Urban Heat Variation and Temperature Lapse Rate in the Kathmandu Valley

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ABSTRACT

The rate of urbanization growth has accelerated and made urban areas comparatively warmer than surroundings which are the main issues of urban heat worldwide. The Kathmandu Valley is one of the million plus cities with the fastest rate of urbanization and consequent extreme heat. In this study, urban heat was analyzed using both in-situ and satellite-based observation and estimated temperature lapse rate. The Mann Kendell test, Sen's slope, raster image analysis and lapse rate estimation methods were used. The results showed that average temperature difference in between urban core and surrounding was 4.07°C from 1990 to 2020. Likewise, the summer day temperature in Putalisadak was 8.8°C higher than the Nagarkot. The maximum temperature has increased in all stations where Godavari station has increased significantly (0.073°Cyr^{-1}, p<0.0001). During all seasons, the daytime temperature is higher than the nighttime temperature. The maximum 32.86°C daytime temperature was recorded on August 4, 1pm and the minimum temperature was 3.67°C on Jan 20, 6am, 2020 at the city core. Similarly, the highest temperature was recorded at 31°C in Bagbazar and 33°C in Patan on July 10 and July 11, 2022 respectively when the humidity was lower. Satellite-based observation also shows that the urban heat scenario of the Kathmandu Valley was higher in the urban core which was ranges from 21.06 to 26.09 during 2000-2020. The temperature of the city has increased. However, temperature lapse rate in response to Nagarkot (reference station) is normal i.e decreased temperature in response to increased height. The higher lapse rate is generally found in the Godavari and lower was observed in the Machhegaoun. Overall, the Kathmandu Valley is getting more warmer compared to the surroundings. This comprehensive study is useful to explore the understanding of urban heat islands and temperature lapse rate in the major cities in compared to the surroundings in Nepal.
Keywords: Urban Heat, Temperature lapse rate, Inversion, Kathmandu Valley, Nepal.

1. Introduction

The urban heat island represents warmer cities compared to the surroundings (Oke, 1982; Heisler and Brazel, 2010). The urban heat island (UHI) form of a city is composed of its construction materials, surface features including structure, size and separation, thermal characteristics, and green infrastructure zones (Singh et al., 2020). The primary urban area is located on a low-lying valley floor surrounded by higher hills (Liu et al., 2017). Because of the increased heat in urban areas, more energy consumed to cool buildings, which bolster negative effects on health and worsen the health quality (Spiru and Simona, 2017; Barton, 2009; Cardelino and Chameides, 2000; Lo and Quattrochi, 2003). Urbanization is the primary factor in the world that has a considerable detrimental environmental impact (Fenoglio et al., 2020). The natural landscape has been significantly changed around the world because of human disturbance brought on by urbanization (Zhang et al., 2020). In the United States, industries and shopping malls occupy 71-95% of the total area; the highways, streets, parks, and parking areas comprise approximately two-thirds of all impermeable surfaces (Getter and Rowe, 2006). Urban surface and earth's atmosphere exchange processes determine the characteristics of urban heat island (Voogt and Oke, 1997). The urban heat island effect was originally recognized during the industrial revolution in London in the 18th century (Howard, 1889). In the southern metropolitan region of Singapore, one of the first urban heat island research was conducted in 1964 (Nieuwolt, 1966). A city's urban heat islands (UHI) frequently change as time and space change (Kim and Brown, 2021). Urban and global climate change contributes to a rise in the severity of urban heat islands (Kim and Brown, 2021). The rise in land surface temperature (LST), particularly in

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big cities, has led to the urban heat island effect (Bokaie et al., 2016; Grover and Singh, 2015).

The temperature lapse rate is a function of altitude (Kattel et al., 2013). As a result, areas near hill slopes frequently experience lower temperatures than lowland city areas (Stone and Carlson, 1979; Pepin and Losleben, 2002). Generally, temperatures drop as altitude rise (Stone, 2008). Due to this effect, there are sizable diurnal temperature differences in free air atmosphere (Blandford et al., 2008; Harlow et al., 2004). The air cools with temperature changes to a different extent depending on humidity, which ranges from 6.5 to 10°C km^{-1} in dry air (Kattel et al., 2013; Pepin and Losleben, 2002). Many studies (e.g. Flohn, 1957; Flohn and Reiter, 1968; Kitoh, 1997; Ye et al., 1979 insisted that the Himalayas and Tibetan Plateau (HTP) largely affect the durability and potency of the temperature lapse rate (Kattel et al., 2013). The alteration of land surfaces is a significant component regulating the urban heat island effect (Lo and Quattrochi, 2003). The area and average temperature of a population center often increase as it becomes dense, populous and overwhelming pollutant (Elsayed, 2012). The impact of urban heat islands is a significant environmental issue that affects all the major cities (LI et al., 2012). The development of the UHI is the result of the city center being the hottest (Grover and Singh, 2015). In urban areas, concrete, brick, and pavement absorb heat and release it less efficiently than plants, grasses, and waterways (Solecki et al., 2005). The canyon-like shape that taller structures give off improves warming by increasing the number of sun reflections and, subsequently, the number of absorption possibilities (Chapman, 2005). Urban temperature, especially surface temperature, which governs and controls a range of ecological processes is the salient factor influencing urban climate (Blocken et al., 2007; Li et al., 2005; Pickett et al., 2001). More significantly, alterations to the composition and functioning of the urban ecological system will also effect on city people's health (Kong et al., 2014). The urban heat island (UHI) effect has also a significant impact on microclimate (Grimmond, 2007; Oke, 1982). In summer, the increased temperature raises concerns about the deterioration of the urban thermal environment and economic losses (Laaidi et al., 2012; Soto-Estrada et al., 2017; Tan et al., 2010).

