$$

iv. **NDBaI:** NDBaI is an index that uses SWIR and TIR range of electromagnetic spectrum to differentiate barren area from any other features present. It can be estimated as shown in eq. 6.

$$NDBaI = \frac{SWIR - TIR}{SWIR + TIR} \quad (6)$$

f) Urban growth modeling and prediction: SLEUTH model involves various steps to arrive at future urban growth map. (i) Preparation of input layers. As the acronym suggests model stands for slope, land use, excluded, urban, transportation and hillshade, are used as input layers. (ii) Model has to be tested, calibrated in three phases viz. course, fine and final with spatial resolution of input images as 120m, 60m and 30m respectively. (iii) Five growth coefficients, governing the model, on a range of 0-100 are narrowed down to a single value used in prediction. (iv) Accuracy and validation of the model are tested with respect to goodness of fit statistics.

4. Analysis and Results

a) Landuse: Temporal land use analysis was performed for 1991, 2000, 2009 and 2017 for the study area using GMLC (supervised classification). Figure 3a illustrates landuse analysis for the study period and figure 3b depicts the area and percentage cover of each class. It was observed that urban area has increased three folds during the study period. Infill type of growth was observed, wherein the core area was densified in all the directions. Sprawling was witnessed in the eastern part wherein New town area is developing at an increased rate. Vegetation has not changed much during the study period but an increased percentage of water class was observed and that can be inferred to the increased wetlands in the eastern part of buffer area. The others category has shown a decline as the open areas within the city is utilized for construction of buildings and roads. Accuracy assessment was performed for all the years using google earth and ground truth data and the kappa coefficient was found to more than 0.85 (figure 3a).

b) ***Land Surface Temperature:*** LST for KMA region with 10km buffer was quantified as shown in figure 4 and it was observed that the mean surface temperature of KMA region ranges from 31-33˚C while with buffer region considered the mean temperature drops down by 1˚C. Table 4 shows the statistical description of the study area. The minimum temperature of the city has shown a rising trend and became 26.50˚C from 18˚C and the maximum temperature has increased from 35.40˚C to 43.50˚C. Post this, LST was analyzed class-wise and apparently the mean surface temperature of all the classes have increased during the study period. As a result of increment in impervious surface across the city and buffer, the mean surface temperature of urban category has increased from 27.70˚C to 34.96˚C. The mean surface temperature of vegetation has increased by 5.75˚C

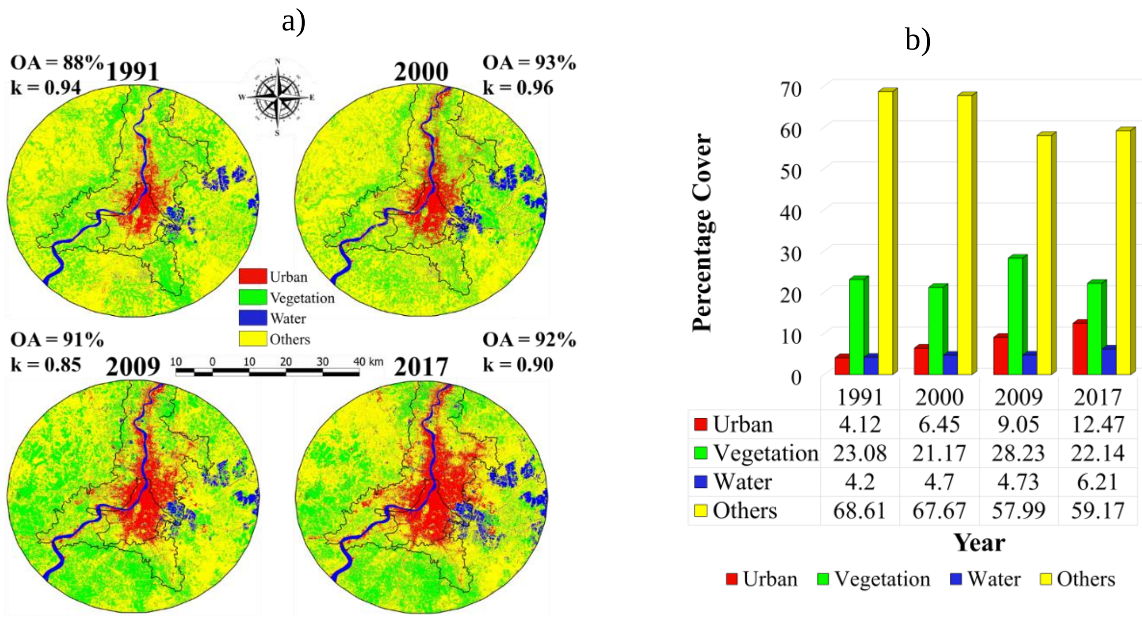

Figure 3:a) Landuse analysis for KMA with 10km buffer from 1991-2017, b) Percentage cover for each landuse class

c) ***Normalized Urban Heat Island Index (NUHII):*** NUHII for 2017 was quantified (figure 5) from eq. 2 and was further divided into 6 categories for better analysis as shown in table 5. It can be observed that only one sixth of the whole region that is close to river Hooghly and has low urban density has negative heat island. Thus, it can be inferred that presence of waterbody or a breathing green or open space nearby an urban area reduces the effect of urban heat islands. Majority of urban area shows low to moderate urban heat islands, while core region of Kolkata city along with Netaji Subhas Chandra Bose International Airport in the east, few small pockets in North and Tikiapara and Alipore region in south experiences high to extreme urban heat island.

