

Long-term Temperature Trends at Four Largest Cities of India during the Twentieth Century

Amit Dhorde, Anargha Dhorde¹ and Alaka S.Gadgil

Department of Geography, University of Pune, Pune - 411 007

¹Post Graduate Department of Geography, Nowrosjee Wadia College, Pune - 411 001

ABSTRACT

Investigations have been carried out by climatologists to find a possible link of climate change with anthropogenic activities by studying trends in different climatic parameters, particularly surface air temperature of densely populated cities. The present research aimed at quantifying the change in surface air temperature at India's four most populated cities - Delhi, Kolkata, Mumbai and Chennai. The cities taken up for study have experienced rapid urbanization in the recent past. Therefore, the main objective of the research was to find the impact of urbanization on temperature trends at these cities. Trends in annual and seasonal temperature series were analyzed using linear trend and Mann-Kendall test. From the population trends Less Urbanized Period (LUP) and More Urbanized Period (MUP) were identified. The average population and surface air temperature of these two periods were used to further assess the urbanization effect. Most of the trends showed positive change in temperature with different rates in different seasons. In some cases, the trends showed asymmetry. For example, the maximum temperature at Mumbai during winter and monsoon is significantly increasing whereas minimum temperature shows significant decrease. On the other hand remaining cities recorded significant increase in minimum temperature during winter. The analysis based on LUP and MUP indicates that, on seasonal scale the difference in temperature of these two periods is significant for post-monsoon and winter seasons. Further the relationship indicates a negative change in temperature with increase in population. This indicates that the effect of urbanization is more pronounced during these seasons, as far as warming is concerned. Thus, an inconsistent climatic response to urbanization is observed at these cities.

INTRODUCTION

Urbanization in the twentieth century established a network of competitive urban centers that set the physical reference points for today's globalization. As estimated by the World Bank (2002), in poor countries as much as 80 per cent of future economic growth will occur in cities. Moreover, 60 percent of the world's population will be residing in cities by 2030 (Population Reference Bureau 2004). No doubt, the cities are playing and will continue to play an important role in shaping a country's economy but, they are also burdened with many problems associated with growth and the physical environment. The major concern is about the emissions of the greenhouse gases, which are found to threaten the local and global climatic regime. A number of studies have revealed increase in the average temperatures in the city with increase in population (Goodridge 1992; Fujibe 1995; Chung, Choi & Yun 2004). In turn, urban population is constantly affected by the change in the temperature which controls the comfort levels of the inhabitants.

According to the latest estimates by IPCC (2007) Earth's linearly averaged surface temperature has increased by 0.74°C during the period 1901-2005. Assessing the impacts of urbanization and land use change on mean surface temperature is a challenging task. Some of the early works related to the influence of urbanization on atmospheric properties were undertaken by Oke (1973, 1979, 1982) and Landsberg (1975, 1981). Few other studies by Mitchell (1953), Dettwiller (1970), Fukui (1970), Cayan & Douglas (1984), Duchon (1986), Kukla, Gavin & Karl (1986) and Chow (1986) have attempted to quantify the effect of increasing levels of urbanization on the temperature record of major cities. These studies demonstrate the importance of isolating and removing the anomalous warmth produced by major cities. However, most of these studies suffer from the difficulty in quantifying urbanization. Considerable amount of research work published in the last two decades (Karl, Gavin & Karl 1988; Balling & Idso, 1989; Goodridge 1992; Karaca, Taya & Toros 1995; Hughes & Balling 1996; Sala et al., 2000; Englehart & Douglas 2003; Kalnay

& Cai 2003; Chung, Choi & Yun 2004) have also attempted to assess the effects of urbanization on local and regional climate. A study by Jones et al., (1990) on urbanization and related temperature variation indicates that the impact of urbanization on the mean surface temperature would be no more than 0.05 °C per 100 years. On the other hand a study by Fujibe (1995) reports a rising trend of 2-5 °C per 100 years in minimum temperature at several large cities of Japan. It is understood that the observed warming is not only due to the increase of greenhouse gases but also due to urbanization (Nasrallah & Balling, 1993). Wilbanks & Kates (1999) showed that the urban effect is pronounced for minimum temperatures, and that the magnitude of the effect is well correlated to the population of the city in which the station is located.

During the last century, surface temperature over India has shown significant increasing trend (Hingane, Rupa Kumar & Ramana Murty 1985) which is attributed to rise in maximum temperature. Rupa Kumar & Hingane (1988) investigated long-term variations of seasonal and annual surface air temperature at six Indian industrial and non-industrial cities each and have concluded that the non-industrial stations did not show significant trends and there was either a cooling tendency or cessation of warming after the late 1950s at most of the Industrial cities. They have used the industrial and population growth data for these cities but they did not attempt to detect any significant change in these parameters (i.e. population and industries). Rao, Jaswal & Kumar (2004) tried to evaluate the effect of urbanization on meteorological parameters for fifteen cities with a population of more than one million. However, they neither related this with population increase nor with industrialization. Some of the urban locations in India are becoming increasingly vulnerable to natural hazards related to extreme events in weather and climate (De & Dandekar 2001). Another study by Sinha Ray & Srivastava (2000) has shown that the frequency of heavy rains during the southwest monsoon showed an increasing trend over certain parts of the country. On the other hand decreasing trend is seen during winter, pre-monsoon and post-monsoon seasons. The authors have tried to attribute dynamical and anthropogenic causes for this variation. Rao, Murty & Joshi (2005) analysed the extreme weather events such as high and low temperatures, heavy rainfall in connection with the climate change over India and concluded that during summer 60-70% of the coastal stations are showing an increasing trend in critical extreme maximum day temperature and increase in night temperatures.

Almost all these studies, both national and

international, though concluded rising temperature trends because of the effect of urbanization, very few of these studies indicated direct statistical relationship with urbanization or industrialization. Some studies, such as one by Rupa Kumar & Hingane (1988) also reported cooling at industrial cities. In view of these differences it was thought to investigate whether the largest cities of India are warming or cooling. An attempt is made here not only to study trends but also to find out the relationship between urbanization and temperature change at India's four largest cities - Delhi, Kolkata, Mumbai and Chennai. One of the objectives is to investigate whether urbanization produces similar effect at all the cities during all seasons.