Kathmandu Valley is one of South Asia's urban hubs with the fastest rate of urbanizing growth (Muzzini and Aparicio, 2013; Sarif et al., 2020). A high population influx in the valley which represents one-third of the nation's entire urban population (Muzzini and Aparicio, 2013). As urbanization increased, the temperature also increased in the Kathmandu Valley (Baniya et al., 2018). Kathmandu Metropolitan city's urban growth rate was 3.94% during 2010-2015; In the valley, the urbanized area increased from 5.1% in 1989 to 26.06 % in 2016 (Ishtiaque et al., 2017). Since 1980, there has been an increase in urban sprawl in the valley (Dixit et al., 2014). As the Kathmandu Valley is a bowl shape with a high concentration of particulate matter and gases, temperature inversion can also accelerate the higher temperature in the cities (Islam et al., 2020). The average temperature fluctuates between 3°C in the winter to 30°C in the summer on average in Nepal (Sheikh et al., 2015). UHIs change the local climate, which affects the environment (Shepherd, 2005), flora (Zhao et al., 2016), water/air quality (Grimm et al., 2008), and energy use (Santamouris et al., 2015). Thermal stress, however, brought on by exposure to intense heat in people can increase the risk of morbidity, mortality and lead to illnesses like sunstroke, dehydration, hyperthermia, and heat stroke (Patz et al., 2005). Urbanization in the Kathmandu Valley is progressing faster (CBS 2021) resulting in extreme heat and associated environmental problems (Bhandari and Zhang, 2022). Therefore, identifying urban heat variation and possible lapse rate estimation is very essential to combat these environmental problems in the valley which are not well investigated and baseline are scarce. In this context, this study has aimed and investigated urban heat variation using both observed and satellite based data and identified lapse rate in response to reference station of the valley top. The findings encourage further investigation in to urban heat extremes and lapse rate in the cities of Nepal.

2. Materials and Methods

2.1. Study Area

The Katmandu Valley is located at 27°42'14"N latitude and 85°18'32"E longitude comprises 933.73 km2 of Kathmandu, Bhaktapur and Lalitpur districts. The average elevation of the valley is 1300masl. The valley occupied 85% of the Kathmandu, entire part of the Bhaktapur and 50% of the Lalitpur district (KVEO, 2008) including all parts of three Metropolitan cities i.e Kathmandu, Bhaktapur and Lalitpur. The core of the valley is a highly populous, covered by densely built-up area and its surroundings are followed by agricultural and forests lands (Figure 1)

Kathmandu Valley accounts for 24% of the total urban population, with Kathmandu Metropolitan city alone accounting for 9.7 % (MoUD, 2017). The Kathmandu Valley experiences subtropical cool temperate weather. On average, 80% rainfall falling during the summer monsoon season has experienced in the valley (Karki, 2015). As shown in figure 2, the following meteorological stations, observed sites and automatic weather stations sites were considered (Table 1)

The automatic weather stations at the core city i.e. at Ghantaghar, Kathmandu were also observed to see a seasonal and daytime/night time temperature variation as a reference in the city. The Kathmandu Valley records up to 35.6°C maximum ambient temperature in summer. The temperature in winter ranges between 2-20°C. The average annual rainfall in the Kathmandy Valley is found to be 1400mm (Baniya et al., 2018).

