CHAPTER - 5

A COMPARATIVE ANALYSIS OF DAY AND NIGHT LAND SURFACE TEMPERATURE IN TWO SEMI-ARID CITIES USING SATELLITE IMAGES SAMPLED IN DIFFERENT SEASONS

5.1 INTRODUCTION

The urban areas with temperatures higher than the neighbouring rural areas are referred to SUHI.The major cause of SUHI formation is the rapid increase in urbanization which has led to the increase in artificial built surfaces, increase in anthropogenic heat discharge by industries, vehicles, buildings and decrease in vegetation (Voogt and Oke, 2003). Improper planning of cities gives rise to air pollutants from industries, power plants and exhaust emissions from vehicles (Taha, 1997; Adina et al., 2009; Akbari et al., 2001). These air pollutants absorb solar radiation contributing to rise in temperature (Kato and Yamaguchi, 2005). The loss of vegetation in urban areas results into the loss of shaded areas and the cooling effect from trees. Hence, it has become important to identify the causes of temperature rise in urban areas which can help in environmental protection and sustainable planning resulting in attenuation of SUHI effect (Kaufmann et al.,2007; Grim et al., 2008; Mountrakis and Luo, 2011; Md. Nuruzzaman, 2015).Thermal bands in remote sensing satellite like Landsat, Aster, AVHRR, MODIS etc. are most important source for determination of LST. Landsat data have been widely used for LST retrieval in urban areas due to its fine spatial resolution of thermal bands to study the spatial variation of LST in urban landscapes (Liu and Zhang, 2011;Jiménez-Muñoz and Sobrino, 2010; Tsou et al., 2017; Mallick et al., 2008).

LST is an important parameter because of its capability to control the biological, chemical and physical processes on the Earth and also essential for study on urban climate (Pu et al. 2006). LST is very sensitive to different land covers. The increase in urbanization has major contribution to the land cover changes and has significant effect on the LST of the region which can affect the ambient habitat of our ecosystem (Alshaikh, 2015). The spatial (local to global scales) and temporal (diurnal, seasonal, and inter-annual) variations of SUHI depend on various factors like impervious surface area, landscape structure, vegetation cover, albedo and climate (Zhou et al., 2019). Various previous studies have been performed to determine the relation of LST with different land cover parameters or indices to understand the behaviour of LST with land covers (Luo and Li, 2014). It is important to analyse the relation of LST with vegetation indices because the vegetation cover has a significant impact on urban LST (Amiri et al., 2009, Zhang et al., 2010, Mathew et al., 2015). LST changes rapidly in both space and time and the knowledge of LST and its variation in space and time are important to understand the interactions between human activities and the environment (Phan et al., 2018). The night LST maps shows clear SUHI patterns in semi-arid regions which were not observed from day LST maps and SUHI is a consequence of urbanisation (Zhou et al., 2015, Ayanlade, 2016; Luintel et al., 2019). So, night LST maps will be more useful to study the effect of urbanisation on SUHI in semi-arid areas. Most of the Indian cities behave like arid or semi-arid areas during summer or pre-monsoon months (Shastri et al., 2017). Therefore, night LST maps would be more applicable for SUHI studies in different Indian cities.

Hung et al. (2006) studied the effect of SUHI in Asian Mega cities using Landsat ETM+ and MODIS day and night time data and found that the day time SUHI was higher in magnitude in summer than in winter in temperate region but day time SUHI was almost same in summer as well as winter in tropical region. Yuan and Bauer (2007) found non-linear relation of LST with NDVI which was strongly affected by season whereas strong linear relation of LST with ISF was found explaining most of the variation in LST dynamics. Amiri et al. (2009) suggested the TVX space to study the temporal variability of thermal data with vegetated cover. Rinner and Hussain (2011) studied that industrial area and commercial land uses have higher temperatures (29.1ºC) whereas parks and recreation land (25.1ºC) and water bodies (23.1ºC) had much lower temperatures. Residential as well as government/institutional land uses had average temperatures (27.4ºC) due to the presence of lawns or trees occurring around built structures. Luo and Li (2014) studied that strong Heat Island centres were at high energy consuming and densely populated areas. Regression models of LST at different spatial scales shows negative correlation with NDVI and NDWI whereas positive correlation with NDBI and the correlation were found to increase with increasing spatial scales. Manteghiet al. (2015) suggested that waterbodies had a cooling effect during day time whereas warming influence at night time on urban climate due to its high heat capacity. Mathew et al. (2015) found significant SUHI effect in semi-arid region using MODIS night LST. Negative correlation of LST with NDVI and positive with NDBI were found which interprets that green spaces reduces SUHI effect and built up surfaces enhances SUHI effect. Zhou et al. (2015) studied the variation in SUHI effect in 32 cities of China and found SUHI more prominent at night time as well as during summer season and temperature was found to decrease exponentially from centre of the city towards outside. Rasul et al. (2016) studied about SUCI and SUHI effect in Erbil, Iraq situated in the semi-arid climate using MODIS images and found that during the daytime dense higher LST of non-urbanised area around the city as compared to built-up areas results in SUCI effect whereas the city experienced higher LST values during night time resulting in significant SUHI effect. The night-time SUHI was found stronger during spring and summer than the autumn and winter season whereas daytime SUCI intensity was found to be higher in the autumn and summer than in winter and turned almost neutral in the spring.

Previous researches have shown the relation of LST with different indices (Yuan and Bauer, 2007; Luo and Li, 2014; Mathew et al., 2015) also used combination of indices to improve the relation with LST (Bonafoni, 2016) which are applicable only for day time. Since, behaviour of day and night LST varies with different land covers (Rasul et al., 2016; Hung et al., 2006), these relations may vary for day and night time. The different behaviour of LST during day and night time reveals the thermal property of each land cover. It is important to understand the behaviour of LST with land cover variation during both day and night time (Shastri et al., 2017, Nandkeolyar et al., 2019). The study on relation of LST with different land cover indices for both day and night time can help in understanding the contribution of each land cover on LST behaviour. The relation of LST with a single land cover index may be useful for study in homogeneous land cover of agricultural region but may not be applicable for heterogeneous urban land cover. This motivates for the study on relation of LST with combination of indices which can better explain the contribution of each land cover on LST for both day and night time (Xu et al., 2013).

Therefore, the present study focuses on the comparative study of day and night LST based on land covers and indices in two different semi-arid urban regions i.e. Ahmedabad and Gandhinagar cities of India using Landsat 8 and MODIS satellite images. The relation of LST with NDVI, NDBI and ISF were studied for both day and night time to develop the models using the combination of the above variables to explain the day and night LST efficiently in urban landscapes using two images for each city obtained from Landsat 8 data (one for day time and other for night time) in the post-monsoon season of year 2015. Since, LST shows strong seasonal variation, hence the developed relations were also evaluated for three different seasons (i.e. summer, post-monsoon and winter) using 12 images obtained from MODIS satellite data. Two images (one for day time and other for night time) for each season of one city were used for the investigation of developed models. Thus, six images of MODIS satellite data for three different seasons were used for the evaluation of the developed models for each city.

