

Trends in surface temperature variability over Mumbai

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सार – प्रेक्षणात्मक प्रमाणों से भूमंडल पर सतह तापमानों में उष्ण प्रवृत्ति का पता चलता है। इस शोध पत्र में मुंबई के अधिकतम और न्यूनतम तापमानों की प्रवृत्तियों को स्पष्ट किया गया है। इसमें एक दशक से लेकर प्रतिदिन तक के विभिन्न कालिक मापक्रमों पर तापमान प्रवृत्तियों की जाँच की गई है। विषम घटनाओं के घटित होने की आवृत्ति में प्रवृत्तियों के लिए मौसम के समान गुणों के तत्वों की भी जाँच की गई है। सामान्यतः मुंबई में तापमान की बढ़ती हुई प्रवृत्ति पाई गई है जिसमें न्यूनतम तापमानों की अपेक्षा अधिकतम तापमान अधिक पाया गया है तथा यह 95 प्रतिशत की विश्वस्तता स्तर पर सांख्यिकीय रूप से महत्वपूर्ण है। जाँच की अंतर-वार्षिक और अंतरा मौसम मानों दोनों पर मॉनसून पूर्व और मॉनसून ऋतुओं की अपेक्षा शीत ऋतु और मॉनसूनोत्तर ऋतुओं में उष्णता सहित मौसमी भिन्नता स्पष्ट रूप से अधिक देखी गई है। चरम तापमान के विश्लेषण में मौसमी भिन्नता भी स्पष्टतः देखी गई है। गर्म दिनों और गर्म रातों में घटनाओं की आवृत्ति शीतऋतु और मॉनसूनोत्तर ऋतुओं की अपेक्षा मॉनसून पूर्व और मॉनसून ऋतुओं में अधिक स्पष्ट रूप से देखी गई है। सभी ऋतुओं में दोनों स्टेशनों पर दिन और रात दोनों के समय के तापमानों में संतुलित उष्ण प्रवृत्ति पाई गई है हॉलांकि मॉनसूनोत्तर ऋतु में सांताक्रुज में यह भिन्नता सांख्यिकीय रूप से नगण्य पाई गई है।

ABSTRACT. Observational evidence points to a warming trend in surface temperatures over the globe. This paper focuses on the trends in Maximum and Minimum temperatures over Mumbai. The temperature trends were investigated at different temporal scales from decadal to daily. The seasonal series were also investigated for trends in frequency of occurrences of extreme events. In general an increasing trend is observed over Mumbai, with the increase in Maximum temperatures more than the Minimum temperatures and statistically significant at 95% confidence level. A seasonal distinction is evident with the warming more in the Winter and Post Monsoon seasons as compared to the Pre Monsoon and Monsoon seasons at both the inter-annual and intra-seasonal scales of investigation. The seasonal distinction was also evident in the extreme temperature analysis. The frequency of occurrences in the hot days and hot nights were more pronounced in the Pre Monsoon and Monsoon seasons as compared to the Winter and Post Monsoon seasons. Symmetric warming trend was observed for both the daytime and nighttime temperatures at both the stations in all the seasons though the variations at Santacruz are statistically insignificant in the Post-Monsoon season.

Key words – Climate change, Colaba, Santacruz, Maximum temperature, Minimum temperature, Hot day, Hot night, Cold day, Cold night

1. Introduction

One of the most vigorously debated topics on Earth is the issue of Climate Change as scientists perceive it as one of the greatest threats to our planet. While it is widely accepted that there is an urgent need to tackle climate change and lot of efforts are being directed at model projections of future climate change scenarios, scientists also acknowledge the global changes in climate are extremely variable in different parts of the world. Since responses to global climate change in terms of mitigation and adaptation measures will be based on actions taken at local or regional scales efforts should be directed at gaining a better understanding of climate sensitivity of regions at finer spatial scales. In spite of a surge in international interest and concern about the implications

of climate change, the policy makers in both the developing and developed countries have paid little attention to climate change at local or the regional levels. One of the direct impacts of climate change is an increase in temperatures across the regions of the world and an expected increase in extreme weather events. Though the earth has always been warming, the global surface temperatures have increased in the recent decades. Since the late 1970's the temperature of the Earth's surface has been increasing steadily and there is a consensus within the scientific community that this warming can be attributed to the anthropogenic emissions of greenhouse gases. In 2007, the Intergovernmental Panel on Climate Change (IPCC) issued its fourth assessment report indicating that analysis of observational evidence points to major changes in the global climate. The report mentions

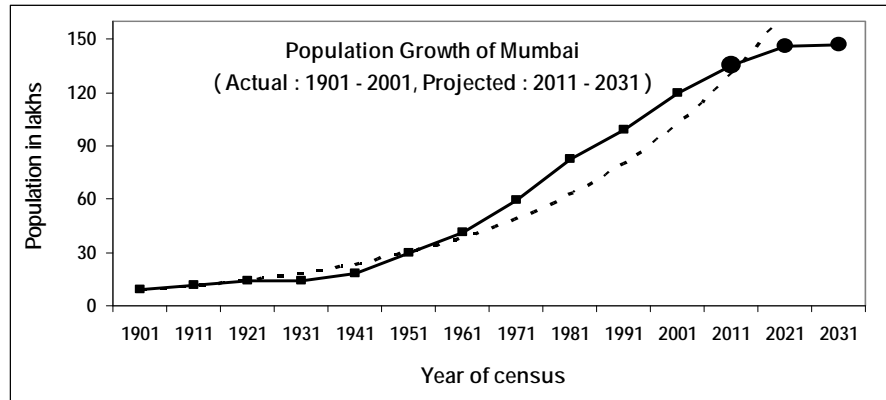


Fig. 1. Population trends in Mumbai, observed and expected

a 0.74°C rise in temperatures over the 20th century and projects a warming of 0.2°C every decade for the next two decades. Cities are particularly vulnerable to Climate Change. Altered Land cover and Land use patterns disrupt the natural radiation balance of the surface resulting in warmer cities leading to a clear threat in urban sustainability. Studies aimed at documenting the changing climate at dense mega cities can help urban policy makers frame mitigation policies for enhanced urban sustainability.

Considerable research has been done to assess the trends of surface temperatures at global, regional and local scales. For the sake of brevity a few studies that have been conducted over Asia are mentioned. Klein Tank *et al.* (2006) studied trends over central and south Asia, Fujibe (1995) and Fukui (1970) over Japan, Qian & Lin (2004) over China, Chung *et al.* (2004) over Korea and Chow (1986) over Shanghai. Over India also trends in temperature have shown a significant rising trend in the last century (for the period 1901-1982) as noted by Hingane *et al.* (1985). Rupa Kumar and Hingane (1988) also investigated long-term variations of seasonal and annual surface air temperatures at major industrial and non-industrial cities and concluded that non-industrial cities did not show significant trends, whereas the industrial cities either showed a cooling tendency or cessation of warming after 1950. However India's mega cities, which are the engines of the nation's economic growth, saw a major spurt in urbanization in the late 80's which could have altered the temperature profiles. Another study by Kothawale and Rupa Kumar (2005) noted that the surface temperature trends over India as a whole for the period 1901-2003 showed a significant warming with accelerated warming in the later period of 1971-2003. They also noted that, the accelerated warming was equally manifest in both daytime and nighttime

temperatures. IPCC reports state that after 1998, the next nine warmest years are all in the most recent decade 2001-2010. It will be interesting to investigate the response of mega cities to warming trends in temperatures in recent years. Though Dhorde *et al.* (2009) have tried to quantify the change in surface air temperature at the four major metros of India with respect to urbanizations and found an inconsistent climatic response to urbanization at these cities; their study did not deal with extreme event analysis. Analysis of long-term temperature trends at Pune by Gadgil and Dhorde (2005) revealed a pronounced decrease in temperature in winter season and a warming in the monsoon season.

