# THERMAL SHARPENING OF MODIS LAND SURFACE TEMPERATURE USING STATISTICAL DOWNSCALING TECHNIQUE IN URBAN AREAS

## 4.1 INTRODUCTION

Thermal-remote-sensing has gained popularity for its importance in numerous applications like environmental monitoring ( Liu et al. 2016; Voogt and Oke 2003; Weng 2009), forest-fire detection (Justice et al. 2002), climate change (Zhou et al. 2019; Rajasekar and Weng 2009; Rasul et al. 2017) and also for soil-moisture estimation and agricultural applications (Wang and Qu 2009; Kauffman et al. 2007; Zhang et al. 2015; Nuruzzaman 2015). Various satellites containing thermal-sensors like MODIS, AVHRR, Landsat TM/ETM+ and Landsat-8 TIRS and ASTER have been used for determining LST at different spatial-resolution (SR) and temporal resolution (Yao et al. 2017, 2018; Julien and Sobrino 2009). Urbanization has led to the change in land-cover and also increase in anthropogenic heat discharge at large scale which has significant impact on urban temperatures. The heterogeneity of land-cover in urban areas has increased demand for the LST at fine spatial resolution (FR) from satellite data. The lack of satellite thermal images at FR triggered the evolution of various downscaling techniques for increase in spatial details from the original coarse spatial resolution (CR) LST image (Zhan et al. 2013; Atkinson 2013).

The land-cover indices derived from visible, NIR and SWIR bands are available at FR from different optical satellite images. Hence, different disaggregation methods like Distrad-Model (Essa et al. 2012; Eswar et al. 2016; Kustas et al. 2003), Tsharp ( Agam et al. 2007a) and PBIM algorithm (Stathopoulou and Cartalis 2009) were developed for thermal-sharpening of LST using the relationship of LST with various indices. The Distrad-Model was developed from the relation of LST with NDVI (Kustas et al. 2003). This method was used by various researchers for thermal-sharpening of LST determined from the satellite-data over the vegetated or natural land-covers based on relation of the LST with indices like NDVI, EVI, FVC etc. and the results depicts that this method worked with acceptable accuracy (Agam et al. 2007a, 2007b; Jeganathan et al. 2011). Due to higher heterogeneity in land-cover of urban areas, the LST-NDVI relation may not explain all the variations of LST in urban regions (Bonafoni 2016; Zhang et al. 2009).

Stathopoulou and Cartalis (2009) tried to downscale coarser AVHRR-LST to the SR of Landsat-TM data using PBIM method to study the SUHI effect. Error in SUHI was decreased from 2.4 $^0$C to 0.94 $^0$C when determined from the downscaled-MODIS-LST image in comparison with the original AVHRR LST data. Essa et al. (2012) used the relation of LST with percent-impervious-surface-area (%ISA) and various indices for assessment of performance of the Distrad-method over urban areas using Landsat-ETM+ data. %ISA showed reasonable result when compared with other indices. Mukherjee et al. (2014) evaluated the performance of five different regression methods i.e. Distrad, Tsharp, Tsharp-with-local-variant, LMSR and Pace regression for the downscaling of Landsat and MODIS-LST images using LST-NDVI over a heterogeneous region of India. The model was found suitable for the agricultural or vegetated landscapes but have limitations for sandy-open-areas or water bodies. Eswar et al. (2016) compared the performance of five different indices i.e. NDVI, FVC, SAVI, MSAVI and NDWI for downscaling LST using Distrad-method. The MODIS-LST at 960 m was disaggregated to 120 m and then compared with the LST from Landsat-7 images for different sites in India. NDVI/FVC showed better result for wet areas and NDWI showed better result for dry areas. Mukherjee et al. (2017) used the LST-NDVI relation by LMSR to downscale MODIS-LST image to the SR of 250 m to study the SUHI effect which enhances the usage of MODIS-LST for continuous monitoring of SUHI-effect. Yang et al. (2017) downscaled the aggregated Landsat-8-TIRS image (360 m) to the SR of 90 m using the relation of LST with multiple-scale-factors in mixed land-covers. The downscaled-MODIS-LST image was compared with the actual Landsat-LST and satisfactory result was obtained with low RMSE (1.13 K) and high coefficient-of-determination ($R^2$) of 0.87. The spatial variability increased in the downscaled-MODIS-LST image from the actual MODIS-LST image which makes it suitable for study of the SUHI-effect. Bonafoni (2016) used various regressive techniques from multiple indices for downscaling of the upscaled-Landsat-LST and the MODIS-LST to the SR of 480, 240 and 120 m during summer season in the urban part of Milan, Italy and RMSE was found higher for MODIS image than downscaled-MODIS-LST image obtained from Landsat data.

Various previous studies have been performed on thermal-sharpening from satellite images using different indices in agricultural region where LST-NDVI relation was found beneficial. The negative linear relation of LST with NDVI in agricultural areas makes it suitable for thermal sharpening in agricultural areas. However, NDVI cannot explain all variations in LST in an urban area because of the non-linear relation of LST with NDVI due to greater heterogeneity in urban areas. The relation of LST with different indices depends on the kind of land-cover present in an area (Bala et al. 2018). The relation of LST with one SI can address the contribution of one type of land cover but may not be useful for other land cover types. Thus, the combination of different SI may be beneficial for including the contribution from different type of land covers on LST in an urban area. In the present analysis, different regression based on multiple indices has been compared for thermal-sharpening of coarser MODIS-LST to FR of Landsat-8-TIRS LST data in different cities of India i.e. Bikaner, Vadodara, Hyderabad and Varanasi. The natural land-cover within or outside the city also influences the relation of LST with the indices. Previous studies have also discussed different thermal-sharpening methods in the heterogeneous urban land-cover. Essa et al. (2012) studied that %ISA performs better for downscaling in urban areas with very high vegetation-cover. Bonafoni (2016) downscaled MODIS-LST using different regressive methods and the combination of SI i.e. $a + b \times NDVI^2 + c \times NDBI$ performed best for MODIS disaggregation of LST. These studies performed well in regions with vegetated rural surroundings but may not be applicable in urban cities with different natural surroundings. The four urban regions selected had different type of surrounding land-covers. Hence, the present work focused on determining downscaling method that can be applicable for heterogeneous urban cities located at different climatic-zones.

