

Time series analysis of observed maximum and minimum air temperature at four urban cities of India during 1951-2015

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सार – इस शोध पत्र में भारत मौसम विज्ञान विभाग (IMD) द्वारा प्रेक्षित किए गए पैंसठ वर्ष (1951-2015) के मासिक न्यूनतम तापमान (TMIN) और अधिकतम तापमान (TMAX) के बृहद डेटा का सांख्यिकीय विश्लेषण भारत के चार शहरी स्टेशनों जैसे: भुवनेश्वर, दिल्ली, मुंबई और चेन्नै के लिए किया गया है। सभी स्थानों पर अधिकतम तापमान और न्यूनतम तापमान के लिए मौसमी प्रकृति में एक बायमॉडल प्रकृति देखी गई है। अधिकतम तापमान और न्यूनतम तापमान के दो शीर्ष मान मई और सितंबर में देखे गए हैं। मुंबई में मई और नवंबर के दौरान अधिकतम तापमान के शीर्ष मान को और दिल्ली में जून और सितंबर के दौरान न्यूनतम तापमान के शीर्ष मान को असाधारण रूप से दिखाता है। अधिकतम तापमान के लिए उच्च मानक विचलन (एसडी) दिल्ली में मार्च में अधिकतम (1.78 डिग्री सेल्सियस) के साथ नोट किया गया है, जबकि चेन्नै में न्यूनतम तापमान मानक विचलन (एसडी) अन्य शहरों की तुलना में कम है। दो अलग-अलग अवधि 1951-1980 (पी-1, अध्ययन अवधि का पहला भाग) और 1981-2015 (पी-2, अध्ययन अवधि का दूसरा भाग) में अधिकतम तापमान और न्यूनतम तापमान दोनों की समय श्रृंखला से पहचाने गए थे। मुंबई में न्यूनतम तापमान के अलावा सभी शहरों में पी-1 की तुलना में पी-2 के दौरान वृद्धि की उच्च प्रवृत्ति देखी गई है। P1 समय के दौरान मुंबई में न्यूनतम तापमान के लिए उच्चतम वृद्धि की प्रवृत्ति (0.040 °C/ वर्ष) देखी गई है, लेकिन P2 समय के दौरान प्रवृत्ति लगभग स्थिर (0.001 °C/ वर्ष) रही है। मुंबई में न्यूनतम तापमान के लिए सबसे अधिक वृद्धि की प्रवृत्ति मुख्य रूप से मानसून और पी1 में सर्दियों के महीनों में वृद्धि की प्रवृत्ति के कारण है। आश्चर्यजनक रूप से, पी 1 और पी 2 दोनों में, सभी शहरों के लिए मानसून के महीनों के दौरान रुझान कम हैं। तटीय शहर भुवनेश्वर, मुंबई (चेन्नै) में तरंगिका शक्ति स्पेक्ट्रम में लगातार 5-वर्षी (3-वर्षी) बैंड देखा जाता है। हालाँकि, 5 साल का संकेत दिल्ली में संगत नहीं है और यह केवल वर्ष 1975-1980 के दौरान देखा गया है। वैश्विक तरंगिका शक्ति स्पेक्ट्रम से पता चला है कि चेन्नै में न्यूनतम तापमान में 3 वर्ष के सिग्नल की तुलना में कम बिजली (0.6 °C²) और मुंबई में अन्य शहरों की तुलना में 5 वर्ष के सिग्नल की तुलना में उच्चतम शक्ति (12 °C²) रही है।

ABSTRACT. A sixty - five year (1951-2015) long data for monthly minimum temperature (TMIN) and maximum temperature (TMAX), observed by the India Meteorological Department (IMD), is statistically analyzed at four urban stations namely Bhubaneswar, Delhi, Mumbai and Chennai of India. A bimodal nature in seasonality is noticed for TMAX and TMIN at all locations. Two peaks for TMAX and TMIN are observed in May and September. Exceptionally, Mumbai shows TMAX peaks during May and November and Delhi shows TMIN peaks during June and September. Higher standard deviations (SD) for TMAX is noted at Delhi with a maximum in March (1.78 °C), while for Chennai, the SD for TMIN is lesser compared to other cities. Two different periods 1951-1980 (P1, the first half of the study period) and 1981-2015 (P2, the second half of the study period) were identified from the time series of both TMAX and TMIN. A higher increasing trend is observed during P2 than P1 in all the cities except in TMIN at Mumbai. The highest increasing trend (0.040 °C/year) is observed for TMIN in Mumbai during P1 time, but the trend is almost constant (0.001 °C/year) during P2 time. The highest increasing trend for TMIN at Mumbai is mainly contributed by the increasing trend in post-monsoon and winter months in P1. Surprisingly, in both P1 and P2, the trends are less during monsoon months for all the cities. A consistent 5-year (3-year) band is observed throughout the wavelet power spectrum at the coastal cities Bhubaneswar, Mumbai (Chennai). However, the 5-year signal is not consistent at Delhi and it is observed only during the year 1975-1980. The global wavelet power spectrum showed that TMIN at Chennai has less power (0.6 °C²) corresponding to 3-year signal and Mumbai has highest power (12 °C²) corresponding to the 5-year signal in comparison to other cities.

