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Impact of urbanization and land-use/land-cover change on diurnal temperature range: A case study of tropical urban airshed of India using remote sensing data

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HIGHLIGHTS

- Significant converging trend of DTR observed across Delhi during 2001-2011
- Annually averaged DTR of entire Delhi reduced from 12.48 °C to 10.34 °C
- Converging trend of DTR infers a net increase in the heat-related mortality rates
- DTR of urban areas was below 11 °C while that of rural areas was above 13 °C

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ABSTRACT

Diurnal temperature range (DTR) is an important climate change index. Its knowledge is important to a range of issues and themes in earth sciences central to urban climatology and human–environment interactions. The present study investigates the effect of urbanization on the land surface temperature (LST) based DTR. This study presents spatial and temporal variations of satellite based estimates of annually averaged DTR over megacity Delhi, the capital of India, which are shown for a period of 11 years during 2001–2011 and analyzes this with regard to its land-use/land-cover (LU/LC) changes and population growth. Delhi which witnessed massive urbanization in terms of population growth (decadal growth rate of Delhi during 2001–2011 was 20.96%) and major transformations in the LU/LC (built-up area crossed more than 53%) are experiencing severity in its micro and macroclimate. There was a consistent increase in the areas experiencing DTR below 11 °C which typically resembled the 'urban class' viz. from 26.4% in the year 2001 to 65.3% in the year 2011 and subsequently the DTR of entire Delhi which was 12.48 °C in the year 2001 gradually reduced to 10.34 °C in the year 2011, exhibiting a significant decreasing trend. Rapidly urbanizing areas like Rohini, Dwarka, Vasant Kunj, Kaushambi, Khanjhawala Village, IIT, Safdarjung Airport, etc. registered a significant decreasing trend in the DTR. In the background of the converging DTR, which was primarily due to the increase in the minimum temperatures, a grim situation in terms of potentially net increase in the heat-related mortality rate especially for the young children below 15 years of age is envisaged for Delhi. Considering the earlier findings that the level of risk of death remained the highest and longest for Delhi, in comparison to megacities like Sao Paulo and London, the study calls for strong and urgent heat island mitigation measures.

1. Introduction

With the onset of urbanization there has been a substantial change in the entire urban fabric which has resulted into many environmental changes such as narrower diurnal temperature range or DTR (Runnalls and Oke, 2000). DTR is an important index of climate change (Karl et al., 1984) and is susceptible to urban effects (Intergovernmental Panel on Climate Change, 2001). It is also affected by land use changes (Kalnay and Cai, 2003), vegetation (Collatz et al., 2000), soil moisture, clouds (Dai et al., 1999; Trenberth, 2003; Stone and Weaver, 2003), aerosols (Huang et al., 2006; Stenchikov and Robock, 1995) and solar radiation (Wild, 2009; Makowski et al., 2008). Urbanization has increased the concentration of the tropospheric aerosols that has influenced the local climate and also played an important role in decreasing the DTR. This happens because of the well known 'urban heat island effect' which prominently takes place at night when buildings and streets release the solar heat absorbed during the day and lower sky-view factor trapping that heat within the urban canopies thereby increasing the

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Table 1
Details of the locations across Delhi selected for investigation.

No.	Station name	Station code	Latitude	Longitude	Type of urban canopy/land-use land-cover
1.	Sitaram Bazar*	SB	28.648	77.228	Dense canopy
2.	Adarsh Nagar*	AN	28.718	77.175	Medium dense urban canopy — I
3.	Rohini*	RN	28.720	77.083	
4.	Parmanand Hospital*	P Hos	28.710	77.207	
5.	Kaushambi*	K	28.643	77.320	
6.	Connaught Place*	CP	28.635	77.220	
7.	Janakpuri*	JP	28.633	77.096	
8.	Dwarka*	Dwarka	28.591	77.057	
9.	Bhikaji Cama*	BC	28.568	77.189	
10.	Lajpat Nagar*	LN	28.562	77.237	
11.	Neb Sarai*	NS	28.512	77.202	Medium dense urban canopy — II
12.	Inter-State Bus Terminus	ISBT	28.669	77.230	
13.	New Moti Nagar*	NMN	28.662	77.141	
14.	Red Fort	RF	28.656	77.241	
15.	Parliament House	PH	28.617	77.208	
16.	Safdarjung Airport	SAF	28.584	77.206	
17.	Yusuf Sarai*	YS	28.563	77.207	
18.	Okhla Extension Terminal	OET	28.547	77.307	
19.	Chirag Delhi*	CD	28.540	77.229	
20.	Vasant Kunj*	VK	28.517	77.160	
21.	Kauturi Ram College	KRC	28.840	77.093	Less dense urban canopy
22.	Bhavan Industrial Area	BIA	28.788	77.059	
23.	Indian Institute of Technology*	IIT	28.547	77.191	
24.	NTPC Badarpur*	NTPC	28.520	77.295	
25.	Asola Wild-life Sanctuary	AWS	28.448	77.234	Medium dense forest
26.	Buddha Jayanti Park*	BP	28.616	77.179	
27.	Sanjay Van*	SV	28.534	77.188	
28.	Raj Ghat	RG	28.641	77.248	Park and garden
29.	Lodi Garden	LG	28.592	77.219	
30.	District Park*	DP	28.557	77.190	
31.	Kanjhawala Village	KV	28.734	77.006	Urban outskirts (resembling rural areas)
32.	Mundhela Kalan	MK	28.612	76.895	
33.	Ghumanhera Village	GV	28.532	76.926	
34.	Jawaharlal Nehru University*	JNU	28.550	77.165	Open area
35.	Najafgarh Jheel	NJ	28.508	76.942	Riverside area
36.	Majnu Ka Tila*	MKT	28.697	77.228	

(* stations which were earlier considered in the field campaigns conducted by Mohan et al. in the year 2008 and 2010) (Mohan et al., 2012, 2013).

night-time temperatures. The slight cooling which happens in the day-time owing to the shading effect, presence of aerosols etc. further helps in inducing lower values of DTR. As more and more areas across the world are getting urbanized, a downward trend of the global and local DTR has been observed (Kalnay and Cai, 2003; Jones et al., 1999; Easterling et al., 1997; Vose et al., 2005; Wang et al., 2012; Sun et al., 2006).

Till recently, most of the information on DTR came from station observations of surface air temperature or from numerical model simulations. Station observations are sparse, unevenly distributed and suffer from differences in elevation, time of observation and nonstandard siting (Peterson, 2003). Thus it is of larger interest to use satellite for evaluating DTR because of their ability to provide consistent and full spatial coverage for large areas over a period of time (Gallo and Owen, 1999). It is in this background, the present study of assessing the changing DTR over megacity Delhi using remote sensing data has been undertaken as it has witnessed an exponential rate of urbanization with major transformations in the land use/land cover (Mohan et al., 2011a). The current study supersedes the previous temperature studies (eg. Mohan et al., 2011b, 2014; Kumar and Hingane, 1988; Kumar et al., 1994) done over Delhi with the surface air temperature data of few locations and presents a comprehensive analysis of the spatio-temporal variation of the DTR across Delhi having deeper implications in evolving measures for improving the local urban climate thereby reducing the heat-related mortality rates.