## 4.2 STUDY AREA AND DATA USED

### 4.2.1 Study area

The study areas comprise of cities from four different parts of India i.e. Bikaner, Vadodara, Hyderabad and Varanasi as shown in Figure 4.1. The fcc images obtained from Landsat 8 OLI data are shown for the four cities. Bikaner lies at the north-west part of India in the middle of the Thar-Desert with center coordinates 28.01 $^0$N, 73.31 $^0$E. Hyderabad lies at the south-east part of India with center co-ordinates 17.37 $^0$N, 78.48 $^0$E. The city lies on small hills of grey and pink granite and also consists of numerous lakes. Vadodara lies in the west India with semi-arid region having center coordinates 22.30 °N, 73.19 °E. Varanasi lies in the north-part of India at the bank of river Ganges with center coordinates 25.28 $^0$N, 82.96 $^0$E. Different cities are located at different climatic-zones in India i.e. sub-tropical arid, tropical semi-arid, tropical wet & dry and humid subtropical for Bikaner, Vadodara, Hyderabad and Varanasi, respectively and consist of different neighbouring natural land-covers.

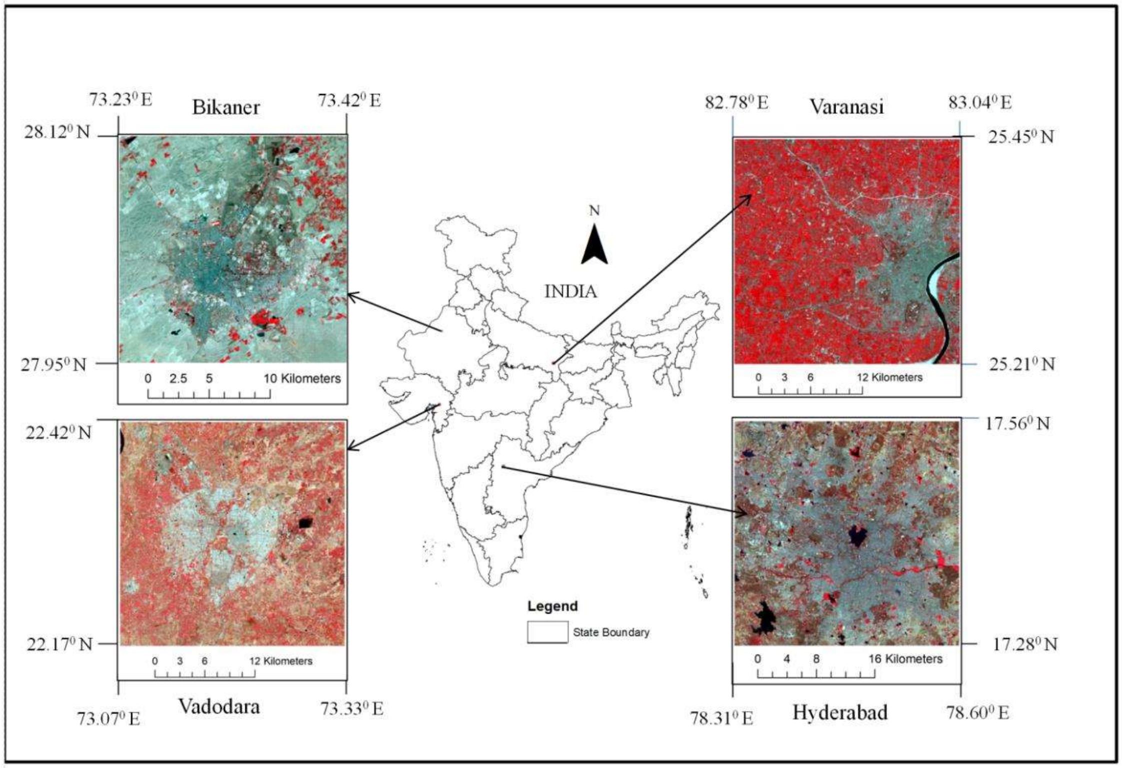


**Figure 4.1**. Location map of the study areas

The four cities were selected based on their surrounding natural land covers. The major land cover surrounding the Bikaner city is the sand/ bare soil whereas Varanasi city is surrounded mostly by vegetated land cover. The Vadodara city is surrounded by sparse vegetated or bare land and the Hyderabad city consists of various hills. The different land covers shows significant variation towards LST. Thus, the present study aims at determining the downscaling methods that can be applicable in urban areas with widely different natural surroundings.

### 4.2.2 Data used and image preprocessing

MODIS-Terra-satellite LST (MOD11A1) and surface-reflectance products (MOD09A1) were downloaded from the USGS Land-Processes-Distributed-Active-Archive-

Center website (LPDAAC) i.e. https://lpdaac.usgs.gov/ for the locations of the study. MOD09A1 product provides 8-day-composite surface-reflectance from visible and IR bands at SR of 465 m which was resampled using cubic-convolution resampling method to 500 m. MOD11A1 product provides daily per-pixel LST data at 930 m SR which was further resampled to 1000 m. The rescaling factor used to obtain MODIS-LST was 0.02. All the MODIS images were re-projected and resampled using the MODIS Reprojection Tool (MRT).