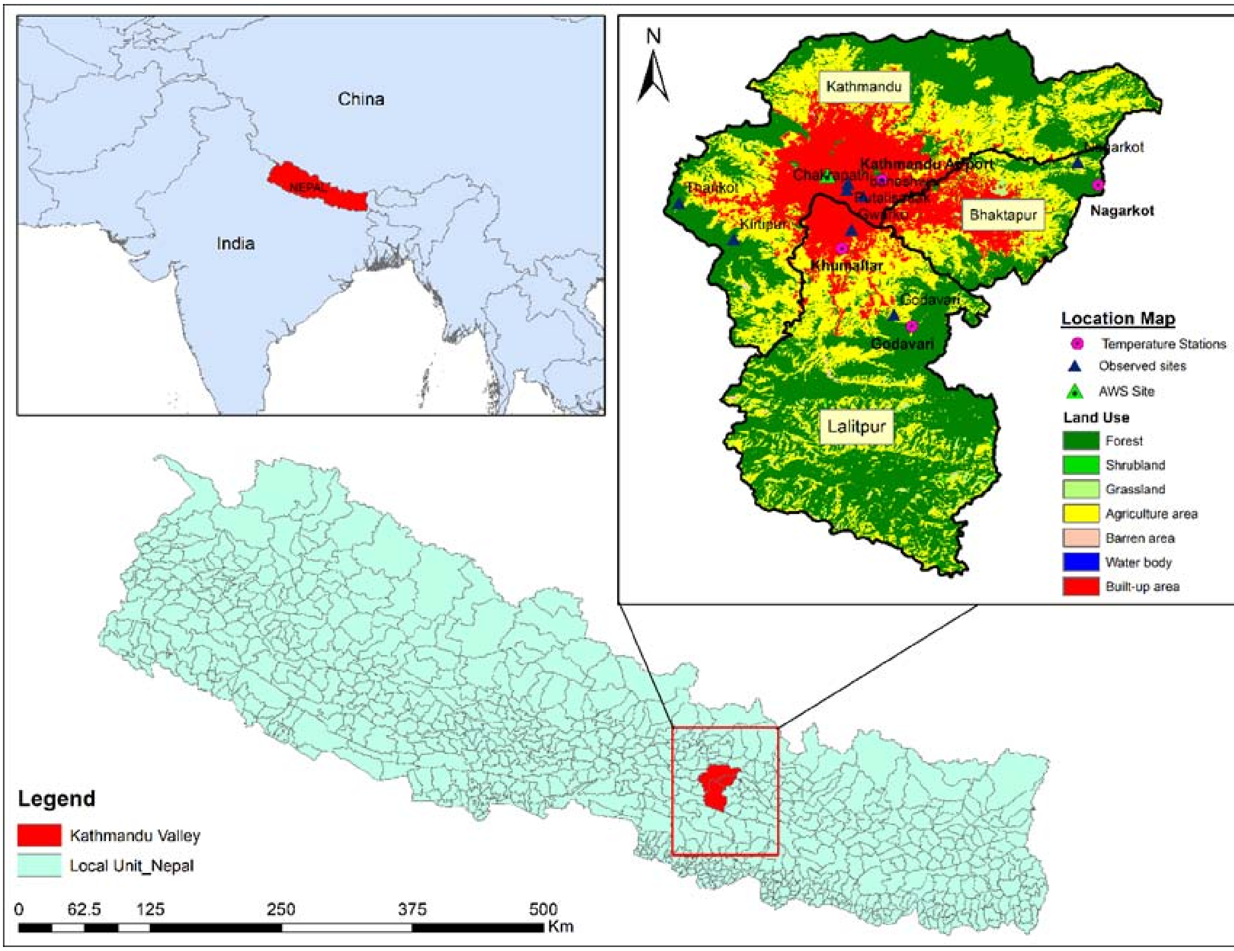

Fig. 1. Location map of the study area; top right inset map is the location of temperature stations, observed sites (urban and sub-urban) and Automatic Weather Station (AWS) site in LULC map.

Table 1. Name and location of the Meteorological stations and observed sites in urban and surrounding areas of the Kathmandu Valley.

A. Name and location of the Meteorological stations				
Name of Stations	Latitude	Longitude	Altitude (m)	Remarks
Kathmandu Airport	27.70	85.35	1337	Urban
Godavari	27.59	85.37	1527	Surrounding
Khumaltar	27.65	85.32	1334	Urban
Nagarkot	27.7	85.52	2163	Surrounding
B. Name and location of the observed sites				
Kirtipur	27.65	85.24	1511	Surrounding
Thankot	27.68	85.20	1337	Surrounding
Godavari	27.60	85.36	1515	Surrounding
Nagarkot	27.71	85.50	2195	Surrounding
Maharajgunj	27.69	85.32	1314	Urban
Gwarko	27.66	85.33	1300	Urban
Putalisadak	27.70	85.33	1276	Urban
Baneshwor	27.69	85.34	1316	Urban

2.2. Data

The average daily maximum and minimum temperature of the meteorological stations during 1990-2020 were collected from the Department of Hydrology and Meteorology, Nepal. The real-time temperature during the summer days of an hourly interval was measured using a temperature data logger on an urban core and surrounding using a transect. For 2020, the temperature recorded from the automatic weather station at Ghantaghar, Kathmandu was also collected as the reference. For the lapse rate, the temperature and altitude were measured in the several locations (8 sites) of the valleys. The Nagarkot was considered as the reference base station. Land Surface Temperature (LST) data, daily L3 global 1km Aqua Prod 1D/DAAC and MYD11A1 data sets during 2000-2020 were downloaded from https://modis.gsfc.nasa.gov/data. The daily LST was converted in to monthly and annual and calculated UHI using mean and standard deviation relationships. Then, the UHI of the Kathmandu Valley was clipped using the ArcGIS tool. The auxiliary data of the GIS layer file from the Department of Survey and LULC, 2010 from the ICIMOD were taken.