Extreme weather events are destructive to human health and well being. Very few studies of extreme temperature analysis have been done over India. A very recent study on temperature extremes for the pre-monsoon season by Kothawale *et al.* (2010) has shown that over the seven homogeneous regions of India in general the frequency of occurrence of hot days & hot nights have shown widespread increasing trends and cold days & cold nights have shown widespread decreasing trends, however this study was restricted to only one season. IPCC predicts that occurrence of extreme temperature events will be on the rise due to factors like urbanization and proportion of population. Therefore it will be worthwhile to assess these trends over the megacities of India. In spite of researchers observing a marked seasonal variance in temperature trends, there are rarely any studies that investigate the trends at the intra-seasonal scales. Quantifying the intra-seasonal variances can help provide vital links to mechanisms that are responsible for driving these changes. The present study is an attempt to assess the long term temperature variance at city level in most recent decades at timescales ranging from decadal to daily and to evaluate the frequency of occurrence of extreme events.

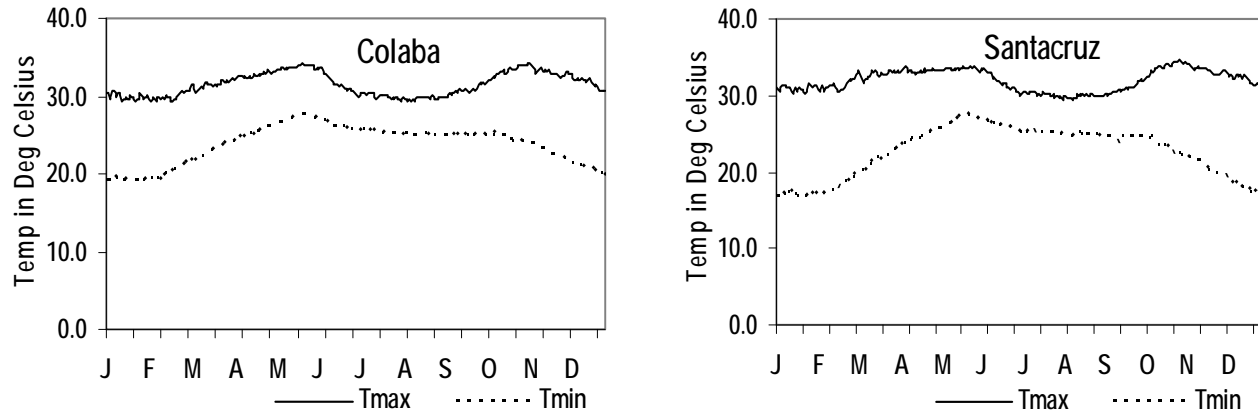


Fig. 2. Annual cycle of maximum and minimum temperatures at Colaba and Santacruz

One of the chief contributions of this analysis is the attempt to assess the variability at intra-seasonal scales.

Mumbai is one of the largest and densest metropolises of South Asia and India's major financial and industrial hub. Its functioning and sustainable development is crucial to India's development. The early development of Mumbai was mainly confined to the south. Slowly as Mumbai developed into an urban conglomerate, there was a rapid urban sprawl from South to the North in the last few decades. Most of this growth has been a result of conversion of agricultural land or reclamation of wetlands. Greater Mumbai witnessed rapid growth of built up area during the recent decades from 1971-2001 with the rate almost doubling from 25 percent in 1971 to 52 percent in 2001. The city experienced exponential growth rates between 1950-1981 chiefly due to industrialization and dense settlements in the suburban areas of Mumbai. From estimates projected by a study on the demography of Mumbai the population of Mumbai is expected to grow to about 14.69 million (least estimate) by 2031 (as reported by Brihanmumbai Municipal Corporation website). Fig. 1 illustrates the population trends in Mumbai and the projected estimates (least).

As Mumbai continues to grow rapidly, one of the greatest challenges to the civic authorities will be putting in place effective environmental management strategy plans and actions. Changes in the temperature are the first obvious indicators of altered climate and it is the nature of these changes in time that will drive a society's response to climate change. In view of these, there is a critical need to understand the long-term temperature variability and occurrence of extreme temperature events over Mumbai. The present study focuses on analyzing the daily

maximum and minimum temperature trends at a small regional scale, Mumbai.

2. Data and methodology

The daily time series of Maximum and Minimum temperatures for both the meteorological stations Colaba and Santacruz is analysed for the period 1969-2010. Though temperature records are available for longer periods, the region under study saw a spurt of industrialization and urbanization in the period mentioned above. IPCC in its fourth assessment report also states that a steep change was noticed in annual global temperatures around 1975 with a cooling period during 1940 to 1970. It is felt that this sharp change in temperature trends can mask the trends for the period 1969-2010 if longer recording periods are considered. The daily temperature series for the study were obtained from the archives of the Technical Section of Regional Meteorological Centre, Mumbai. Inhomogenities in a data set can be induced due to changes in site location, observing practices or a change in instrumentation. However it was verified that for the investigation period there was no change in site, observing practice or instrumentation. Data quality is checked by appropriate quality controls.

As a first step the data was checked for gross errors (Maximum and Minimum temperatures exceeding unlikely threshold values over the region. Given the climatology of the region, Maximum temperatures over Mumbai are not expected to exceed 45° C and Minimum temperatures were checked for a lower threshold of 0° C). The data series was then checked for internal consistency by verifying that all days at both stations had Maximum temperature exceeding the Minimum temperature. Data

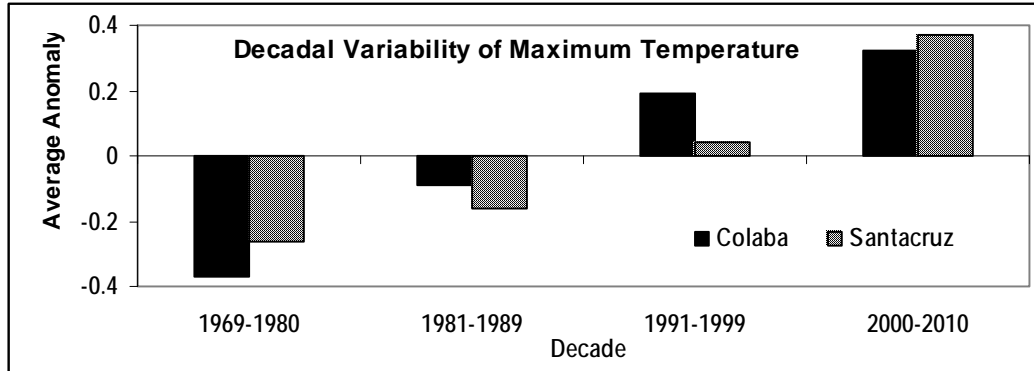


Fig. 3. Decadal variability of maximum temperature

reliability was also checked by examining the data series for data tolerance wherein the data is examined for periods recording exactly the same temperature on consecutive days (a period of 3 days was considered acceptable taking into account the precision negligence possible while reporting the recorded observation). Temporal coherency in the data was inspected by checking for consecutive records with a difference of not more than $\pm 10^\circ \text{C}$. No outliers were identified in the quality control process. The quality controlled data was then examined for missing values, as a large number of missing values can introduce artificial trends. Linear interpolation was used to fill the small proportion of missing values (less than 1%) as all the missing values were found to be within a given meteorological season. Fig. 2 shows the annual cycle of temperatures over Mumbai for both Colaba, a coastal station in South Mumbai and Santacruz, a suburban station.