METHODOLOGY

The location of cities under investigation is depicted in Fig.1. For this study, monthly data of maximum and minimum temperature on century scale were obtained from India Meteorological Department (IMD). Data for Delhi were available only upto 1990. Population data were collected from the Census of India (2001) publication. After checking the homogeneity and homogenizing the series the climatic data were put to trend analysis. Linear regression method which is widely used across the globe (Rupa Kumar & Hingane 1988; Sahai 1998; Brunetti et al., 2000; Kaiser 2000; Pielke et al., 2002; Englehart & Douglas 2003; Malmgren et al., 2003; Qian & Lin 2004; Rio, Penas & Fraile 2005; Gadgil & Dhorde 2005) to find long-term trends is utilized in this study for deriving trends in temperature. In the present study, the magnitude of the trends was derived from the slope (value of 'b') of the regression line. The value of 'b', which represented the rate of change per unit time for the climatic parameter under consideration, was further multiplied by number of years to find the absolute change. This analysis was carried out for annual and seasonal series.

The Mann-Kendall test, which is another popular statistical method used by contemporary climatologists (Kadioglu, 1997; Brunetti et al. 2000; Salinger & Griffiths 2001; Wibig & Glowicki 2002; Lu et al., 2004; Domroes & El-Tantawi, 2005; Gadgil & Dhorde 2005; Tomozeiu et al., 2006 and many others) is used here as a significance test. As it also gives the overall trend, it also proves to be a second check on the trends obtained by linear regression. The major advantages of this test highlighted by Rio, Penas & Fraile. (2005) are: i) No assumptions about distribution are necessary and ii) it is directly applicable to climate data for a given month or season. The procedure of carrying out this statistical test is outlined by Mitchell

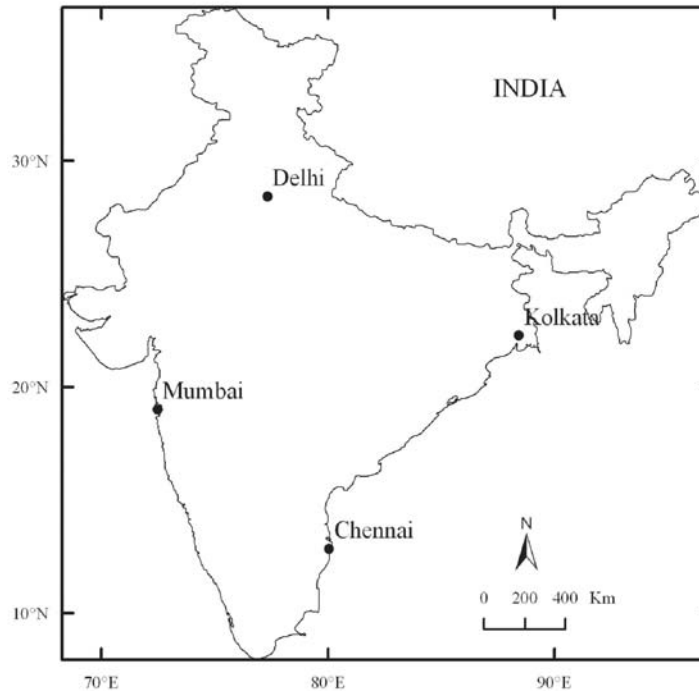


Figure 1. Location of the Selected Cities

et al., (1966). The method of moving average, also known as running mean, was used to smoothen the temperature series. This method helped to highlight the periodic variations in the series.

In this study population of the city has been used as an index of urbanization. Several other parameters such as land cover, land use change, automobile registration, energy consumption and construction activities can be used as indices to indicate the degree of urbanization. But individual effects of each statistics can not be added to make a single meaningful quantity, that is, the urbanization effect. Secondly, it is not possible to get the data of these parameters over a longer period for majority of cities in India. Instead, one may select population of the city, where the climatological station is situated, as population implies most of the activities related to urbanization. One of the important analyses performed in the study was associated with identification of less urbanized period (LUP) and more urbanized period (MUP). The less and more urbanized periods are identified based on the population trends. The population trends for all the cities depict consistent pattern, and therefore, the pattern for one city, Mumbai, is illustrated in Fig.2. It is noticed that, up to 1941 the population was stable or increased very slowly. But after 1941 i.e. from the census year of 1951 the population started increasing rapidly as compared to 1941. Taking into consideration this

variation in the growth pattern, the period from 1901 to 1940 is identified as less urbanized period (LUP) as compared to the period between 1941 and 2000. This phase, with significant rise in population can be considered as more urbanized period (MUP). Thus, the main criterion to define LUP and MUP is the population of the city. The period between 1901 and 1941 is characterized by very low population and is referred as LUP and period thereafter with high population was considered as MUP. The average population during LUP and MUP can be imagined as an index of urbanization which has been used in statistical analysis. Student's t-test has been applied to detect whether the average population, temperature and rainfall during LUP and MUP varied significantly. This Student's t-test is usually applied to compare the means of two data sets which are related to each other. After comparing the means by applying this test, it can be concluded whether these two means differ significantly. The test proceeds with a null hypothesis that there is no significant difference between the two means.

The t-test based on paired observations is defined by the following formula:

$$t = \frac{\bar{d} - 0}{S} \times \sqrt{n} \quad \text{or} \quad t = \frac{\bar{d} \sqrt{n}}{S}$$

where \bar{d} = the mean of the differences

S = the standard deviation of the differences.