**Table 4.1.** Details about the satellite data acquired for the study

| Cities | Landsat 8 OLI data | | MODIS data (MOD11A1) | | Projection UTM WGS84 |
|---|---|---|---|---|---|
| | Date | Path/Row | Date | Tiles | |
| Hyderabad | 19/02/2017 | 144/48 | 20/02/2017 | h25v07 | Zone - 44 |
| Bikaner | 22/02/2017 | 149/41 | 21/02/2017 | h24v06 | Zone - 43 |
| Vadodara | 03/03/2017 | 148/45 | 02/03/2017 | h24v06 | Zone - 43 |
| Varanasi | 21/02/2017 | 142/42 | 22/02/2017 | h25v06 | Zone - 44 |

Landsat-Level-1 Data products and Landsat-Higher-Level data products (Collection-1-Higher-Level) were acquired from the US Geological Survey website i.e. https://earthexplorer.usgs.gov/ for the year 2017 during the day time of winter season for the four study areas with the same dates as that of MODIS data. The collection-1-higher-level Landsat data products were used to acquire the surface reflectance from visible and IR bands and thermal band data was acquired from Landsat-Level-1 data products. Landsat-Level-1 data are geometric, radiometric and terrain corrected. Landsat-Collection-1-Higher-Level data are also atmospheric corrected. Landsat-8 images has SR of 30 m for bands 1 to 7 (visible, NIR and SWIR) and 100 m for thermal bands. All the images were acquired with cloud cover less than 1 percent. Details about the satellite data acquired are shown in Table 4.1.

## 4.3 METHODOLOGY

Various methods were involved in the thermal-sharpening of CR MODIS-LST (930 m) to that of FR of Landsat-8-TIRS data (100 m). The land-cover indices from MODIS indices were computed at 500 m SR. The indices computed from Landsat-8-OLI data at 30 m SR was resampled to 100 m after aggregating to 120 m for inter-calibration process. The MODIS-LST was downscaled using the statistical-downscaling-technique and compared with the reference-Landsat-LST.

### 4.3.1 Calculation of spectral indices

Nine different SI were obtained from different combination of visible, NIR and SWIR bands of satellite data as shown in Table 4.2. Here, $\rho_n$ depicts the reflectance of $n^{th}$ band of MODIS or Landsat data respectively.

### 4.3.2 Inter-calibration of sensors

The disaggregation process requires data from two different sensors. Here, MODIS-Landsat inter-sensor calibration is required to convert the Landsat SI into its MODIS equivalent. The linear relation was developed between indices obtained from both the sensors at CR and this relation was used to determine MODIS equivalent indices at FR (Steven et al. 2003).

**Table 4.2** Equations used for calculation of the SI

| Selected Indices (SI) | Landsat 8 OLI | MODIS |
|---|---|---|
| NDVI | $\frac{\rho_5 - \rho_4}{\rho_5 + \rho_4}$ | $\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ |
| SAVI | $1.5\frac{\rho_5 - \rho_4}{\rho_5 + \rho_4 + 0.5}$ | $1.5\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1 + 0.5}$ |
| MSAVI | $0.5\left[(2\rho_5 + 1) - \sqrt{(2\rho_5 + 1)^2 - 8(\rho_5 - \rho_4)}\right]$ | $0.5\left[(2\rho_2 + 1) - \sqrt{(2\rho_2 + 1)^2 - 8(\rho_2 - \rho_1)}\right]$ |
| EVI | $2.5\frac{\rho_5 - \rho_4}{\rho_5 + 6\rho_4 - 7.5\rho_2 + 1}$ | $2.5\frac{\rho_2 - \rho_1}{\rho_2 + 6\rho_1 - 7.5\rho_3 + 1}$ |
| NDBI | $\frac{\rho_6 - \rho_5}{\rho_6 + \rho_5}$ | $\frac{\rho_6 - \rho_2}{\rho_6 + \rho_2}$ |
| UI | $\frac{\rho_7 - \rho_5}{\rho_7 + \rho_5}$ | $\frac{\rho_7 - \rho_2}{\rho_7 + \rho_2}$ |
| NDWI | $\frac{\rho_3 - \rho_5}{\rho_3 + \rho_5}$ | $\frac{\rho_4 - \rho_2}{\rho_4 + \rho_2}$ |
| NDSI | $\frac{\rho_7 - \rho_3}{\rho_7 + \rho_3}$ | $\frac{\rho_7 - \rho_4}{\rho_7 + \rho_4}$ |
| BI | $\frac{(\rho_6 + \rho_4) - (\rho_5 + \rho_2)}{(\rho_6 + \rho_4) + (\rho_5 + \rho_2)}$ | $\frac{(\rho_6 + \rho_1) - (\rho_2 + \rho_3)}{(\rho_6 + \rho_1) + (\rho_2 + \rho_3)}$ |

### 4.3.3 Statistical downscaling technique

An empirical regression based method using the correlation of LST with suitable SI was adopted for the present analysis to downscale MODIS-LST (1 km) to the SR of Landsat-8-LST (100 m). The relation of LST with each index SI*(i)* was studied using the ordinary least-square regression function at CR from satellite image. (Bonafoni 2016)

$$LST_{CR} = a_0 + a_1 \times SI_{CR}(1) + a_2 \times SI_{CR}(2) + \ldots\ldots + a_n \times SI_{CR}(n) \quad (4.1)$$

$$\Delta LST_{CR} = LST_{REF} - LST_{CR} \quad (4.2)$$

Here, $SI_{CR}$ represents the spectral index and $LST_{CR}$ represents LST at CR estimated from the satellite data. LST at FR ($LST_{FR}$) could be estimated by replacing the $SI_{CR}(i)$ with the corresponding SI at FR $SI_{FR}(i)$. However, the effects of sharp discontinuities in the image could be neglected due to the consideration of mainly average conditions in the least square regression. This spatial variation can be considered by addition of residual of LST ( $\Delta LST_{CR}$) in the FR LST image. $\Delta LST_{CR}$ is the difference of the calculated LST ($LST_{REF}$) and $LST_{CR}$ at CR shown in Equation (4.2). $LST_{REF}$ is the reference LST calculated from the selected indices and the corresponding coefficients derived from Equation (4.1). Further, the FR LST image is obtained by applying the regression model obtained from CR LST and SI images to the FR intercaliberated SI ($SI_{FR}$) shown in the Equation (4.3). The residual error is added to improve the estimation accuracy.

$$LST_{FR} = a_0 + a_1 \times SI_{FR}(1) + a_2 \times SI_{FR}(2) + \ldots .+ a_n \times SI_{FR}(n) + \Delta LST_{CR} \quad (4.3)$$

The relation of LST with one SI may be useful for one type of land cover but not for other land cover types. The urban area has greater heterogeneity due to the presence of different land cover types. Different land cover shows different reflectance property. A particular SI can represent LST variation for a specific land cover. The relation of LST with multiple SI can incorporate the contribution of radiation from different land covers in heterogeneous urban areas. Thus, the linear relation of LST with a single SI may not show good behaviour in heterogeneous urban areas. The multiple linear regression uses combination of different SI which can include the contribution from different type of land covers on LST in an urban area. Thus, multiple linear regression was considered between LST and powers of SI (i) to improve the correlation.

