

## Signal of urban heat island (UHI) effect : A case study of Mumbai metropolitan region

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**सार** – शहरी ऊष्मा द्वीप (UHI) प्रभाव की घटना की जाँच करने के लिए मुंबई महानगरीय क्षेत्र के 32 वर्षों (1976-2007) के अधिकतम और न्यूनतम तापमानों के आँकड़ों का अध्ययन किया गया है। मुंबई महानगर जिले और उपमहानगरीय जिले में क्रमशः कोलाबा और सांताक्रूज में दो मौसम स्टेशन हैं और दो स्टेशन महानगर से लगे मुंबई महानगरीय क्षेत्र (एम एम आर) के बाहरी कनारे पर स्थित स्टेशन अलीबाग और दहाणु को चुना गया है। इन चार स्टेशनों के अधिकतम और न्यूनतम तापमानों के मासिक औसत आँकड़ों की समय श्रृंखला के महत्वपूर्ण ट्रेन्ड्स की पहचान करने के लिए मैन केनडल ट्रेन्ड टेस्ट का उपयोग किया गया है। इन चार स्टेशनों के ऋतुनिष्ठ अधिकतम और न्यूनतम तापमानों के औसत की गणना की गई है और उसकी तुलना स्वतंत्र सैम्पल्स टी-टेस्ट की मदद से की गई है। इसके अलावा कोलाबा और सांताक्रूज के अधिकतम और न्यूनतम तापमानों के मासिक औसत की और आमने-सामने के दो निकटस्थ स्टेशनों के आँकड़े ग्राफ द्वारा दर्शाए गए हैं और उनकी तुलना की गई है। इन चार स्टेशनों के वर्ष 1971-2001 तक की अवधि के विंड रोज डायग्राम्स के भी विश्लेषण किए गए हैं। इस अध्ययन से यह पता चला है कि सर्दी और गर्मी में सांताक्रूज में दिन का समय अलीबाग, दहाणु और कोलाबा से अधिक गर्म रहता है जबकि सर्दी और गर्मी में कोलाबा में रात्रि का समय अलीबाग, दहाणु और सांताक्रूज से अधिक गर्म रहता है।

**ABSTRACT.** A study of maximum and minimum temperatures of Mumbai Metropolitan Region has been carried out taking 32 years (1976-2007) data to examine the incidence of Urban Heat Island (UHI) effect. Two meteorological stations *viz.*, Colaba and Santacruz, located in Mumbai city district and Suburban district, respectively and two stations located away from city on the periphery of Mumbai Metropolitan Region (MMR) *viz.*, Alibag and Dahanu have been selected. Mann-Kendall trend test has been used for detecting the significant trends in the time series of mean monthly maximum and minimum temperatures of four stations. The means of seasonal maximum and minimum temperatures of four stations have been calculated and compared with the help of Independent-Samples *t*-test. In addition, monthly averages of maximum and minimum temperatures of Colaba (Mumbai) and Santacruz *vis-à-vis* two peripheral stations have been plotted graphically and compared. Also the wind rose diagrams of four stations for the period 1971-2001 have been analysed. The study reveals that during day time in winter and summer Santacruz is warmer than Alibag, Dahanu and Colaba while during night time in winter and summer Colaba is warmer than Alibag, Dahanu and Santacruz.

**Key words** – Mumbai metropolitan region, Urban heat island effect, Mann-Kendall trend test, Independent-Samples *t*-test, Maximum and minimum temperature, Wind rose diagrams.

### 1. Introduction

The metropolitan cities in India in general and particularly Mumbai experienced rapid growth of population along with urban infrastructure in the last four decades. The growth has spilled beyond the city boundary and brought many undesirable changes in the land-use pattern within the city as well as its surrounding areas. This has resulted in decrease of urban space, natural vegetation, changes in the flow of surface water. These undesirable changes in the land use pattern brought

corresponding changes in the levels of temperature and rainfall.

Several observations have been made in this regards by various authors (Lei *et al.*, 2008; Kishtawal *et al.*, 2009; Mohapatra *et al.*, 2010) and reports like Third Assessment Report of Intergovernmental Panel on Climate Change (IPCC). From these observations it is clear that urban areas are noticeably warmer than the surrounding hinterland. This phenomenon has been described as Urban Heat Island (UHI) effect. It is well-

known that compared to non-urban areas Urban Heat Islands raise night-time temperatures more than daytime temperatures (IPCC, Third Assessment Report, 2001). The main cause of the UHI is the modification of land surface due to urban development, which uses materials that effectively retain heat. As a result of urban sprawl, the areas adjacent to cities also experience changes in land use functions, which may lead to changes in the microclimate of cities and towns in metropolitan area (Li and Zhao, 2012). UHI is seen during both summer and winter but is more prominent during calm nights of winter season.

Several recent studies have shown that urban areas due to generation and storage of more heat alter the microclimate of the region with enhanced temperature and Convective Available Potential Energy (CAPE) that gives rise to convective rainfall. Urban Heat Islands are often weak during the late morning and throughout the day and become more pronounced after sunset due to the slow release of heat from urban landscape.

Dr. J. Marshall Shepherd and colleagues at NASA's Goddard Space Flight Center observed that cities tend to be one to ten degrees Fahrenheit [0.56 to 5.6° Celsius] warmer than surrounding suburbs and rural areas and the added heat can destabilize and change the way air circulates around cities (NASA Press Releases, June 18, 2002). Sen Roy *et al.* (2011) have analysed the spatial pattern of urban heat island development within rapidly changing urban landscape of the Delhi Metropolitan Region. Deosthali (2000) has examined the impact of rapid urban growth on heat and moisture islands in Pune city. Mohapatra *et al.* (2010) found that during October, 2005 monthly mean maximum and minimum temperatures over Bangalore city were slightly higher than that of Bangalore airport. The study confirms that UHI effect leads to moisture convergence and occurrence of heavy rainfall over the city centre and also attributes enhanced rainfall to higher concentration of pollutants. An analysis of heavy rainfall events over Indian cities during the monsoon season carried out by Kishtawal *et al.* (2009) indicated that all locations where the frequency of heavy precipitation has increased during the monsoon season show a significant increase in population density, which is an indicator of fast urbanization in their vicinity. Lei *et al.* (2008) observed that the urban effects interacted with the Sea Surface Temperatures (SSTs) causing a meso-scale convergence zone over Mumbai and concluded that this convergence zone appears to be the major reason for the moisture transport and heavy rain to centre over Mumbai on 26<sup>th</sup> July, 2005. Devi (2006) studied the nature and intensity of heat island at Visakhapatnam and found that the intensity of heat island varies from 2 °C to 4 °C and intensity is high during winter season compared to summer and monsoon.