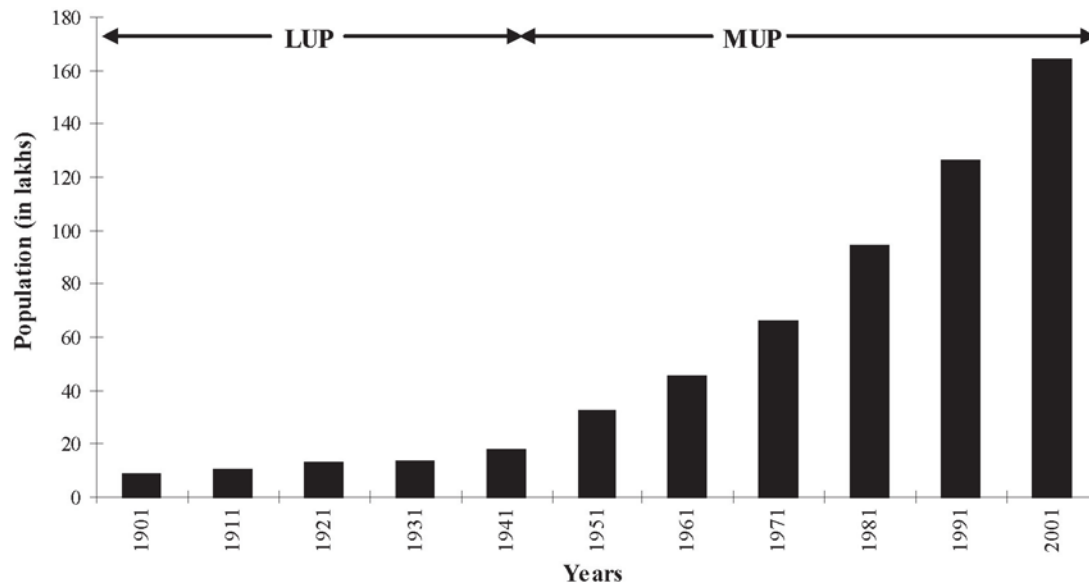


Figure 2. Less Urbanized Period (LUP) and More Urbanized Period (MUP) - Mumbai

The value of standard deviation is calculated as follows:

$$S = \sqrt{\frac{\sum (d - \bar{d})^2}{n-1}} \text{ or } \sqrt{\frac{\sum d^2 - n(\bar{d})^2}{n-1}}$$

The calculated value of t has to be compared with the table value. If the computed value is higher than the table value for a given significant level the null hypothesis is rejected and therefore it can be concluded that there is significant difference between the two means. It should be noted that t is based on $n-1$ degrees of freedom.

This test is used here to find out whether the level of urbanization varied significantly between the two periods in the selected cities. Further, it is also used to test whether the average temperature and rainfall between the two periods defined differ significantly.

RESULTS AND DISCUSSION

Trend Analysis

Figures 3a-e show the observed trend in TM (mean temperature), TMAX (maximum temperature) and TMIN (minimum temperature) in annual and seasonal series of the cities. 11-year running mean was plotted to identify decadal variations in the series. Table 1 represents the change in temperature observed during the last century. The temperature series of Delhi had a break, and therefore, the temperature change observed during the recent series is taken into consideration.

Table 1. Temperature Change (°C) observed during the last century

	TM	TMAX	TMIN
Annual			
Delhi	0.2	-0.5 *	0.99 *
Kolkata	0.99 *	1.3 *	0.72 *
Mumbai	0.6 *	1.62 *	-0.4 *
Chennai	0.56 *	0.57 *	0.54 *
Summer			
Delhi	-0.38	-1.31 *	0.6
Kolkata	1.4 *	0.5	1.0 *
Mumbai	0.42 *	1.11 *	-0.28
Chennai	1.49 *	2.0 *	1.0 *
Monsoon			
Delhi	0.08	-0.13	0.28
Kolkata	0.71 *	1.3 *	0.14
Mumbai	0.3 *	0.89 *	-0.3 *
Chennai	-0.2	-0.3	-0.04
Post-Monsoon			
Delhi	0.9	-0.4	2.27 *
Kolkata	1.5 *	2.1 *	0.9 *
Mumbai	1.07 *	2.46 *	-0.32
Chennai	0.37 *	0.25	0.49 *
Winter			
Delhi	0.39	-0.4	1.3 *
Kolkata	1.24 *	1.38 *	1.09 *
Mumbai	0.95 *	2.45 *	-0.55 *
Chennai	0.74 *	0.54 *	0.94 *

* Significant at 95% confidence level

A positive change in annual TM is observed at all the cities (Fig.3a.) This change was significant at Kolkata, Mumbai and Chennai with a temperature increase of 1°C, 0.6°C and 0.56°C respectively (Table 1). A steeper significant increase in annual TMAX was observed at these three cities, whereas Delhi recorded a significant decrease in annual TMAX. At this location, TMAX decreased significantly by 0.5°C. But the same location recorded a significant secular increase of 1°C in annual TMIN. More than half a degree increase in annual TMIN was also seen at Kolkata and Chennai. On the other hand, Mumbai defied positive change by recording a decreasing trend in TMIN. 11-year running mean revealed no major variations, except that, at Delhi the TMIN was higher during 1950s.

During summer (Fig.3b) TM was again observed to have increased at Kolkata, Mumbai and Chennai. But the increase was higher at Kolkata (1.4°C) and Chennai (1.49°C) as compared to Mumbai (0.42°C). Interestingly, Kolkata and Chennai are located on the east coast, whereas Mumbai on the west coast. On the other hand, Delhi with a continental location, showed decreasing trend which was not found to be significant. This decrease in TM was mainly due to a steep decrease in summer TMAX (-1.3°C) at this city. Other cities recorded increase in TMAX; higher rates were observed at Mumbai (1.1°C) and Chennai (2°C). Summer TMIN increased at three locations except Mumbai where it has decreased insignificantly. An increase of 1°C at Kolkata and Chennai was statistically significant. Overall, it can be said that summer days at Kolkata, Mumbai and Chennai are warming and at Delhi they are cooling. Summer nights have shown warming signs at all locations except Mumbai.

Summer is followed by the season of rains, monsoon. Monsoon TM showed significant rise at Kolkata (0.7°C) and Mumbai (0.3°C), negligible insignificant rise at Delhi and insignificant decrease at Chennai (Table 1, fig. 3c). Similar trends were observed in TMAX, but increase at Kolkata and Mumbai was higher and Delhi registered insignificant decrease along with Chennai. Minimum temperature during monsoon has significantly decreased at Mumbai and insignificantly at Chennai. At Delhi and Kolkata an insignificant increase was noticed.

October and November are considered as post-monsoon season. This is the time when rain ceases, sky becomes clearer and temperature rises. Under these circumstances if the temperature continues to rise it will lead to lowering of comfort levels in the cities. This has what exactly happened in the post-monsoon season. All cities have registered rise in

post-monsoon TM which is significant at Kolkata (1.5°C), Mumbai (1.1°C) and Chennai (0.4°C). The trend is almost secular at these cities as the 11-year running mean does not show any major temporal variations (fig. 3d). The trend of post-monsoon TMAX at Delhi continued to be insignificant but shifted on negative side. A significant positive trend with a very high increase, more than 2°C, was observed at Kolkata and Mumbai (Table 1). The trend for Chennai was positive but insignificant. However, at the same location post-monsoon TMIN significantly increased by 0.5 °C. Rise in TMIN was also noticed for Kolkata and Delhi. At Delhi the rise was very steep, about 2.3°C.