5.2 STUDY AREA AND DATA USED

5.2.1 Study area

In this study, an attempt has been made to understand the diurnal variability of LST in two different cities i.e. an old metropolitan city of Ahmedabad and a relatively new planned city of Gandhinagar. Gandhinagar, the capital city of Gujarat state, is located 30 km north of Ahmedabad city. Both the cities lie in semi-arid climatic region. The location map of study area is shown in Figure 5.1. Ahmedabad is the sixth largest city and seventh largest metropolitan area in India. It lies at the coordinates 23.03^0 N, 72.58^0 E and at an elevation of 53 m. Sabarmati river passes through the centre of the city. Gandhinagar is India’s tree capital with 54% green cover and lies at the coordinates 23.223^0 N 72.650^0 E and at an elevation of 81 m. It is situated at the western bank of the Sabarmati River.

5.2.2 Data used and image preprocessing

Landsat 8 satellite data have been used in the present study provided by the U.S. Geological Survey (USGS). Atmospheric corrected surface reflectance was obtained from Collection 1 Higher Level Landsat data and thermal images were obtained from Landsat Level 1 data from the USGS website i.e. https://earthexplorer.usgs.gov/ which are radiometric, geometric and terrain corrected. Landsat 8 acquires data in both descending and occasional ascending nodes. Descending nodes provide day time data and ascending node provides night time data. Day time Landsat 8 data is available at interval of 16 days for the locations all over the globe but night time data is available occasionally for limited locations. Landsat 8 images have 11 bands of which band 10 and band 11 are thermal bands. Landsat-8 OLI images have 30 m spatial, 16-day temporal and 12-bits radiometric resolution. The spatial resolution of Landsat 8 TIRS image is 100m, and is resampled to 30 m for distribution. All the images acquired were taken for clear sky condition.

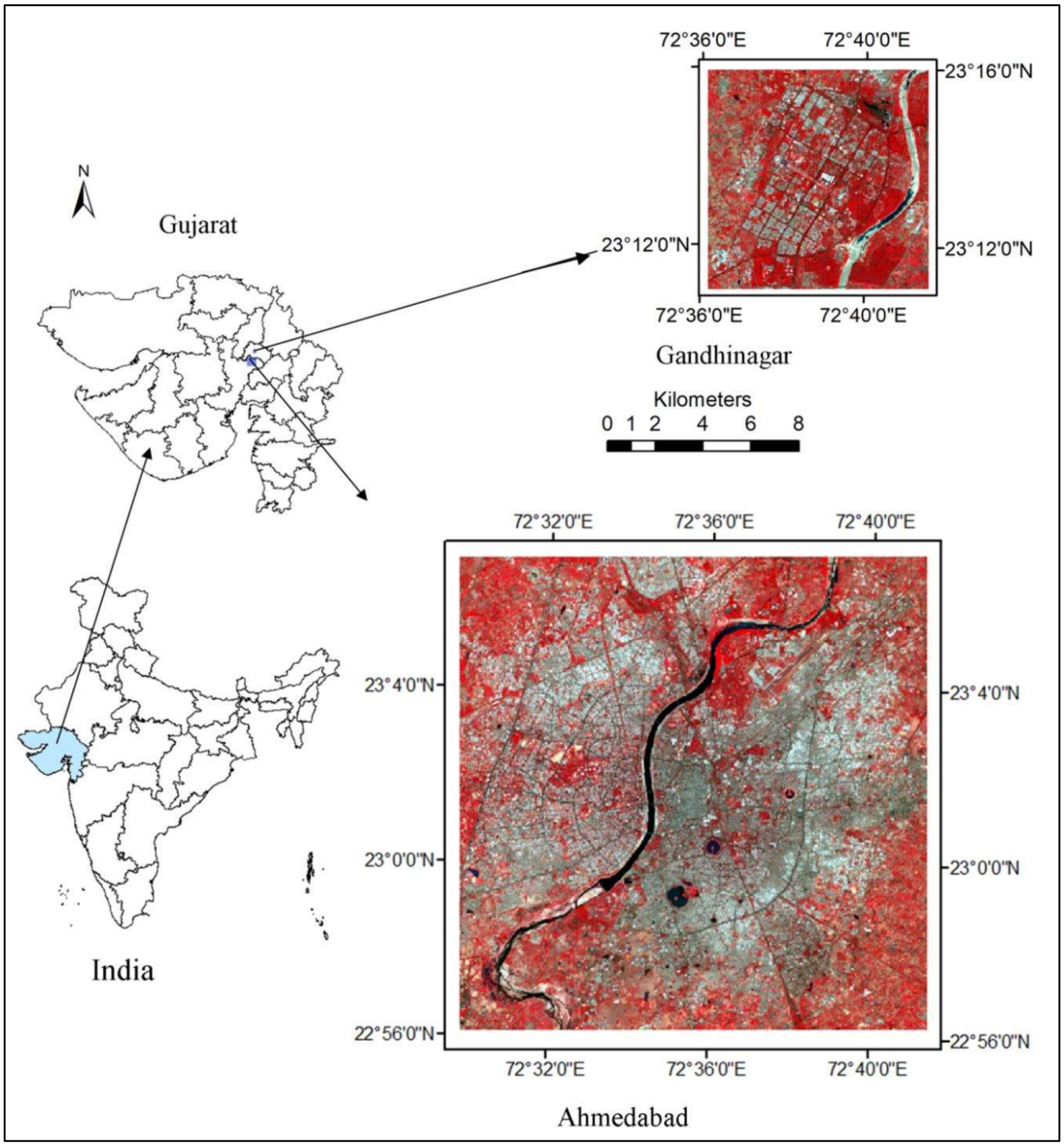

Figure 5.1. Location map of the study area

MOD11A2 and MOD09A1 products of MODIS sensor on board Terra satellite were downloaded from the website of USGS LPDAAC. MOD11A2 product provides 8-day composite LST images with spatial resolution of 930 m. MOD09A1 product provides 8-day composite surface reflectance images of visible and infrared band with spatial resolution of 465 m. All the MODIS images were re-projected and re-sampled using MRT software.

Table 5.1 Datasets used in the study

Satellite	Date	Season	Day/Night
Landsat 8	31 October 2015	Post-Monsoon	Day
	3 November 2015	Post-Monsoon	Night
	1 November 2015	Post-Monsoon	Day/Night
MODIS	24 April 2016	Summer	Day/Night
	12 February 2016	Winter	Day/Night
Sentinel- 2A	28 April 2016	Summer	Day

Sentinel- 2A data was downloaded from the ESA Sentinel Scientific Data Hub that contains 13 bands. This provides 4 reflective bands (3 visible and 1 NIR) at spatial resolution of 10 m, 6 reflective bands (4 NIR and 2 SWIR) at spatial resolution of 20 m and 3 bands (aerosol, water vapour and cirrus) at spatial resolution of 60 m. Sentinel- 2A provides blue, green, red and NIR reflective bands at a spatial resolution of 10 m (Yadav et al., 2019). The datasets used in this study is provided in Table 5.1.