The focus of most of the existing works on UHI has been establishing the relationship between the enhanced temperature of cities and resultant rainfall and determining the role of local environmental factors in shaping of micro-climate of cities. The present study attempts to analyse the spatial pattern of differences in the temperature with reference to Mumbai city and periphery of MMR for the period 1976-2007.

The study aims to:

- (i) Estimate the trends in maximum and minimum temperatures of four selected stations *viz.*, Colaba, Santacruz, Alibag and Dahanu.
- (ii) Compare means of maximum and minimum temperatures of four stations.
- (iii) Examine the differences in the monthly averages of maximum and minimum temperatures of four stations.

## 2. Data and methodology

Data on mean monthly maximum and minimum temperatures for Alibag, Dahanu and Colaba for the period 1976-2007 have been obtained from India Met. Department (IMD), Pune. Data for Santacruz for the same period (1976-2007) have been obtained from Regional Meteorological Centre (RMC), Santacruz.

### 2.1. Region of study

A study of Mumbai and Suburban districts with respect to the warming of cities has been presented in this paper taking the Mumbai Metropolitan Region (MMR) as the study area. The Mumbai Metropolitan Region as defined by the Mumbai Metropolitan Region Development Authority Act, 1974 covers full districts of Mumbai City and Mumbai Suburbs (Greater Mumbai) and part of the Districts of Thane and Raigad. It is an urbanized area with 13 Municipal Councils, 7 Municipal Corporations and a few non-municipal towns. In addition, there are more than 900 villages in this region.

For the present study two meteorological stations *viz.*, Colaba and Santacruz, located in Mumbai city district and Suburban district and two stations located away from city on the periphery of MMR *viz.*, Alibag and Dahanu have been selected. Alibag is a coastal town located about 30 km south of Mumbai on the southernmost boundary of MMR. Dahanu is a major town in Thane district located about 65 km north of MMR (Map 1).

### 2.2. Test of significance for evaluation of trends

A non-parametric test - Mann-Kendall test - has been used here for detecting the significant trends in the time

series of mean monthly maximum and minimum temperatures of four stations. Mann-Kendall test is a statistical test widely used for the analysis of trend in climatological and in hydrological time series. There are two advantages of using this test. First, it is a non-parametric test that does not require data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to non-homogeneous time series (Karmeshu, 2012). According to this test, the null hypothesis  $H_0$  assumes that there is no trend (data are independent and randomly ordered) and this is tested against the alternative hypothesis  $H_1$ , which assumes that there is a trend.

In Mann-Kendall test data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values. If a data value from a later time period is higher than a data value from an earlier time period, the statistic  $S$  is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value sampled earlier,  $S$  is decremented by 1. The net result of all such increments and decrements yields the final value of  $S$ .

The Mann-Kendall  $S$  Statistic is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

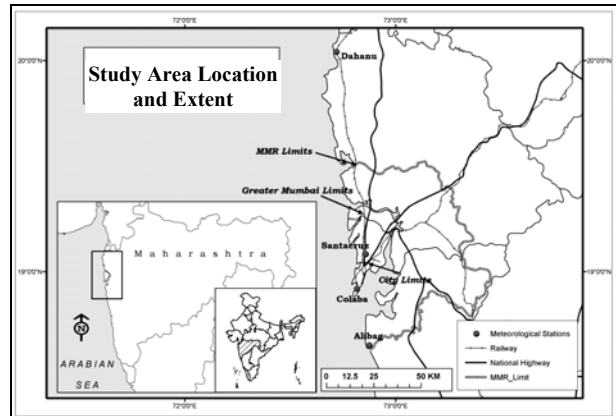
where,  $x_j$  and  $x_i$  are the annual values in years  $j$  and  $i, j > i$  respectively.

If  $n < 10$ , the value of  $|S|$  is compared directly to the theoretical distribution of  $S$  derived by Mann and Kendall. A two tailed test is used. At certain probability level  $H_0$  is rejected in favour of  $H_1$ , if the absolute value of  $S$  equals or exceeds a specified value  $S_{\alpha/2}$ , where  $S_{\alpha/2}$  is the smallest  $S$ , which has the probability less than  $\alpha/2$  to appear in case of no trend. A positive (negative) value of  $S$  indicates an upward (downward) trend.

For  $n \geq 10$ , the statistic  $S$  is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0$$

The variance ( $\sigma^2$ ) for the  $S$ -statistic is defined by:



Map 1. Study Area: Extent of MMR and location of stations

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i(i-1)(2i+5)}{18}$$

in which  $t_i$  denotes the number of ties to extent  $i$ . The summation term in the numerator is used only if the data series contains tied values. The standard test statistic  $Z_s$  is calculated as follows:

$$Z_s = \begin{cases} \frac{s-1}{\sigma} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{s-1}{\sigma} & \text{for } S < 0 \end{cases}$$

The presence of a statistically significant trend is evaluated using standardized test statistic  $Z$ . A positive (negative) value of  $Z$  indicates an upward (downward) trend. To test for either an upward or downward monotone trend (a two-tailed test) at  $\alpha$  level of significance,  $H_0$  is rejected if the  $|Z| > Z_{1-\alpha/2}$ , where  $Z_{1-\alpha/2}$  is obtained from the standard normal cumulative distribution tables (Karmeshu, 2012).

### 2.2.1. Sen's Slope estimator

Mann-Kendall test is usually combined with Theil-Sen trend estimate. In non-parametric statistics, the Theil-Sen estimator, also known as Sen's slope estimator, is an unbiased estimator of the true slope in simple linear regression. It can be computed efficiently and is insensitive to outliers; it can be significantly more accurate than simple linear regression for skewed and heteroskedastic data, and competes well against non-robust least squares even for normally distributed data in terms of statistical power.

**TABLE 1**  
**Mann-Kendall Trend Statistic for maximum temperature series of four stations**

Station	Time series	Mann-Kendall trend statistic		Sen's Slope	
		Test Z	$Z_{1-\alpha/2}$	Significance	Q
Colaba	Winter	3.04	2.5	**	0.03
	Summer	1.53	3.8	n.s	0.02
	Monsoon	-0.13	3.8	n.s.	0.00
	Post-monsoon	2.21	1.9	*	0.03
Santacruz	Winter	3.27	2.5	**	0.05
	Summer	1.90	1.6	+	0.02
	Monsoon	2.86	2.5	**	0.02
	Post-monsoon	2.50	1.9	*	0.03
Alibag	Winter	3.55	3.3	***	0.04
	Summer	2.70	2.5	**	0.04
	Monsoon	3.13	2.5	**	0.02
	Post-monsoon	3.33	3.3	***	0.05
Dahanu	Winter	2.00	1.9	*	0.03
	Summer	1.25	3.8	n.s	0.01
	Monsoon	1.75	1.6	+	0.01
	Post-monsoon	1.90	1.6	+	0.03