During winter a rise in TM was recorded at all stations, but was significant at Kolkata, Mumbai and Chennai (Table 1). 11-year running revealed that the temperature, at Kolkata, decreased recently but registered an overall increase in the last century. This is mainly due to rise in temperature between late 1930s and early 1960s. Though winter TM showed insignificant increase at Delhi, winter TMIN at this location recorded significant rise of 1.3 °C. The increase in winter TM at Kolkata and Chennai is due to both, significant increase in TMAX as well as TMIN. But, the increase at Mumbai is mainly due to higher significant increase in TMAX (2.5°C) though TMIN has decreased significantly (-0.6°C). At Mumbai the decrease in winter TMIN is without major variations, but winter TMAX showed decrease between mid 1950s and early 1970s and thereafter it has increased (Fig 3e). On the other hand, winter TMAX has decreased at Kolkata in the recent decades in spite of an overall increase.

In general it can be said that most of the tendencies showed increase in temperature. The effect of urbanization is usually reflected in the increase in night-time temperatures represented by TMIN (Wilbanks & Kates 1999; Sinha Ray, Mukhopadhyay & Chowdhury 1997). The present work also revealed that majority of the tendencies witnessed significant increase in TMIN, but with inconsistent rates. For example, during post-monsoon, the highest significant increase was registered at Delhi in post-monsoon TMIN (2.3°C) and lowest significant increase was recorded at Chennai (0.5°C) in the same season. This inconsistency is further revealed by the decreasing trends in TMIN during all seasons at Mumbai. This decrease is significant during winter and monsoon season. From these results it can be inferred that though urbanization is leading to warming, it is not the case always. Secondly, the rate of change in temperature, in rapidly urbanizing cities may vary. The urbanization effect was also dealt with by adopting a

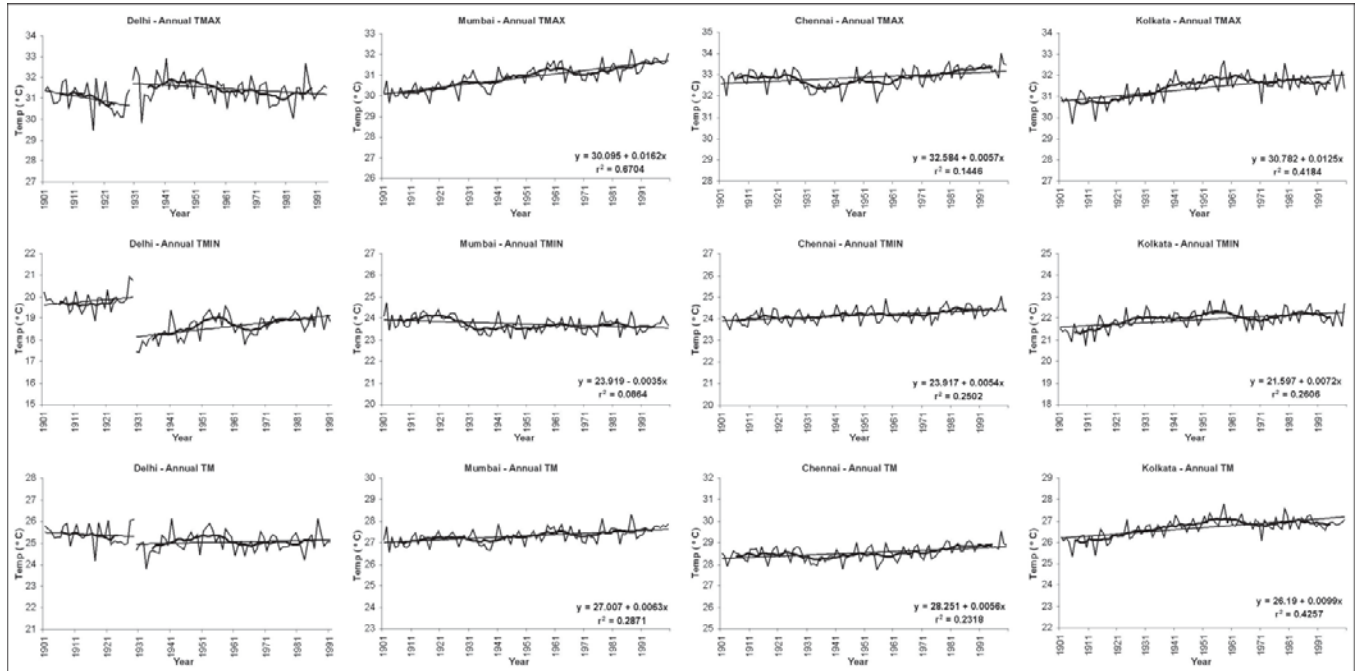


Figure 3a. Annual temperature series (thin line) with 11-year running mean (thick line), linear trend (straight line) and equations