In order to understand the relation of LST with different indices and land cover, fine spatial resolution of LST data is required which can contain pure pixels. Therefore, LST obtained from Landsat data can be useful to understand the relation of LST with different indices to develop relation which can better explain the behaviour of LST with the combination of indices for both day and night time. The relation of LST with indices depends on the land cover present in a region. The agricultural land cover surrounding the city changes throughout the year with seasons which has significant impact on the LST. Since, Landsat do not acquire night time data at periodic interval, it is not possible to validate the developed relations at different seasons from Landsat data. Thus, MODIS data was acquired for three different seasons to compare the behaviour of relations developed using combination of indices for different seasons.

LST depends on the land covers present in the region. Most of the natural land cover consists of fallow land in summer and vegetated land in winter. During post-monsoon, the natural land covers consist of combination of fallow as well as vegetated land cover. The urban built-ups remain almost same in a year. The presence of vegetation or fallow land in the agricultural region surrounding the cities varies with season which has significant effect on LST. A small change in the present land cover is observed throughout a season which may result in some minor change in LST. The MODIS data used for the study provides 8-day composite images. The MODIS image was selected for a date in summer season when maximum contribution of fallow land and minimum contribution of vegetated land is observed in the study area. The date selected for winter season had maximum contribution from vegetated land. Whereas, the date selected for post-monsoon season had significant contribution of both fallow and vegetated land. Thus, one image was processed for each season which accounts for maximum changes in land cover possible in the study area in a year.

5.3 METHODOLOGY

The determination of the NDVI, NDBI, ISF and LST from Landsat and MODIS satellite images have been discussed in the second chapter of the thesis.

5.3.1 Classification of impervious surface fraction

A NSMA method given by Wu (2004) was used for classification of ISF from the mixed spectrum which was modelled as a linear combination of vegetation, high albedo impervious surface, low albedo impervious surface and soil endmembers. The fraction of impervious surfaces were determined by adding the fractions of low and high albedo impervious surfaces as suggested by Wu and Murray (2003). The mean residual errors were observed as 0.003 and 0.005 for Ahmedabad and Gandhinagar, respectively. The lower value of residual error represents good performance of the LSMA model.

The accuracy of the ISF was evaluated using area of interest (AOI) samples obtained from Sentinel-2A optical satellite data. False colour composite (fcc) image was obtained using the green, red and NIR reflective bands. This fcc image helps in better interpretation of land covers in the study area. Thus, the pixels containing impervious surfaces could be clearly identified. The Sentinel- 2A image was co-registered with that of Landsat image. The 3×3 pixel in Sentinel data can be equivalent to 1 Landsat pixel. The impervious surfaces within each AOI were digitized for the calculation of ISF and the impervious surface area in a polygon was divided by the total area of the AOI. For this study, 200 random samples were obtained from the entire image for both the cities. The accuracy of the Landsat classified image of ISF was determined by comparing the ISF obtained from the Sentinel-2A data with the Landsat estimated ISF for both the cities i.e. Ahmedabad and Gandhinagar as shown in Figure 5.2. The higher correlation of the two measurements (R^2 = 0.96 and 0.91 for Ahmedabad and Gandhinagar, respectively) indicates accurate classification of ISF in both the cities.

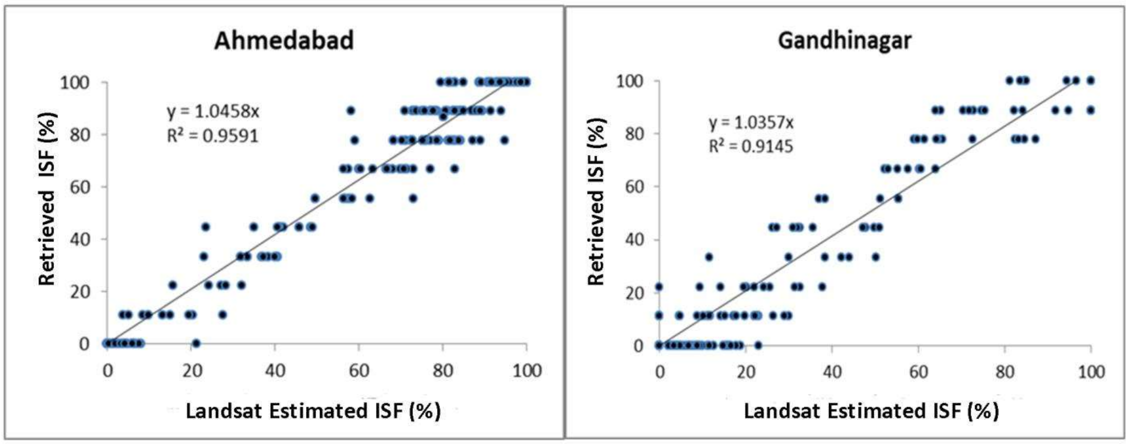

Figure 5.2 Relation of Sentinel-2A retrieved ISF and the Landsat estimated ISF

5.4 RESULTS AND DISCUSSION

5.4.1 Diurnal LST variation of land cover

Day and night time LST maps were generated for Ahmedabad and Gandhinagar using Landsat 8 TIRS data for the post-monsoon season in year 2015 to study the diurnal variation of LST as shown in Figure 5.3. SUHI effect was found significant during night time but not during day time in both the cities. This SUHI behaviour was found similar to the work performed by Mohammad et al. 2019 for day and night LST for summer and winter season from 2003 to 2018 in Ahmedabad city using MODIS data. This explains that the SUHI effect shows similar pattern for day and night time at different seasons. During night time, SUHI intensity was found greater in Ahmedabad than Gandhinagar. This is due to greater vegetation present in Gandhinagar which contributes in lowering of urban temperatures (Taha H., 1997; Kalota, 2017).