Q is the slope of trend line (change per unit time); For the four tested significance levels the following symbols have been used: \*\*\* for  $p < 0.001$ ; \*\* for  $p < 0.01$ ; \* for  $p < 0.05$ ; + for  $p < 0.1$ ; n.s. for  $p \geq 0.1$

**TABLE 2**  
**Mann-Kendall trend statistic for minimum temperature series of four stations**

Station	Time series	Mann-Kendall trend statistic		Sen's Slope	
		Test Z	$Z_{1-\alpha/2}$	Significance	Q
Colaba	Winter	2.38	1.9	*	0.05
	Summer	1.66	1.6	+	0.02
	Monsoon	1.40	3.8	n.s	0.01
	Post-monsoon	0.10	3.8	n.s	0.00
Santacruz	Winter	0.00	3.8	n.s	0.00
	Summer	1.28	3.8	n.s	0.02
	Monsoon	3.75	3.3	***	0.03
	Post-monsoon	-0.80	3.8	n.s	-0.02
Alibag	Winter	2.26	1.9	*	0.03
	Summer	1.96	1.9	*	0.02
	Monsoon	1.28	3.8	n.s	0.01
	Post-monsoon	-0.28	3.8	n.s	-0.004
Dahanu	Winter	1.62	3.8	n.s	0.02
	Summer	1.38	3.8	n.s	0.02
	Monsoon	1.88	1.6	+	0.01
	Post-monsoon	-0.41	3.8	n.s	-0.01

Q is the slope of trend line (change per unit time); For the four tested significance levels the following symbols have been used: \*\*\* for  $p < 0.001$ ; \*\* for  $p < 0.01$ ; \* for  $p < 0.05$ ; + for  $p < 0.1$ ; n.s. for  $p \geq 0.1$

TABLE 3

Difference of means (1976-2007) – Maximum temperature

	Winter	Summer	Monsoon	Post-monsoon
C-A	0.9* (30.7- 29.8)	0.5* (32.5-32.0)	0.1 (30.6-30.5)	0.4 (33.2-32.8)
C-D	2.0* (30.7- 28.7)	-0.1 (32.5-32.6)	-0.6 (30.6-31.2)	0.6 (33.2-32.6)
C-S	-0.8* (30.7-31.5)	-0.5* (32.5-33.0)	-1.0 (30.6-30.7)	-0.3 (33.2-33.5)
S-A	1.7* (31.5-29.8)	1.0* (33.0-32.0)	0.2 (30.7-30.5)	0.7 (33.5-32.8)
S-D	2.8* (31.5-28.7)	0.4* (33.0-32.6)	-0.5 (30.7-31.2)	0.9 (33.5-32.6)
A-D	1.1* (29.8-28.7)	-0.6* (32.0-32.6)	-0.7 (30.5-31.2)	0.2 (32.8-32.6)

C-A→Colaba-Alibag, C-D→Colaba-Dahanu, C-S→ Colaba- Santacruz, S-A→Santacruz-Alibag, S-D→Santacruz-Dahanu, A-D→Alibag-Dahanu; \* indicates values significant at  $\alpha = 0.05$

If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple nonparametric procedure developed by Sen (1968). This means that linear model  $f(t)$  can be described as:

$$f(t) = Qt + B$$

where,  $Q$  is the slope and  $B$  is a constant.

To derive an estimate of the slope  $Q$ , the slopes of all data pairs are calculated

$$Q_i = \frac{x_j - x_k}{j - k}, 1, 2, \dots, N, j > k$$

If there are  $n$  values of  $x_i$  in the time series we get as many as  $N = n(n - 1)/2$  slope estimates  $Q_i$ . The Sen's estimator of slope is the median of these  $N$  values of  $Q_i$ . The  $N$  values of  $Q_i$  are ranked from the smallest to the largest and the Sen's estimator is

$$Q = \begin{cases} \frac{Q_{N+1}}{2} & \dots \text{If } N \text{ is odd} \\ \frac{1}{2} \left( \frac{Q_N}{2} + \frac{Q_{N+2}}{2} \right) & \dots \text{If } N \text{ is even} \end{cases}$$

A  $100(1-\alpha)\%$  two-sided confidence interval about the slope estimate is obtained by the non- parametric technique based on the normal distribution. Data are processed using an Excel macro named MAKESENS created by Finnish Meteorological Institute (2002).

### 2.3. Comparison of means

Independent-Samples  $t$ -test has been used for the comparison of the seasonal means of maximum and minimum temperatures of four stations. The significance of the difference of the means between the two stations is tested by Student's  $t$ -test. In the present study, Independent Sample  $t$ -test assuming unequal variance has been used. The two-sample  $t$ -test is fairly robust to departures from normality.

This test also known as Welch's  $t$ -test is used only when the two population variances are assumed to be different (the two sample sizes may or may not be equal) and hence must be estimated separately. The  $t$ -statistic to test whether the population means are different can be calculated as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}}$$

$$\text{where, } S_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

where,  $s^2$  is the unbiased estimator of the variance of the two samples,  $n$  = number of participants, 1 = group one, 2 = group two. In this case  $S_{\bar{X}_1 - \bar{X}_2}^2$  is not a pooled variance. For use in significance testing, the distribution of the test statistic is approximated as being an ordinary Student's  $t$  distribution with the degrees of freedom calculated using Welch - Satterthwaite equation as;

$$d.f. = \frac{\left( \frac{S_1^2}{n_1} + \frac{S_2^2}{n_2} \right)^2}{\frac{\left( \frac{S_1^2}{n_1} \right)^2}{(n_1 - 1)} + \frac{\left( \frac{S_2^2}{n_2} \right)^2}{(n_2 - 1)}}$$

## 3. Results and discussion

### 3.1. Trends in mean maximum temperature

The results of the analysis of the trend coefficients along with the values of Mann-Kendall trend statistics ( $Z$ ) and trend values ( $Q$ ) for seasonal series of mean maximum temperature of four stations are depicted in Table 1. The series of mean maximum temperature with  $Z$  value greater than  $Z_{1-\alpha/2}$  value show statistically significant trends with different levels of significance. The winter mean maximum temperature at all four stations exhibit

TABLE 4

## Difference of Means (1976-2007) – Minimum temperature

	winter	summer	monsoon	Post-monsoon
C-A	2.4* (20.6-18.2)	1.2* (25.0-23.8)	0.2* (25.5-25.3)	1.6* (24.1-22.5)
C-D	2.6* (20.6-18.0)	0.9* (25.0-24.1)	-0.3* (25.5-25.8)	1.6* (24.1-22.5)
C-S	2.4* (20.6-18.2)	0.9* (25.0-24.1)	0.1* (25.5-25.4)	1.4* (24.1-22.7)
S-A	0.0 (18.2-18.2)	0.3 (24.1-23.8)	0.1 (25.4-25.3)	0.2 (22.7-22.5)
S-D	0.2 (18.2-18.0)	0.0 (24.1-24.1)	-0.4* (25.4-25.8)	0.2 (22.7-22.5)
A-D	0.2 (18.2-18.0)	-0.3 (23.8-24.1)	-0.5* (25.3-25.8)	0.0 (22.5-22.5)