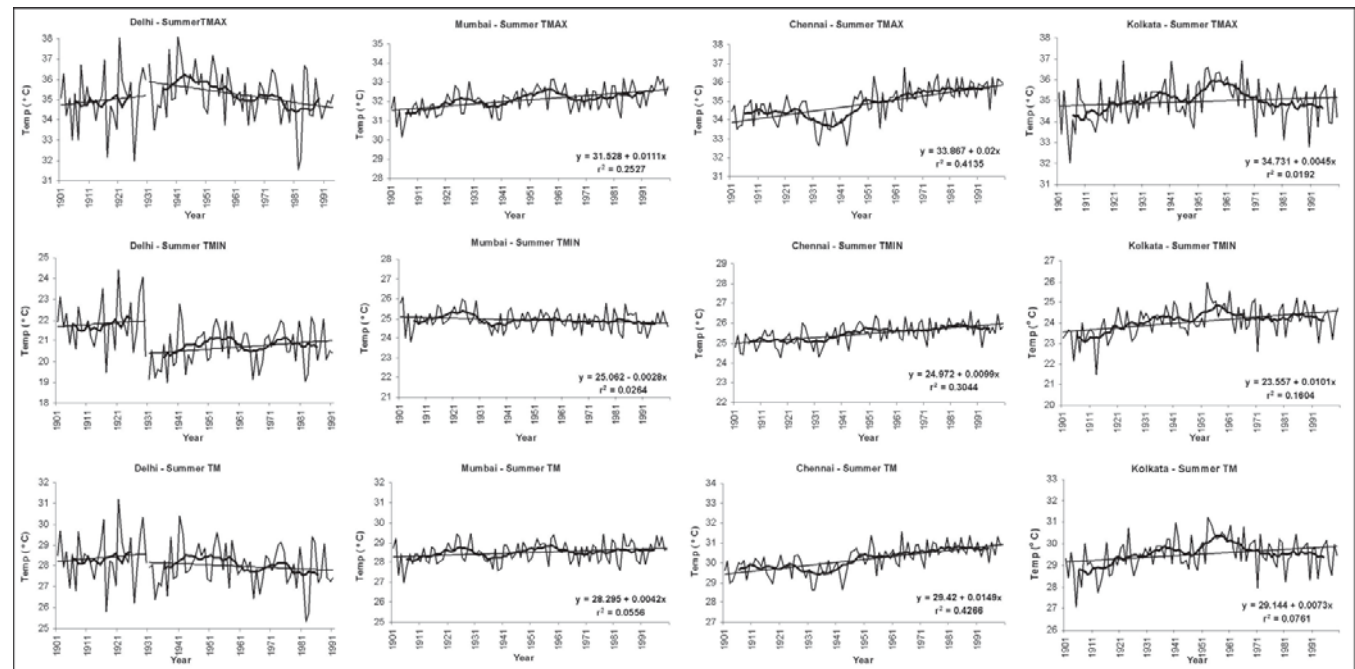


Figure 3b. Summer temperature series (thin line) with 11-year running mean (thick line), linear trend (straight line) and equations

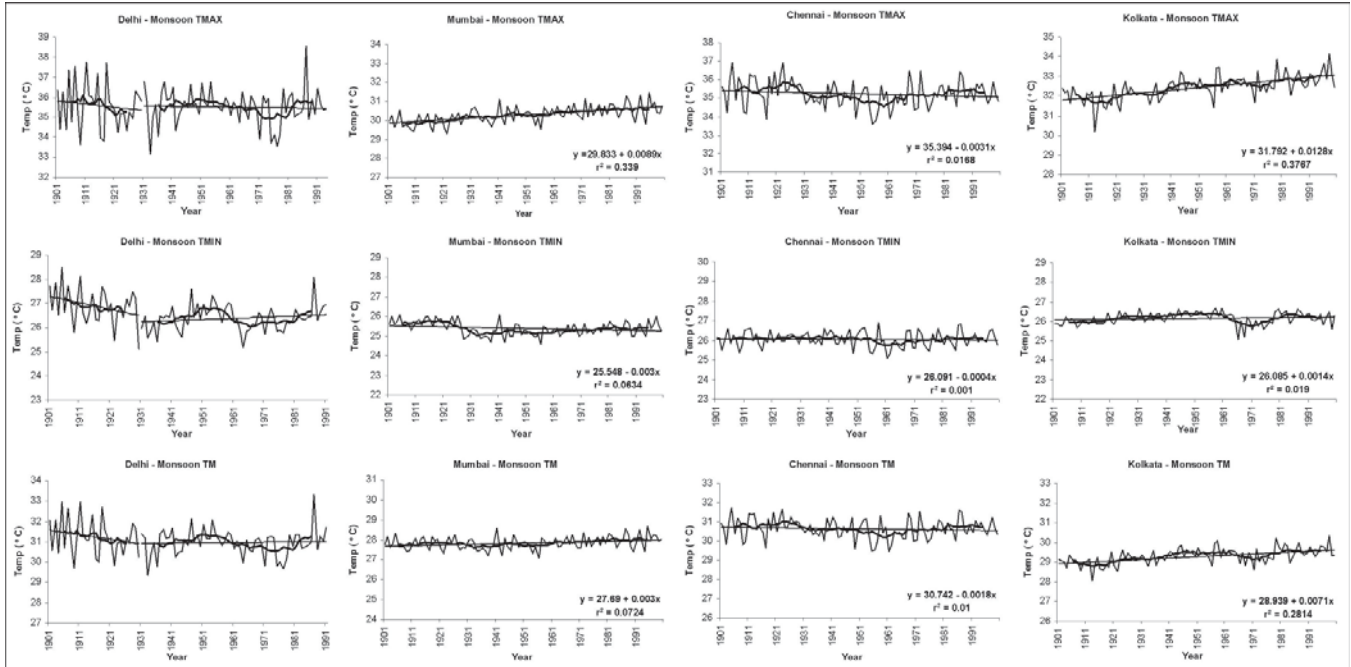


Figure 3c. Monsoon temperature series (thin line) with 11-year running mean (thick line), linear trend (straight line) and equations