2. Study area

The present study has been carried out on Delhi, the capital city of India located between the 28°24′17″N and 28°53′00″N latitudes and 76°48′30″E and 77°21′30″E longitudes. Delhi which is situated near the western bank of river Yamuna spreads over an area of around 1490 km^2. It is surrounded by the Himalayas in the North and the Aravali ranges in South-West. Delhi has typical tropical climate. Summers are extremely hot with temperatures reaching up to 45 °C, while winters are extremely cold with temperatures dipping down to 2 °C or even less in extreme cases. Average annual rainfall over Delhi is about 61 cm, most of which occurs during the monsoon months of July to September (Pandey et al., 2012). Delhi is one of the many megacities of the world struggling with rapid urbanization and gigantic levels of pollution from industrial, residential and transportation sources (Mohan et al., 2007). It has witnessed an accelerated rate of urbanization which is evident from the increasing population viz. 9.42 million in 1991, 13.78 million in 2001 and 16.75 million in 2011 (Delhi Statistical Hand Book, 2009; Census of India, 2011). The rapidly increasing population has significantly altered land use pattern and as on year 2008, the share of built-up area in Delhi has reached around 53% (790 sq km) (Mohan et al., 2011a). These changes in the LU/LC have significantly altered the micro and macroclimate of Delhi.

3. Data used

For the present study, remotely sensed annually averaged land surface temperature (LST) data for the nighttime and daytime has been used for a period of 11 years (2001–2011). The annually averaged LST data has been retrieved from the Monsoon Asia Integrated Regional Study program which utilizes Terra and Aqua Moderate-Resolution Imaging Spectroradiometer (MODIS) with 1 km spatial resolution. This dataset consists of 8-day period averages of land surface temperature and is available from the online database of Goddard Earth Sciences

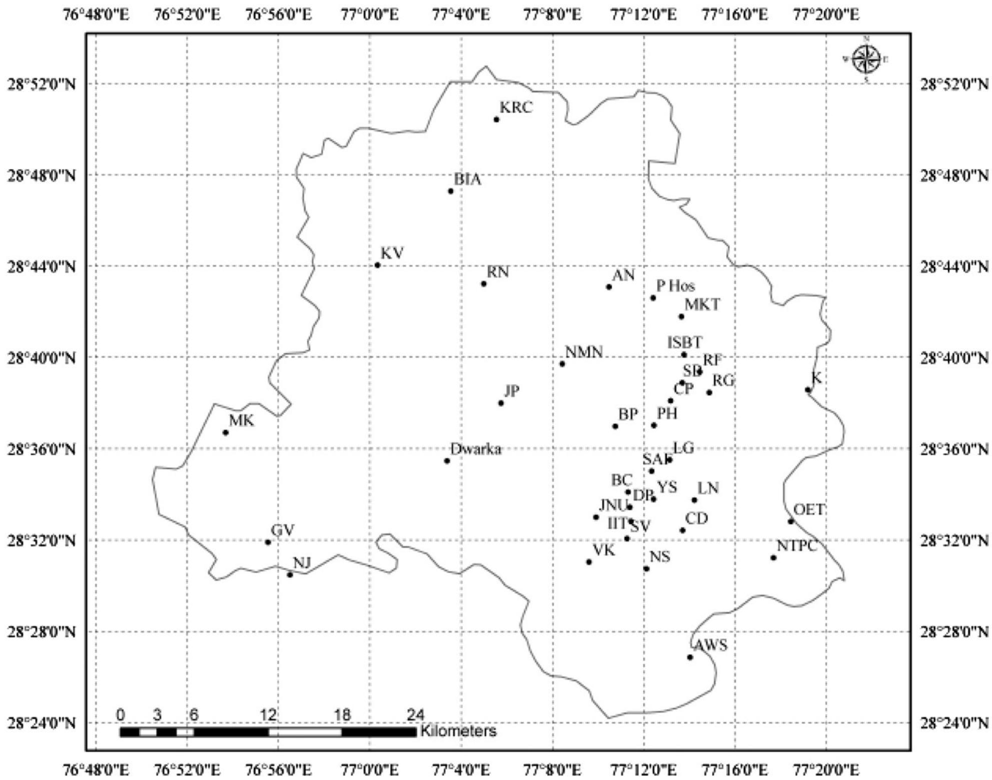


Fig. 1. Map of Delhi showing the location of the stations selected for detailed investigation.

Data and Information Services Center Interactive Online Visualization and Analysis Infrastructure (GIOVANNI) of NASA (GIOVANNI, 2011). The respective LST data has been validated within 1 K in multiple validation sites in relatively wide ranges of surface and atmospheric conditions (Wan et al., 2002, 2004; Coll et al., 2005; Wan, 2008). The MODIS Terra spacecraft passes over the region of Delhi during 1000 to 1130 h approximately during daytime and similarly from 2200 to 2330 h during nighttime (by local time).

4. Methodology

For the present study, a database of the annually averaged LST (for both day-time and night-time) retrieved from the Monsoon Asia Integrated Regional Study program for Delhi region was prepared for the study period. The DTR was calculated by subtracting the nighttime LST from the daytime LST (Sun et al., 2006). The DTR mapping was done using the Arc GIS 9.2 software. Though the mapping was done for all the years, however for detailed analysis the maps for the years 2001, 2004, 2008 and 2011 were used. Further, 36 locations representing the 5 types of dominant LU/LC viz. urban built-up areas (which include Dense Canopy, Medium Dense Urban Canopy — I, Medium Dense Urban Canopy — II, Less Dense Urban Canopy), green areas (which include Medium Dense Forest, Parks and Gardens), open areas, riverside areas and urban outskirts (resembling rural areas) existing in Delhi were considered for the detailed study. The present study adopts the same classification of the LU/LC as adopted by Mohan et al. (Mohan et al., 2009, 2012, 2013) however, for including few rural sites in the study, an addition of one class is made i.e. 'urban outskirts' which relatively resembles rural areas. Table 1 gives the details of these stations i.e. their latitude and longitude and the type of urban canopy or land-use/land-cover which they represent while Fig. 1 shows the location of these stations on the map of Delhi. Of these 36 locations, 22 locations (which are marked with * in Table 1) were also considered by Mohan et al. in the field campaigns conducted during 2008 and 2010 (Mohan et al., 2012, 2013) and a detailed description of various LULC classification is also covered in these studies.

For analyzing the impact of the changing LU/LC on DTR, DTR anomaly maps were prepared for the years 2004, 2008 and 2011 taking the DTR of the year 2001 as the reference. For having statistical significance of the trends of DTR during the study period, Mann–Kendall trend test at 95% confidence level has been performed on the computed annually averaged DTR values of these 36 stations. Mann–Kendall trend test at the same confidence level was also performed on the respective annually averaged nighttime and daytime LST values. Mann–Kendall trend test is a nonparametric test (Mann, 1945; Kendall, 1975) which has been suggested by the World Meteorological Organization to assess the trend in environmental time series data (Yu et al., 2002). In the present study, the Mann–Kendall trend test was performed using the Minitab 14 with the macro MKTREND (Environmental Protection Agency, 2006)

5. Results and discussion

Fig. 2 shows the annually averaged DTR for entire Delhi during the study period while Fig. 3(a–d) displays the spatio-temporal variation of DTR across Delhi for the year 2001, 2004, 2008 and 2011 and

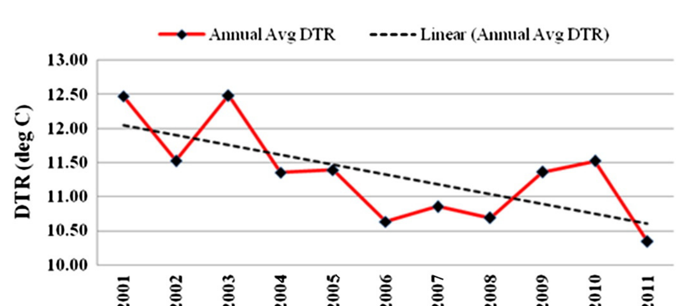


Fig. 2. Annually averaged DTR of Delhi.