C-A→Colaba-Alibag, C-D→Colaba-Dahanu, C-S→ Colaba- Santacruz, S-A→Santacruz-Alibag, S-D→Santacruz-Dahanu, A-D→Alibag-Dahanu

statistically significant trend with different levels of significance and Santacruz is showing the highest trend value of 0.05 °C per year as indicated by  $Q$  statistics. A statistically significant trend in summer mean maximum temperature is present for Santacruz and Alibag but absent for Colaba and Dahanu. The trend for Alibag is significant at 99% confidence level, while trend for Santacruz is less significant, *i.e.*, at 90% confidence level. The trend value for Alibag (0.04 °C/year) is greater than that of Santacruz (0.02 °C/year). The monsoon mean maximum temperature shows statistically significant trends at Santacruz, Alibag and Dahanu (at 99% of confidence level for Santacruz and Alibag and 90% confidence level for Dahanu) but statistically non-significant trend at Colaba. The post-monsoon and winter mean maximum temperatures at all stations show statistically significant trend. Post-monsoon trend is significant at Alibag at 99.9% confidence level, Colaba and Santacruz at 95% confidence level while Dahanu at 90% confidence level. Alibag shows highest trend in post-monsoon mean maximum temperature of 0.05 °C/year. The winter trend values are also quite high; 0.03 °C/year at Colaba and 0.05 °C/year at Santacruz at 99% significance level each, 0.04 °C/year at 99.9% significance level at Alibag and 0.03 °C/year at 95% significance level at Dahanu.

### 3.2. Trend in mean minimum temperature

The results of the analysis of the trend coefficients along with the values of Mann-Kendall trend statistics ( $Z$ ) and trend values ( $Q$ ) for seasonal series of mean minimum temperature of four stations are depicted in Table 2. A statistically significant positive trend in winter minimum temperature is seen only at Colaba (0.05 °C/year) and

TABLE 5

## Difference of Means (1976-2007) – Mean temperature

	winter	summer	monsoon	post-monsoon
C-A	1.9* (25.5-23.6)	0.8* (28.7-27.9)	0.2* (28.0-27.9)	1.0* (28.7-27.6)
C-D	2.2* (25.5-23.3)	0.3* (28.7-28.4)	-0.4* (28.0-28.5)	1.1* (28.7-27.6)
C-S	0.7* (25.5-24.8)	0.1 (28.7-28.6)	-0.1 (28.0-28.1)	0.6* (28.7-28.1)
S-A	1.2* (24.8-23.6)	0.7* (28.6-27.9)	0.2* (28.1-27.9)	0.5* (28.1-27.6)
S-D	1.5* (24.8-23.3)	0.2 (28.6-28.4)	-0.4* (28.1-28.5)	0.5* (28.1-27.6)
A-D	0.3 (23.6-23.3)	-0.5* (27.9-28.4)	-0.6* (27.9-28.5)	0.0 (27.6-27.6)

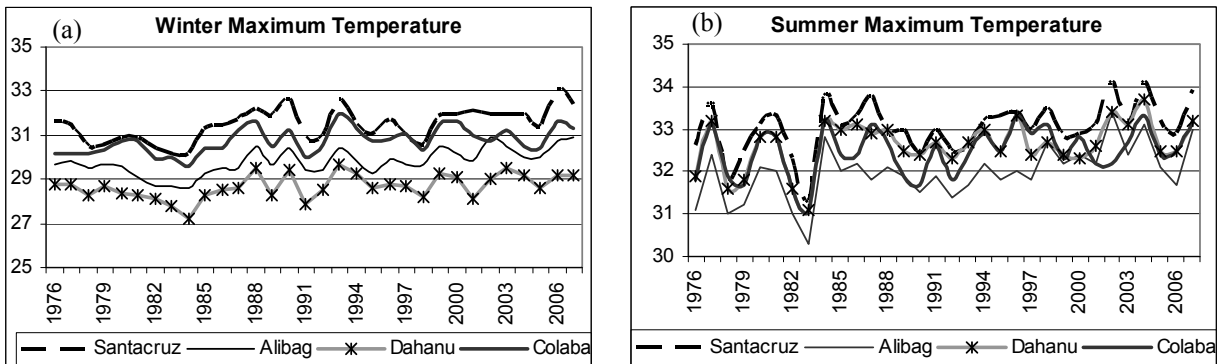
C-A→Colaba-Alibag, C-D→Colaba-Dahanu, C-S→ Colaba- Santacruz, S-A→Santacruz-Alibag, S-D→Santacruz-Dahanu, A-D→Alibag-Dahanu

Alibag (0.03 °C/year) at 95% significance level. The summer minimum temperature shows significant and positive trends at Colaba (0.02 °C/year) and Alibag (0.02 °C/year); the trend for Alibag is significant at 95% confidence level but for Colaba less significant with 90% confidence level. A highly significant trend in monsoon minimum temperature of 0.03 °C/year is observed at Santacruz (at 99.9% confidence level) while less significant trend (at 90% confidence level) of 0.01 °C/year is present at Dahanu. None of the stations shows statistically significant trend in post-monsoon minimum temperature.