## 4.4 RESULTS AND DISCUSSION

### 4.4.1 Downscaling of MODIS-LST using various SI employed singly

MODIS-LST was downscaled to the SR of Landsat-LST data using the disaggregation approach with nine different SI employed singly in first as well as second order regression for Bikaner, Vadodara, Hyderabad and Varanasi, respectively. In order to analyze the performance of each SI, the downscaled-MODIS-LST image was compared with reference-Landsat-LST image to determine RMSE for each SI for different location in study. The second order regression showed better performance than the first order. Thus, the RMSE obtained from downscaling of MODIS-LST using second order regression is shown in Figure 4.2 for comparing the potential of different indices. The variation in the behaviour of SI used in the present analysis was observed for different cities. Thus, LST relation with SI depends on the kind of land-cover present.

The original MODIS LST was compared with that of Landsat LST at the same time and RMSE values were obtained to be 1.82, 1.22, 1.43 and 1.26 for Bikaner, Vadodara, Hyderabad and Varanasi, respectively. The RMSE values obtained from the downscaled MODIS LST for each SI was compared with that obtained from original MODIS LST. It was observed that the SI except SAVI, MSAVI and NDWI used in the study showed improvement in downscaling in Bikaner. All SI evaluated in this study showed improved result in Hyderabad and Vadodara whereas all SI except NDSI showed improvement in Varanasi in downscaling of the MODIS LST. However, lower RMSE values for NDBI, UI and BI reveals good downscaling results in all the four study areas (Bonafoni et al. 2016).

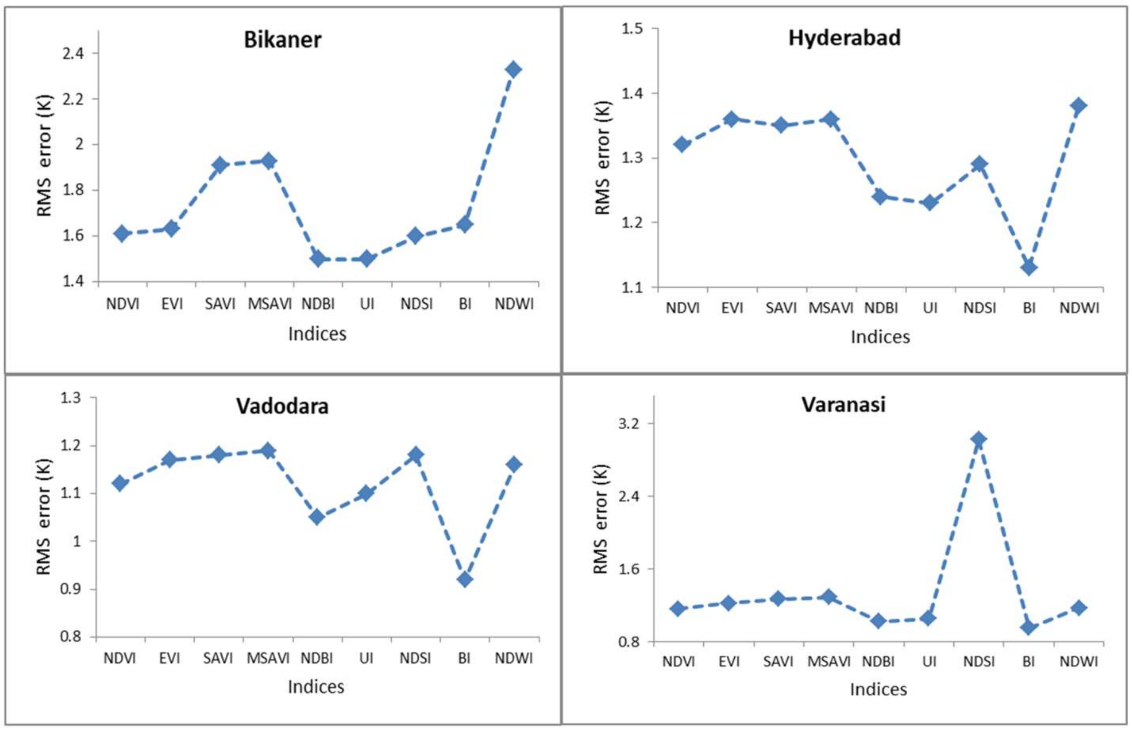


**Figure 4.2**. RMSE of LST obtained from downscaled MODIS-LST and reference-Landsat-LST for Bikaner, Vadodara, Hyderabad and Varanasi

The downscaling results of MODIS-LST obtained using single SI were compared with the reference-Landsat-LST to assess the performance of each SI in different cities. The SD of the reference-Landsat-LST image was found to be 2.97, 2.87, 2.85 and 2.47 of Bikaner, Vadodara Hyderabad and Varanasi, respectively. Hence, the RMSE values were found significantly below the SD of the reference-LST image for the four study areas except for NDSI in the Varanasi. The urban land-covers and bare-land are highly sensitive to SWIR bands. The indices NDBI, NDSI, UI and BI contain SWIR band for their determination. Thus, built-up and soil indices may explain better land-cover variation in Bikaner, Vadodara and Hyderabad as compared to other indices. This resulted in improved downscaling results for the built-up/soil indices. Varanasi constitutes of vegetation and urban region as the major land-cover. Vegetation is highly sensitive to NIR band. SWIR and NIR band were involved in the calculation of NDBI, UI and BI whereas not in case of NDSI. Hence, NDSI do not have much potential to explain land-cover variation in Varanasi resulting in a very high RMSE for downscaling of MODIS-LST. Therefore, NDBI, UI and BI have the capability to consider the land-cover variations in the four different cities under study providing improvement in the downscaling results (Ogashawara and Bestos 2012).