2.3. Methods

2.3.1. Mann Kendall Test and Sen's Slope

Meteorological stations located at the Kathmandu Valley for temperature records were selected and used to find the air temperature trends. For the trends, the Mann-Kendall trend test (Mann 1945, Kendall 1975) and Sen's (Sen, 1968) slope estimation method were used to detect the trend and determine the significance. For the Mann Kendell test, the univariate MK statistic for a time series zk, k = 1, 2. . . n of data is defined as

$$S = \sum_{j<i} \operatorname{sgn}\left(Z_i - Z_j\right) \tag{1}$$

where, Z_i andZ_j are the annual values in the year i and j, i>j respectively

$$\operatorname{sgn}\left(Z_i - Z_j\right) = \begin{cases} 1, & \text{if } Z_i - Z_j > 1, \\ 0, & \text{if } Z_i - Z_j = 0, \\ -1, & \text{if } Z_i - Z_j < 0. \end{cases} \tag{2}$$

To test either an upward or downward monotone trend at level of significance, H_0 (no trend) is rejected if the absolute value of Z is greater than $Z_(1-\alpha)$, where $Z_(1-\alpha)$ is obtained from the standard normal cumulative distribution tables. According to Sen's slope, the true slope (change per unit time) can be estimated by using a simple nonparametric procedure developed by Sen (1968).

$$\text{Sen's slope} = \text{Median}\left(\frac{X_i - X_j}{i-j}\right), i > j \tag{3}$$

where, X_i and X_j are the air surface temperature values at the time i and j respectively (i>j). The median is the median function. The negative value of Sen's slope indicates a negative trend and the positive value indicate positive trend. The presence of a statistical significance of the trend will be evaluated using a significant level of 0.05

2.3.2. Estimation of UHI from MODIS LST

The daily satellite-based MODIS LST data sets during 2000-2020 were downloaded and batch processed in ArcGIS software. The daily data was converted into monthly and annual data through raster processing. Then, the following equation was applied to convert LST in to UHI and clipped for the Kathmandu valley.

$$UHI = \frac{T_s - T_m}{SD} \tag{4}$$

where, UHI is urban heat islands; T_s is the land surface temperature; T_m is the mean of the land surface temperature and SD represents the standard deviation of the LST. The grater than zero (positive) value indicates presence of UHI and negative value indicates non UHI condition.

2.3.3. Temperature Lapse Rate

The temperature was measured at an altitude of the different locations and calculated lapse rate using a relationship between temperature response to height. The following equations were used to calculate lapse rate.

$$T_{O_s} = T_{R_s} + (h_{O_s} - h_{R_s}) \cdot \lambda \tag{5}$$

where T_{Rs} represent the temperature of the reference station, T_{Os} represent the temperature of the observed station, h is the height and λ is the temperature lapse rate which can be further calculated as follows

$$TLROs(\lambda) = \frac{T_{Rs} - T_{Os}}{h_2 - h_1} \tag{6}$$

where, h_2 is the height of the reference station and h_1 is the height of the observed station. In this study, Nagarkot was taken as the reference station because of higher altitude and lower temperature records. The city-based stations were taken as the observed stations. The average temperature of the stations was measured to identify lapse rate using a temperature data logger. The seasonal, annual and daily temperatures including day/night temperature variations of automatic weather station data were calculated using an Excel analysis sheet.

3. Results

3.1. Temperature Trends and Variation in The Valley

The maximum temperature difference in the urban and sub-urban areas of the Kathmandu Valley was found to be

TABLE 2. Mann Kendell test and Sen's Slope of an average maximum temperature and temperature difference between urban core and sub-urban during 1990-2020.

S.N.	Stations	Average and Mean Max Temperature (°C) (1990-2020)		MK Trend Test and Sen's Slope				Urban and Sub-urban Different Temperature (°C)
		Ave. Max. Tem($^\circ C$)	Mean Tem($^\circ C$)	Kendall's tau	Sen's Slope	p-value	Remarks	
1	Kathmandu Airport	27.406	25.986	0.292	0.026	0.082	Insignificant	
2	Khumaltar	25.796	24.832	0.159	0.015	0.225	Insignificant	4.07°C
3	Godawari	24.335	22.887	0.563	0.073	<0.0001	Significant	
4	Nagarkot	20.729	19.992	0.076	0.003	0.637	Insignificant	

4.07°C during 1990-2020. The mean and average maximum temperature were higher in the Kathmandu airport i.e 25.9°C and 27.4°C respectively in compared to other stations during the last three decades. The maximum temperature has increased in all stations where Godavari station has increased significantly by 0.073°C yr^{-1} ($p<0.0001$). The other stations have also found increased annual average surface temperature; however, it is insignificant in trends (Table 2). The positive annual maximum trends and urban-sub-urban temperature difference show that the valley is getting hotter compared to the surrounding i.e urban heat island has increased.

Real-time temperature observation during summer days also shows that the city core has a higher temperature than the surrounding. The city core of Putalisadak, Gwarko and Baneshwor shows the maximum day time summer temperature of 31.694°C, 30.82°C and 30.82°C, respectively. The lowest temperature was recorded at Nagarkot and Machhegau which is followed by Thankot and Godavari (Figure2)

In compared to the surroundings, the urban core has more temperature in both air surface and land surface temperature observation which shows a higher urban heat in the Kathmandu valley. The station records that the average maximum temperature of the urban core is 27.4°C at the Kathmandu airport. However, the direct measured maximum temperature in the urban core is 31.69°C in the Putalisadk. The temperature difference in urban and sub-urban area is higher during both observations. Figure 2 shows that day time temperature difference during summer in Putalisadak and Nagarkot is found to be 8.8°C.

3.2. Day/Night Temperature and Lapse Rate in Kathmandu Valley

The average annual day and nighttime temperature was 21.04°C and 16.52°C, respectively during 2020. This shows that the daytime temperature was warmer than the nighttime temperatures. The annual average temperature peaked in the summer months of June, July, August, and September. On the other contrary, January, December, February showed a minimum temperature trend. During the summer, daytime maximum temperature was 25.4°C and nighttime temperature was found 22.3°C which are followed by temperature records during the Fall and Spring season. Likewise, the daytime winter temperature was 14.1°C which was 9.2°C during nighttime in 2020 (Figure 3).