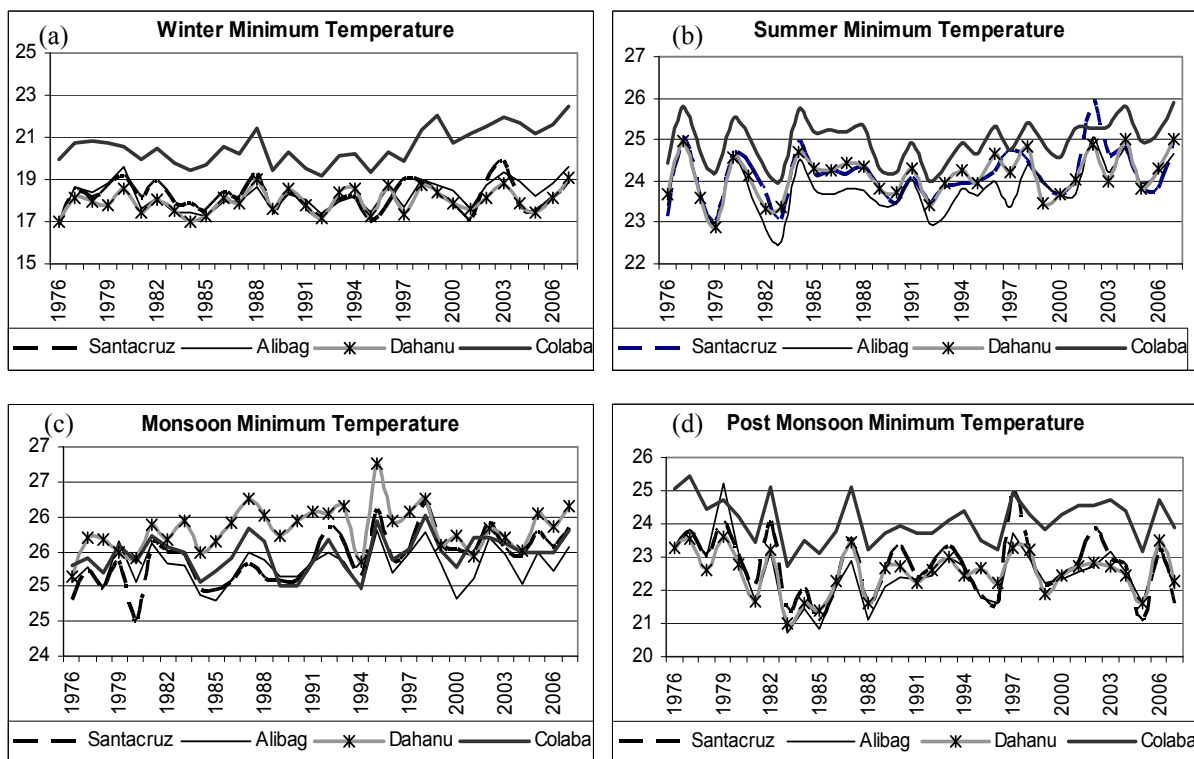
### 3.3. Comparison of mean temperatures

Comparison of means of seasonal maximum temperature series of four stations are shown in Table 3. The difference of means of winter maximum temperature of Colaba and Alibag, Colaba and Dahanu is positive and statistically significant suggesting that Colaba is warmer than Alibag and Dahanu by 0.9 °C and 2 °C, respectively. The difference of means of maximum temperature of Colaba and Santacruz is statistically significant but negative suggesting that Santacruz is warmer than Colaba by 1.7 °C. Difference of means of Santacruz and Alibag, Santacruz and Dahanu is statistically significant and positive with large differences of 1.7 °C and 2.8 °C, respectively.

During summer, the difference of means of maximum temperature of Colaba and Alibag is positive and statistically significant indicating that Colaba is warmer than Alibag during day time. A statistically significant, negative difference between means of Colaba and Santacruz imply that Santacruz is warmer than Colaba



Figs. 1(a&b). Mean monthly maximum temperature (°C) series of four stations for (a) winter season and (b) summer season

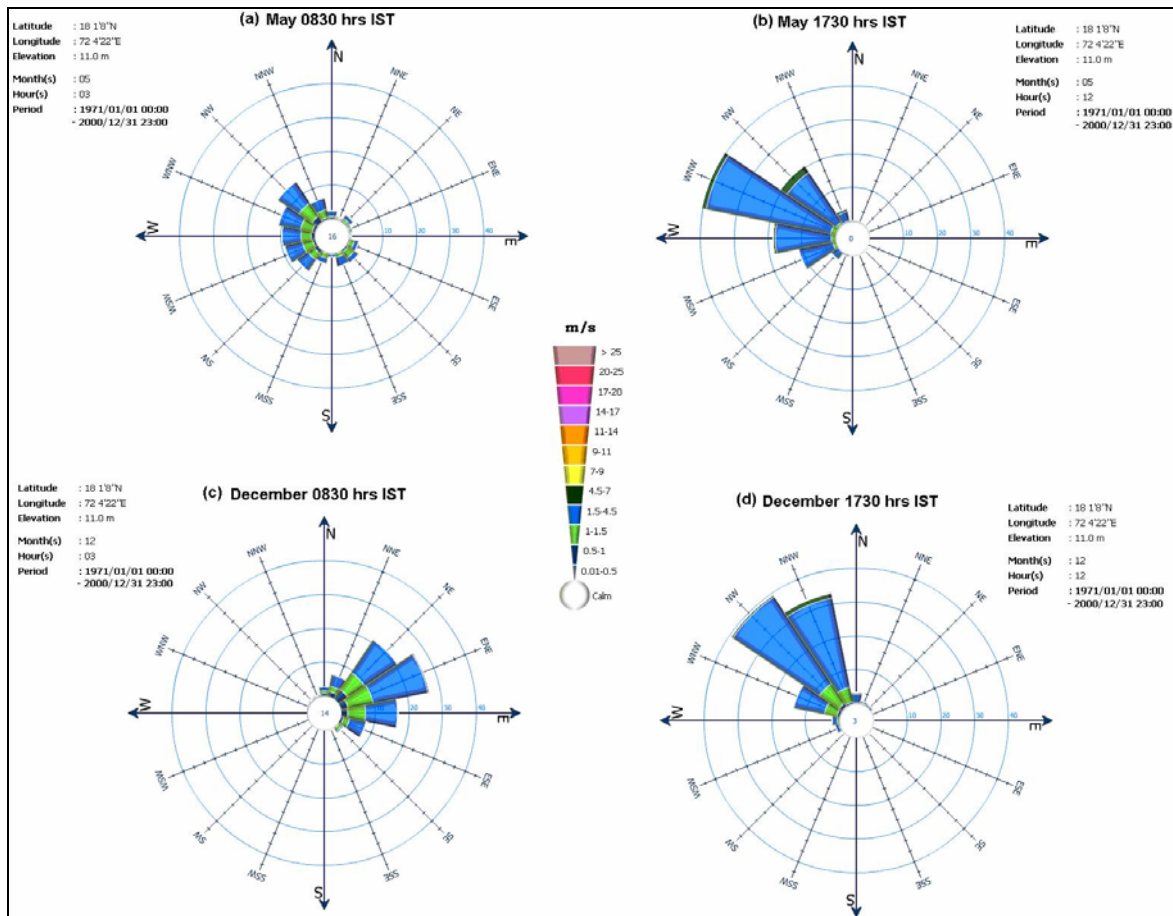


Figs. 2(a-d). Mean monthly minimum temperature (°C) series of four stations for (a) winter season, (b) summer season, (c) monsoon season and (d) post-monsoon season

by 0.5 °C. Statistically significant positive differences between means of Santacruz and Alibag and Santacruz and Dahanu indicate that Santacruz is warmer than both the peripheral stations *viz.*, Alibag and Dahanu.