However, the performance of downscaled MODIS-LST was found to vary for different cities due to its dependence on relation of LST with different SI on the type of land-cover available in a region. Previous work concluded that NDBI performed better than other SI for all the seasons in mixed urban landscapes (Govil et al. 2019) whereas NDSI was found suitable for downscaling LST in arid regions (Pan et al. 2018). The LST-NDVI relation was found useful for agricultural or vegetated areas (Eswar et al. 2016; Mukherjee et al. 2014) whereas built-up or soil indices was found useful for urban areas (Chen et al. 2013; Bala et al. 2018). Therefore, the results obtained from the present analysis were found in agreement to the previous work on downscaling of MODIS-LST.

### 4.4.2 LST maps

Figure 4.3 depicts the reference-Landsat-LST map of the four study areas. The Thar Desert surrounding the urban part of Bikaner indicates higher LST than the urban part of city resulting in the formation of Urban-Heat-Sink (UHS). In Hyderabad, lower LST areas within the city depict water bodies whereas urban areas and bare regions show higher LST. The pixels having lowest LST in Vadodara were due to waterbody whereas highest LST pixels were due to bare land. The agricultural land around the city consists of sparse-vegetation which shows slightly lower LST than the urban land-cover. The presence of waterbody and densely vegetated agricultural land surrounding the cities shows lower LST than the urban areas resulting in SUHI effect.

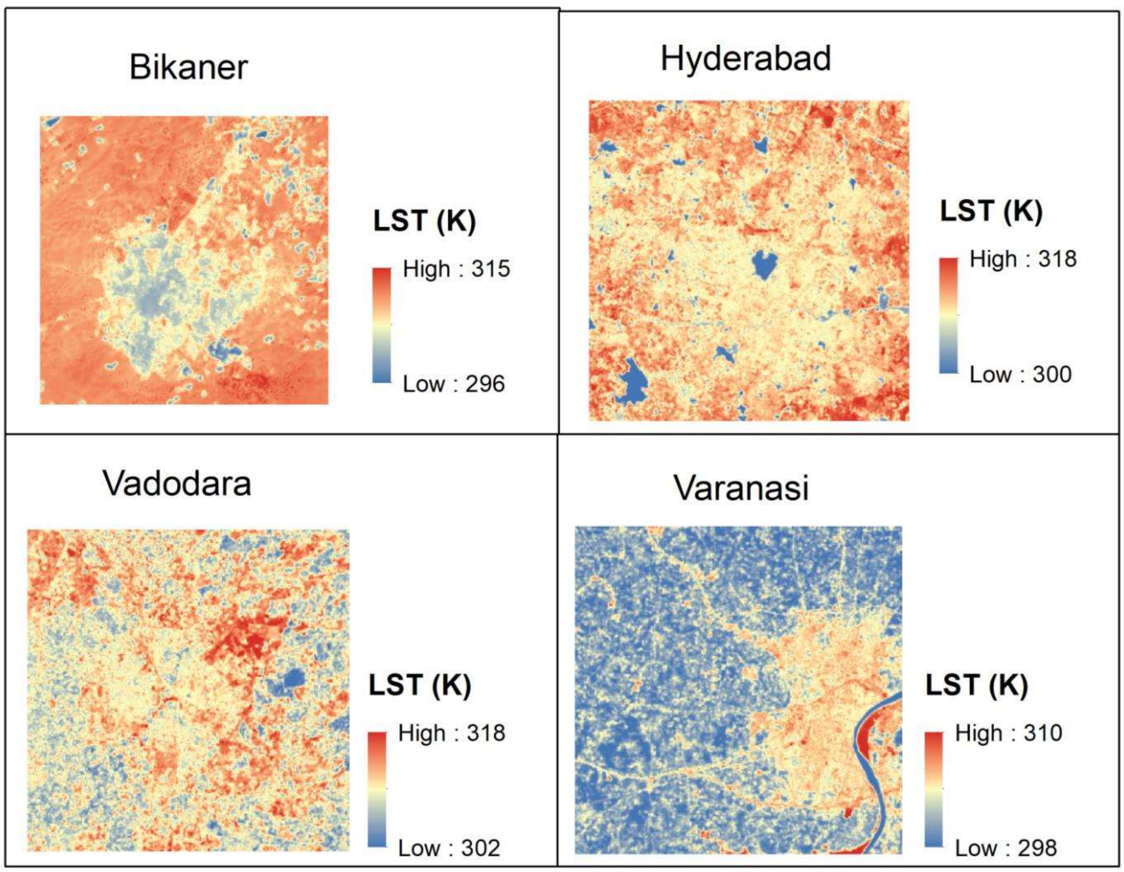


**Figure 4.3**. Landsat-LST map of Bikaner, Vadodara, Hyderabad and Varanasi

The behaviour of LST varies for different land-covers depending upon the heat-capacity of the material (Rasul et al. 2017). The amount of energy or heat required to increase or decrease the temperature of a system by 1 K is known as heat-capacity. Water bodies show the lowest LST values due to its high heat-capacity (4.2 kJ $kg^{-1}$ $K^{-1}$) and bare soil/sand or granite rocks show highest LST values due to their low heat-capacity (0.8 kJ $kg^{-1}$ $K^{-1}$). The heat-capacity values of urban built-up materials lie in the range of (0.9 to 1.7 kJ $kg^{-1}$ $K^{-1}$). The vegetated land-cover showed lower LST values due to its tendency of evapotranspiration (Rinner and Hussain 2011).