Figure 3 shows that daytime urban heat is higher than nighttime urban heat in the city core of the Kathmandu Valley. The maximum daytime temperature 32.86°C was recorded on August 4, 1pm and the minimum temperature 3.67°C was observed during Jan 20, 6am 2020. The temperature variations are also affected by the humidity. During nighttime, the humidity seems higher which alter the temperature variation and vice versa (Figure 4). In figure 4, the blue line represents temperature (°C) and green line represent humidity percentage.

Figure 4 shows that, the temperature is higher in the days and lower in the night in both observed site at the Bagbazar and Patan during July 10 and 11, 2022. The relationship between temperature and humidity found reverse when the humidity increased temperature decreased. The highest 31°C temperature was recorded in Bagbazar and 33°C in Patan when the humidity found lower. As Kathmandu is a bowl-shaped topography and is highly urbanized, temperature inversion (i.e. increased temperature with increased height) also played a role to increase surface and boundary layer temperature. The temperature lapse rate in observed stations at the city in reference to Nagarkot (base station) is found normal i.e decreased temperature in response to height increased which indicate that the valley has no temperature inversion at that time. The higher lapse rate of -12°C/km was found in the Godavari and the lowest lapse rate of -2.74°C/km was found in the Machhegau (Table 3). The elevation and temperature reference are taken from Nagarkot station (TRs)

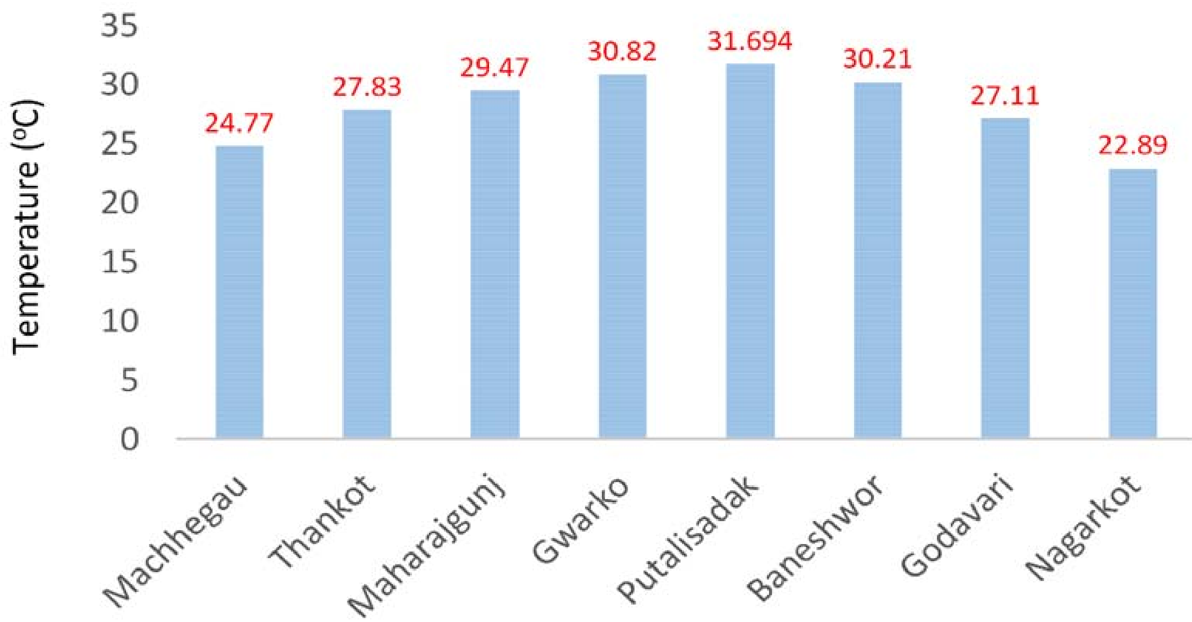

FIG. 2. Average summer days temperature in the core city and surrounding obtained from data logger during August, 2021.