Comparison of means of seasonal minimum temperature series of four stations are shown in Table 4. The differences of means of winter minimum temperature of Colaba and Alibag, Colaba and Dahanu and Colaba and Santacruz are positive, quite large and statistically significant (2.4 °C, 2.6 °C and 2.4 °C respectively). During summer, differences of means of minimum

temperatures of Colaba and Alibag, Colaba and Dahanu and Colaba and Santacruz are positive and statistically significant. During monsoon, difference in the means of minimum temperature of Colaba & Alibag and Colaba & Santacruz is positive and statistically significant. Statistically significant negative differences between means of monsoon minimum temperatures of Colaba-Dahanu and Santacruz-Dahanu suggest that Dahanu is warmer than Colaba & Santacruz during monsoon nights. Statistically significant differences between means of post-monsoon minimum temperatures of Colaba-Alibag, Colaba-Dahanu & Colaba-Santacruz are evident (Table 4).



**Figs. 3(a-d).** Wind direction and speed at Colaba (monthly averages 1971-2001) for (a) May 0830 hr IST, (b) May 1730 hr IST, (c) December 0830 hr IST and (d) December 1730 hr IST

Comparison of means of seasonal mean temperature series of four stations are shown in Table 5. The differences between means of winter mean temperature of Colaba and Alibag, Colaba and Dahanu and Colaba and Santacruz are positive and statistically significant. The differences between means of winter mean temperature of Santacruz-Alibag and Santacruz-Dahanu are positive and statistically significant. The differences between means of summer mean temperature of Colaba and Alibag, Colaba and Dahanu are positive and statistically significant but Colaba and Santacruz are not statistically significant. A Statistically significant difference between means of summer mean temperature of Santacruz-Alibag is evident but difference between means of summer mean temperature of Santacruz-Dahanu is not statistically significant. The difference between means of winter mean temperature of Alibag and Dahanu is not statistically significant.

Mean monthly averages of maximum and minimum temperatures of the four stations for the study period have been plotted graphically. The series of mean maximum

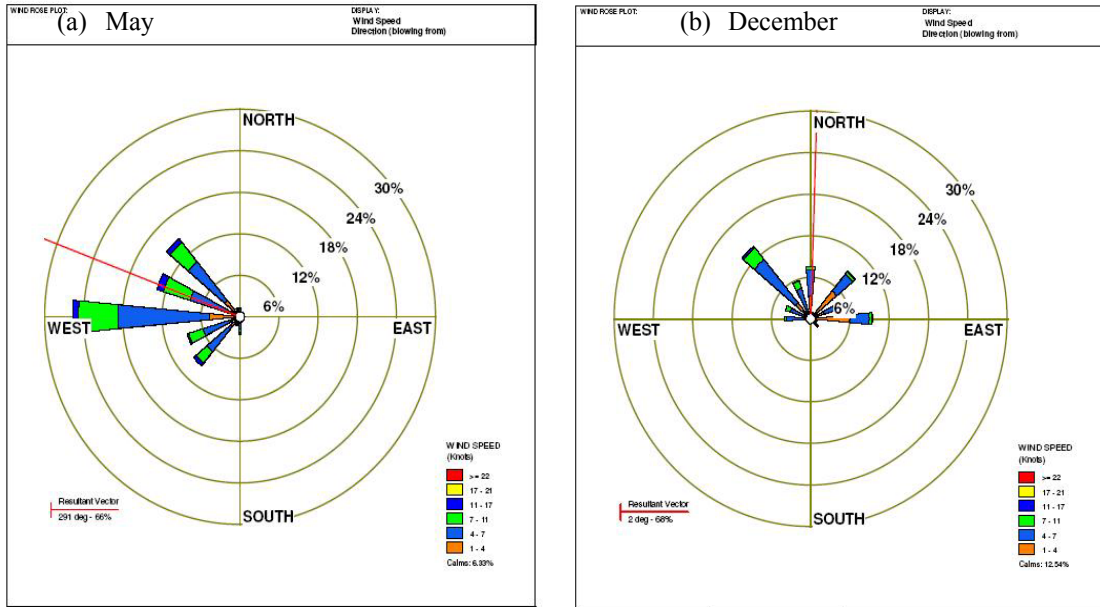
temperature of winter and summer are plotted graphically since differences in the means of monsoon and post-monsoon maximum temperatures are not statistically significant.

#### 3.4. Interannual variation of maximum and minimum temperatures of four stations

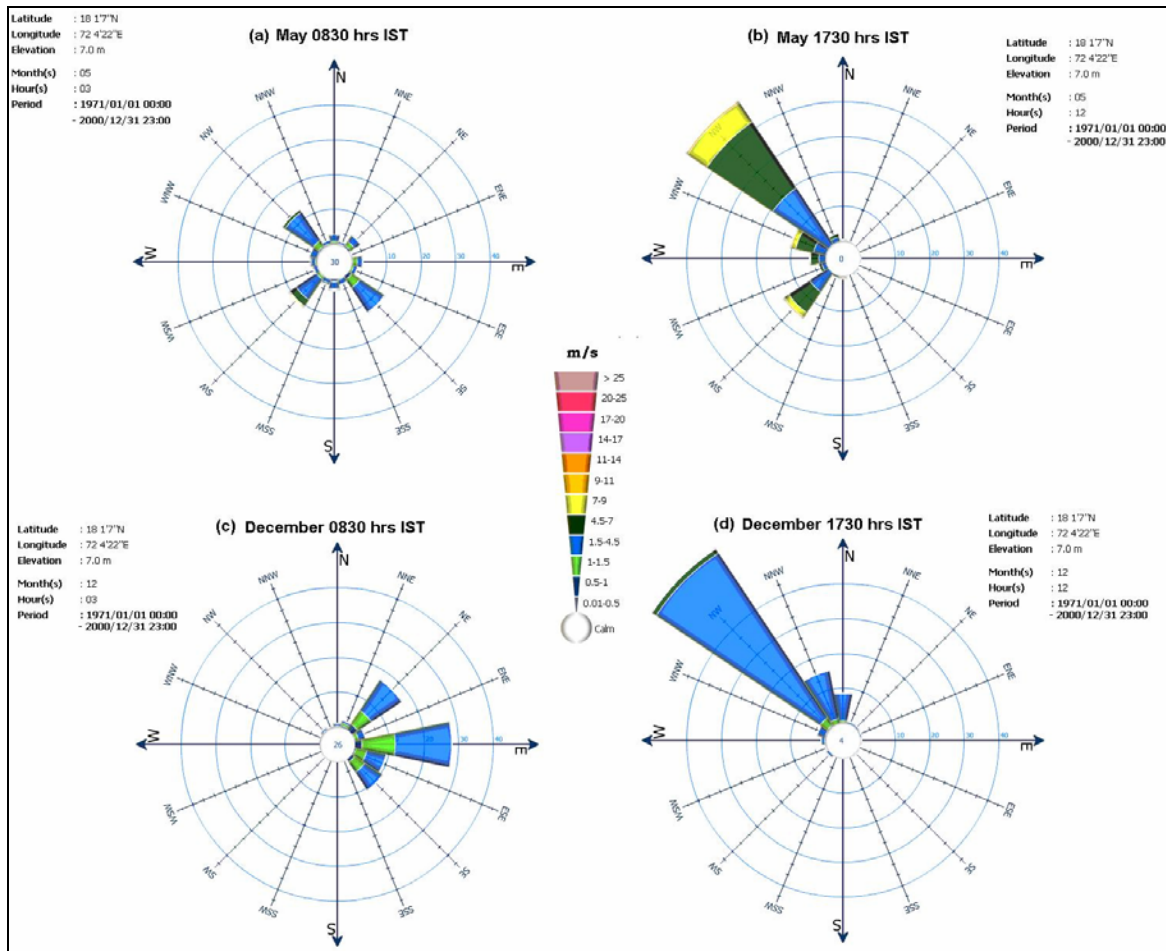
Winter maximum temperature of city station – Colaba - is more than that of two peripheral stations viz., Alibag and Dahanu [Fig 1(a)]. But Santacruz which is a suburban station shows slightly more temperature than Colaba as well as peripheral stations. During summer Colaba is warmer than Alibag but Dahanu is slightly warmer than Colaba. Santacruz is warmer than the two peripheral stations as well as Colaba [Fig. 1(b)].