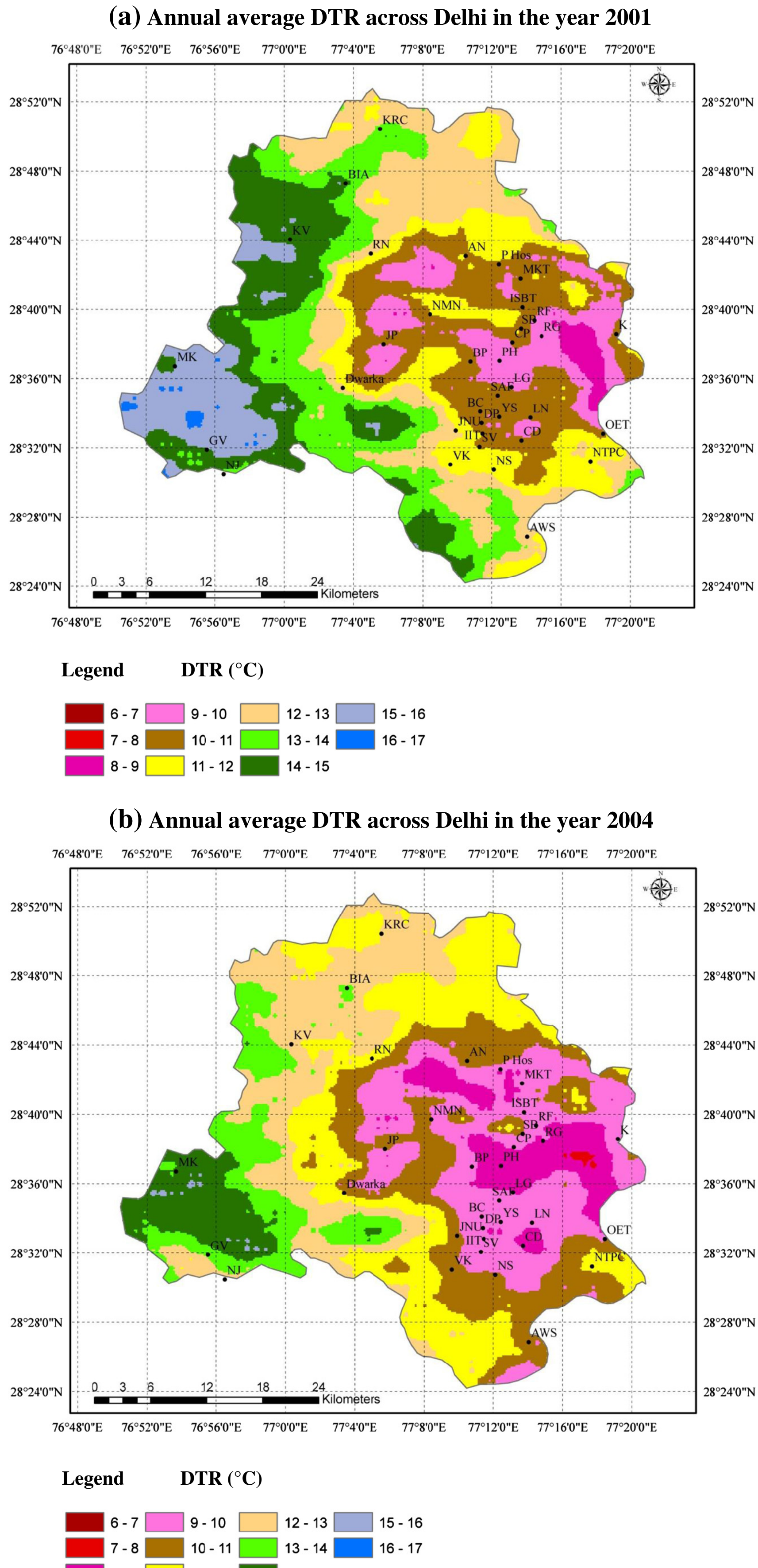
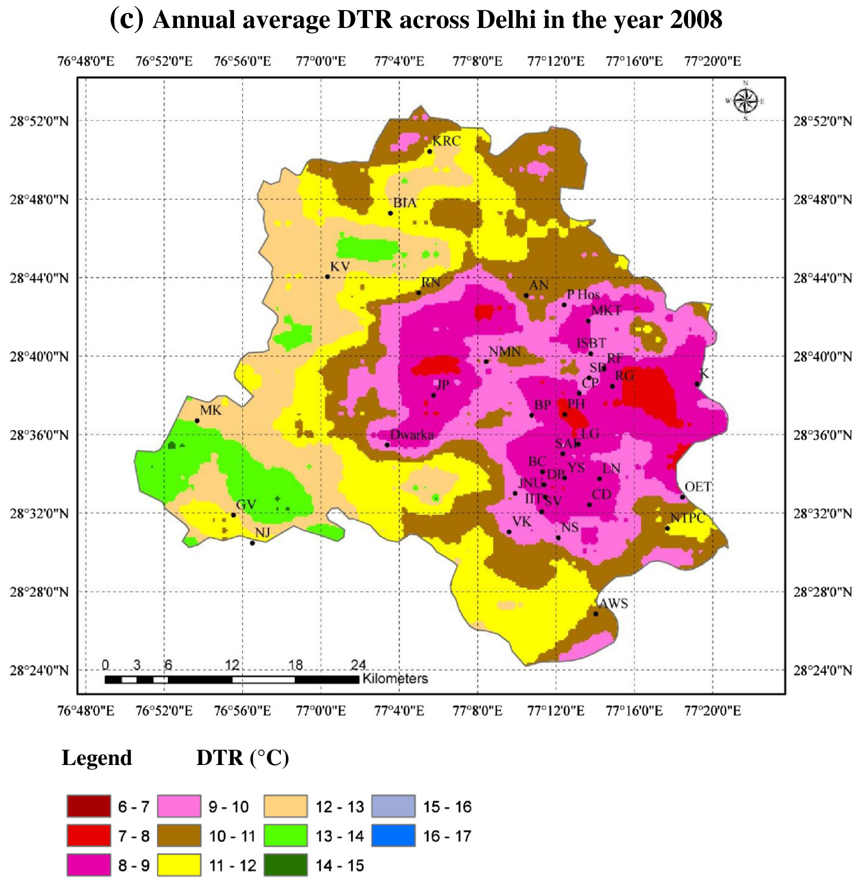


Fig. 3. (a) DTR across Delhi in the year 2001. (b) DTR across Delhi in the year 2004. (c) DTR across Delhi in the year 2008. (d) DTR across Delhi in the year 2011.