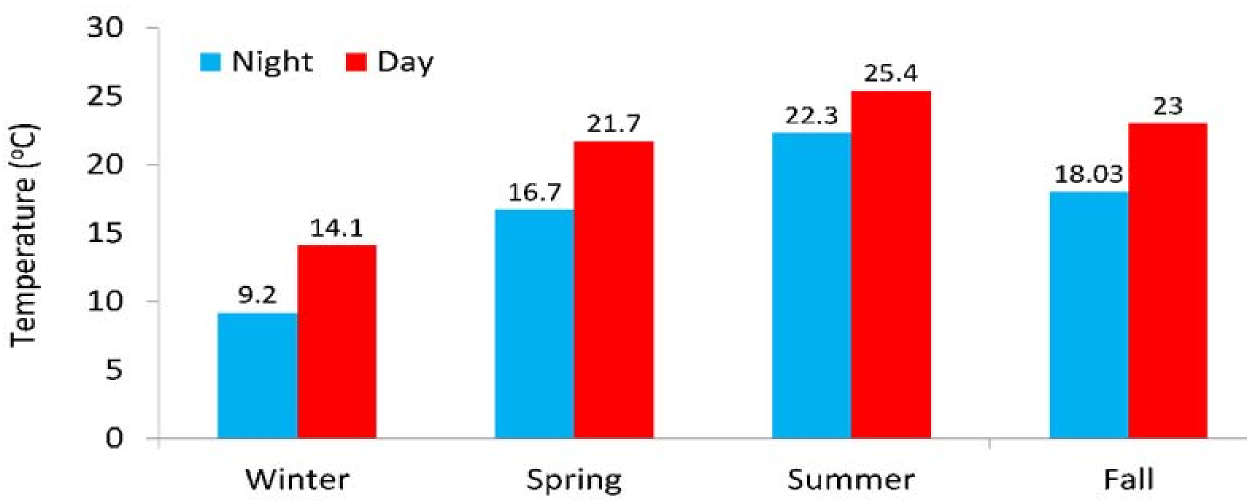

FIG. 3. Average seasonal daytime and nighttime temperature (°C) difference in Ghantaghar, Kathmandu during 2020.

TABLE 3. Temperature lapse rate (λ) of the observed stations (TO_s) in response to reference station (TR_s: Nagarkot) in the Kathmandu Valley

Station	Elevation	TO_s	TR_s	Elevation Baseline	h (h_2-h_1)	Lapse Rate (λ)/km
Maharajgunj	1334	31.346	22.89	2195	861	-9.8°C/km
Baneshwor	1310	30.21	22.89	2195	885	-8.2°C/km
Putalisadak	1276	31.694	22.89	2195	919	-9.5°C/km
Thankot	1481	28.83	22.89	2195	714	-8.31°C/km
Gwarko	1300	31.55	22.89	2195	895	-9.67°C/km
Godawari	1521	27.11	22.89	2195	674	-12°C/km
Machhegau	1511	24.77	22.89	2195	684	-2.74°C/km

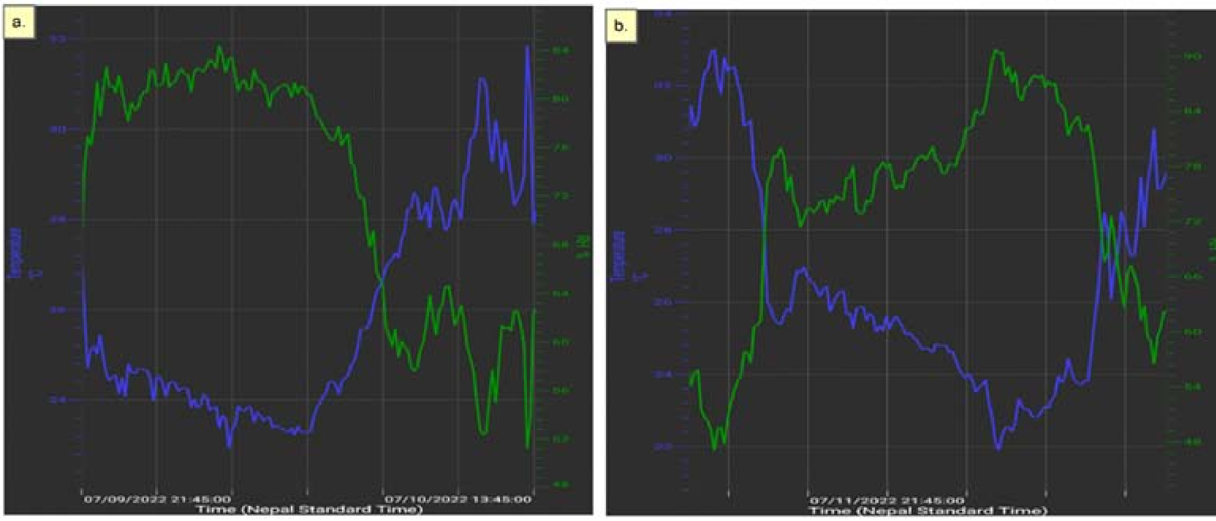

Fig. 4. 24 hrs day and nighttime temperature variation; a) temperature variation in Bagbazar, Kathmandu and b) temperature variation in the Krisna Mandir, Patan.