Key words – Air temperature, IMD, Trend analysis, Wavelet analysis.

1. Introduction

Under the severe influence of global warming, a particular focus was put forward to understand the

trends and variabilities of air temperatures in the urban areas throughout the globe in the past few decades (Sala *et al.*, 2000; Frich *et al.*, 2002; Englehart and Douglas, 2003; Kalnay and Cai, 2003; Chung *et al.*, 2004;

Dhorde *et al.*, 2009). A significant increase in the global temperature (in this study temperature means air temperature at 2 m above from the ground) during the past century is widely noted by the scientific community (Angell, 1988; Alexander *et al.*, 2006; Mahlstein *et al.*, 2013; Rahmstorf *et al.*, 2017). However, variations in global temperature are not spatially or temporally uniform as specified by observed changes and modeling studies (Folland *et al.*, 2002). One of the most important characteristics of global climate change is the increase in maximum (TMAX) and minimum air temperature (TMIN). In recent times, much attention is received towards the study of global warming with the changes in global as well as extreme regional air-temperature, which play a unique role for maintaining the ecological balance in human society (Easterling *et al.*, 2000; Meehl *et al.*, 2000). Many studies indicated that there are higher increasing trends in TMIN as compared to TMAX in Europe (Weber *et al.*, 1997), China (Qian and Lin, 2004) and Turkey (Turkes and Sumer, 2004). One such example stated that during 1951-1990, daily mean air temperature (in global daytime) increased by 0.28 °C whereas, the daily minimum temperature (in night time) increased by three times to 0.84 °C (Karl and Easterling, 1999).

Over the Indian subcontinent, several studies have been conducted on the investigation of the variability and trends of TMAX and TMIN using India Meteorological Department (IMD) observations. Srivastava *et al.* (1992) first showed the diurnal asymmetry of temperature trends over India is quite different than that of the other parts of the globe. They showed that northern (southern) India has significant decreasing (increasing) trend 0.2 (0.4) °C in 100 years during 1901-1986. Increase in temperature in the post-monsoon and winter seasons resulted in the rise of mean temperature during 1901-1987 (Kumar *et al.*, 1994). Numerous studies reported that increasing trends of the TMAX and TMIN in different parts of India (Kothiyari and Singh, 1996; Kothawale and Kumar, 2005; Rao *et al.*, 2005). A majority of locations over northern India showed an increasing trend in the extremes in night temperature. Dhorde *et al.* (2009) studied the impact of urbanization on temperature trends at four most populated cities - Chennai, Delhi, Kolkata and Mumbai in India.

Interestingly, they reported that in winter and monsoon seasons Mumbai has significant increasing (decreasing) trends in maximum (minimum) temperature whereas, other cities have significant increasing trends in minimum temperature during winter seasons. Also from the relationship between urbanizations and temperature trend they have concluded that decreasing trend in temperature is related to the increase in populations. Using the daily maximum and minimum temperature from IMD observations, Kothawale *et al.* (2010) reported that the

frequency of hot days and nights have significantly increased throughout India while the frequency of cold days and nights flow a decreasing trend. Subash *et al.* (2011) reported that maximum temperature over Central Northeast (CNE) India has a significant rising trend of 0.008 °C/year (0.014 °C/year) in monsoon (post-monsoon) and minimum temperature shows 0.012 °C/year in post-monsoon season with significant falling trend of 0.002 °C/year in monsoon seasons during the period 1914-2003. Recently, Srivastava *et al.* (2017) showed that the annual TMAX and mean temperature are increased by 1.0 and 0.6 °C/100 years respectively whereas, the TMIN is increased by 0.18 °C/100 years over the whole India during 1901-2010.