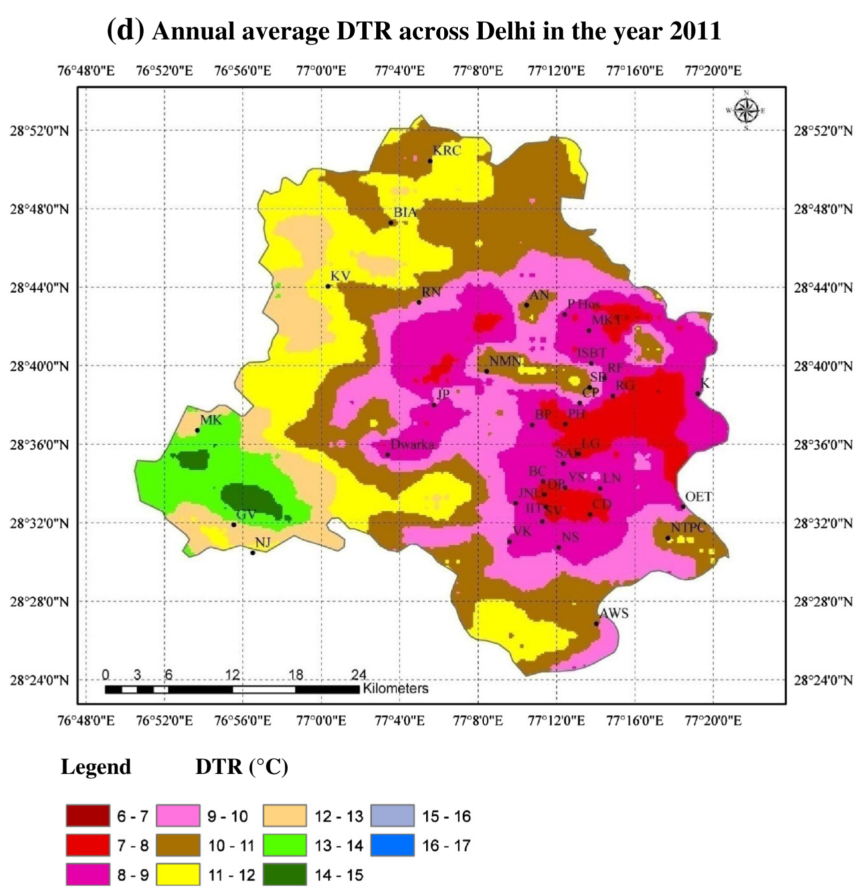


Fig. 3 (*continued*).

Table 2
Area under the various DTR categories across Delhi.

DTR (°C)	Area (sq km)			
	2001	2004	2008	2011
6–7	–	–	–	6 (0.4%)
7–8	–	5 (0.3%)	54 (3.6%)	103 (6.9%)
8–9	30 (2.0%)	122 (8.2%)	222 (14.9%)	255 (17.1%)
9–10	144 (9.7%)	258 (17.3%)	238 (16.0%)	242 (16.3%)
10–11	219 (14.7%)	241 (16.2%)	328 (22.0%)	367 (24.6%)
11–12	209 (14.0%)	322 (21.6%)	298 (20.0%)	290 (19.5%)
12–13	279 (18.7%)	286 (19.2%)	241 (16.2%)	126 (8.5%)
13–14	236 (15.8%)	150 (10.1%)	101 (6.8%)	75 (5.0%)
14–15	221 (14.8%)	90 (6.0%)	8 (0.5%)	25 (1.7%)
15–16	135 (9.1%)	17 (1.1%)	–	–
16–17	17 (1.1%)	–	–	–
Total	1490 (100%)			

Table 2 puts forward the area statistics for the various categories of the DTR for the respective years.

From Fig. 2, it can be seen that the annually averaged DTR of Delhi is exhibiting a statistically significant 'downward trend' during 2001–2011. At 95% confidence level, the results of the Mann–Kendall Trend test for the DTR values were $Z = -1.95217$, $P_{down} = 0.0254$ (P_{down} indicates the significance level for the downward trend). The DTR which was 12.48 °C in the year 2001 reduced to 10.34 °C in the year 2011. From Table 2, it can be observed that there is a gradual decline in the DTR which ranged between 8 and 17 °C in the year 2001, 7–16 °C in the year 2004, 7–15 °C in the year 2008 and 6–15 °C in the year 2011. The converging tendency of the DTR which is a typical characteristic of the urbanization process (Kalnay and Cai, 2003; Easterling et al., 1997; Sun et al., 2006; Karl et al., 1991, 1993; Gallo et al., 1996) can be clearly seen over Delhi. It is worth noting that during this period, both the population and built-up areas in Delhi increased substantially. The population of Delhi which was 13,850,507 in the year 2001 increased to 16,753,235 in the year 2011, registering a decadal growth rate of 20.96% (Census, 2011), while the built area increased from 677.6 km^2 in the year 2001 to 791.96 km^2 in the year 2008, registering a growth rate of 16.86% during 2001–2008 (Mohan et al., 2011a).

Superimposing the LU/LC map of Delhi for the years 2004 and 2008 (Mohan et al., 2011a) with the corresponding DTR map for year 2004 [Fig. 3(b)] and year 2008 [Fig. 3(c)], it was found that the DTR of the urban areas represented by Sitaram Bazar, Connaught Place, Janakpuri, Bhikaji Cama, Red Fort, Parliament House was around 8–11 °C while that of the areas resembling the rural locations like Ghumanhera Village, Mundhela Kalan and Kanjhawala Village was around 13–17 °C; the narrower DTR being a distinct comparative feature of the urban–rural areas (Easterling et al., 1997; Sun et al., 2006; Gallo et al., 1996). Further, from Table 2 and Fig. 3(a–d), it can be seen that there was a prominent increase in the areas experiencing the DTR below 11 °C inferring the increase in the 'urban class'. In the year 2001, 26.4% of the total area was experiencing the DTR below 11 °C which increased to 42.0% in the year 2004, 56.5% in the year 2008 and 65.3% in the year 2011. The results of the increase in the 'urban class' coincide well with the previous study of land use/land cover change detection using IRS LISS-III data where it was reported that the built-up area in the year 2008 was around 53% (Mohan et al., 2011a).

For having a comprehensive view of the impact of the land use/land cover changes in Delhi on DTR during the study period, DTR anomalies were calculated across Delhi for the years 2004, 2008 and 2011 taking the DTR of the year 2001 as the reference. Fig. 4(a–c) is the respective DTR anomaly maps for the years 2004, 2008 and 2011. In addition to this, the annually averaged DTR values along with the annually averaged nighttime and daytime LST of the 36 locations (as described earlier) were analyzed using the Mann–Kendall trend test at 95% confidence level. Table 3 contains respective Mann–Kendall Trend test results. Fig. 6 (a–n) displays the temporal variation of the DTR of few selected locations representing the 9 urban canopies of Delhi.

From Fig. 4(a–c), it can be seen that there is an overall lowering in the DTR observed across Delhi, however, the areas in North-West and South-West Delhi are having the maximum reduction. The DTR in these zones reduced to a tune of 2.5 to 4.0 °C. Incidentally, these are the zones which have registered both the major transformations in the LU/LC to built-up areas as shown in Fig. 5(a) (Mohan et al., 2011b) and high population growth as shown in Fig. 5(b) (Census, 2011).