The decadal variability of temperature anomalies for both maximum and minimum temperatures was calculated for each decade (the first decade and the last included 11 years to adjust the 42-year period) at Colaba and Santacruz. Linear regression method was used for evaluating the trends and the trend is given by the slope of the regression line. The statistical significance of the trends obtained was assessed by using a two-tailed t -test at 95% confidence level. The inter-annual variability of maximum and minimum temperature was analysed at annual scale and at seasonal scales for the different meteorological seasons: Winter (Jan - Feb), Pre-Monsoon (March - May), Monsoon (June - September) and Post-Monsoon (October - December). Temperature anomalies were used to depict the year-to-year seasonal variations at both the stations (baseline period for anomaly calculation was the period under study 1969-2010). The temperature anomalies were used rather than the actual temperatures to emphasize the inter-annual fluctuations. Generally monthly, seasonal or annual timescales are preferred

scales of analysis for temperatures with very few studies assessing trends at daily time scales. These types of evaluations can be particularly relevant in identifying the spells of calendar days that contribute to the overall trends in the seasonal patterns. The daily trends for each calendar day have been calculated.

There are several ways to defining extreme events. Some use arbitrary thresholds whereas some use fixed thresholds. In a fast changing climate scenario, fixed thresholds can make it difficult to statistically determine whether an event falls in the natural range of variability or whether it's truly an extreme event in its frequency of recurrence. Therefore, extreme temperature events for the present study were based on the percentile method wherein an extreme event was defined as a value which exceeds the 90th percentile or falls below the 10th percentile. The 90th and the 10th percentiles are calculated for each calendar day and the following temperature indices are calculated:

- Hot day : Days exceeding the 90th percentile of maximum temperature
- Cold Day : Days below the 10th percentile of maximum temperature
- Hot Night : Days exceeding the 90th percentile of minimum temperature
- Cold Night : Days below the 10th percentile of minimum temperature

The monthly frequencies of hot/cold days and hot/cold nights were estimated with the above defined thresholds and later cumulated to form the seasonal time series. This time series of frequencies of extreme temperature events was then tested for long term trends. The trends are expressed per year. The trends obtained

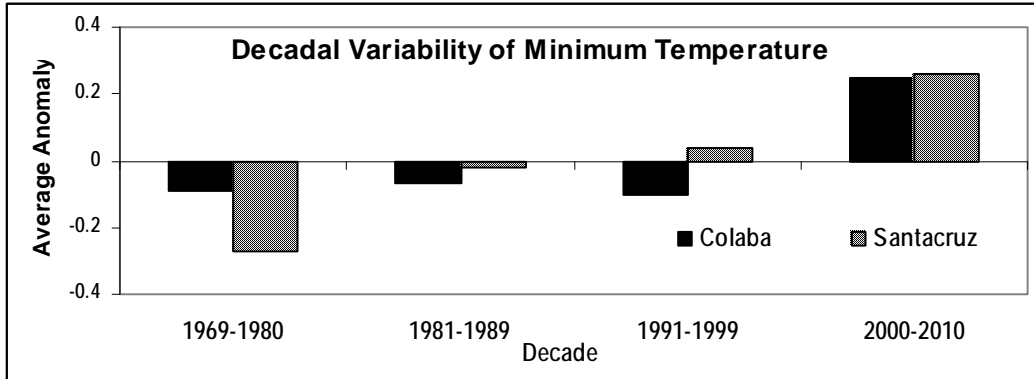


Fig. 4. Decadal variability of minimum temperature

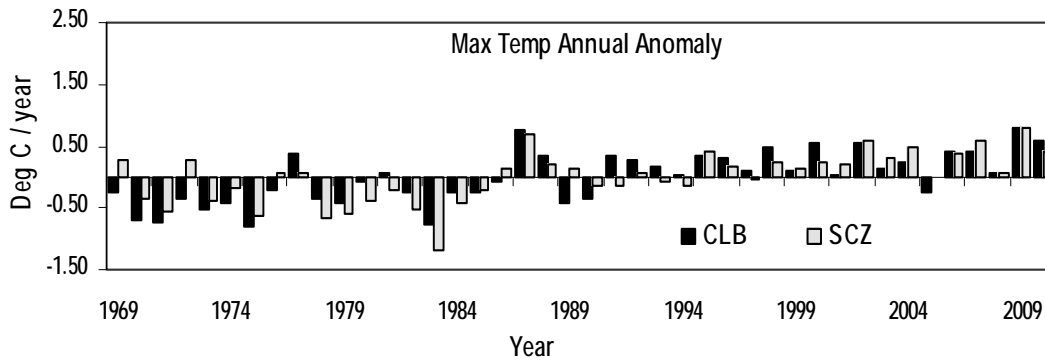


Fig. 5. Annual maximum temperature anomaly relative to the period 1969-2010

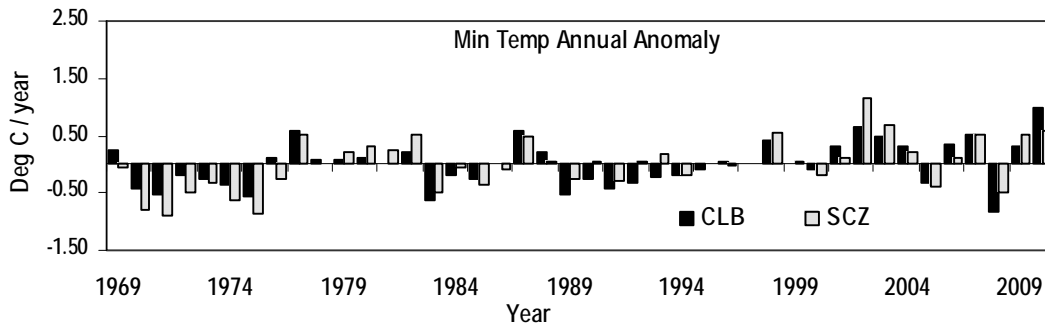


Fig. 6. Annual minimum temperature anomaly relative to the period 1969 – 2010

from extreme event analysis were also tested for statistical significance by using a two-tailed *t*-test at 95% confidence level.

3. Results and discussions

3.1. Decadal trends in temperature variability

The decadal variability of temperature anomalies were calculated for each decade and are illustrated in

Figs. 3 & 4. The phase of variation in the decades is the same at both the stations, except in the decade 1991-1999 for minimum temperature. The average maximum temperature anomaly is negative at both the stations for the first two decades and positive for the remaining two decades at both the stations. The average minimum temperature anomaly is negative for the first three decades at Colaba and positive for the last decade. However at Santacruz, it turns positive in the third decade itself. The anomalies for both maximum and minimum temperatures