Winter mean minimum temperature of Colaba is significantly higher than Santacruz, Alibag and Dahanu [Fig. 2(a)]. Summer mean minimum temperature of Colaba is also higher than Santacruz, Alibag and Dahanu [Fig. 2(b)]. Monsoon minimum temperature of Colaba is

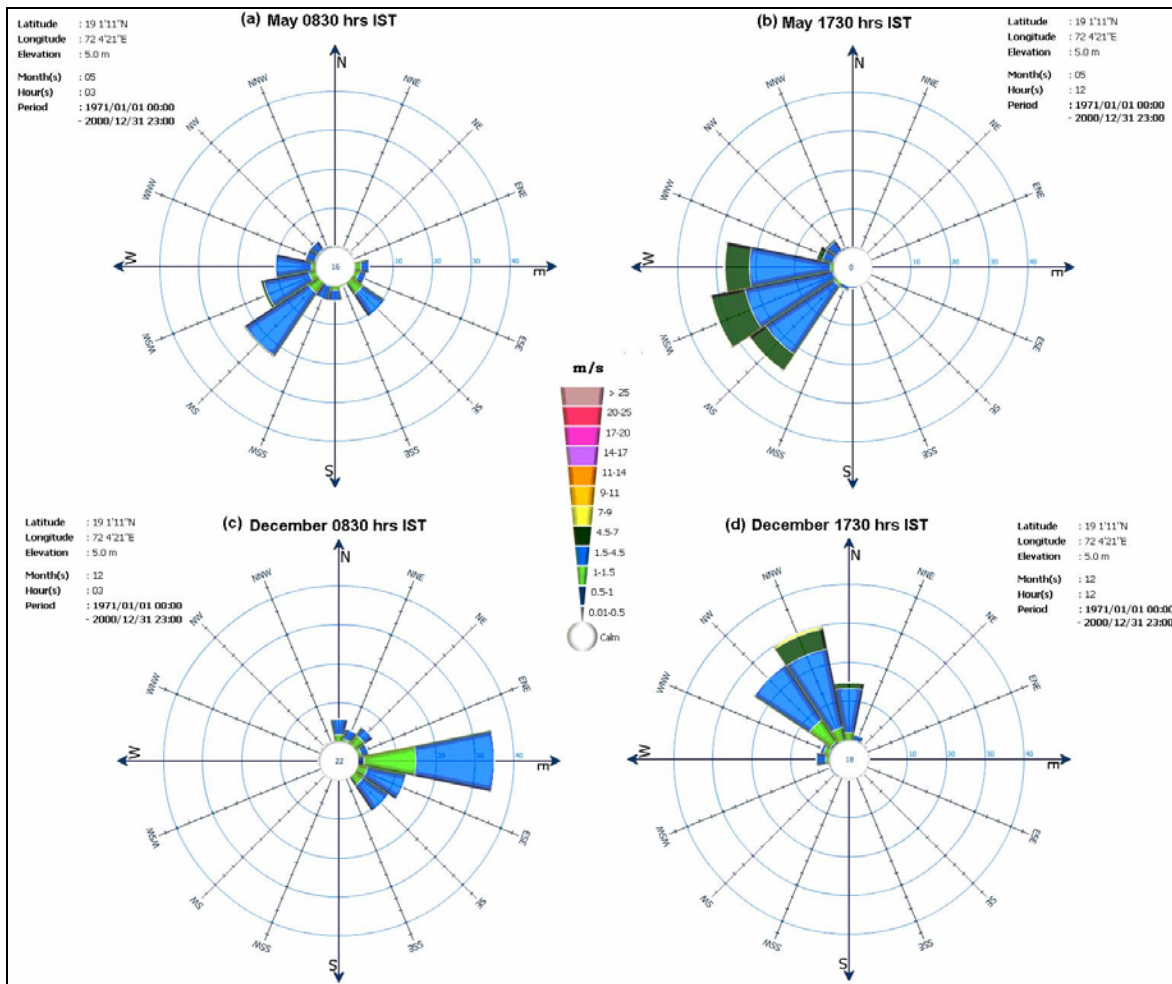




Figs. 4(a&b). Wind direction and speed at Santacruz (monthly averages 1971-2001) for the months of (a) May and (b) December



Figs. 5(a-d). Wind direction and speed at Alibag (monthly averages 1971-2001) for (a) May 0830 hr IST, (b) May 1730 hr IST, (c) December 0830 hr IST and (d) December 1730 hr IST



**Figs. 6(a-d).** Wind direction and speed at Dahanu (monthly averages 1971-2001) for (a) May 0830 hr IST, (b) May 1730 hr IST, (c) December 0830 hr IST and (d) December 1730 hr IST

higher than Alibag and Santacruz but monsoon minimum temperature of Dahanu is higher than Colaba and Santacruz [Fig. 2(c)]. During post-monsoon season minimum temperature of Colaba is higher than Santacruz, Alibag and Dahanu [Fig. 2(d)].

### 3.5. Wind rose diagrams for four stations

The wind roses depicting direction and wind speed at 0830 hrs IST and 1730 hrs IST for the months of May and December are shown below for Colaba - Figs. 3(a-d); Santacruz - Figs. 4(a&b); Alibag - Figs. 5(a-d); and Dahanu - Figs. 6(a-d).