The important areas of South-West Delhi zone registering substantial lowering of DTR are Dwarka, Bhikaji Cama, Safdarjung Airport and Lodi Garden while that of the North-west Delhi are Rohini, Bhavan Industrial Area, Khanjwala Village, Ghevra and Jaunti. Dwarka is the Asia's largest residential colony which came up gradually during the last decade while Safdarjung airport witnessed a major increase in the built-up area with the development of the total parking area of around 170,000 sq m which will accommodate around 3000 cars, 6000 two-wheelers and 450 buses. The variation in the DTR of Dwarka during the study period can be specifically seen in Fig. 6(c). Major areas of South Delhi like Indian Institute of Technology, Jawaharlal Nehru University, Sanjay Van, Vasant Kunj, Chirag Delhi also witnessed a decreasing trend of DTR. These areas witnessed an increase in the built-up areas along with the growth in population. Sanjay Van which is a notified reserve forest in South Delhi has been subjected to land encroachments and has undergone severe degradation due to the excessive and fast proliferation of *Prosopis juliflora*, an exotic Mexican fast growing tree which has pushed the groundwater level down thereby drying the soil surface. Its DTR variation for the study period can be seen in Fig. 6(i).

From the Mann–Kendall trend test results, Fig. 4(a–c) and Fig. 6(a, b and d) it can be seen that the built-up areas in the central Delhi having very less scope of urbanization like Sitaram Bazar, Connaught Place and Red Fort did not have any significant change in the DTR during the study period. From Fig. 5(a) which depicts the temporal variations in the LU/LC over Delhi during 1997–2008 using IRS LISS-III data (Mohan et al., 2011a), it can be seen that no major LU/LC changes were seen in these areas. Moreover, from Fig. 5(b) which depicts the temporal variation in population of Delhi, it can be seen that the central Delhi witnessed a reduction in the population. It is interesting to correlate this observation with the positive Z value of the Mann–Kendall Trend test for the annually averaged DTR values for Sitaram Bazar which represents a dense urban canopy of Central Delhi.

5.1. Urbanization induced heat-related mortality and adverse impacts

Mortality increases with hot weather, however, only few researchers have attempted to advance our understanding of spatial, temporal, environmental, social, behavioral dimensions of heat-related health risks (e.g., Anderson and Bell, 2009; Harlan et al., 2013; Hondula et al., 2012) and very few have quantified the extent to which lives are shortened (e.g. Hajat et al., 2005). For Maricopa County, Arizona, anchor to the fastest growing megapolitan area in the United States, a study reveals that all projections based on minimum and mean temperatures were associated with increasing heat-related mortality, projected increase exceeding 350% above the present day, while all projections based on maximum temperature were associated with declining heat-related mortality of about 94% (Hondula et al., 2014). The study done on temperature related mortality done by Hajat et al. reports significant raised risk of heat-related and cold-related mortality in all regions. In the absence of any adaptation of the population, heat-related deaths would be expected to rise by around 257% by the 2050s from a current annual baseline of around 2000 deaths (Hajat et al., 2014).

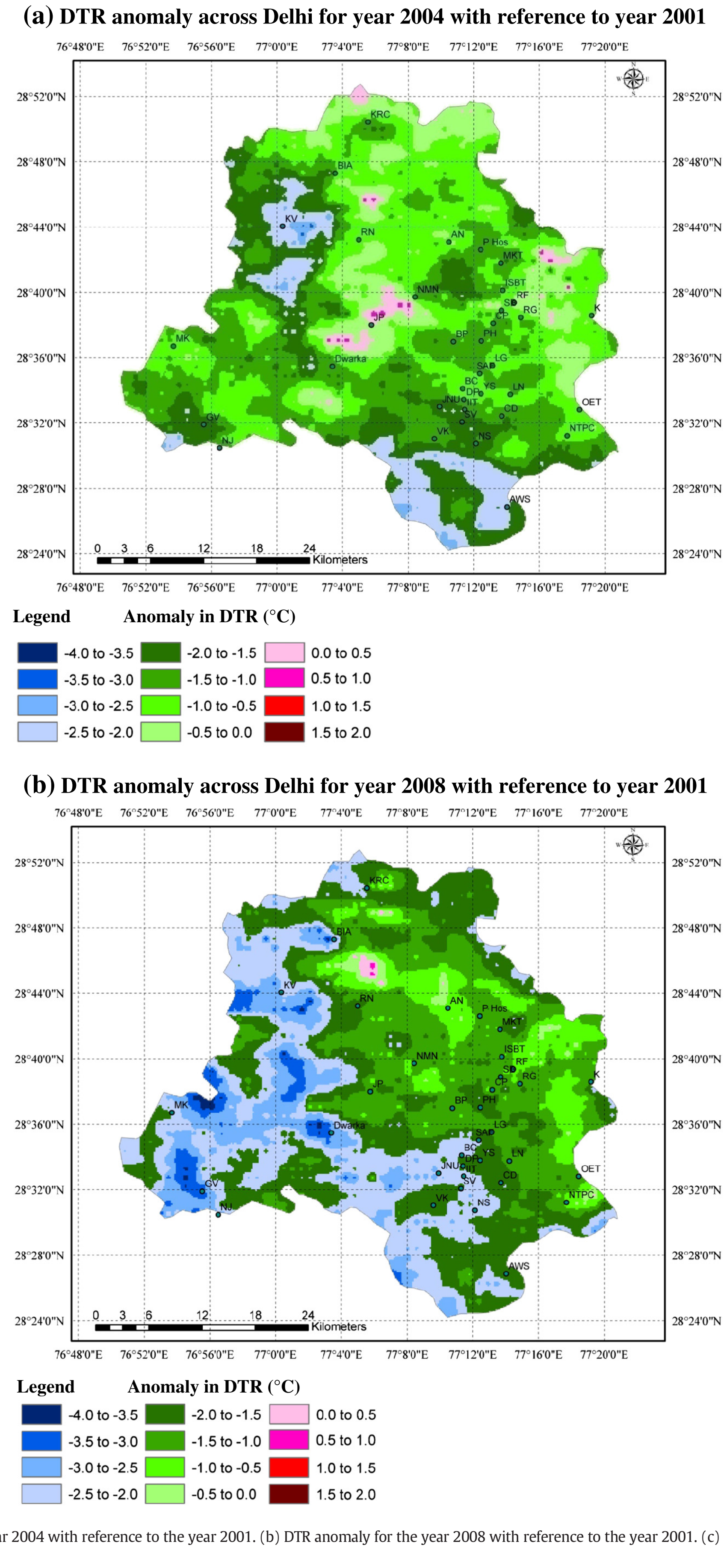


Fig. 4. (a) DTR anomaly for the year 2004 with reference to the year 2001. (b) DTR anomaly for the year 2008 with reference to the year 2001. (c) DTR anomaly for the year 2011 with reference to the year 2001.