Apart from the trend analysis, one of the advanced techniques in time series analysis is wavelet transform (Grossmann and Morlet, 1984; Santos *et al.*, 2001; Azad *et al.*, 2008), which has received much attention from its theoretical development to practical implementation in various fields. Using this transformation monthly rainfall over Matsuyama city is dominated by an annual signal was identified by Santos *et al.* (2001). Chellali *et al.* (2010) described the synoptic oscillations between 2 to 16 days in both temperature and wind during the cold seasons at Adrar, Algeria. Also, Subash *et al.* (2011) reported that CNE India has no significant periodicity in seasonal rainfall except Western UP, with 4-8 years periodicity in September and Bihar with 30- 34 years periodicity in July during 1914-2003. They pointed out that, the production of Kharif crop during May-October is decreased over Jharkhand region due to significant decreasing rainfall trend of 4.6 mm/year.

The previous studies have mainly concentrated on the trend analysis of TMAX and TMIN at seasonal and annual scales and its relationship with rainfall, urbanization and economic productions. In view of this, the current study focuses on the statistical as well as spectral analysis of monthly air temperature during 1951-2015 at four major cities in India using observed data from IMD (details in section 2). The month-wise frequency of occurrence and detailed statistics of TMAX and TMIN and their relative contributions on the overall trends are analyzed. This work also presents wavelet analyses to identify long-term variability and their associative durations. The paper is broadly divided into the following sections, section 2 comprises of the data used and methodology, section 3 contains the results & discussions and the concluding remarks are given in section 4.

2. Data and methodology

The overall spatial trend of mean temperature and annual averaged winds over the study domain were

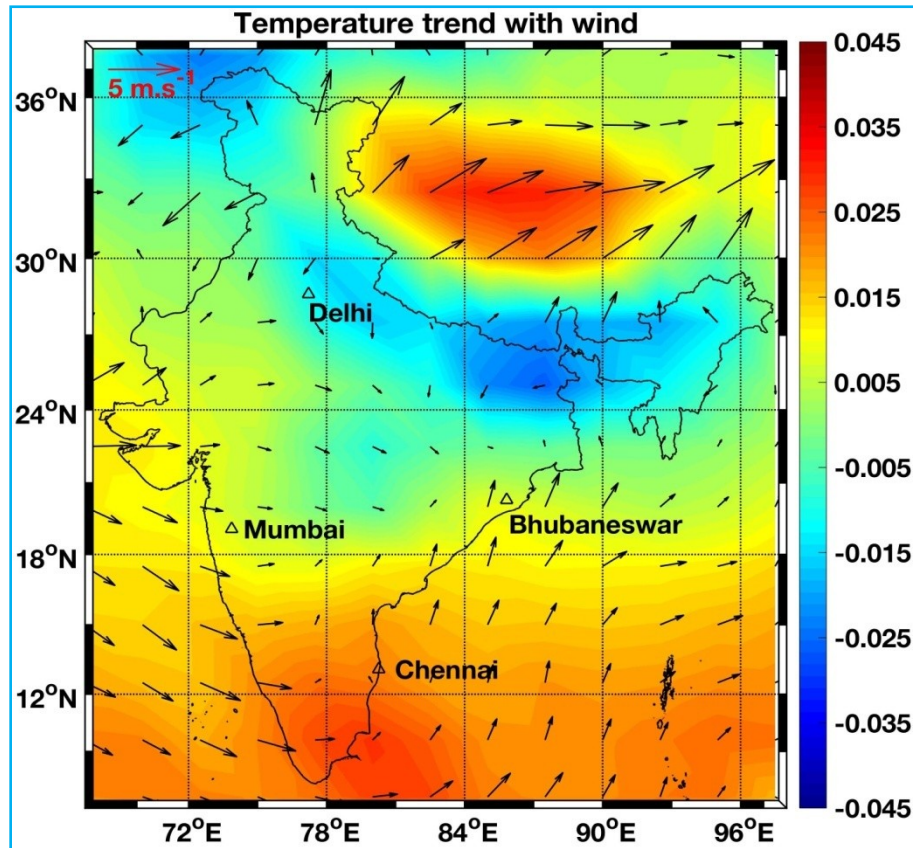


Fig. 1. Location of observations cities: Mumbai (West India), Bhubaneswar (East India), Delhi (North India) and Chennai (South India). Background color and vectors represents the temperature trend and average wind during 1951-2010 from NCEP