Relationship between land cover and LST: Various land cover (LC) as shown in figure 6 were estimated using eq. 11-14. To obtain relationship a scatterplot was created between LST and various LC types as shown in figure 7. Figure 7, A) shows that as the value of NDBI increases (NDBI is high for urban area), LST increases; B) shows for higher values of NDVI (vegetation sparse to dense) LST reduces, for few lower values LST is low as values close to zero corresponds to water category (NDVI of water is close to zero), C) shows lower values of LST for higher NDWI values (NDWI is high for water) and D) shows higher LST values for higher NDBaI. It can be inferred that LST was positively correlated with NDBI (high) and NDBaI (low) while negatively correlated with NDVI and NDWI. Positive correlation signifies that as the value of NDBI and NDBaI increases, surface temperature of the region increases while a negative correlation as observed for LST and NDVI and NDWI implies that as the value of NDVI and NDWI increases the temperature reduces. This determines that paved surfaces including buildings, roads, etc. and barren areas such as open fields, unsowed agricultural land, mining areas, etc. contributes to high temperature and increases overall temperature of the region while presence of water body and breathing space in terms of vegetation (mini-forest, parks and gardens) helps in regulating the microclimate of the region by reducing the thermal heat wave and UHI.

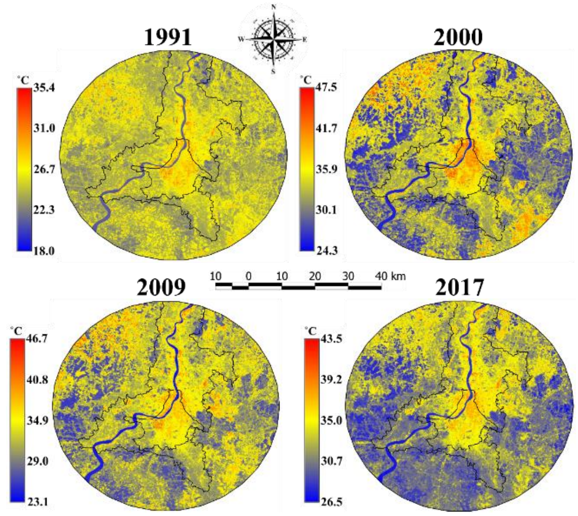

Figure 4: LST for KMA with 10km buffer from 1991-2017

Table 2: Statistical description of LST over KMA with 10km buffer region

Year	Landuse class	Min. Temp. (˚C)	Max. Temp. (˚C)	Mean Temp. (˚C)	Standard Deviation	Coefficient of Variation
1991	Urban	18.61	35.38	27.70	1.47	5.31
	Vegetation	18.00	31.66	24.31	1.04	4.29
	Water	18.00	31.66	22.80	1.59	6.96
	Others	18.00	33.74	25.11	1.54	6.12
2000	Urban	24.69	47.47	37.31	3.16	8.47
	Vegetation	24.69	44.83	31.70	2.72	8.56
	Water	24.78	45.21	28.70	2.44	8.50
	Others	24.26	46.72	32.49	3.52	10.85
2009	Urban	23.49	46.72	35.42	2.50	7.07
	Vegetation	24.69	41.35	29.12	1.90	6.52
	Water	23.05	44.06	27.86	2.94	10.56
	Others	24.35	44.44	32.99	2.55	7.73
2017	Urban	27.24	43.49	34.96	1.74	4.96
	Vegetation	27.30	40.04	30.06	1.49	4.95
	Water	26.49	39.58	29.68	1.81	6.08
	Others	26.74	42.12	32.23	1.89	5.85

d) Modelling and Prediction:

Model showed successful test results suggesting input layers were fit enough to conduct calibration and prediction. By the end of three phase calibration, optimum five growth coefficients of diffusion, spread, breed, slope resistance and road gravity were chosen as 1, 1, 27, 8 and 52 respectively. Since Kolkata is located on Indo-Gangetic plains, lower coefficient of slope is justified. Spreading and road gravity-oriented growth type dominates future land use change as it is evident from major roads passing across the region (figure 8). As far as the validation of the model is considered, regressed population, urban edges, cluster and cluster size also showed acceptable values of greater than 0.7 in all phases of calibration suggesting high agreement between modeled urban areas versus actual urban area. Predicted urban growth, 2025 (urban area 757.91 km2) in comparison with 2017 (494.73 km2) are depicted in figure 6.