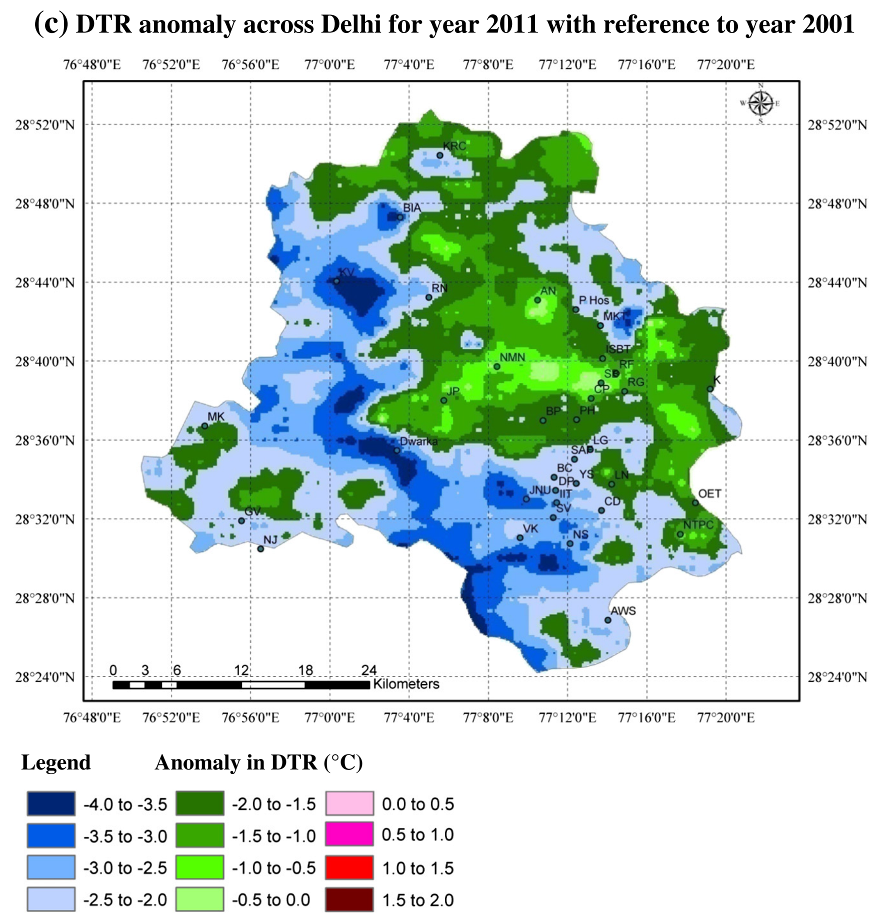


Fig. 4 (*continued*).

Comparing Delhi, Sao Paulo and London for the heat related mortality, Hajat et al. observed that the level of risk of death remained highest and longest for Delhi (Hajat et al., 2005). The study opined an increase in all-cause mortality with same day (lag 0) and previous day (lag 1) temperatures greater than the threshold temperature of 20 °C. Though heat-related mortality remains poorly documented and understood in Delhi, few news articles throw some light on this issue (Sharma, 2014). While the deaths of homeless people make headlines during the winter months, data for the last three years shows that the deaths of unidentified people on the streets of Delhi peak in the summer (Scroll.in, 2014). A heat wave hit Delhi on June 6, 2014 sending temperatures soaring above 45 °C. There was a sharp correlation between a rise in temperatures and a rise in deaths on the streets. In the five days that the heat wave lasted, 130 unidentified people died — an average of 26 deaths a day (Scroll.in, 2014). The last time Delhi saw a sustained spike in the deaths was in the closing days of June 2012. In 12 days, 369 unidentified bodies were found, an average of 30 deaths a day. Though the reasons of deaths are not clear, the role of heat waves can't be ruled out. In the year 2010 also, correlation between high temperature and ill-health was observed when on one hand Delhi recorded its highest April temperature in nearly past 60 years and on the other hand City doctors said they had admitted 10–20% more patients suffering from heatstroke than last year (Williams, 2010). In addition, increasing higher temperatures may increase transmission window for malaria and other diseases (Patwardhan and Harit, 2007). Moreover, reduction in comfortable hours and increasing cooling energy demand could further deteriorate the situation by increasing anthropogenic heat emissions resulting into higher ambient temperatures and thus triggering a vicious cycle of increasing temperature and energy demand (Mohan et al., 2012, 2013).

It is expected that the heat-related mortality rate would increase everywhere, rather only in urban area. However, the reduction in DTR prominently noticed in urban areas points out to the fact that built-up areas due to urbanization would possibly exacerbate the already increased high temperatures at night-time. This could mainly be due to built-up structures releasing the solar heat at night and lower sky-view factor trapping that heat within the urban canopies thereby resulting into higher night-time temperatures. Hence, less built areas such as rural or outskirts of the city may realize lower changes in DTR in comparison to urbanized areas coupled with lower population may witness less impact on heat-wave related mortality.

In the background of the increasing built-up areas in Delhi, almost reaching to 83% by the year 2031 (DDA, 2021) and noting the strong direct correlation between built-up areas, temperature and mortality, the present study calls for urgent and strong policy measures to deal with reducing ambient temperatures in megacities and to obtain the co-benefits on energy, emissions, health and reduced heat stress related mortality.

6. Conclusions

In this paper, the effect of urbanization on the LST based DTR was investigated. This is the first attempt where the spatial and temporal variations of satellite based estimates of annually averaged DTR over megacity Delhi, the capital of India are shown for a period of 11 years during 2001–2011. These DTRs show geographical patterns which are highly

Table 3
Trend analysis of DTR, nighttime LST and daytime LST across Delhi.

No.	Station	Canopy	DTR		Nighttime LST		Daytime LST	
			Z_{MK}	Trend	Z_{MK}	Trend	Z_{MK}	Trend
1.	SB	Dense canopy	0.156	NT	0.275	NT	−0.069	NT
2.	CP	Medium dense urban canopy — I	−0.778	NT	0.000	NT	−0.617	NT
3.	JP		−1.090	NT	0.343	NT	−1.166	NT
4.	P Hos		−1.868	NT	1.029	NT	−0.891	NT
5.	AN		−0.156	NT	0.891	NT	−0.069	NT
6.	LN		−1.557	NT	0.754	NT	−1.303	NT
7.	RN		−2.958	**DT**	1.852	**UT**	−2.400	**DT**
8.	K		−3.270	**DT**	2.537	**UT**	0.000	NT
9.	Dwarka		−3.270	**DT**	1.989	**UT**	−3.223	**DT**
10.	BC		−2.647	**DT**	1.577	NT	−1.440	NT
11.	NMN	Medium dense urban canopy — II	0.000	NT	0.412	NT	-0.343	NT
12.	RF		−1.713	NT	1.166	NT	−0.343	NT
13.	PH		−1.868	NT	1.029	NT	−0.343	NT
14.	NS		−2.491	**DT**	1.650	**UT**	−1.440	NT
15.	ISBT		−2.180	**DT**	0.891	NT	−0.617	NT
16.	YS		−2.180	**DT**	1.512	NT	−1.989	**DT**
17.	OET		−2.335	**DT**	2.812	**UT**	0.754	NT
18.	SAF		−2.958	**DT**	1.714	**UT**	−1.852	**DT**
19.	CD		−2.803	**DT**	1.440	NT	−1.989	**DT**
20.	VK		−3.270	**DT**	1.303	NT	−1.577	NT
21.	KRC	Less dense urban canopy	−1.557	NT	1.303	NT	−0.754	NT
22.	BIA		−2.180	**DT**	2.537	**UT**	−1.577	NT
23.	IIT		−3.270	**DT**	1.577	NT	−1.029	NT
24.	NTPC		0.934	NT	2.263	**UT**	0.754	NT
25.	JNU	Open area	−2.647	**DT**	0.617	NT	−1.989	**DT**
26.	AWS	Medium dense forest	−1.401	NT	−0.207	NT	−0.891	NT
27.	BP		−2.335	**DT**	0.275	NT	−0.206	NT
28.	SV		−3.270	**DT**	1.714	**UT**	−2.126	**DT**
29.	RG	Parks and gardens	−2.958	**DT**	1.989	**UT**	−0.891	NT
30.	LG		−3.114	**DT**	1.512	NT	−1.714	**DT**
31.	DP		−2.958	**DT**	1.577	NT	−1.925	**DT**
32.	NJ	Riverside area	−2.180	**DT**	0.343	NT	−1.714	**DT**
33.	MKT		−2.647	**DT**	1.303	NT	−0.754	NT
34.	KV	Urban outskirts resembling	−2.868	**DT**	1.648	**UT**	−2.126	**DT**
35.	MK		−1.401	NT	1.440	NT	−1.303	NT
36.	GV	Rural areas	−1.557	NT	0.617	NT	−1.989	**DT**