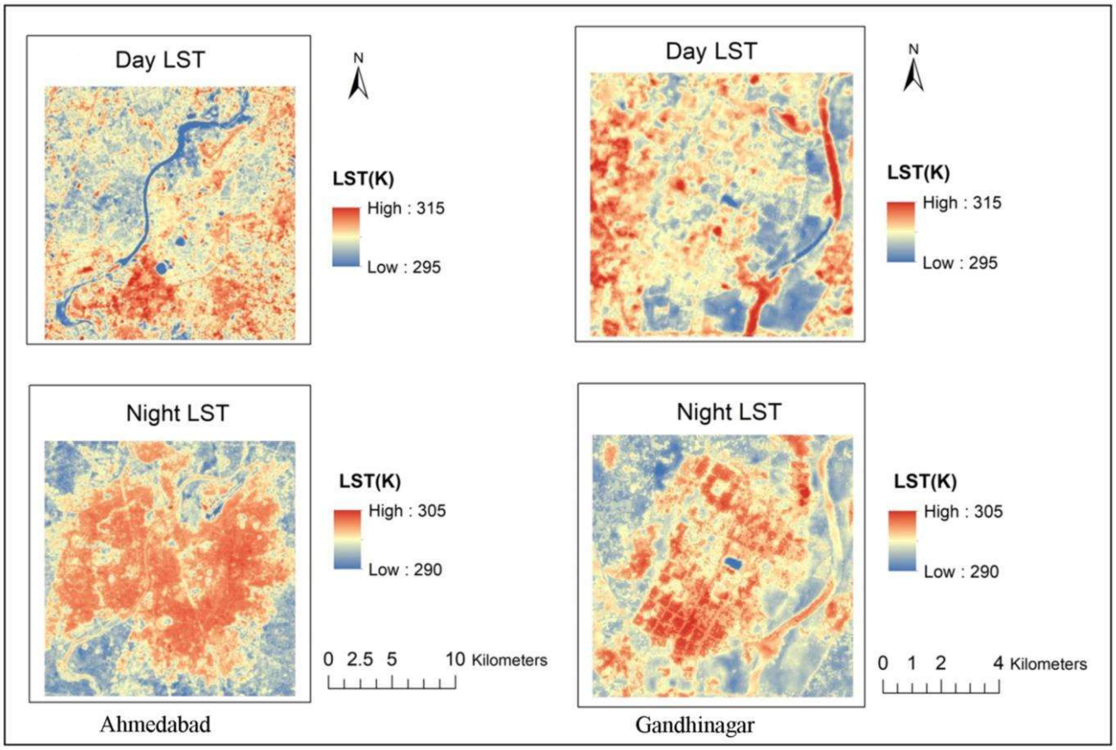

Figure 5.3. Day and Night LST maps of Ahmedabad and Gandhinagar from Landsat 8 TIRS data for the post-monsoon season (31/10/2015 for day time and 01/11/2015 for night time)

The classified maps of Ahmedabad and Gandhinagar cities were obtained using MLC technique and the mean LST for each land cover were obtained using zonal statistics. Figure 5.4 was drawn to study the variation of day and night time LST with land cover. The natural land cover constitutes of soil, water and vegetation. Water and vegetation showed lower LST than the built surfaces whereas bare land or soil was found to be the hottest land cover during the day time (Amiri et al., 2009). The high albedo built up surfaces showed lower LST than other artificial built surfaces during the day time (Taha et al., 1992). All the natural land covers showed lower temperatures than the built surfaces during the night time (Rasul et al., 2016). The land covers acquire heat from the sun during day time resulting rise in temperatures, however, temperature of the land covers decreases due to the absence of heat energy during the night time. The rate of increase or decrease in temperature depends on the heat capacity of the material of each land cover. Very high heat capacity of water (4.2 kJ kg^{-1} K^{-1}) results in lower LST during the day time (Manteghi et al., 2015), however higher LST among the natural land covers was observed during the night time. The low heat capacity of dry soil/sand (0.80 kJ kg^{-1} K^{-1}) resulted to very high temperatures during the day time but lower temperatures during the night time. The vegetated land cover showed lower temperature during both day and night time. Artificial built ups are mainly made up of materials like asphalt, concrete, brick, cement whose heat capacities lies in the rangeof 0.75 to 1.5 kJ kg^{-1} K^{-1} which explains the LST lower than the bare soil during day time but higher during night time.

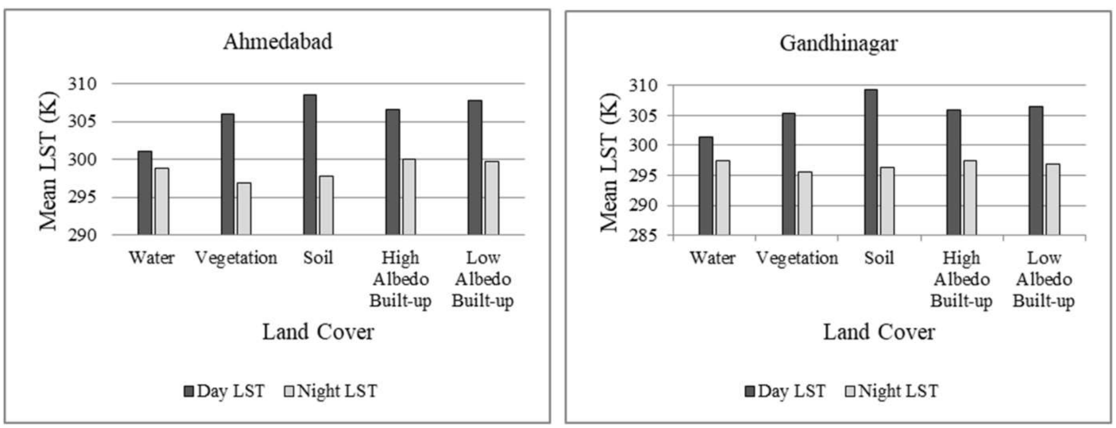

Figure 5.4 Mean day LST for each land cover of Ahmedabad and Gandhinagar obtained from Landsat 8 data for the post-monsoon season (31/10/2015 for day time and 01/11/2015 for night time)

Thus, higher LST values of dry bare soil and lower LST values of high albedo built up resulted lower differences in the LST for rural and urban areas during the day time. But during night time, pervious surfaces i.e. soil, water and vegetation showed lower LST and impervious surfaces show higher LST values. Thus, the significant difference in LST of pervious and impervious surfaces causes the formation of SUHI during night time.

5.4.2 Relation of LST with indices and ISF

The behaviour of LST with different land covers was found varying during day and night time. Thus, the relation of LST with the independent variables like NDVI, NDBI and ISF should also vary for day and night time. The parameters NDVI, NDBI and ISF were determined from the Landsat-8 OLI data for the post-monsoon season in year 2015. In order to understand the diurnal relation of LST with the three independent variables, the mean LST for each 0.02 increment in NDBI and NDVI were determined. The mean LST for each 2% increment in ISF were also determined and plotted for Ahmedabad and Gandhinagar cities as shown in Figures 5.5 and 5.6, respectively.

Figures 5.5 (a, b) and 5.6 (a, b) showed good negative linear relationship between the NDVI and LST during the night time (R^2 = 0.70, 0.86) (Mathew et al., 2015), whereas non-linear relation was observed during the day time (Yuan and Bauer, 2007). However, good second order polynomial relations between the NDVI and day LST were observed in both the cities (R^2 = 0.87, 0.90). NDVI value for water has negative values, urban has positive NDVI value less than 0.2, bare soil has NDVI value around 0.2 and vegetation has NDVI from 0.3 to 1. During day time, the presence of waterbody whose LST is quite lower than the urban or bare land results in non-linear (second order) relation of LST with NDVI in both the cities. During night time, water shows LST value higher than vegetation and bare soil but slightly lower than urban surfaces which results in good negative linear relation of night LST with NDVI in both cities. Mohammad et al. 2019 also discussed the relation of LST with NDVI for day and night time from 2003 to 2018 using MODIS data and found that strong negative correlation was observed during night time and weak negative relation was observed during day time in both summer and winter seasons. This behaviour was similar to the LST-NDVI relation obtained for the post-monsoon season in the present study using Landsat data. Thus, this explains the strong negative correlation of night LST with NDVI and second order polynomial relation of day LST with NDVI for different seasons.