**Table 4.3** RMSE and the correlation coefficient (R) obtained from the downscaled MODIS-LST and the reference-Landsat-LST for Bikaner and Hyderabad cities. The combinations of spectral indices with best results were reported

| Bikaner | | | Hyderabad | | |
|---|---|---|---|---|---|
| Regression | RMSE (K) | R | Regression | RMSE (K) | R |
| a + b*NDVI + c*NDBI | 1.30 | 0.82 | a + b*NDVI + c*$NDVI^2$ + d*NDSI | 1.04 | 0.77 |
| **a + b*$NDVI^2$ + c*BI** | **1.27** | **0.84** | **a +b*$NDVI^2$ + c*BI** | **1.02** | **0.76** |
| a + b*NDVI + c*NDSI | 1.28 | 0.84 | a + b*NDVI + c*NDSI | 1.03 | 0.73 |
| a + b*NDVI +c*NDBI + d*NDSI | 1.28 | 0.83 | a + b*$NDVI^2$ + c*BI + d* NDSI | 1.03 | 0.75 |
| a + b*$NDVI^2$+ c*BI + d*NDSI | 1.27 | 0.82 | a + b*NDVI + c*BI | 1.03 | 0.76 |
| a + b*NDVI + c*BI + d*NDSI | 1.32 | 0.84 | a + b*NDSI + c*NDBI | 1.05 | 0.73 |

The greater heat-capacity of urban materials as compared to the desert area resulted to formation of UHS in Bikaner. Hyderabad city shows various low LST pixels due to the presence of numerous lakes within the city. The presence of hills made up of granite rocks with lower heat capacity show higher LST values as compared to that of built-ups and is non-uniformly distributed within and outside the city. The high LST pixels within the city due to the presence of hills prevented the formation of UHS in Hyderabad city. The presence of bare land as well as sparse vegetated land in Vadodara resulted to lower variation in the urban and rural land-cover. The higher LST of urban land-cover than the vegetation or water bodies resulted to SUHI formation in Varanasi.

**Table 4.4.** RMSE and the correlation coefficient (R) obtained from the downscaled MODIS-LST and the reference-Landsat-LST for Vadodara and Varanasi cities. The combinations of spectral indices with best results were reported

| Vadodara | | | Varanasi | | |
|---|---|---|---|---|---|
| Regression | RMSE (K) | R | Regression | RMSE (K) | R |
| a + b*NDVI$^2$ + c*NDBI | 0.74 | 0.82 | a + b*NDVI + c*NDVI$^2$ + d*NDBI | 0.65 | 0.91 |
| **a + b*NDVI$^2$ + c*NDSI** | **0.73** | **0.83** | a +b*NDVI + c*NDSI | 0.62 | 0.91 |
| a + b*NDVI + c*NDVI$^2$ + d*NDBI | 0.76 | 0.83 | a + b*EVI + c*NDVI$^2$ + d*NDBI | 0.67 | 0.91 |
| a + b*NDVI +c*NDBI + d*NDSI | 0.73 | 0.82 | **a + b*NDVI$^2$ + c*NDBI + d* EVI$^2$** | **0.62** | **0.92** |
| a + b*NDVI+ c*NDBI + d*UI | 0.76 | 0.83 | a + b*NDVI$^2$ + c*NDBI | 0.67 | 0.91 |
| a + b*SAVI$^2$ + UI | 0.76 | 0.82 | a + b*BI + c*MSAVI$^2$ | 0.66 | 0.91 |

**Table 4.5.** The ratio of the RMSE to the SD determined from the downscaled MODIS-LST image and the reference-Landsat-LST image for best combination. The SD for each reference-Landsat-LST was also reported

| | Bikaner | Hyderabad | Vadodara | Varanasi |
|---|---|---|---|---|
| Reference-Landsat-LST SD (K) | 2.97 | 2.87 | 2.85 | 2.47 |
| RMSE/SD | 0.43 | 0.36 | 0.26 | 0.25 |

### 4.4.3 Disaggregation of MODIS-LST using statistical downscaling technique

The different combinations of SI with different power combinations were considered in Equation (4.1) and the best of downscaling results are reported in Tables 4.3 and 4.4 for the four study areas. The best regression models were obtained by determining the RMSE values as shown in Figure 4.2 for different combination of indices. The combination of SI as $a + b*NDVI^2 + c*BI$ was found best among the regression models for downscaling of the MODIS-LST in Hyderabad and Bikaner. Further, the combination $a + b*NDVI^2 + c*NDSI$ showed best downscaling result in Vadodara and the combination $a+ b*NDVI^2 + c*NDBI + d*EVI^2$ showed best regression model for downscaling MODIS-LST in Varanasi. The regression models that exhibits improved results for downscaling of MODIS-LST were observed to vary for different cities. It is due to variation observed in the relationship between LST and the SI for the present land-cover in areas of study. The ratio of RMSE to the standard-deviation (SD) shown in Table 4.5 for the four study areas shows value quite lower than one which reveals high degree of accuracy in the downscaled MODIS image.

Figures (4.4) and (4.7) represent the original MODIS-LST, Downscaled MODIS-LST and the error in LST for Bikaner, Hyderabad, Vadodara and Varanasi, respectively. The error in LST was obtained from the difference of downscaled MODIS-LST and the reference-Landsat-LST. The downscaled MODIS-LST image was obtained from the best among the regression models for the four cities. The higher LST pixels in Bikaner showed positive error >1 whereas the urban region having mixing pixels of vegetation and bare soil showed negative error < -1. The water and its nearby pixels in Hyderabad show negative error < -1. The bare region surrounding the city showed positive error. Similarly, the lowest LST pixels of water and vegetation in Vadodara showed negative error whereas some pixels of bare land showed positive error. The water body showed positive error >1 whereas the sandy area at the bank of river Ganga showed negative error <-1. Hence, it was observed that the greater error in LST was observed in pixels with extreme (highest for bare land/sand and lowest for water bodies) LST values whereas the other land-covers showed very low or negligible error in LST. The neighbouring land-cover to these extreme LST pixels also showed larger error due to mixing of land-covers with higher LST difference in a MODIS pixel.