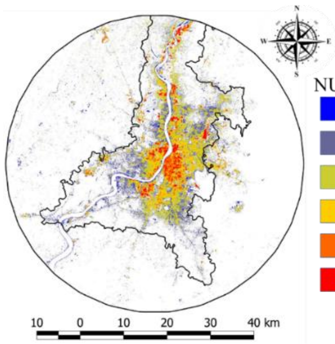

Figure 5: NUHII for KMA region with 10km buffer for 2017

Table 3: UHI types and percentage area covered

Category	Range	UHI type	Percentage area
1	< 0	Negative	16.58
2	0 - 0.1	Weakest	18.70
3	0.1 - 0.2	Low	29.49
4	0.2 – 0.3	Moderate	20.26
5	0.3 – 0.4	High	10.31
6	> 0.4	Extreme	4.65

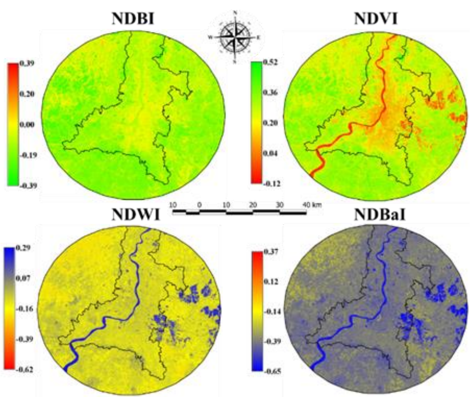

Figure 6: Land Cover types for KMA with 10km buffer for 2017

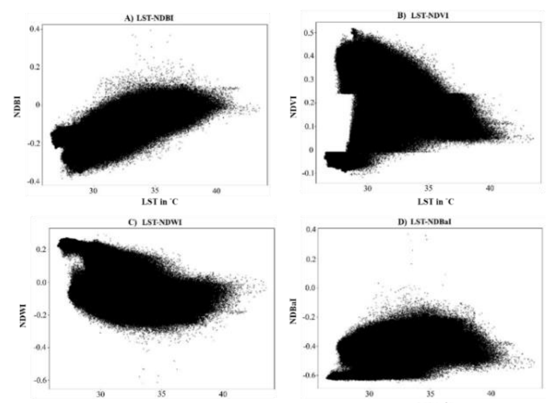

Figure 6: Relationship between LST and various Land cover types

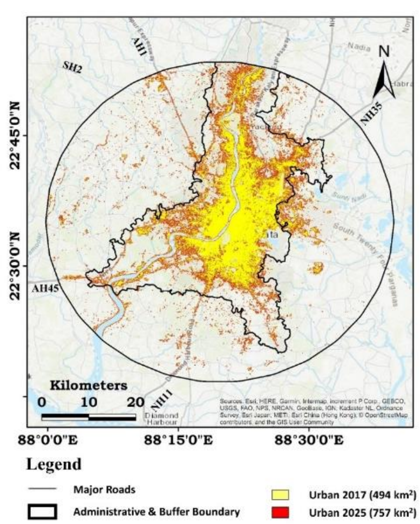

Figure 7: Simulated urban growth for the year 2025

5. Discussion and Conclusion

Over past few decades, Indian cities have undergone dynamic and inadvertent urban growth. It is one of the developed countries that is emerging as a key player in terms of global market with the support of government in the form of various schemes. Indian cities have grown at a remarkable pace but failed to meet the minimum criteria of the residents in terms of basic amenities of water, air and sufficient natural resources. As in the case of Kolkata, urban agglomeration is not very intensive due to diversified approach of development, but it would be an archetypal example of city development and probably would face unplanned urbanization in near future as predicted. As a result of these, the heat waves and surface temperature of the cities have shooted to high values (35-45˚C). The city is facing serious issues in terms of environmental deprivation, air pollution, unavailability of clean water, indecorous waste management, shortage of resources and comfortable thermal environment. This has further increased the problem of warming and altering the microclimate of the metropolitan area. There has been increased cases of casualties due to heat waves. Results of this communication shows a rise of 7˚C in mean surface temperature over a period of 26 years causing heat related issues (heat stress, pulmonary diseases, lethargic). All this can be related to the growing concretization of metropolitan and it can be understood by future prediction that the situation will only be worsening and will result in augmented urban hazards along with increased climate complexity. Future scope of this work can be forecasting LST for various scenarios to identify the vulnerable regions. The findings of this communication in collaboration with other research work and inputs on various environmental variables and climatic parameters will help in yielding better policies and will assist in developing the mitigation measures against climate change to fulfill 11^{th} goal of UN Sustainable development that involve making cities inclusive, resilient and sustainable.

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