Figures 5.5(c) and 5.6(c) showed good positive linear relation of day LST with NDBI in both the cities (R^2 = 0.88, 0.97) because higher day LST land covers of urban and bare soil shows positive value whereas low day LST land covers of water and vegetation shows negative NDBI value. This behaviour results to good positive linear relation of day LST with NDBI. Figures 5.5(d) and 5.6(d) showed non-linear relation of night LST with NDBI i.e. first decreasing and then increasing trend for negative NDBI values and further decreasing trend for positive NDBI values. First peak at negative NDBI value was due to the waterbody and then decreases due to the vegetation land cover which has lower night LST than water. Then, increasing trend approaching towards positive NDBI value is due to higher night LST of urban land cover than vegetation. Further, decreasing trend of night LST for positive NDBI values were due to the low night LST of bare soil as compared to that of urban land cover (Bala et al., 2018).

Figures 5.5 (e, f) and 5.6 (e, f) showed good linear relation of LST with ISF for night time (R^2 = 0.94, 0.97) while poor during day time (R^2 = 0.53, 0.58). The relation of LST with ISF depends on both the pervious and impervious surfaces present in the region. The regions with zero percent impervious mean pure pixels of pervious surface whereas 100% impervious means pure pixels of urban or impervious surfaces. The region with less than 100% impervious surface depicts the combination of impervious surface and pervious surfaces. From the day LST image of Ahmedabad, the urban or impervious part of land cover shows lower LST as compared to most of the pervious surfaces (natural land covers). Therefore, zero percent ISF shows higher LST than 100% ISF. The increase in impervious contribution in a pixel results in lowering of LST which indicates the negative relationship of LST with ISF. The rural areas around Ahmedabad city was mainly covered with bare land or sparse vegetated area due to its semi-arid climate. Among the pervious surface, bare soil contribution is greater than vegetation and the bare land cover shows day LST higher than urban or impervious land cover. This results in negative relation of day LST with ISF in Ahmedabad. The impervious surfaces consist of both high and low albedos built ups. The low albedo built ups show higher day LST values as compared to high albedo built ups which also contributes poor correspondence of day LST with ISF in Ahmedabad. During night time, all the pervious surfaces i.e. vegetation as well as bare land shows lower LST values as compared to the impervious surface which results in good positive linear relation of night LST with impervious surface. Positive slope was observed for day LST with ISF in Gandhinagar due to the presence of greater vegetation in Gandhinagar whereas negative slope was observed in Ahmedabad due to the presence of dry bare land in areas surrounding the city. Both the high and low albedo built ups showed higher night LST and pervious surfaces showed lower night LST resulted to good correlation of night LST with ISF surfaces in both the cities.

Day LST showed good correlation with NDVI (second order) and NDBI (first order), whereas did not show good relation with ISF. The night LST showed good linear correlation with NDVI and ISF while poor correlation with NDVI in both the cities. Therefore, NDVI and NDBI can be used for study of day LST whereas NDVI and ISF can be used for study of night LST.

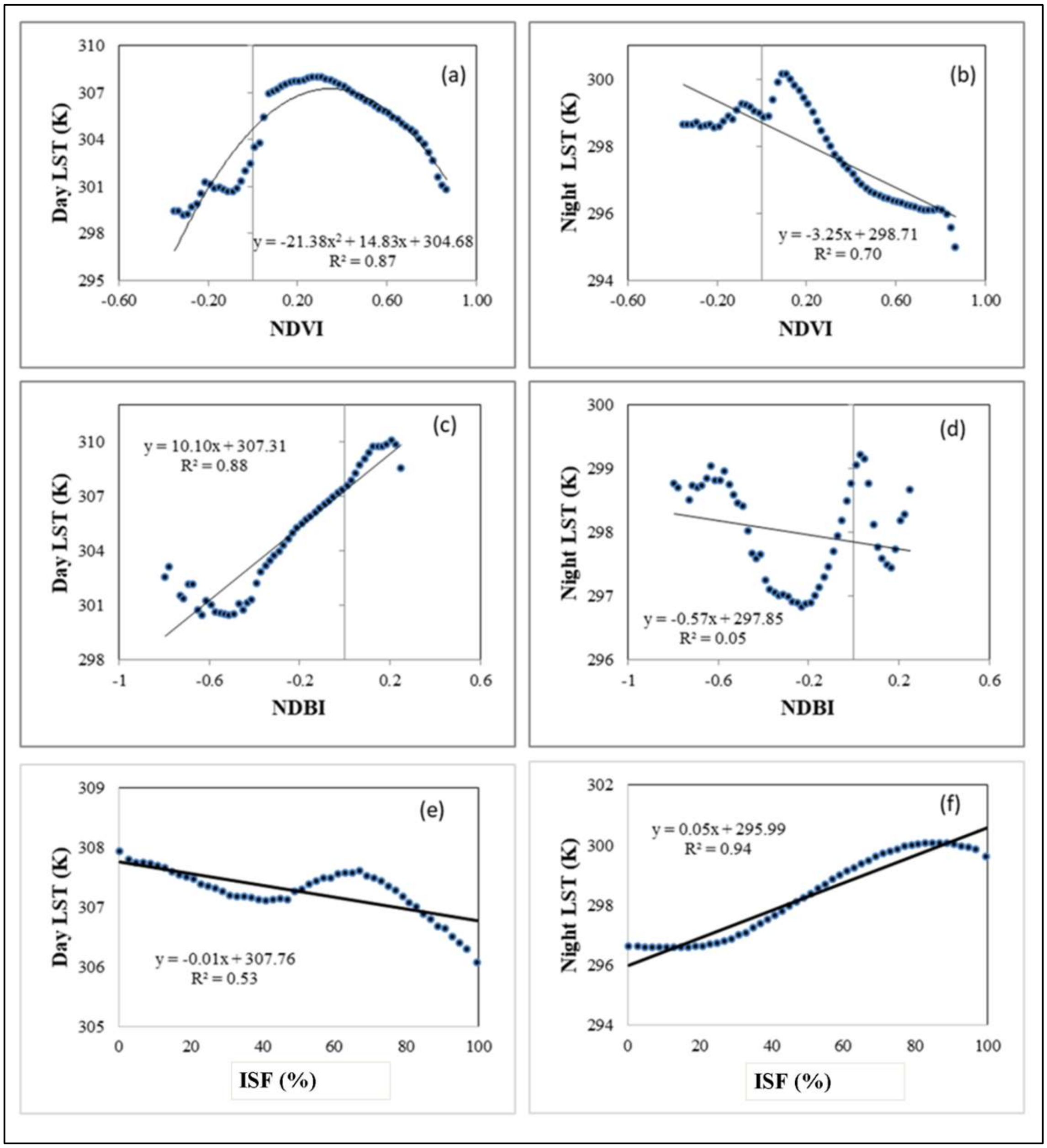

Figure 5.5 (a - f) Relation of day and night LST with NDVI (a, b), NDBI (c, d) and ISF (e, f) in Ahmedabad obtained from Landsat 8 data for post-monsoon season (31/10/2015 for day time and 01/11/2015 for night time)