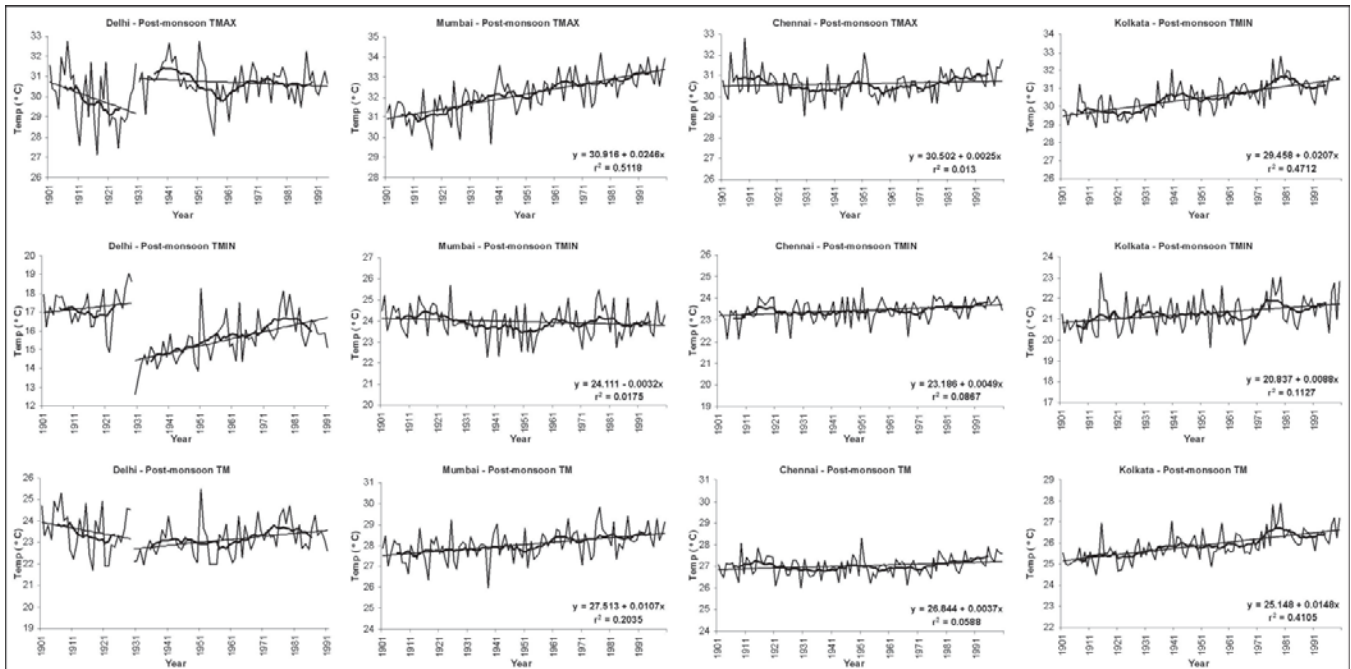


Figure 3d. Post-monsoon temperature series (thin line) with 11-year running mean (thick line), linear trend (straight line) and equations

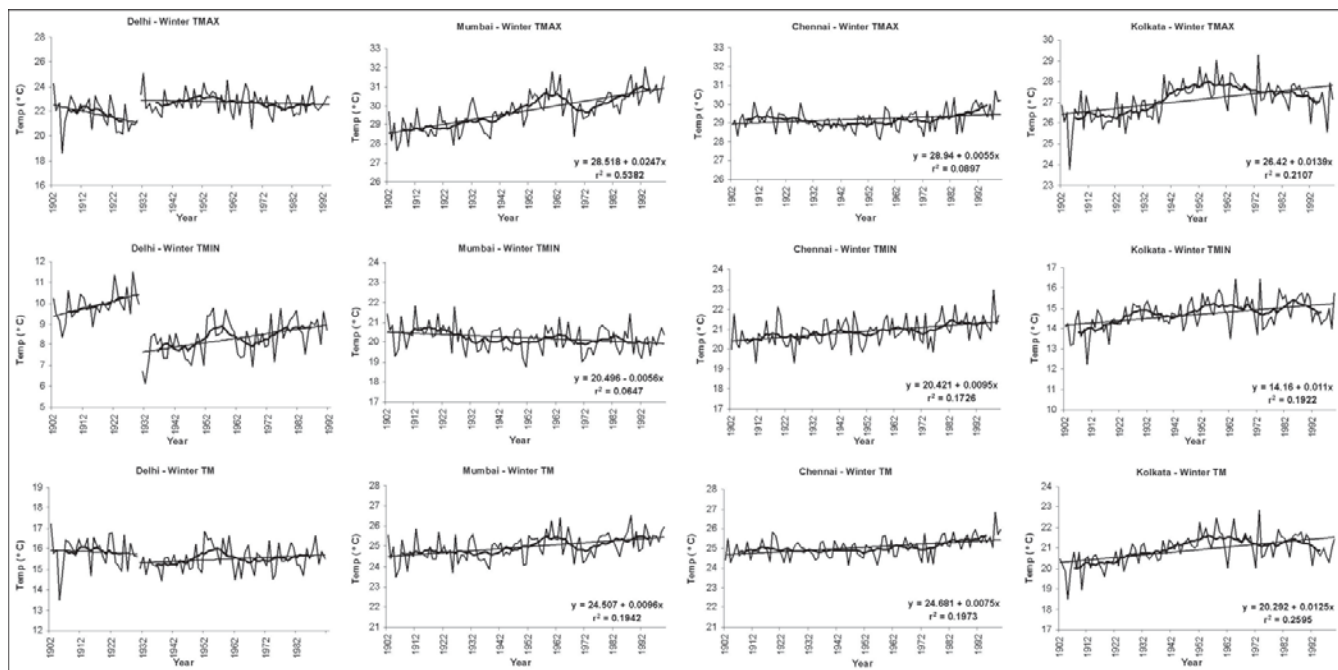


Figure 3e. Winter temperature series (thin line) with 11-year running mean (thick line), linear trend (straight line) and equations

different approach in which combined effect of the population and temperature change at all these cities has been considered. Moreover, the effect on rainfall is also highlighted.

Effect of Urbanization

The four mega cities of India, Delhi, Mumbai, Kolkata and Chennai are different in many ways from other cities of India. Each of these cities has population exceeding six million; in fact Mumbai, Kolkata and Delhi have more than ten million populations. The population density in these cities is very high. With high-rise buildings, the cities are able to absorb more solar radiation. These cities also consume huge resources, particularly the fossil fuels due to large vehicular population. At present, Delhi alone accounts for 7% of all motor vehicles in India (Singh et al., 2005). All these activities would affect the climate of these cities.

As per the LUP and MUP discussed earlier, population and temperature change between these two periods was computed. Since, for Delhi the temperature data during 1901 to 1930 was not available the mean value for the LUP was obtained from IMD. In addition, to study the effect of urbanization during different seasons, temperature change for different

seasons has also been analysed. Average population during LUP and MUP in megacities is compared in Fig.4 and the Students t-test is used to find whether the difference in population between these two periods is significant. It was found that the difference is significant (at 95% level) indicating that the level of urbanization varied significantly between the two periods. The result is also depicted in table 2 a-f, which represents the temperature change at annual and seasonal scales. It is observed that at annual scale the difference between two period temperature averages is significant. The table further shows that the annual mean temperature at all the cities was higher during MUP indicating rise in temperatures with increasing urbanization.

At seasonal scale also temperatures during MUP were higher than those in LUP. The only exceptions are Delhi and Chennai for summer and monsoon seasons respectively (Table 2 c&d). For both these seasons the Students t-test indicated no significant difference between the mean temperatures of LUP and MUP. However, the difference is significant for post-monsoon and winter seasons. This also suggests that the effect of urbanization is more pronounced during post-monsoon and winter season than summer or monsoon season over the megacities.