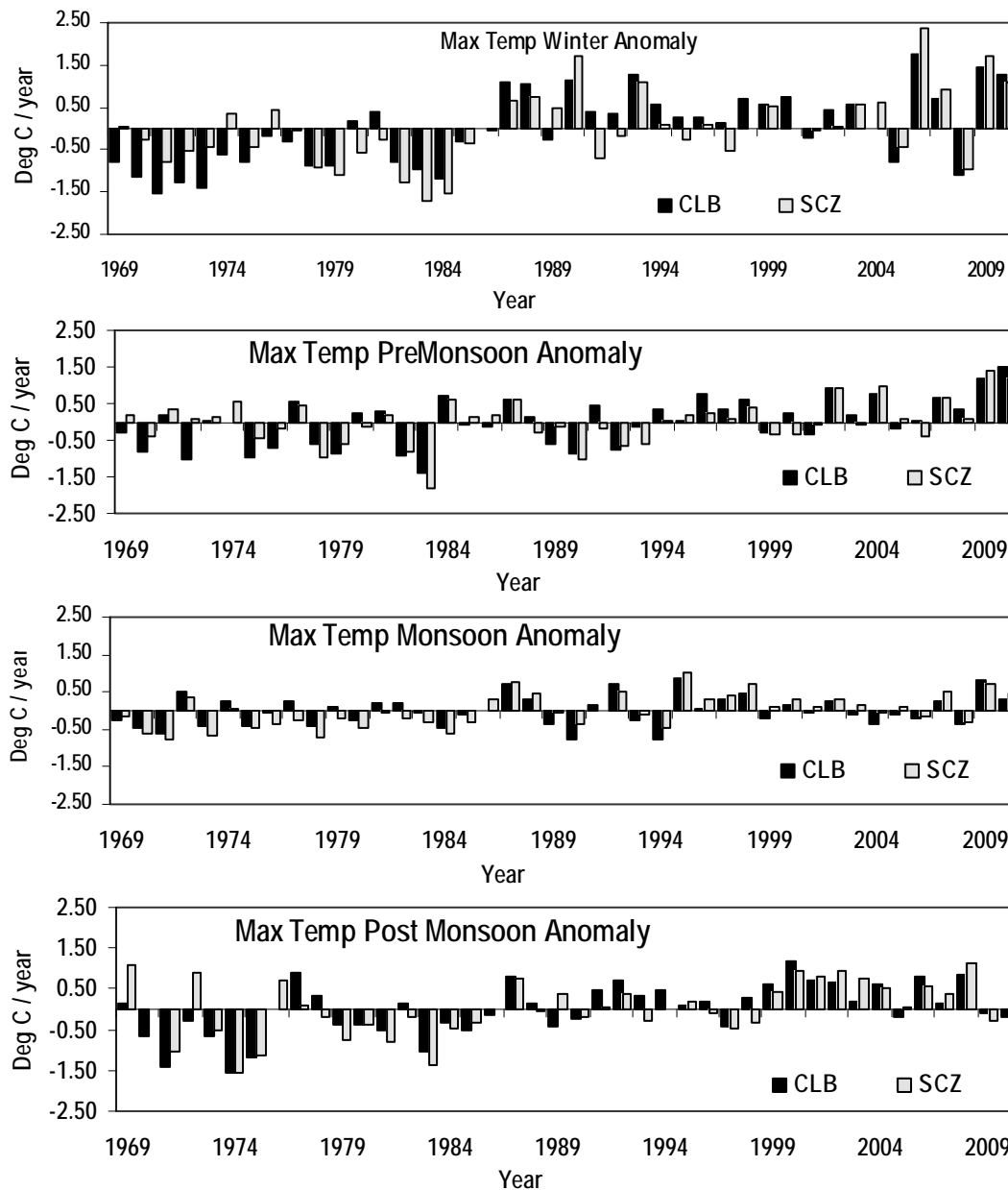


Fig. 7. Inter-annual maximum temperature anomaly relative to the period 1969-2010 for the different meteorological seasons

were the largest in the last decade of the period under study (2000-2010). From Figs. 3 & 4 it is evident that the trend towards warming could have started either at the end of the second decade or the beginning of the third decade. The next section investigates the trends in the temperature series at annual and seasonal scales.

3.2. Annual trends in temperature variability

Fig. 5 & Fig. 6 depicts the year-to-year variations in annual maximum (T_{max}) and minimum (T_{min})

temperatures. The magnitudes of anomalies for T_{max} though not very high, were consistently negative for almost two decades at the beginning of the study period. The latter years in the series have shown consistent positive anomalies. For the T_{min} series no consistent pattern could be discerned though for the first decade the anomalies were chiefly negative. As illustrated in Table 1, at the annual scale the trends are statistically significant and positive for T_{max} and T_{min} at both Colaba and Santacruz (as derived from t -test) and almost similar in magnitude.

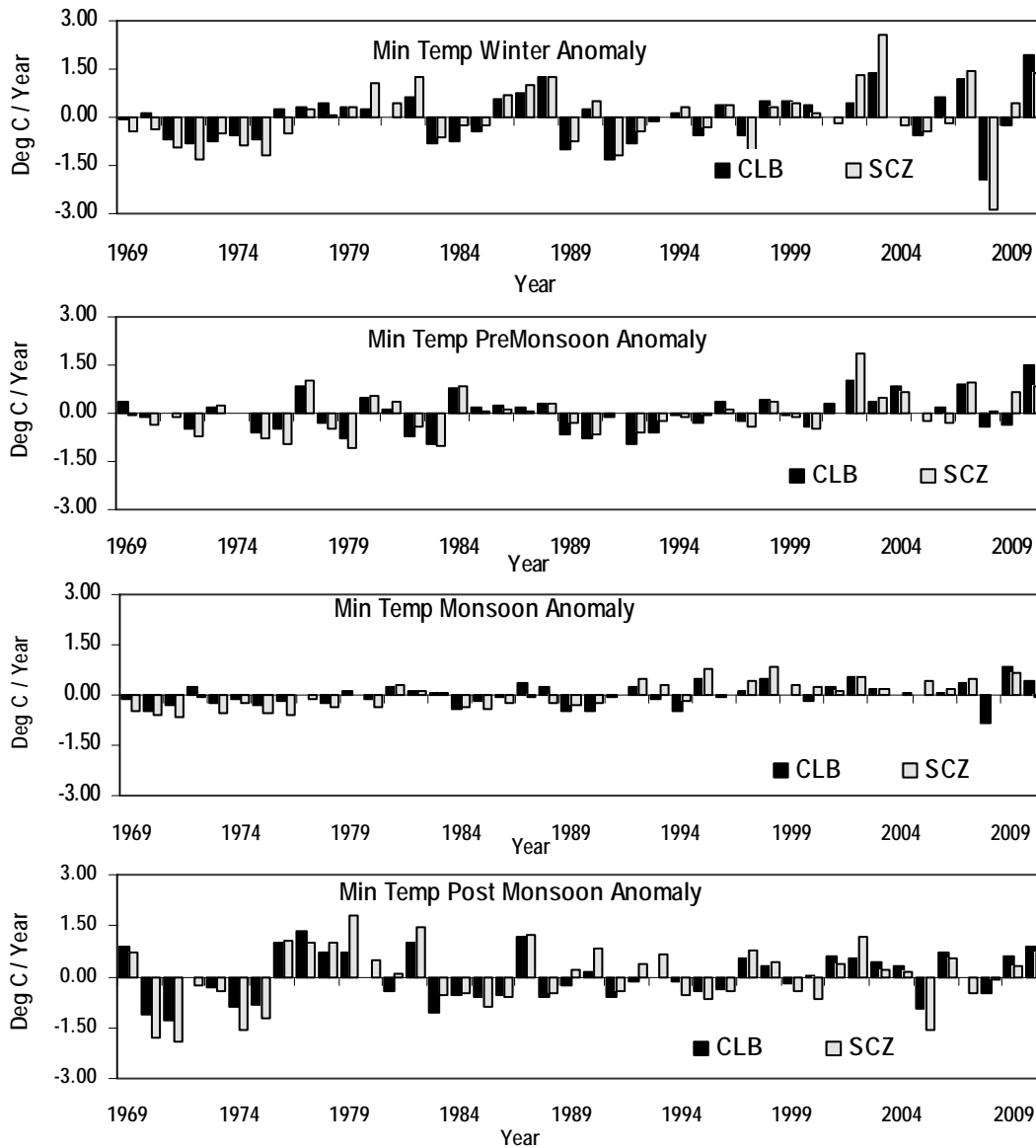


Fig. 8. Inter-annual minimum temperature anomaly relative to the period 1969-2010 for the different meteorological seasons