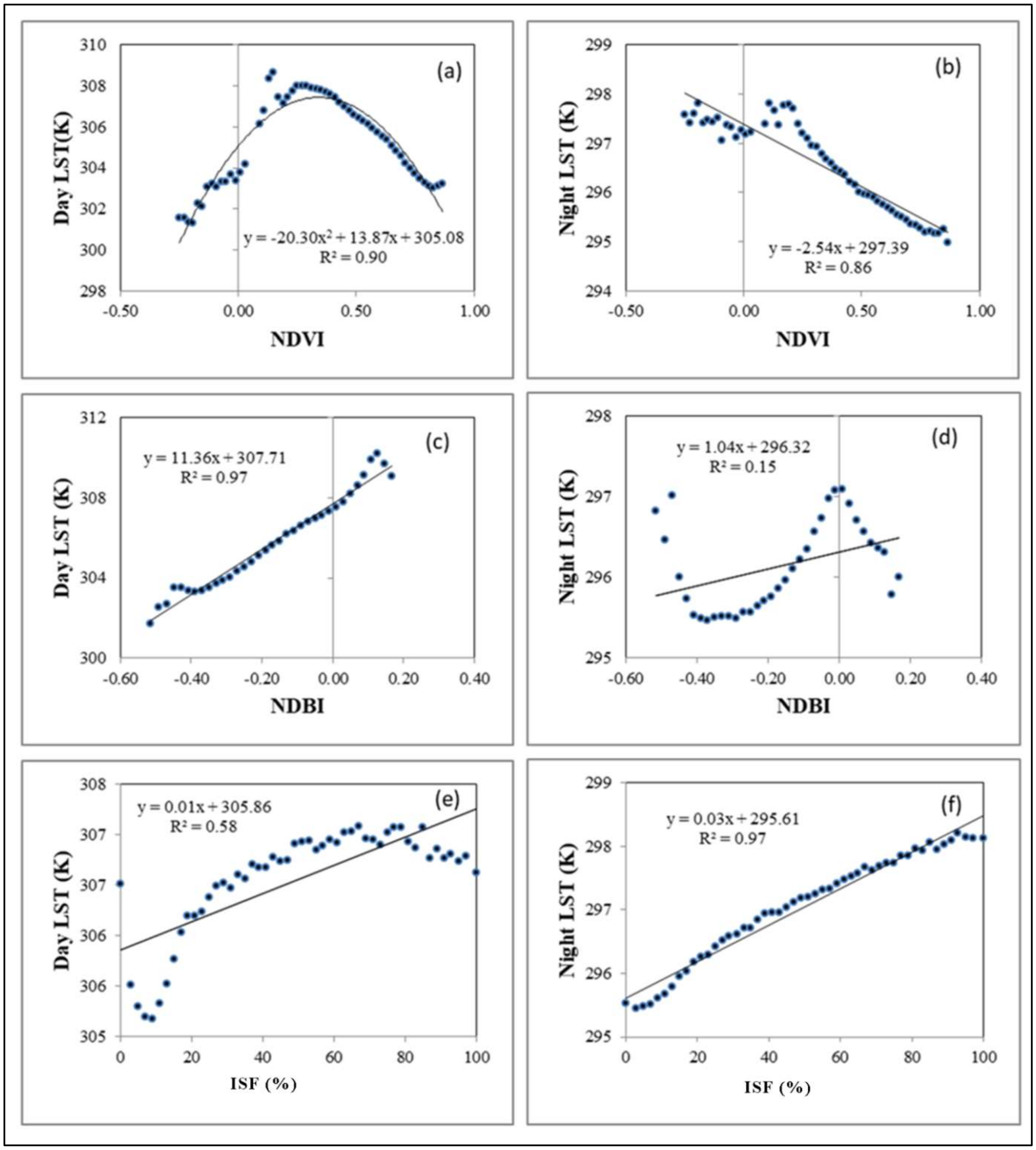

Figure 5.6 (a - f) Relation of day and night LST with NDVI (a, b), NDBI (c, d) and ISF (e, f) in Gandhinagar obtained from Landsat 8 data for post-monsoon season (31/10/2015 for day time and 01/11/2015 for night time)

5.4.3 Development of model for diurnal LST

Based on the relation of LST with the three independent variables (NDVI, NDBI and ISF) determined above, the model was developed for day and night LST using combination of different variables as shown in Equations 5.1 and 5.2.

$$\text{Day LST} = a_o \times \text{NDBI} + a_1 \times \text{NDVI}^2 + a_2 \quad (5.1)$$

$$\text{Night LST} = b_o \times \text{NDVI} + b_1 \times \text{ISF} + b_2 \quad (5.2)$$

Here a_o, a_1, a_2, b_o, b_1, b_2 are the regression parameters. The values of LST and variables of all the pixels were used for the present study. The relation of day LST with NDVI and NDBI were obtained individually and also by combining the variables as mentioned in Equation (5.1). Similarly, the relation of night LST with NDVI and ISF were obtained individually and by combining the variables as mentioned in Equation (5.2). The equations and coefficient of determination (R^2) obtained are presented in Table 5.2.

The model developed for the day and night LST using combination of variables for the post-monsoon season showed improved correlation as compared to the correlation determined using individual variable in both the cities considering all the pixel values in the study site. The correlation of day LST with NDBI was found good (R^2 = 0.52, 0.67), however combining NDBI with the square of NDVI improved the correlation (R^2 = 0.63, 0.79). Similarly, ISF showed good correlation with night LST (R^2 = 0.68, 0.61) but combining the ISF with NDVI improves the correlation for night LST (R^2 = 0.81, 0.75).