(NT = no significant trend, DT = downward trend significant at 95% confidence level, UT = upward trend significant at 95% confidence level).

consistent with the LU/LC transformations and population growth observed over the city. The major findings of the study are as follows:

a) Satellite based annually averaged DTR of entire Delhi shows a significant decreasing trend. The DTR which was 12.48 °C in the year 2001 has gradually reduced to 10.34 °C in the year 2011.
b) The annually averaged DTR of the urban areas was below 11 °C while that of the areas resembling rural areas was above 13 °C.
c) There was a prominent increase in the areas experiencing the DTR of below 11 °C inferring the increase in the urban class. In the year 2001, the area under this DTR was 26.4% which gradually increased to 65.3% in the year 2011.
d) No significant changes in the DTR were observed in those built-up areas having very less scope of urbanization e.g., CP, Sitaram Bazar, Janakpuri, and Parliament House. Other peripheral parts which were protected like Asola Wild-life Sanctuary and the areas resembling the rural locations like Ghumanhera Village, Mundhela Kalan and Kanjhawala Village or had less development also showed no significant change in the DTR trend.
e) Rapidly developing areas like Rohini, Dwarka, Khanjhawala Village, Vasant Kunj, IIT, Safdarjung Airport, Kaushambi, etc. exhibited a highly decreasing trend in DTR which is an inherent characteristic of urbanization.
f) The converging trend of DTR which is primarily due to the increase in the minimum temperatures as a consequence of built structures in the cities could result into an increase in the heat-related mortality rate. Together with an increased cooling energy demand in the warm climatic conditions (e.g., cities in low latitudes or tropics) the situation calls for an urgent policy interventions especially for the rapidly growing cities.

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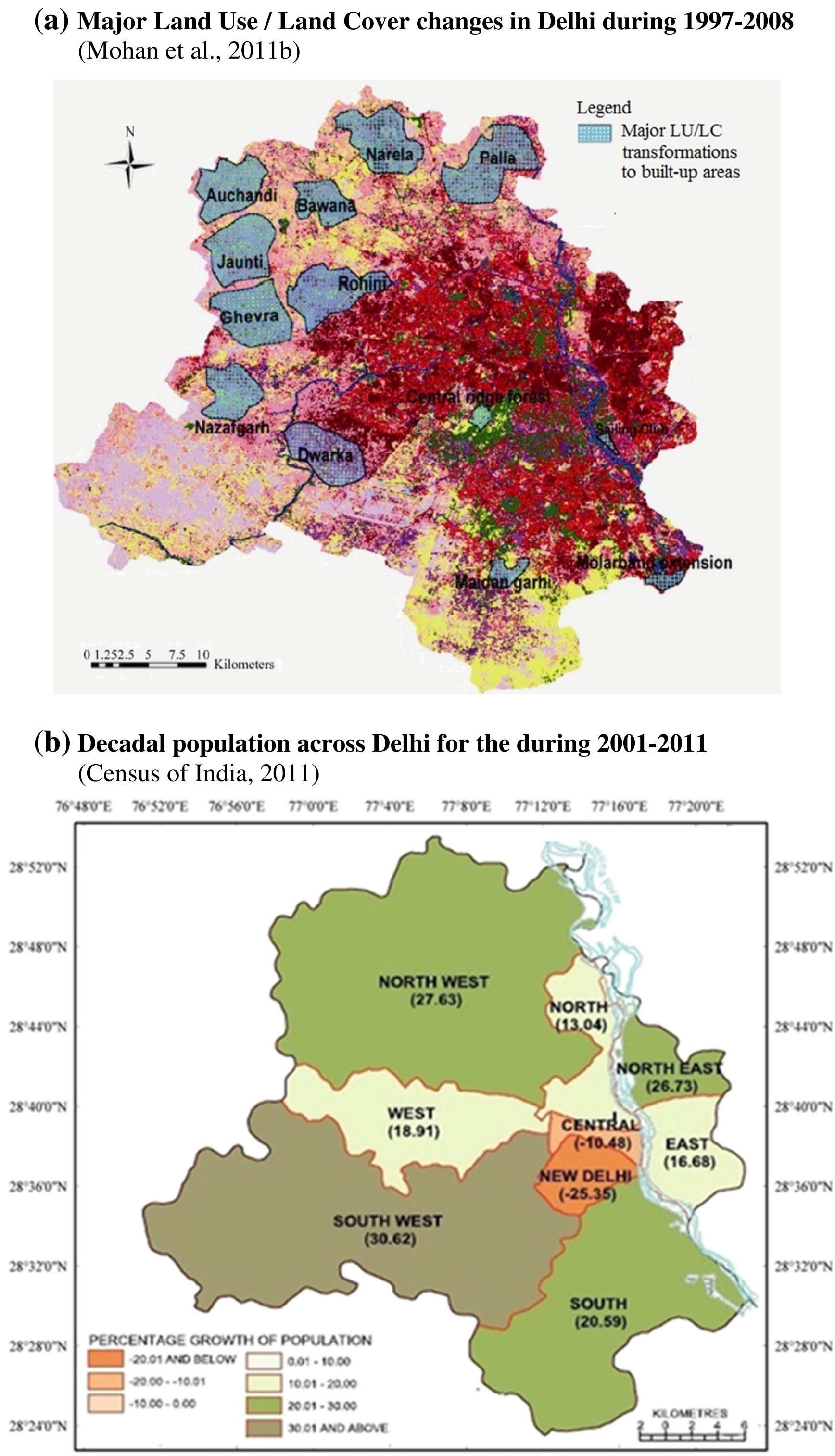

Fig. 5. (a) Major land use/land cover changes in Delhi during 1997–2008. (b) Decadal population across Delhi during 2001–2011.