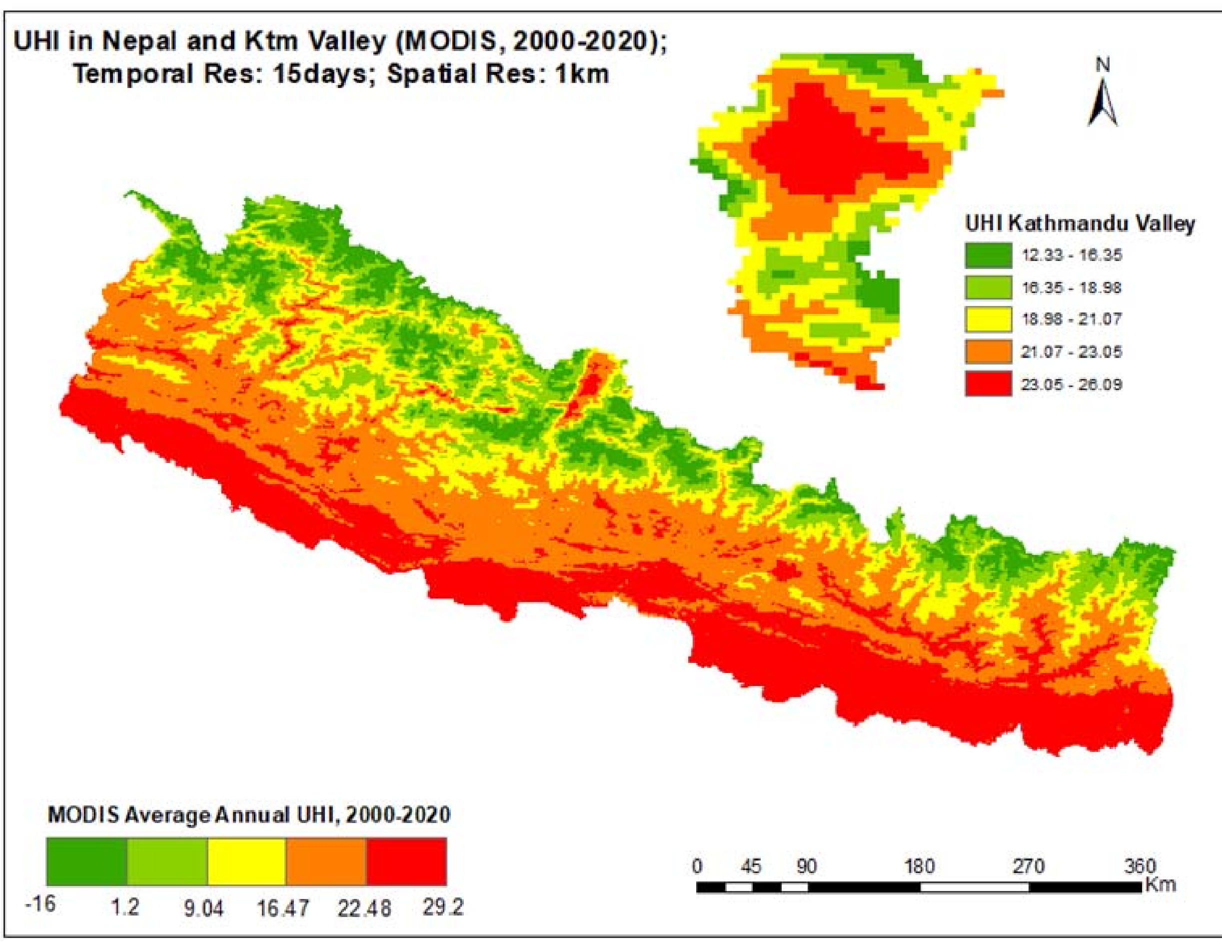

Fig. 5. Temporal average spatial variation of UHI in Kathmandu Valley based on MODIS LST data during 2000-2020.

3.3. Satellite-Based UHI in Kathmandu Valley

Satellite based observation also shows that urban heat scenario of the Kathmanu Valley was higher in the urban core area where the maximum UHI found 26.09. Based on UHI threshold algorithm of equation IV, greater than zero (positive) value indicates presence of UHI in the valley. The urban heat island ranges from 21.06 to 26.09 in most of the core city covered by built-up areas followed in the agricultural lands. The minimum urban heat goes down to 12.33 in the forest area of the valley (Figure 5). During the last 2 decades, satellite records also alarmed and accelerating urban heat bell in the core area of the Kathmandu Valley as shown in the Figure 5.

Figure 5 shows that the inner-city zones of the Kathmandu Valley have higher UHI values than the outer surroundings. The entire valley presents positive UHI during this study time periods where a higher UHI (>23.05) were observed in the core city due to the presence of dense settlements, urban canyons, development activities, concrete and cemented surface and less greening lands. As described above, the higher and increased temperature trends in the city are the fundamental base to increase UHI in the Valley.

4. Discussion

4.1. Urban heat variation in the Kathmandu valley

This study examined temperature variations, UHI and lapse rate which are the fundamental base parameters of the urban heat extreme and environmental problems. The temperature difference between the urban core and surroundings are found approximately 4.07°C which indicates that the urban core has more heat than surrounding. Likewise, direct observation in city cores and surrounding stations shows that Putalisadak is one of the urban cores that has 8.8°C higher temperature than the Nagarkot. Almost all the surrounding stations have lower summer daytime temperature than the urban core regions. In this study, urban areas considered Maharajgunj, Gwarko, Putalisadak and Bagbazar and surroundings areas are Machhegau, Thankot, Godavari and Nagarkot. Both of the station based and real time monitoring shows core city has higher temperature than surrounding which are the fundamental cause for the urban heat island in the Kathmandu Valley. The station records the average maximum temperature of the urban core is 27.4°C at the Kathmandu airport, however, direct measured maximum temperature in the urban core is 31.69°C in Putalisadk and lower temperature was observed in Nagarkot of 22.89°C followed by the Machhegaun by 24.77°C. Similar kind of urban-rural temperature differences were observed in the many cities globally (Kolokotroni et al., 2012; Nieuwolt, 1966). The stations data also showed that average annual maximum temperature of the Kathmandu Valley has increasing in trends during 1990-2020. The maximum temperature has increased in all stations in which the temperature has increased significantly in the Godavari station (0.073°Cyr^{-1},p<0.0001). The rest of the other stations have also found positive annual average surface temperature but insignificant in trends. Previous studies also shows that the Kathmandu Valley has experienced increased temperature (Baniya et al., 2018). The warming trend is high in the inner core of the Kathmandu valley which ranges from 0.5 to 0.8°C yr^{-1} during 1976-2006 (DHM, 2015).