3.3. Seasonal trends in annual temperature variability

Fig. 7 & Fig. 8 illustrates the seasonal trends in the year-to-year T_{max} and T_{min} temperature anomalies respectively over Mumbai at both Colaba and Santacruz. Inter-annual T_{max} anomalies were larger than the T_{min} anomalies over the four decade period. Examining the anomaly series, it was interesting to note a more consistent warming trend in T_{max} after 1987 for all the seasons at both the stations (Fig. 7). The magnitude of

T_{max} anomalies was observed to be comparatively higher for winter season and post monsoon season as compared to the pre-monsoon and monsoon seasons. For the pre-monsoon and monsoon seasons the signatures of temperature variability showed lesser inter-annual variability. Consistent with the results for decadal and annual variability at seasonal scales also some of the highest variabilities were found in the last decade (2000-2010) for all the seasons. Seasonally the trends for T_{max} series were positive and statistically significant in all seasons at both the stations except Colaba (statistically

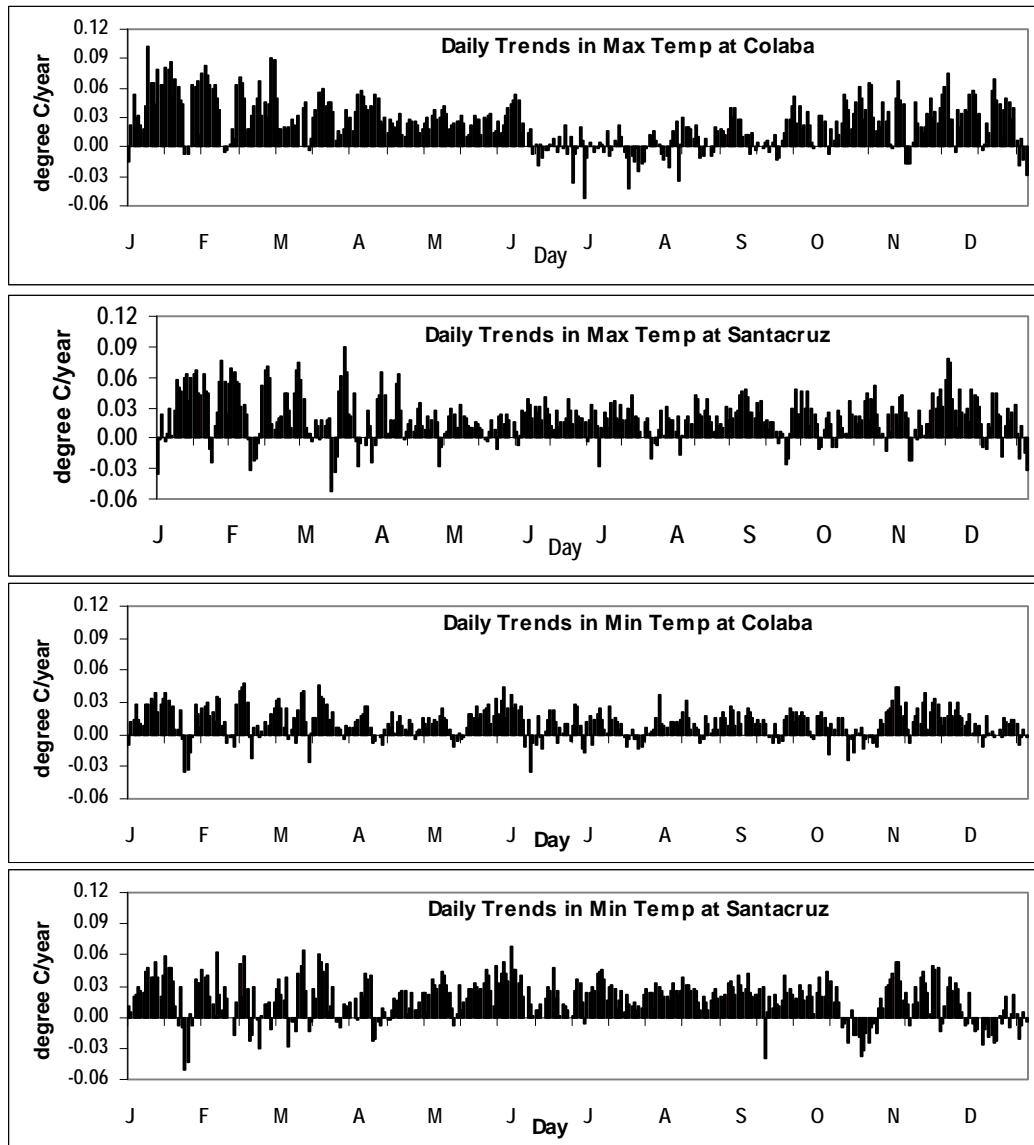


Fig. 9. Distribution of daily trends in maximum and minimum temperatures

insignificant positive trend in monsoon season). The maximum trend was in winter season and the minimum trend was observed in monsoon season.

However, the evolution of the anomaly series for the annual T_{min} temperatures was different from that of the T_{max} series. The T_{min} anomalies were not consistently negative in the early decades of the study period as observed in the T_{max} series. Though it is difficult to locate a consistent trend in the fluctuations of T_{min} over Mumbai, seasonal variations in magnitude and direction were evident (Fig. 8). It was interesting to note that though all seasonal trends were positive, at Colaba it was significant only in Monsoon season and at Santacruz in pre-monsoon and monsoon season (Table 1).

TABLE 1

Trends for T_{max} and T_{min} for Colaba and Santacruz

Season	T_{max} Trend ($^{\circ}\text{C}/\text{year}$)		T_{min} Trend ($^{\circ}\text{C}/\text{year}$)	
	Colaba	Santacruz	Colaba	Santacruz
Annual	0.0239*	0.0203*	0.01110*	0.0175*
Winter	0.045*	0.032*	0.143	0.019
Pre-monsoon	0.028*	0.0157*	0.0120	0.0185*
Monsoon	0.008	0.019*	0.009*	0.0224*
Post-monsoon	0.0286*	0.0194*	0.0102	0.0093

* Significant at 95% level

TABLE 2

Trends in occurrence of extreme temperatures at Colaba and Santacruz

Seasons	Colaba (days/year)				Santacruz (days/year)			
	Hot days	Cold days	Hot nights	Cold nights	Hot days	Cold days	Hot nights	Cold nights
Winter	0.2018*	-0.2625*	0.2395*	-0.0156	0.1501*	-0.0945	0.1617*	-0.0338
Pre-monsoon	0.4477*	-0.3609*	0.3070*	-0.1054	0.1624*	-0.2126	0.2298*	-0.2212*
Monsoon	0.5122*	0.0679	0.4291*	-0.0694	0.5545*	-0.1153	0.5316*	-0.4510*
Post monsoon	0.2349*	-0.2646*	0.0296	-0.1916	0.1852	-0.2310*	0.0196	-0.1062

*Significant at 95% level

So at seasonal scales the maximum warming of daytime temperatures at Colaba is a maximum in winter and least in monsoon, whereas at Santacruz though maximum daytime warming occurs in Winter, the least occurs in pre-monsoon. Like daytime temperatures, nighttime warming for Colaba is also a maximum in winter and a minimum in monsoon. However for Santacruz the maximum warming is in monsoon and the least in post-monsoon season. The results discussed above clearly reflect the variations in temperature showed marked seasonal variance. Amidst increasing evidence on seasons shifting with researchers finding spring arriving early and autumns setting in late, particularly in regions where temperature rises are more, it will be meaningful to examine the trends of T_{max} and T_{min} in the individual months of the season. So a further analysis of trends was carried out at the daily time scales. T_{max} and T_{min} temperatures were analysed for daily trends at both Colaba and Santacruz and the results are presented in Fig. 9. The trends were calculated for each calendar day.