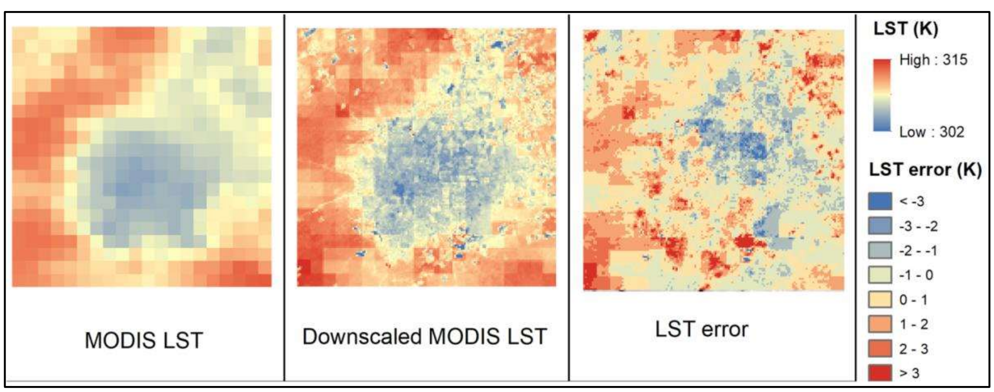


**Figure 4.4**. The original MODIS-LST, Downscaled MODIS-LST obtained using the transfer function a + b*NDVI$^2$ + c* BI and the error in LST map of Bikaner

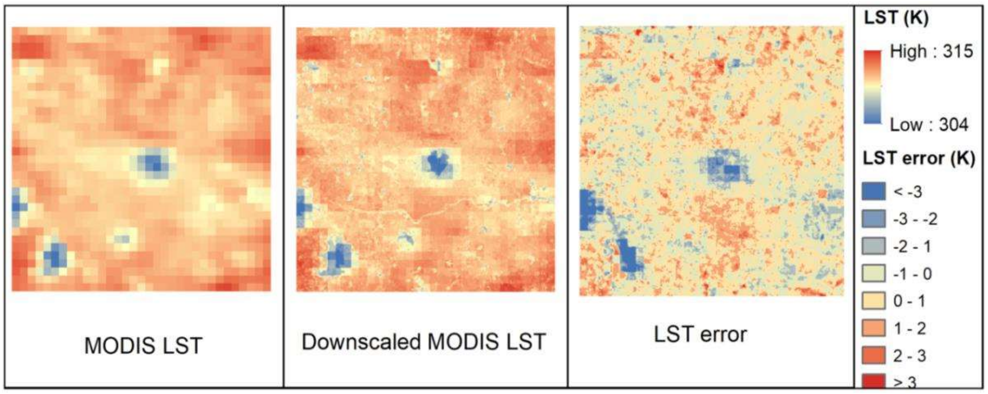


**Figure 4.5**. The original MODIS-LST, Downscaled MODIS-LST obtained using the transfer function a + b*NDVI$^2$ + c* BI and the error in LST map of Hyderabad

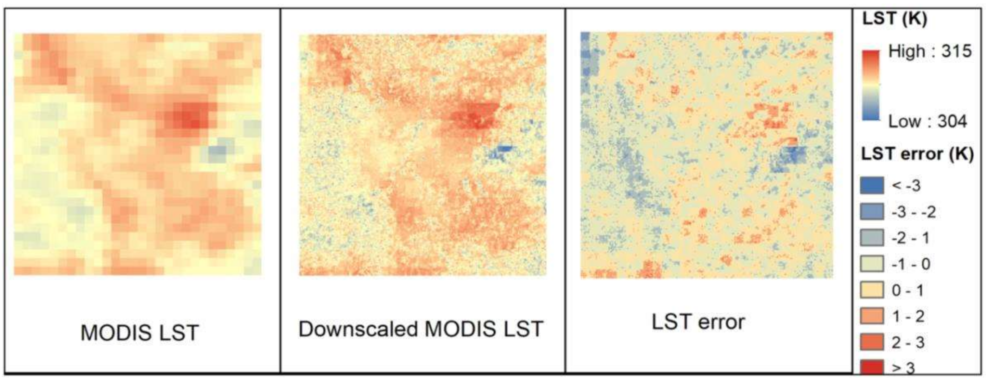


**Figure 4.6.** The original MODIS-LST, Downscaled MODIS-LST obtained using the transfer function a + b*NDVI$^2$ + c* NDSI and the error in LST map of Vadodara

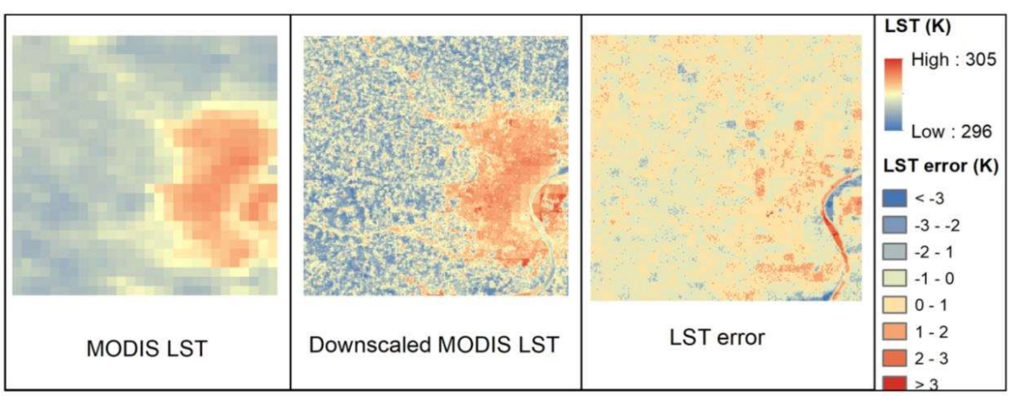


**Figure 4.7**. The original MODIS-LST, Downscaled MODIS-LST obtained using the transfer function a + b*NDVI$^2$ + c* NDBI + d*EVI$^2$ and the error in LST map of Varanasi