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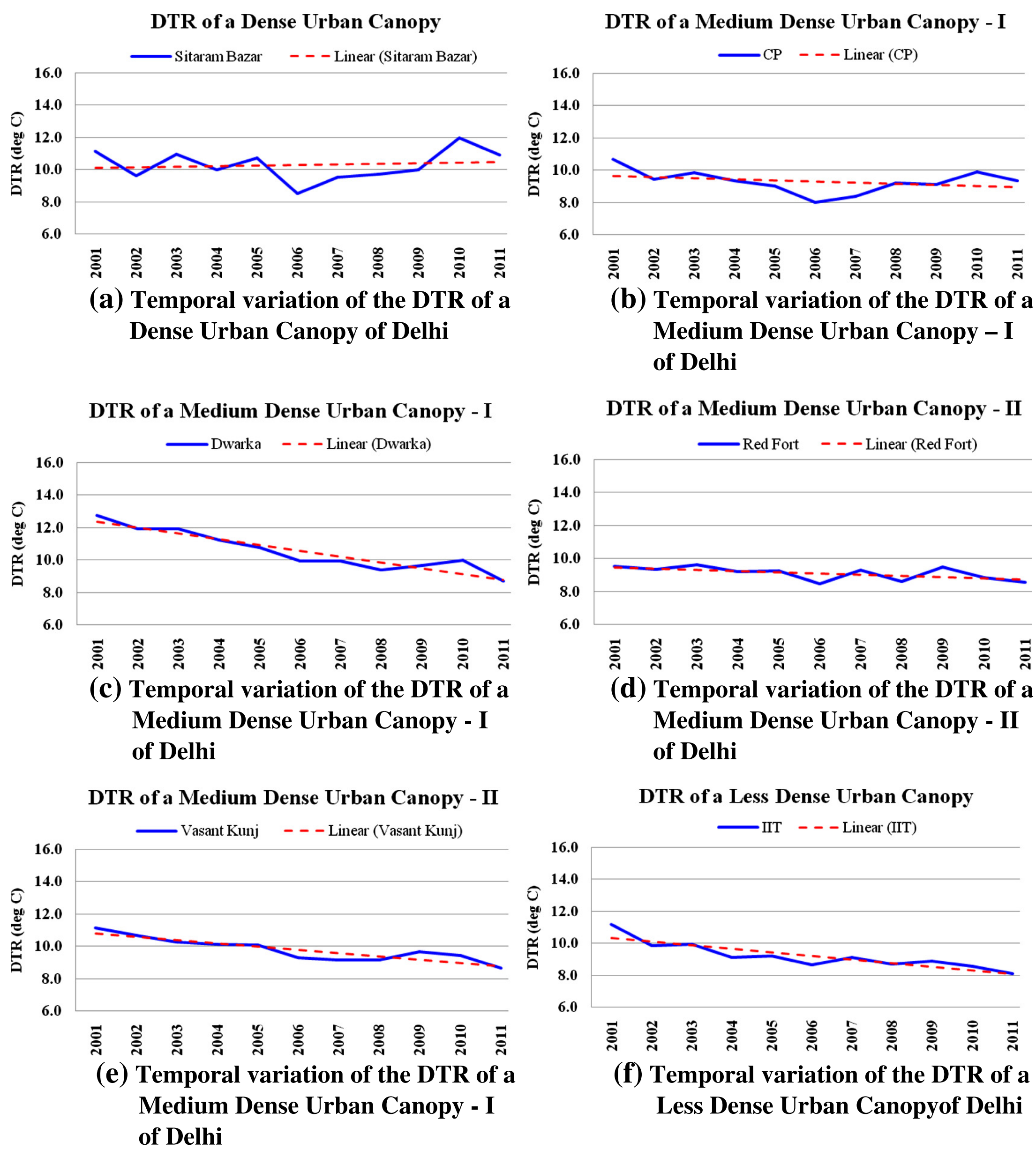

Fig. 6. (a–n) Temporal variation of DTR of various canopies across Delhi during 2001–2011.

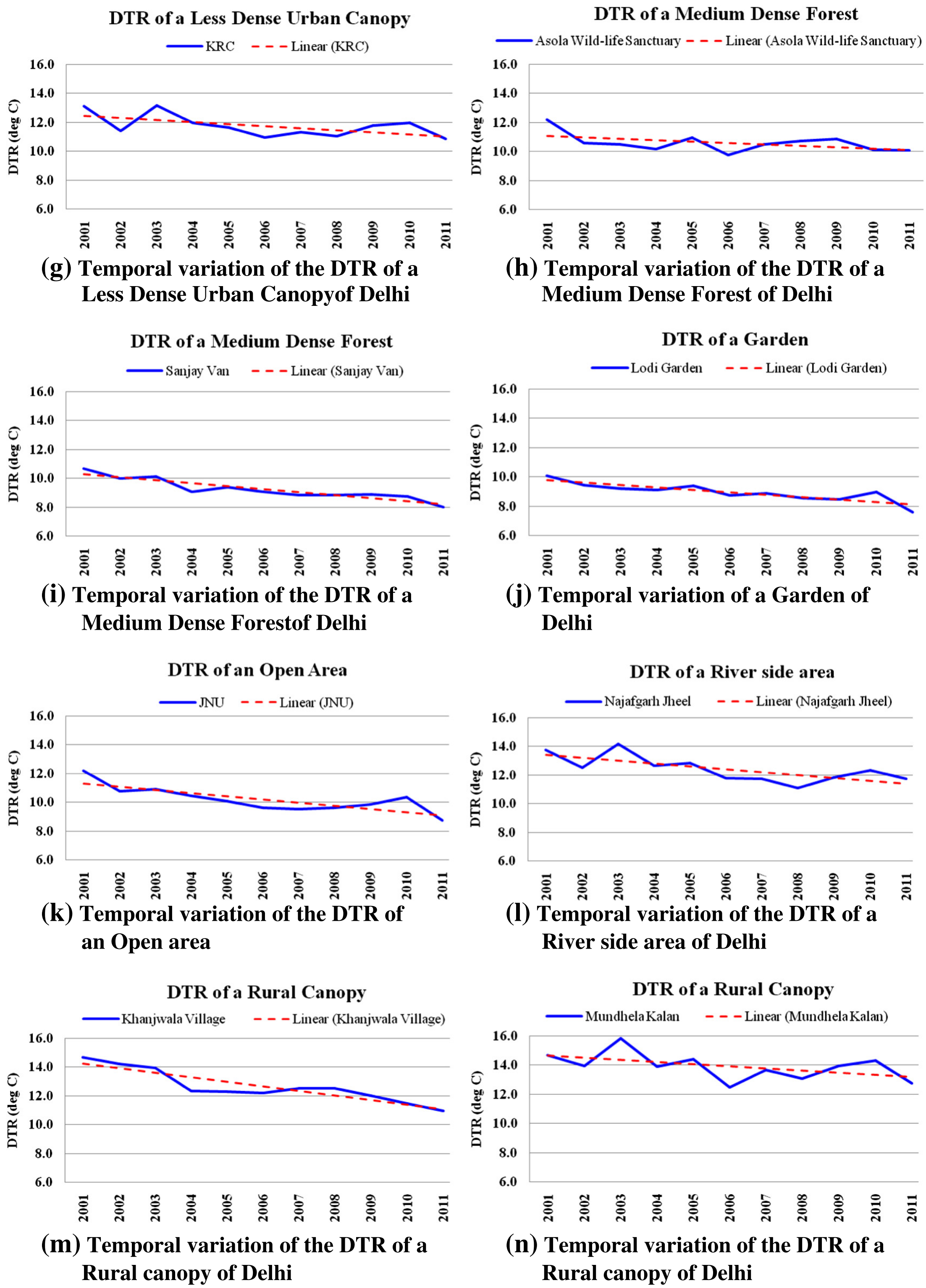

Fig. 6 (*continued*).

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