3.4. Daily temperature trends

Fig. 9 depicts the trends for each calendar day in T_{max} and T_{min} at both the stations. A prominent feature noticed from the distribution of daily trends along the year is the predominance of positive trends for both T_{max} and T_{min} with noticeable seasonal fluctuations. The trends were distinctly higher for T_{max} series as compared to the T_{min} series. As is evident from Fig. 9, most of the days in the Winter season (from January to February) are dominated by some of the largest positive trends. Larger contributions to trends for the Post Monsoon season were noticed towards end of the season (from end of November). Pre-monsoon trends in T_{max} were found to be more uniformly spread for the entire season at Colaba as compared to Santacruz where the chief contribution to the seasonal trends appears to be at the beginning of the season. Despite the magnitude of trends being lower in the monsoon season, the evolution of the daily trends through the season was not in phase at both the sites. Colaba showed more positive trends at the beginning and end of

the monsoon season whereas Santacruz shows a near uniform positive trend through the season. For the T_{min} series the direction of trend through the entire year is in phase at both the sites. But unlike the T_{max} series, some spells of calendar days with negative trends were also observed. These negative trends were observed at the end of the Winter season and the beginning of the Post Monsoon season. Unlike the case with maximum temperatures for the pre-monsoon season the trends are more uniformly positive at Santacruz than at Colaba. However the chief contribution to the season is at the beginning of the season at both the sites. For the monsoon season also some of the highest trends of the season were observed in the beginning of the season for both the stations with the trends being more uniformly positive at Santacruz.

Having quantified the nature of the intra-seasonal fluctuations in relation to the observed seasonal variance in T_{max} and T_{min} , an insight into the patterns observed in the extreme events will be of particular relevance as extreme temperature events are more sensitive to climate changes than the mean values. Extreme events are receiving more attention at global and regional scales because human society, ecosystems and all living creatures are sensitive to the frequency, severity and persistence of extreme temperature events. In a warming climate, an important aspect in the characteristics of temperature variability will be the changing attributes in the distribution of temperature extremes. IPCC's fourth assessment report warns of an increase in the number of heat waves and a rise in warm nights. The temporal trends in extreme temperature events over Mumbai were analysed on a seasonal basis.

3.5. Extreme temperature trends

The trends in the four extremes were calculated for each season and the results are presented below. The magnitude of trends for each extreme temperature index for both Colaba and Santacruz along with the results of t -test is shown in Table 2.

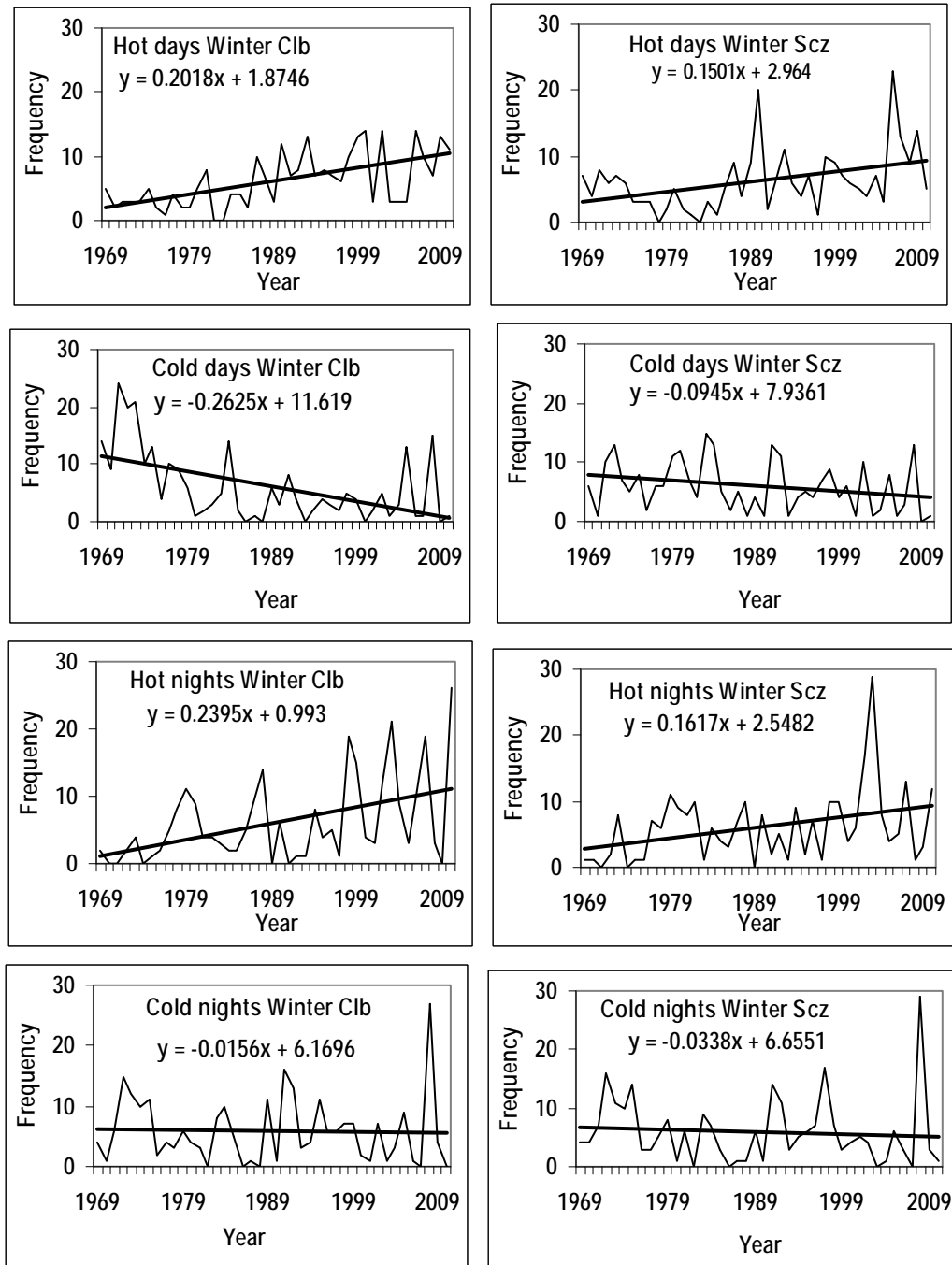


Fig. 10. Trends in temperature extremes for the winter season

3.5.1. Winter

The trends in temperature extremes for both Colaba and Santacruz are shown in Fig. 10. During daytime for the winter season hot days tend to increase both at Colaba and Santacruz, 2.0 days/decade & 1.5 days/decade

respectively and were found to be statistically significant at 95% significance level. Both the stations show a tendency for cold days to decrease, but the decrease in cold days is greater and also significant at Colaba (2.6 days /decade). The nights are also getting warmer at both the stations with Colaba showing a greater increase (2.4