Table 5.2. The correlation of diurnal LST with combination of variables in Ahmedabad and Gandhinagar obtained from Landsat data for post-monsoon season (31/10/2015 for day time and 01/11/2015 for night time)

City	Day		Night	
	Equation	R^2	Equation	R^2
Ahmed-abad	$LST = 15.47 \times NDBI + 307.7$	0.52	$LST = 0.05 \times ISF + 295.9$	0.68
	$LST = -29.94 \times NDVI^2 + 18.05 \times NDVI + 305.2$	0.34	$LST = -8.85 \times NDVI + 301.0$	0.60
	$LST = 6.38 \times NDVI^2 + 20.99 \times NDBI + 307.1$	0.63	$LST = 0.03 \times ISF - 4.81 \times NDVI + 298.2$	0.81
Gandhi-nagar	$LST = 14.68 \times NDBI + 308.0$	0.67	$LST = 0.04 \times ISF + 295.3$	0.61
	$LST = -20.12 \times NDVI^2 + 10.70 \times NDVI + 306.4$	0.57	$LST = -4.32 \times NDVI + 298.3$	0.48
	$LST = 1.97 \times NDVI^2 + 17.21 \times NDBI + 307.7$	0.79	$LST = 0.03 \times ISF - 2.091 \times NDVI + 296.5$	0.75

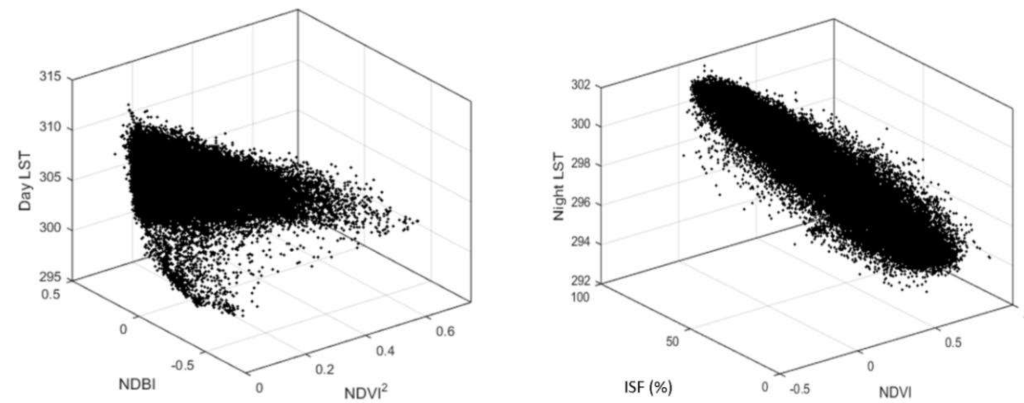

Figure 5.7 3D scatterplot of (a) day LST with NDVI and NDBI and (b) night LST with NDBI and ISF for Ahmedabad obtained from Landsat data (31/10/2015 for day time and 01/11/2015 for night time)

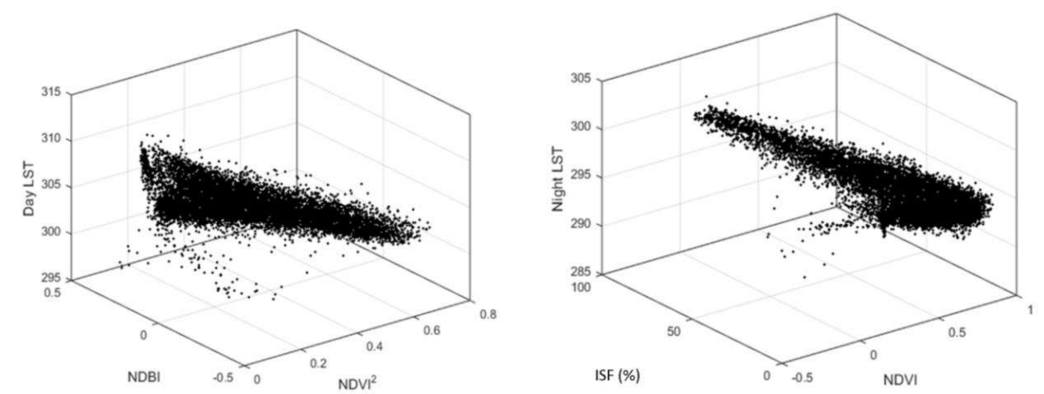

Figure 5.8 3D scatterplot of (a) day LST with NDVI and NDBI and (b) night LST with NDBI and ISF for Gandhinagar obtained from Landsat data (31/10/2015 for day time and 01/11/2015 for night time)

Figures 5.7(a) and 5.8(a) showed the 3D plot of day LST with $NDVI^2$ and NDBI for Ahmedabad and Gandhinagar cities, respectively for the post-monsoon season. Due to lower vegetation in Ahmedabad, very few pixels were observed at higher $NDVI^2$ with negative NDBI values. The points at negative NDBI and lower $NDVI^2$ values were observed due to the water pixels. The points at low $NDVI^2$ and positive NDBI values were due to the bare soil or built up pixels (low and high albedo built-ups). Figures 5.7(b) and 5.8(b) showed the 3D plot of night LST with NDVI and ISF for Ahmedabad and Gandhinagar, respectively. Pixels with higher NDVI and lower ISF values showed low LST values due to vegetation. Pixels with higher ISF and low NDVI values showed high LST values due to built-up regions. Higher vegetation in Gandhinagar resulted to greater number of pixels at high NDVI and low ISF values. The pure pixels for built up region was low resulting to lesser points at high ISF and low NDVI values.

The models developed for day LST showed lower correlation with the variables due to the presence of a large waterbody in Ahmedabad. The model for day LST showed very good correlation for the regions having no waterbody. The model for night LST showed very good correlation in both the cities. Therefore, the developed models were found very useful for study of SUHI during day and night time.

5.4.4 Seasonal behaviour of the developed relation of LST with combination of indices

LST depends on the land covers present in the region. The presence of vegetation or fallow land in the agricultural region surrounding the cities varies with season. This change in natural land covers results in change in indices value as well as LST which may affect the relation of LST with indices. Since, LST shows significant seasonal variation, it is important to study the seasonal behaviour of LST with the indices. Landsat do not acquire nighttime data at periodic interval. Thus, MODIS data was acquired to compare the behaviour of relations developed using combination of indices for different seasons i.e. summer, post-monsoon and winter. The equations and R^2 values obtained for summer, post-monsoon and winter season were presented in Table 5.3 and Table 5.4 for Ahmedabad and Gandhinagar cities, respectively.