The maximum daytime temperature of 32.86°C was recorded on August 4, 1pm and the minimum temperature was 3.67°C during Jan 20, 6am, 2020 in the core of the Kathmandu. The urban heat island in the valley has increased because of high population growth and increased built-up areas (Timsina et al., 2020). The population of the valley is projected to reach 3.79 million in 2020 and 6.24 million by 2030 (KVDA, 2016). Kathmandu Valley's urban area was expanded up to 412% in last three decades and the most of this expansion occurred with the conversions of 31% agricultural land (Ishtiaque et al., 2017). During 1999-2009, the Kathmandu Valley saw 117% growth in built-up areas, the built-up area increased approximately 8% during 2009-2016 (KVDA, 2016), The total built-up area in the Kathmandu Valley was 26.06% during 2016 which was 5.10% in 1989, 11.15% in 1999 and 24.16% in 2009 and it is increasing in trends (Ishtiaque et al., 2017). These urban growth and activities are the main cause of increasing urban heat in the valley (Elsayed, 2012). Satellite-based MODIS data also showed that Kathmandu valley mainly in the core city is an urban hub for trapping heat where the maximum UHI found 26.09. The urban heat island ranges from 21.06 to 26.09 in the city center. The spatial and temporal distribution of UHI is determined based on the LST threshold in which positive values indicates presence of UHI and negative value absence UHI (Labib et al., 2022). Landsat images also showed higher LST ranges from 15.84°C to 39.17°C in 2000 and 16 to 33.98°C in 2014. In built up area, the highest mean temperature was 28.63°C in 2000 and 28.08°C in 2014 (Thapa, 2017). Our results and previous findings are corroborated and shows the Kathmandu Valley is one of the rising urban hubs and accelerating urban heat extreme in Nepal.

4.2. Temperature lapse rate and day/night temperature variation

This investigation shows that daytime temperature was warmer than nighttime temperatures in the valley. During the summer, daytime maximum temperature was 25.4°C and nighttime maximum temperature was found to be 22.3°C. These results are also supported by 24 hours real time monitoring of temperature at Bagbazar and Patan Krishna Mandir, where the daytime temperature found higher in compared to the nighttime temperature when the humidity has revers in trends as shown in figure 4. The highest temperature was recorded 31°C in Bagbazar and 33°C in Patan when less than 60% humidity were observed. The urban heat tends to be more intense during the day under the incidence of sunlight and pollution emissions in compared to night (Amorim et al., 2021). The urban temperature variation is also depending on the lapse rate fluctuation and temperature inversion phenomena in the cities (Rendón et al., 2014). The rate of temperature lapse is a function of altitude (Kattel et al., 2013) and urban emissions (Rendón et al., 2014). The high altitudinal areas near foothills and hill slopes frequently experience lower temperatures than the cities (Pepin and Losleben, 2002). In this investigation based on Nagarkot base stations, the observed stations showed natural lapse rate i.e. decreased temperature in response to height increased. The magnitude of the normal lapse rate is not found steepest i.e. rapid decrease in temperature in response to height increased in all the observed stations (Table 3). The higher lapse rate of -12°C/km was found in the Godavari and the lowest lapse rate of -2.74°C/km was found in the Machhegau. This natural lapse rate shows that the Kathmandu city was not experienced temperature inversion at least in that study time period of 2021. The magnitude of temperature lapse rate are affected by latitude, surface characteristics, elevation, moisture content, wind speed, cloudiness, distance from the sea, slope, aspect and the effects on solar insolation (Stone and Carlson, 1979).

5. Conclusion

This study has carefully examined the urban heat scenario in the Kathmandu Valley compared to surrounding and determined the temperature lapse rate. In-situ observed, real time monitoring and satellite based urban heat variation were analyzed. The result shows that the average annual temperature has increased in all the stations of the valley in which the temperature in Godavari has significantly increased at the rate of 0.073 yr^{-1} during 1990-2020. The urban and sub-urban temperature differences were found to be 4.07°C. During summer days, the highest urban core temperature was found to be 31.694°C followed by Gwarko at 30.82°C and Baneshowor at 30.21°C. In contrast, sub urban areas like Machhagaun, Thankot, Godavari and Nagarkot have observed a lower temperature. The daytime temperature was higher in all the season compared to nighttime temperature in the core area of the Kathmandu Valley. The temperature lapse rate in the observed stations at the city in response to Nagarkot (base station) is normal i.e decreased in response to height increased. The higher lapse rate of -12°C/km was found in Godavari and lowest lapse rate of -2.74°C/km was found in the Machhegau. Satellite based observation also shows urban core is getting hotter where the urban heat island ranges from 21.06 to 26.09 in built-up areas of the valley. The higher temperature scenario indicates that the core city is getting more warmer which is the fundamental base of formation urban heat island and possible inversion in the Kathmandu valley.

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