The general wind direction at Colaba is northwesterly that is from sea to land. In May at 0830 hrs IST 14% of time wind blows from northwest and from westnorthwest at the speed of 0.5-4.5 m/s 11% of time. In May at 1730 hrs IST wind blows from westsouthwest to

northwest, 41% of time from westsouthwest, 21% of time from northwest with a speed ranging from 1 to 7 m/s.

In December at 0830 hrs IST wind direction at Colaba is eastnortheasterly (27%) and northeasterly (21%) with a speed of 0.5-4.5 m/s. In December at 1730 hrs IST wind blows from westnorthwest to northnorthwest -40% of time from northwest and 34% of time from northnorthwest with a speed ranging from 0.5 to 7 m/s.

The general wind direction at Santacruz during May is west-northwest (66%) with average speed of 4.75 Knots (2.5 m/s). In December it is mainly northwesterly but is very weak with average speed of 2.75 Knots (1.4 m/s).

Due to its proximity to the water body the land-sea breeze circulation is a perennial feature over Mumbai. The land gets heated more than ocean during day time. There is a rapid heating of air over the coastal area of Colaba but

the air over the adjacent strip of water is much less warmed. This gives rise to a sharp temperature difference between them. The day time pressure gradient is therefore from cooler sea to warmer land, which generates sea breeze. This effect keeps Colaba cooler in day time. Santacruz being located in the inner suburb remain comparatively warmer than Colaba. This movement is reversed during night time and air blows from land to sea as it would in normal convectional system. So, Colaba is warmer than Santacruz and two peripheral stations namely Alibag and Dahanu at night time.

In May at 0830 hrs at Alibag direction of wind varies. Wind blows from prominently three directions - southeast (13%), southwest (11%) and northwest (13%) with a speed of 1-7 m/s. At 1730 hrs IST in May wind direction is from southwest (16%), west-northwest (11%) and northwest (50%) with a speed ranging from 1.5 to 9 m/s.

In the month of December at 0830 hrs IST at Alibag general wind direction is easterly. Wind blows from north-east (17%), east (28%), eastsoutheast (10%) and southeast (11%) with a speed of 0.5 - 4.5 m/s. At 1730 hrs IST wind direction is northwest (61%), north-northwest (15%) and north (9%) and wind speed is ranging from 1 to 7 m/s.

In May at 0830 hrs IST at Dahanu wind is variable but shows prominently southwesterly direction (23%), with a speed of 1-4.5 m/s. Wind also blows from southeast (11%), west-southwest (15%) and west (10%) with a speed of 1-4.5 m/s. At 1730 hrs IST in May wind direction at Dahanu is mainly southwesterly. Wind blows from southwest (27%), west-southwest (32%) and west (28%), with a speed ranging from 1.5 to 7 m/s.

At Dahanu in the month of December at 0830 hrs IST general wind direction is easterly and southeasterly. Wind blows from east (35%), east-southeast (13%) and southeast (11%) with a speed of 1-4.5 m/s. At 1730 hrs IST in December wind direction at Dahanu is mainly northwesterly - northwest (25%), north-northwest (30%), and north (15%) and wind speed is ranging from 1 to 9 m/s.

The two peripheral stations viz., Alibag and Dahanu both being coastal stations experience land and seas breeze. In May the general wind direction at Alibag is northwesterly and at Dahanu is southwesterly; this means that both the stations experience cool sea breeze which keeps them cooler than the city and suburbs. In the month of December at 0830 hrs IST at both the stations general wind direction is easterly meaning wind blows from land to sea. At 1730 hrs IST wind direction is northwesterly meaning wind blows from sea to land.

### 3.6. *Impact of population and infrastructure on microclimate of Mumbai*

There are several anthropogenic factors that contribute to UHI. One of the important factors is the pressure of population. Population of Greater Mumbai increased from 2.9 million in 1951 to 12.4 million in 2011. During last four decades population growth in island city declined whereas population growth in the suburbs is fairly high. At present 26% of the population live in island city and 43.2% in western suburbs and 31% in eastern suburbs.

It is well known that the progressive replacement of natural surface by built surface through the growth and development of city in the process of urbanisation contribute to the formation of UHI. This is more prevalent in case of colonial city like Mumbai where city grew in an unplanned and haphazard manner. The city grew from the southern tip of the island and subsequently pushed towards the north by joining the isolated island and engulfing the surrounding rural areas. This momentum of city growth continued even after independence because of wave of migrant population. In 1950, city administrative boundary crossed the island and entered into adjacent Salsette and continues to replace natural landscape by built up areas.

According to the findings of a study "Spatial Changes in Mumbai city", carried out by Mukhopadhyay (Simon, 2005), during 1970-2001 there was an astronomical rise in the built up area from 28.93% to 52.38%, which indicate a rise of 23.55%. This rise of built up area has led to shrinkage of marshy areas (24.65% to 12.61%) and open space (from 20.91% to 7.28%) as well as hilly area. The inter-tidal zone within the city were reclaimed and used for residential building construction which has changed the configuration of coastal area. There is increased use of materials like concrete and asphalt for construction that absorb a lot of heat which is released during night time. There is a general decrease in the vegetation and open areas in the city and suburb due to increase in built up area which reduces the natural cooling effect.

The government changed the F. S. I. both for city and suburb (from 1 to 1.5 for plot size upto 2000 sq mts. and from 1.5 to 2 for plot size above 2000 sq. mts. for residential as well as commercial land use) This led to rush for suburban land and rapid urban renewal took place, high rise buildings started coming up accommodating commercial complexes and multinational companies. The construction of high rise buildings along narrow roads of old residential areas prevent reflected heat to escape from urban surface to space and enhance the

urban heat. The production of waste heat from air conditioning and refrigeration systems and also from the vehicular traffic adds to the urban heat. Thus, change in the city landscape is responsible for the change in the micro-climate of the city.

#### 4. Conclusions

It is evident from the trend analysis and comparison of means of maximum and minimum temperatures of four stations under study that during day time in winter and summer Santacruz is warmer than Alibag, Dahanu and Colaba while during night time in winter and summer Colaba is warmer than Alibag, Dahanu and Santacruz.

The study reveals that the rapid and potent day time heating of the air over the coastal region contribute to the rise of day temperature at Colaba, while adjacent water stretch remain less warm. This natural contradiction contributes to the rise of UHI.

It further reveals that city and suburbs of Mumbai remain warmer than the peripheral areas namely Alibag and Dahanu. This difference in temperature is due to not only natural factors but also anthropogenic interference. The progressive replacement of natural surface by built up surface and increasing population pressure through the process of urbanisation modified the physical and chemical properties of the environment of city and suburbs of Mumbai. This negatively impacted the environment and cumulative effect of all this is the creation of UHI.

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