Table 5.3 The correlation of diurnal LST with combination of variables in Ahmedabad for different seasons i.e. summer, post-monsoon and winter

Season	Day		Night	
	Equation	**R^2**	**Equation**	**R^2**
Summer	LST = 30.4 × NDBI + 315.6	0.58	LST = 0.045 × ISF + 295.5	0.66
	LST = -47.2 × $NDVI^2$ + 26.6 × NDVI + 313	0.27	LST = -12.73 × NDVI + 300.5	0.47
	LST = 26 × $NDVI^2$ + 46.7 × NDBI + 313.8	0.70	LST = 0.042 × ISF – 1 × NDVI + 296	0.76
Post-monsoon	LST = 14.3 × NDBI + 309	0.43	LST = 0.06 × ISF + 293.9	0.85
	LST = 5.54 × $NDVI^2$ - 5.1 × NDVI + 310	0.23	LST = -13.5 × NDVI + 300.8	0.70
	LST = 5.64 × $NDVI^2$ + 20.3 × NDBI + 308.4	0.65	LST = 0.05 × ISF – 2.53 × NDVI + 295.1	0.89
Winter	LST = 17.1 × NDBI + 303.6	0.46	LST = 0.057 × ISF + 288.4	0.82
	LST = -26.8 × $NDVI^2$ + 10.05 × NDVI + 302.9	0.42	LST = -13.4 × NDVI + 294	0.71
	LST = 18.5 × $NDVI^2$ + 37 × NDBI + 302	0.69	LST = 0.044 × ISF – 4 × NDVI + 290	0.91

Table 5.4. The correlation of diurnal LST with combination of variables in Gandhinagar for different seasons i.e. summer, post-monsoon and winter

Season	Day		Night	
	Equation	**R^2**	**Equation**	**R^2**
Summer	LST = 30.7 × NDBI + 317	0.62	LST = 0.03 × ISF + 296.4	0.51
	LST = -54.8 × $NDVI^2$ + 22.5 × NDVI + 316	0.40	LST = -5.9 × NDVI + 299	0.33
	LST = 2.5 × $NDVI^2$ + 32.5 × NDBI + 316.7	0.72	LST = 0.02 × ISF – 2.65 × NDVI + 297.3	0.68
Post-monsoon	LST = 12.5 × NDBI + 308.7	0.51	LST = 0.04 × ISF + 293.8	0.59
	LST = -10.2 × $NDVI^2$ + 3.82 × NDVI + 308.3	0.36	LST = -2.71 × NDVI + 295.9	0.36
	LST = 1.93 × $NDVI^2$ + 14.7 × NDBI + 308.4	0.68	LST = 0.04 × ISF – 0.80 × NDVI + 293.4	0.71
Winter	LST = 11.3 × NDBI + 303	0.54	LST = 0.255 × ISF + 280.6	0.63
	LST = -14 × $NDVI^2$ + 4.5 × NDVI + 303	0.59	LST = -64.2 × NDVI + 307.6	0.49
	LST = 10.6 × $NDVI^2$ + 22.6 × NDBI + 302	0.77	LST = 0.14 × ISF – 47.9 × NDVI + 299	0.76

The correlation of LST with the combination of variables was found to vary for different seasons due to the change in natural land covers with change in season. However, the models developed for day and night LST were found to show improvement in the correlation as compared to the individual variables. The correlation for day LST was found higher in summer (R^2 = 0.70) and lower in post monsoon season (R^2 = 0.65) for Ahmedabad. The water content in Sabarmati River was lower in summer and higher in post monsoon season. Hence, the increase in water content in the city decreases the correlation of day LST using this model. The correlation for day LST in Gandhinagar was lower during post-monsoon (R^2 = 0.68) due to the increased moisture content whereas higher in winter season (R^2 = 0.77) due to the increased vegetation content. The relation of LST with NDVI was found lower in summer whereas higher in winter in both the cities during day as well as night time. This reveals that the increase in vegetation content in a region increases the LST-NDVI correlation. The relation of day LST with NDBI was found higher in summer as compared to other seasons in both the cities. This reveals that day LST was better correlated to NDBI during dry season. Therefore, the combining the two variables NDVI and NDBI improves the relation of day LST in the different seasons. The correlation for night LST was found higher in winter (R^2 = 0.91 and 0.76) than in summer (0.76 and 0.68) for both Ahmedabad and Gandhinagar. The correlation of night LST with ISF and NDVI used singly shows higher correlation during winter than in summer. During night time, bare soil shows very low LST than other natural land covers. The presence of more of bare soil during summer can result in lower correlation of night LST with ISF. The increased vegetation content in winter results in improved correlation of LST with NDVI. Hence, the combination of the two variables provides improved correlation for night LST in both the cities.

The equation and the correlation obtained were found to vary for the three seasons due to the variation in land cover. The date selected for each season to study using MODIS data accounts for the maximum possible land cover variation in the study area. The developed model performs well both during day and night for three seasons in two different cities of semi-arid region irrespective of the land cover variation. Further studies can be performed for other months and years to understand the behaviour and the significance of the developed model for other dates in semi-arid urban areas.

5.5 CONCLUSION

The present study was performed to analyze the day and night LST in two semi-arid cities i.e. Ahmedabad and Gandhinagar. SUHI effect was found more prominent during night time in comparison to day time in both the cities. The behaviour of each land cover towards LST was found different for day and night time. Thus, higher temperatures of dry bare soil of fallow agricultural fields surrounding the cities and lower temperatures of high albedo built up areas results in lower deviation of temperatures in urban and rural areas during day time. However, during night time, pervious surfaces i.e. soil and vegetation shows lower temperatures as they enable circulation of air to cool the temperatures. While, the impervious surfaces showed higher temperatures as they hold the heat for longer duration thereby resulting in formation of SUHI during the night time.

The semi-arid urban region shows greater heterogeneity in land cover and thus a single spectral index cannot explain the LST in this region. Hence, the relation of LST with NDVI, NDBI and ISF were determined for both day and night time using Landsat data. The correlation of day LST was found good with second order of NDVI and first order of NDBI. The night LST showed good linear relation with NDVI as well as ISF surfaces. Based on this relation of LST with NDVI, NDBI and ISF, the models were developed for day and night LST. Therefore, the combination of first order of NDBI and second order of NDVI resulted into better correlation with day LST (R^2 = 0.63 and 0.79 for Ahmedabad and Gandhinagar cities, respectively) as compared to the correlation determined using individual variables. Similarly, combination of first order of NDVI and ISF surfaces showed better correlation with night LST (R^2 =0.81 and 0.75 for Ahmedabad and Gandhinagar, respectively).This relation was further studied for three different seasons using MODIS data and found that the combination of indices improves the correlation of day and night LST. The greater moisture content during post-monsoon season resulted in lower correlation during day time in both the cities. The greater vegetation content shows higher correlation for the night LST in winter season in both cities.

During day time, NDBI explains the LST behaviour for the urban and the bare land covers and NDVI accounts for the vegetation part and the combination of both the indices includes the contribution from most part of the land cover which improves the correlation. During night time, ISF distinguishes the LST behaviour of pervious and impervious land cover and NDVI accounts for the LST variation among the pervious surfaces and the combination of NDVI and ISF includes the contribution from most of the land cover resulting in improvement in the correlation as compared to the individual variable. Therefore, the models developed have potential to explain the day and night LST in semi-arid urban areas with high accuracy.

Thus, one image of MODIS data processed for each season adequately accounts for maximum changes possible in land cover affecting the LST in the present study area. The developed model performed well both during day and night time for three seasons in two different cities of semi-arid region irrespective of the land cover variation indicating its capability for the study of SUHI during day as well as night time robustly. However, the relations established in this study can be further investigated for other months and years with more images within each season to understand its behaviour and their significance for other dates in semi-arid urban areas.