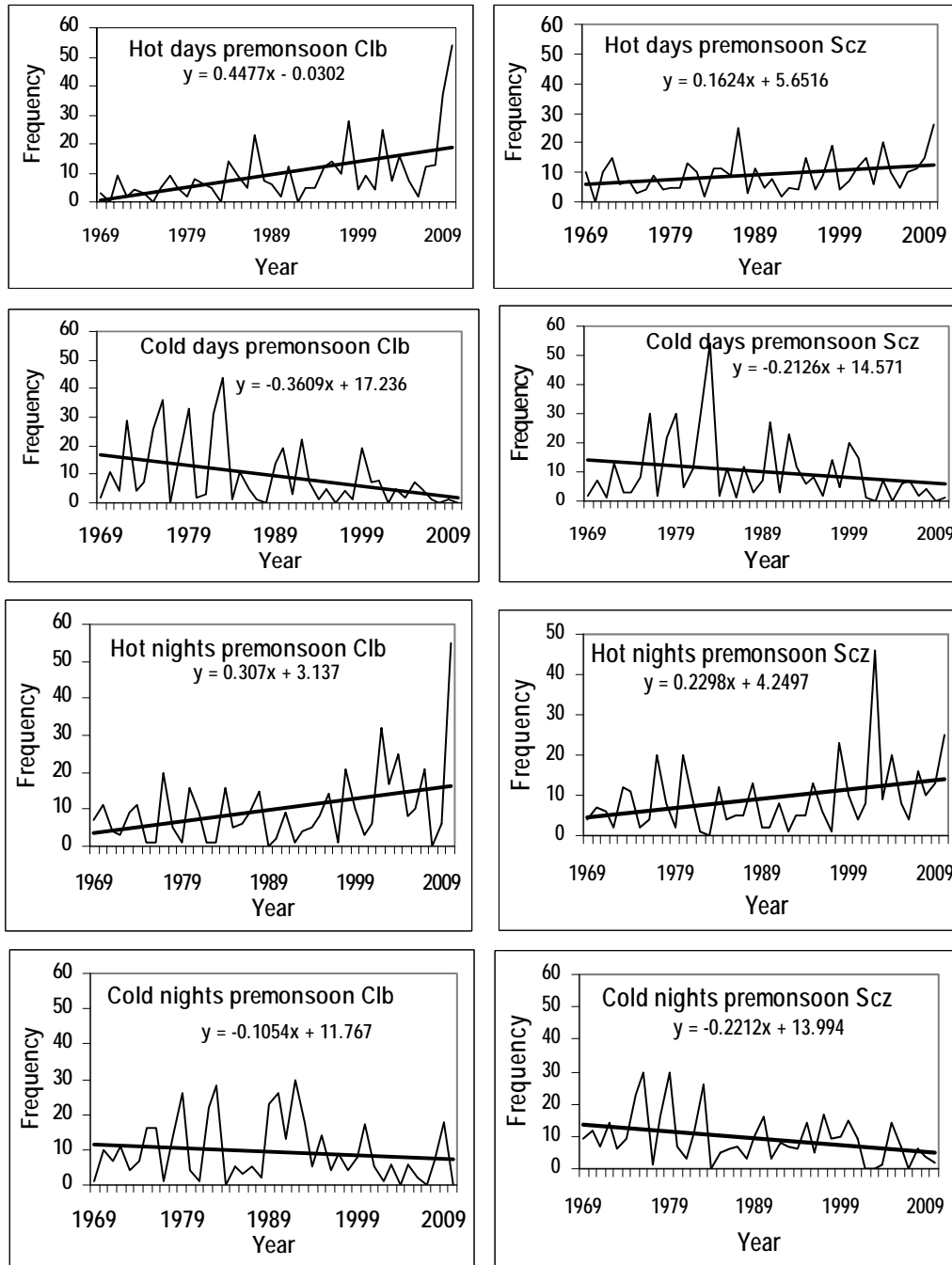


Fig. 11. Trends in temperature extremes for the pre-monsoon season

days/decade). The cold nights at both the stations showed a tendency to decrease which was not statistically significant.

3.5.2. Pre-monsoon

Fig. 11 shows the trends in extreme temperature events for the Pre-monsoon season. During the Pre

Monsoon season the trends in occurrence of hot days over Colaba shows a remarkable increase (4.5 days/decade) as compared to Santacruz (1.6 days/decade) though both are statistically significant. The decrease in the occurrence of cold days is also more at Colaba (3.6 days/decade) and statistically significant as compared to Santacruz (2.1 days/decade). During the night, frequency of hot nights at Colaba and Santacruz show the same pattern of increase

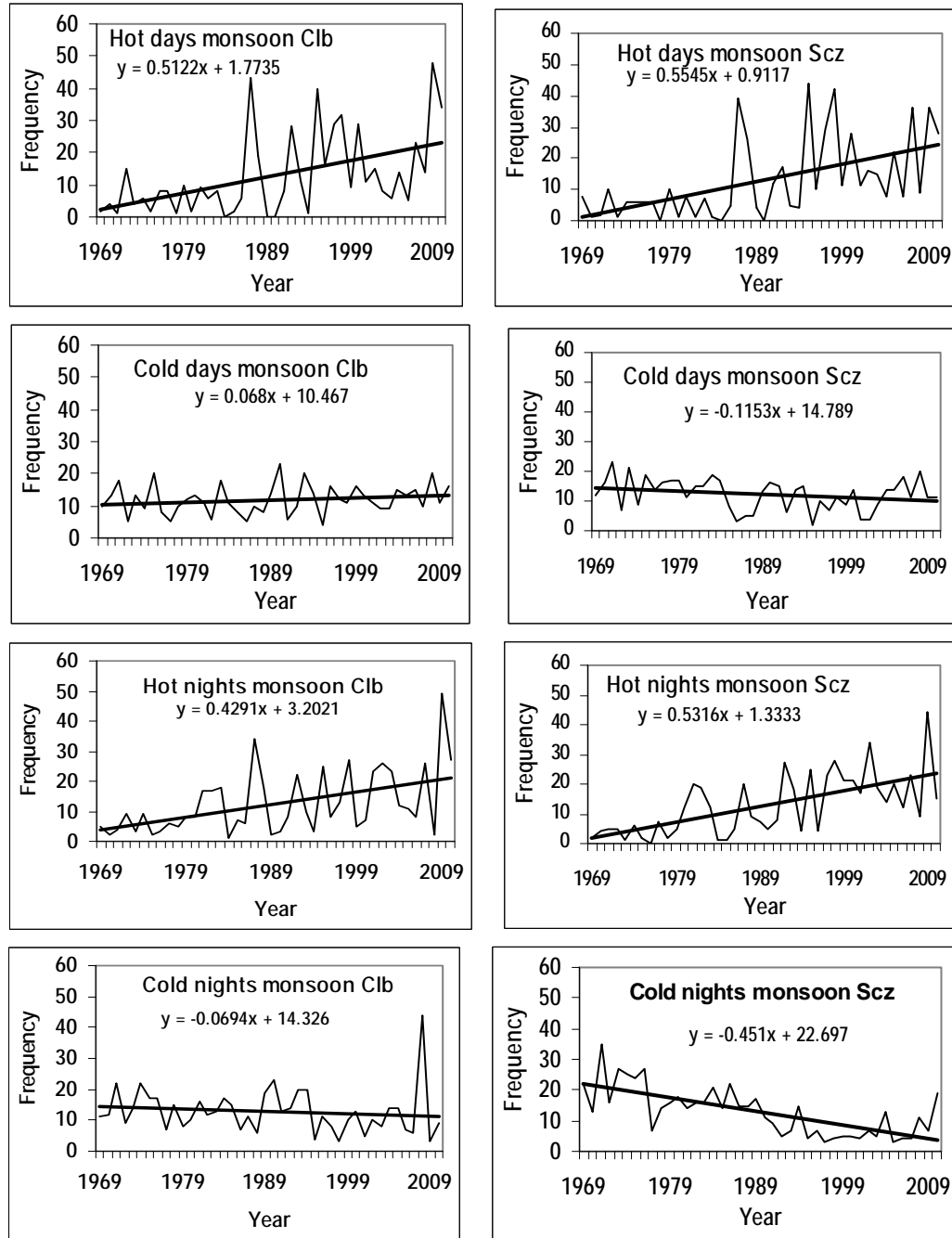


Fig. 12. Trends in temperature extremes for the monsoon season

and significance, but the decrease in frequency of cold nights is slightly greater and significant at Santacruz as compared to Colaba.