The downscaled MODIS LST from single SI showed best result when using NDBI with RMSE value of 1.5 K and the result obtained from multiple linear regression showed best result with RMSE of 1.27 K in Bikaner. The downscaling of MODIS LST showed best result when using BI with RMSE value of 0.92, 1.13 and 0.95 whereas multiple linear regression showed best result with RMSE of 0.73, 1.02 and 0.62 in Vadodara, Hyderabad and Varanasi, respectively. Thus, the multiple regression based thermal sharpening method was found to show improvement in the downscaling of MODIS LST in the four cities. The combination of vegetation and built-up or soil indices was found useful for the disaggregation of MODIS-LST in heterogeneous urban landscapes. The fundamental contribution was provided by built-up/soil indices as indicated by the computed RMSE and was also confirmed by the greater value of the multiplicative coefficient of built-up/soil indices. The built-up indices include contribution from the bare land and urban land-cover and vegetation-indices include contribution from the vegetated land-cover. The combination of both the indices results in improvement in the downscaling result. Wang et al. used Global Regression method for thermal sharpening using different physical and statistical approach in a city whereas here, a statistical approach has been used and compared in four different cities such that the obtained thermal sharpening approach are applicable for varied cities.

#### 4.4.4 Comparative analysis of downscaling MODIS-LST in different cities

The greater heterogeneity in land-cover was observed in Hyderabad than other cities due to the presence of waterbody, bare land as well as vegetation in the urban areas. Vadodara has mixing of bare soil and vegetation in the urban areas. So, Vadodara has lower heterogeneity in land-cover than Hyderabad. Bikaner and Varanasi have comparatively lower heterogeneity in the land-cover surroundings than other study locations. This resulted in higher correlation coefficient (R) in Varanasi and Bikaner in comparison to Hyderabad and

Vadodara. RMSE values were found lower in Varanasi and Vadodara in comparison to Hyderabad and Bikaner. The mixing of land-covers with greater difference in LST in one MODIS pixel resulted to greater error in the downscaled MODIS-LST image.

Bikaner and Hyderabad consist of greater number of pixels with extreme LST values as compared to Vadodara and Varanasi cities. The mixing of low and high LST land-covers within a MODIS pixel was observed in all the four cities. Thus, larger number of pixels was observed to show greater error in LST in Bikaner and Hyderabad as compared to other study areas. This result was also found consistent with RMSE value obtained by comparing the downscaled MODIS-LST image and the reference-Landsat-LST image for the four cities. Therefore, cities having greater number of pixels with extreme LST values and mixing of land-covers within a MODIS pixel with higher difference in LST showed error in the downscaling of LST. However, the ratio of RMSE to SD reveals higher degree of accuracy for the downscaling results in the four study areas.

The combination of vegetation and built-up/soil indices includes the major contribution from all the land-covers which resulted to better downscaling of MODIS-LST in the cities having distinct natural surroundings. Therefore, this statistical method for downscaling of MODIS-LST may be reasonably worthwhile for accurate mapping of LST image at FR on daily basis for various environmental applications.

**4.5 CONCLUSION**

The major concern of this paper is to study on the thermal-sharpening of CR LST image from MODIS (~ 930 m) to a FR of 100 m for various heterogeneous urban landscapes. The cities with different climatic-zones in India selected for this study are Bikaner, Vadodara, Hyderabad and Varanasi. The LST images generated from MODIS data were downscaled by establishing LST relation with the individual SI. Among the SI used in this study, NDBI, UI and BI showed better disaggregation results in comparison with the other indices for four study areas. Further, the statistical downscaling approach was carried out using the relation of LST with combination of the indices for disaggregation of MODIS-LST images. The combination $a + b \times NDVI^2 + c \times BI$ was observed best among the regression models to downscale MODIS-LST in Bikaner and Hyderabad cities. The combination $a + b \times NDVI^2 + c \times NDSI$ was found best to downscale LST in Vadodara whereas the combination $a + b \times NDVI^2 + c \times NDBI + d \times EVI^2$ showed best regression model to downscale MODIS-LST in Varanasi city. Hence, the best combination of indices for disaggregating LST images was found to vary for different cities indicating its dependence on the existence of the kind of land-cover in a region. The regression model used for downscaling of MODIS-LST includes both vegetation and built-up/soil indices. The fundamental contribution is provided by the built-up/soil index which can be confirmed from the larger value of the multiplicative coefficient of built-up/soil indices as compared to that of vegetation-indices.

The performance of the downscaled-MODIS-LST was evaluated by comparing it with the reference-Landsat-LST to determine the R and the RMSE values. The R values obtained were 0.84, 0.76, 0.83 and 0.92 and the corresponding RMSE values were 1.27, 1.02, 0.73 and 0.62 for Bikaner, Vadodara, Hyderabad and Varanasi, respectively. The decrease in R value was observed with increase in heterogeneity of land-cover in an urban area. This explains the lower value of R for Hyderabad having higher heterogeneity than other cities. The increase in RMSE value was observed due to the mixing of land-covers with large difference in LST in a MODIS pixel. This resulted to higher RMSE values in Bikaner and Hyderabad in comparison with Vadodara and Varanasi. The RMSE for downscaled-LST was found to show values quite lower than the SD of each reference-LST image revealing good degree of accuracy of downscaled-LST image.

The selective use of combination of both vegetation and built-up or soil indices proves to be convenient for thermal-sharpening in different urban areas. Therefore, this method can be effectively used for thermal-sharpening of LST with CR for mapping of LST at FR accurately in different heterogeneous urban areas for various applications. However, the study has been performed on four different cities and the best combinations of SI were found to vary for different cities. Further studies must be performed over different heterogeneous urban regions to obtain a broad overview of the use of SI in thermal sharpening techniques with increased accuracy.