To further understand the relationship between

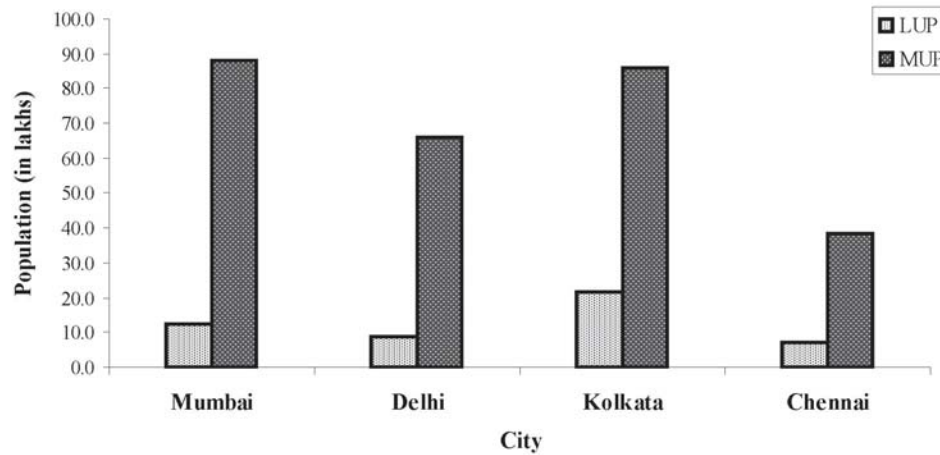


Figure 4. Difference in average population of the cities during LUP and MUP

Table 2 a-f. Population and temperature during Less Urbanized Period (LUP) and More Urbanized Period (MUP) at the cities

a

	Average Population (in lakhs)	
CITY	LUP	MUP
Mumbai	12.47	87.96
Delhi	8.60	66.06
Kolkata	21.80	85.83
Chennai	7.06	38.21

Significant at 95% level by Student's t-test

b

	Mean Temperature (°C) - Annual	
	LUP	MUP
	27.1	27.5
	25.0	25.1
	26.3	26.9
	28.4	28.6

Significant at 95% level by Student's t-test

c

	Mean Temperature (°C) - Summer	
CITY	LUP	MUP
Mumbai	28.3	28.6
Delhi	28.1	27.9
Kolkata	29.2	29.7
Chennai	29.7	30.5

Not significant

d

	Mean Temperature (°C) - Monsoon	
	LUP	MUP
	27.8	27.9
	30.9	31.0
	29.0	29.5
	30.8	30.6

Not significant

e

	Mean Temperature (°C) - Post-monsoon	
CITY	LUP	MUP
Mumbai	27.7	28.3
Delhi	22.8	23.3
Kolkata	25.5	26.2
Chennai	27.0	27.1

Significant at 95% level by Student's t-test

f

	Mean Temperature (°C) - Winter	
	LUP	MUP
	24.7	25.2
	15.3	15.6
	20.4	21.3
	24.9	25.2

Significant at 95% level by Student's t-test

urbanization and temperature change, regression equations were formulated. For this purpose the temperature change between these two periods was taken as dependent variable and the logarithm of population change during the same period as an independent variable. This approach was earlier used by Chung, Choi & Yun (2004) to detect the urbanization effect at some cities in Korea. The analysis was done for mean annual temperature as well as for mean temperature of all the seasons, that is, summer, monsoon, post-monsoon and winter. The Fig.5 shows that, at annual scale the slope of the

regression line is positive indicating increase in temperature change with increase in population change. But on seasonal scale this is applicable for monsoon, post-monsoon and winter season and not for summer season. For summer season, it is observed that the regression line slopes downward revealing a negative relationship between population change and temperature change. Thus, for this season, it can be inferred that the temperature decreased as the population increased. Thus, by using this method it is observed that the effect of urbanization is not same during all the seasons.