3.5.3. Monsoon

Fig. 12 shows the extreme temperature trends in monsoon season. The frequency of hot days at both the

stations shows a very noticeable increase (5.1 days/decade and 5.5 days/decade at Colaba and Santacruz respectively). The cold days at Colaba show a tendency to be positive (0.6 days/decade) but Santacruz shows a decreasing trend in cold days (1.1 days/decade). The positive trends for hot days are significant at both stations and for cold days insignificant. Hot nights at both the stations show a noticeable significant trend (4.2

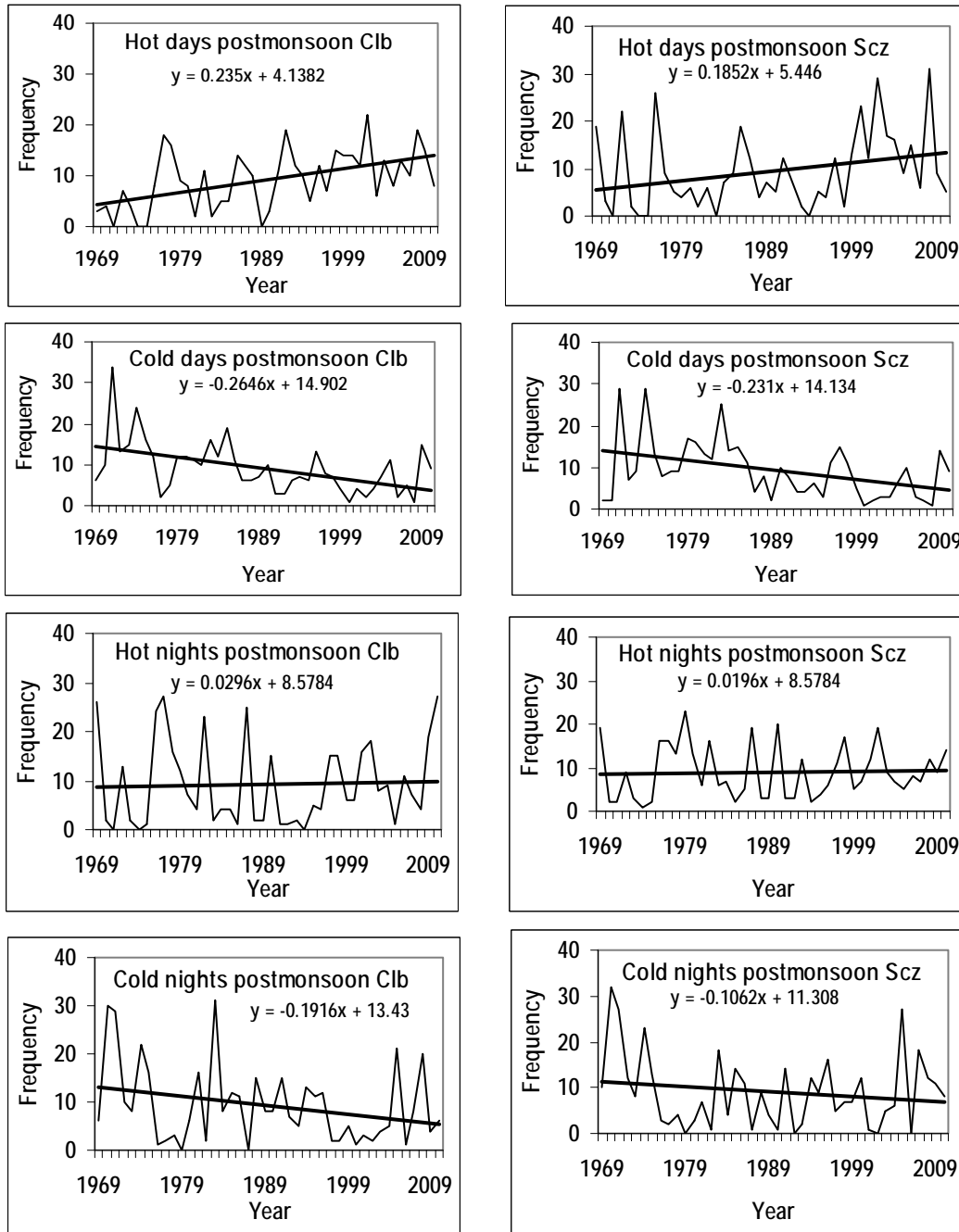


Fig. 13. Trends in temperature extremes for the post monsoon season

days/decade at Colaba and 5.3 days/decade at Santacruz). Cold nights show a tendency to decrease at both the stations though the decrease is more prominent and significant at Santacruz (4.5 days/decade).

3.5.4. Post monsoon

Fig. 13 shows the trends in temperature extremes for the Post monsoon season. The frequency of hot days

shows a tendency to increase and the frequency of cold days shows a decreasing trend at both the stations. Though trend in occurrence of hot days and cold days at Colaba was statistically significant, the results for Santacruz were different. Post monsoon is the only season for Santacruz where hot day trends were not significant and cold day trends significant statistically. The hot nights show a tendency to increase at both the stations though the increase was not significant. The cold nights at both the

stations however showed a greater tendency to decrease at both the stations, but the trends were statistically insignificant. .

4. Conclusions and summary

(i) Trends were derived for the mean seasonal daytime and nighttime temperatures over Mumbai for the period 1969-2010. Maximum and minimum temperature anomalies were coherent at both the sites and showed a significant rising trend particularly in the last decade (2000-2010). The analysis revealed that Mumbai has indeed warmed over the last four decades, with day time temperatures warming at a faster rate than the night time temperatures at all temporal scales of investigation.

(ii) A seasonal distinction in the rate of warming is a common feature with both the daytime and nighttime temperatures at all scales of investigation. Inter-annual variations were more pronounced for the winter and post monsoon seasons as compared to the pre-monsoon and monsoon seasons. Intra-seasonal trend analysis at both the stations showed that the daytime temperatures are warming more particularly in the winter and Post monsoon Seasons.

(iii) When tested for statistical significance at 95 % confidence level using *t*-test, the trends in maximum temperature were found to be statistically significant at both stations for all the seasons except for monsoon season at Colaba. However with minimum temperatures though the magnitude of anomalies were larger, trends for winter and post monsoon season were statistically insignificant at both the stations.

(iv) Through all the seasons a positive trend was seen in the occurrence of hot days and hot nights and a negative trend for the occurrence of cold days and cold nights. However at both the stations trends in frequency of occurrence of hot days and hot nights were found to be a maximum in monsoon season and the least in Winter for Colaba and in Post monsoon for Santacruz (hot nights). Occurrence of Cold days was a maximum in monsoon at Colaba and in winter at Santacruz, whereas occurrence of Cold nights was a maximum in winter at both the stations.

(v) Some of the maximum significant long term trends were observed in the monsoon season, the maximum extreme event trends were found in the monsoon season for both day and night time temperatures.

The chief objective of this research was to investigate the nature of changes in the temperature profile of Mumbai in recent decades. In summary,

Mumbai has shown clear signs of warming with pronounced seasonal distinctions and the rate of warming more with daytime temperatures as compared to the nighttime temperatures. Whether the change can be attributed chiefly to the effects of urbanization or to changes in the lower atmosphere, changes in solar radiation receipts or synoptic conditions that could cause a natural variability in temperature needs to be investigated further.

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