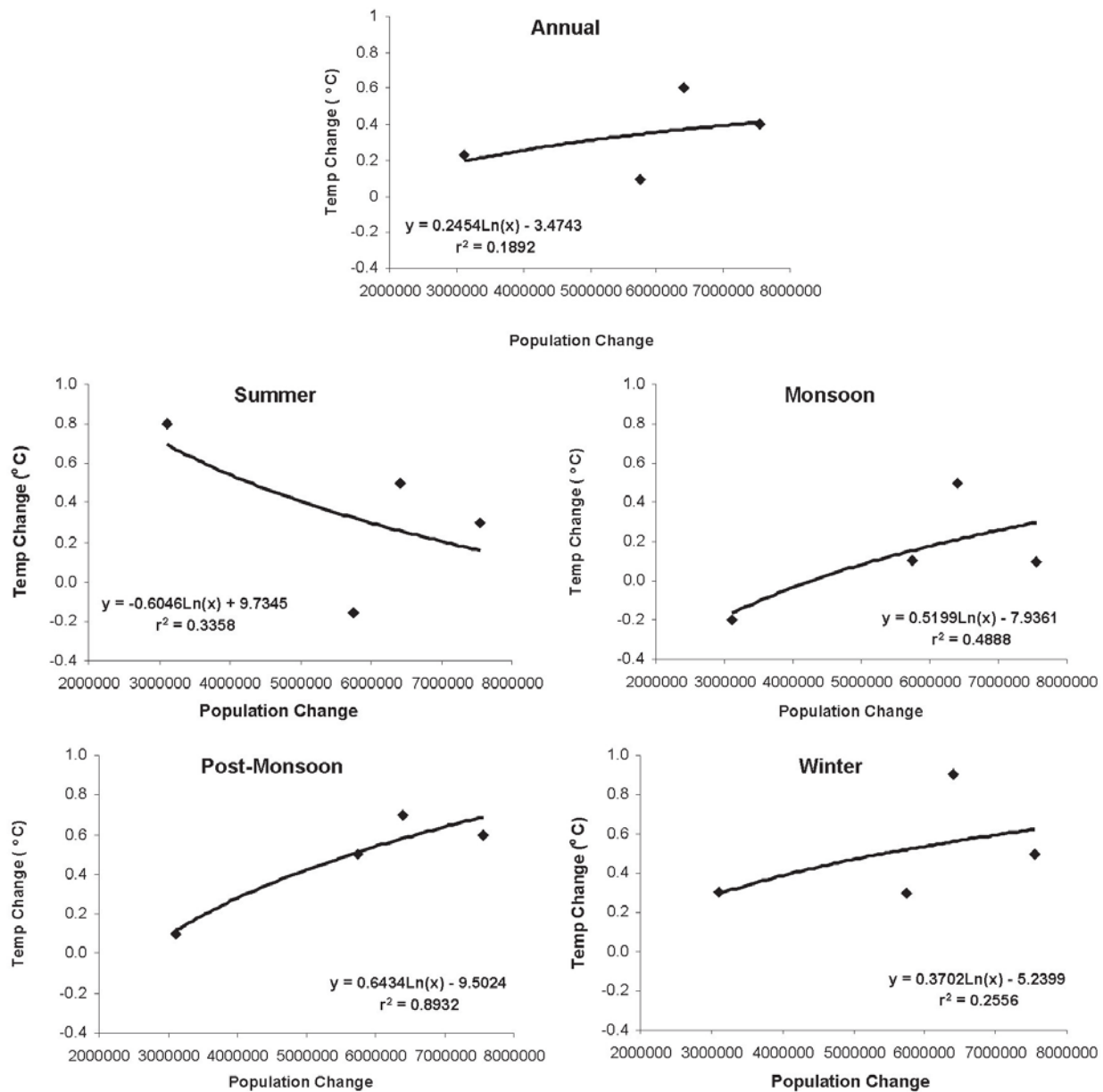


Figure 5. Effects of Urbanization (expressed as the logarithm of population increase from 1901-2001) on the observed warming (expressed as the difference of two normals 1901-1940 and 1941-2000) at the four mega cities.

The effect of urbanization on the rainfall of megacities was evaluated by considering the annual rainfall of the megacities. For this purpose too, the same technique was adopted to detect whether the difference is significant between LUP and MUP average rainfall. The average rainfall during these two periods is represented in Table 3. The table indicates increase in the rainfall during MUP as indicated by higher values for this period. The Student's t-test, which was used to find out whether this difference was statistically significant, revealed that this difference was not significant. Thus, this leads us to conclude that the effect of urbanization is more pronounced on temperature and not on rainfall.

Table 3. Average rainfall during LUP and MUP at the cities

Sr. No.	CITY	Rainfall (mm)	
		LUP	MUP
1	Mumbai	1772.3	2139.4
2	Delhi	656.2	756.1
3	Kolkata	1615.9	1647.9
4	Chennai	1273.0	1330.0
Difference is not significant at 95% level			

CONCLUSIONS

From the above results it is clear that majority of the trends, both annual and seasonal, showed increasing tendency in temperature during the last century. The annual mean temperature at all cities has increased. On seasonal scale this applies to post-monsoon and winter as all cities showed increase in TM, though, significant only at three. One of the effects of urbanization is rise in minimum temperature of the cities. While majority of the trends indicate rise in minimum temperature at annual and seasonal scale, trends at Mumbai consistently show decrease in TMIN. The decrease was observed during all seasons at this location, but it was significant during winter and monsoon. Another aspect of the rise in minimum temperature is that the rates of increase vary considerably at all these locations. For example, during post-monsoon TMIN has increased by 2.3 °C at Delhi whereas it increased merely by 0.5 °C at Chennai. The difference in rates has also led to asymmetry in temperature trends at these cities. In some cases trends in TMAX and TMIN have moved in opposite direction. Moreover, TMAX has increased rapidly as compared to TMIN with some exceptions.

The analysis based on LUP and MUP suggests that the level of urbanization has increased significantly during MUP. It is observed that the temperature difference between the two periods is significant, with higher temperatures in MUP. At seasonal scales the difference is significant for post-monsoon and winter seasons. This indicates that the effect of urbanization is more pronounced during these seasons, as far as warming is concerned. Further, it was noticed for summer, that a negative relationship exists between population change and temperature change. Rainfall analysis based on LUP and MUP indicated no significant change between the rainfall of LUP and MUP.

Above results may seem simple to interpret but are in fact very complex. Rise in minimum temperatures points to urbanization effect. However, trends at Mumbai pose a question. Secondly, if the effect of urbanization is dominant, minimum temperatures should have increased at higher rates than maximum. On the other hand, effect of urbanization is not similar in all the seasons. Moreover, it has not led to any significant change in rainfall. One important aspect of India's climate is its dominance by monsoonal circulation. This in turn is controlled by many other global and regional factors. Study of these factors was outside the scope of this research. It is quite possible that the changes in lower atmosphere may be responsible for the variations observed at these cities. Since the focus of this study was the effect of urbanization, based on the results obtained, it can be said that an inconsistent climatic response to urbanization is observed at these cities.

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Dr. Amit G. Dhorde

Dr. Amit Dhorde is currently working as Lecturer in the Department of Geography, University of Pune. Dr. Dhorde has completed his masters and Ph.D. from the Department of Geography, University of Pune. His field of specialization is climatology and has carried out his doctoral research on long-term trends in selected weather parameters at major cities of India. He has also completed a research project on this topic which was funded by University Grants Commission. Study of urban heat islands (UHI) is also part of his research. One major project related to spatio-temporal variations in the UHI of Pune city using satellite data was completed recently by Dr. Dhorde. His other fields of interests include agro-climatology and environmental studies.



Dr. Anargha A. Dhorde

Dr. Anargha Dhorde is currently working at the Post-graduate Department of Geography, Nowrosjee Wadia College which is affiliated to the University of Pune. She has earlier worked as Lecturer in the Department of Geography, University of Pune. Her field of specialization is coastal geomorphology and she has completed her doctoral research on beach and creek sedimentation processes. She is also interested in environmental studies particularly involving use of remote sensing and GIS. She has completed one research project funded by University of Pune and has also worked as a co-investigator in the urban heat island project of Pune city.



Dr. Alaka Gadgil

Dr. Alaka Gadgil is Emeritus Fellow in the Department of Geography, University of Pune. She retired as Professor from the Department of Geography, University of Pune in June 2007. Her academic carrier spans over almost three decades. She has played a key role in establishing Climatology specialization in the Department of Geography, University of Pune. She has guided more than 10 Ph.Ds in her academic carrier. She has also specialized in air pollution and has been carrying out air pollution monitoring project in Pune city since 1994. The project is funded by Central Pollution Control Board, New Delhi.