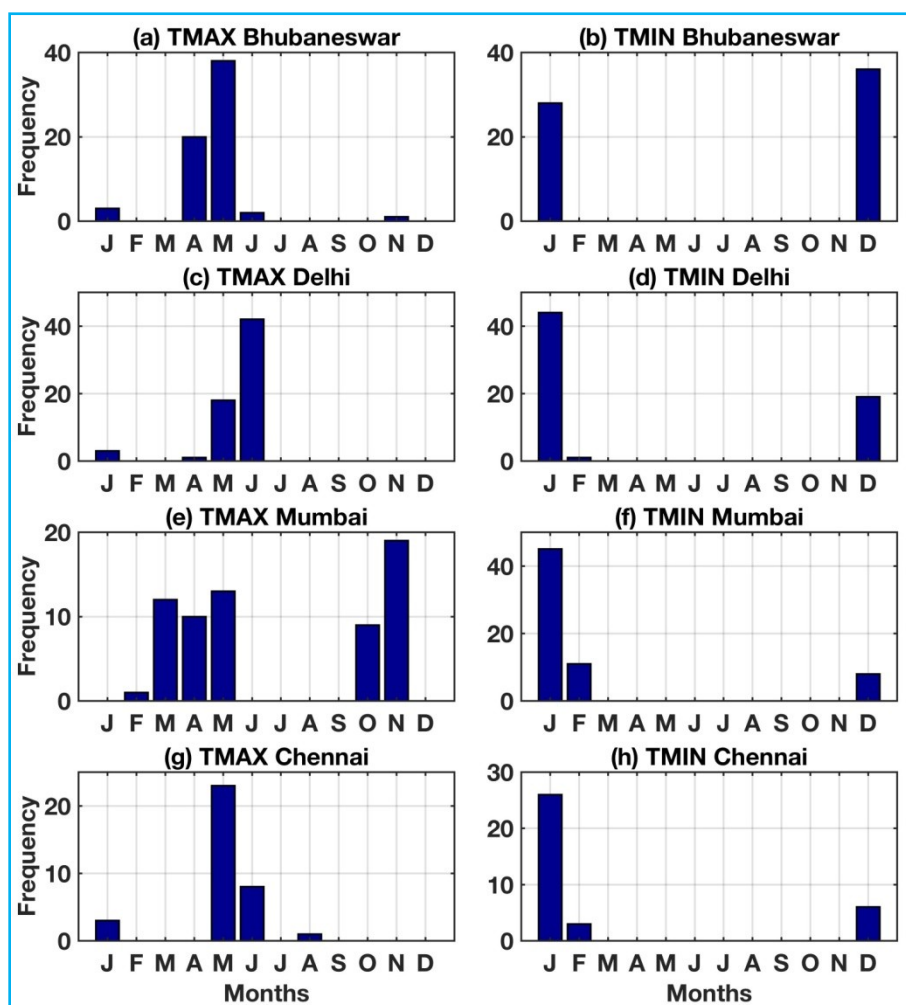
analyzed by using air temperature at 2 m and winds at 10 m from National Centers for Environmental Prediction (NCEP) reanalysis product for the duration of 1951-2015. Trends and variability for TMIN and TMAX are studied at three coastal stations and one in-land city over India: Bhubaneswar (near the east coast of India), Chennai (near the southern side of India), Mumbai (near the west coast of India) and Delhi (in the northern India) (Fig. 1). The datasets are acquired from the IMD, Pune (source: <http://www.imd.gov.in/>) for the duration of 1951-2015 except for Chennai with limited data availability (1980-2012). These four cities are chosen based on the spatial air temperature trend and availability of IMD datasets (Fig. 1) and discussed in section 3.1. Linear regression method (Kumar and Hingane, 1988; Qian and Lin, 2004; del Río *et al.*, 2005; Gadgil and Dhorde, 2005) is used for calculating the trends over the four stations. The statistical significance of the trend is evaluated using Mann Kendall rank statistics (Gadgil and Dhorde, 2005; Tomozeiu *et al.*, 2006). The modes of TMAX and TMIN are calculated on an annual scale. Wavelet analysis (Torrence and Compo, 1998; Subash *et al.*, 2011) is used for analyzing the variations of the power spectral density within the time series.

3. Results and discussion

The temperature trends from NCEP data indicate an increasing trend in the southern and western region and a decreasing trend in the northern region of India (Fig. 1). Nearby Delhi, the monthly mean temperature has a decreasing ($0.017^{\circ}\text{C}/\text{year}$) and Chennai has an increasing ($0.025^{\circ}\text{C}/\text{year}$) trend. The annual mean pattern of 10 m wind indicates that the marine weather influences the Mumbai, Bhubaneswar and Chennai. However, the variations in the TMIN and TMAX cannot be evaluated from NCEP dataset. Therefore, the trend in TMAX and TMIN are studied using IMD observation. The results are discussed in three portions: basic statistics in section 3.1, trend analysis in section 3.2 and section 3.3 consists of wavelet analysis.

3.1. Basic statistics

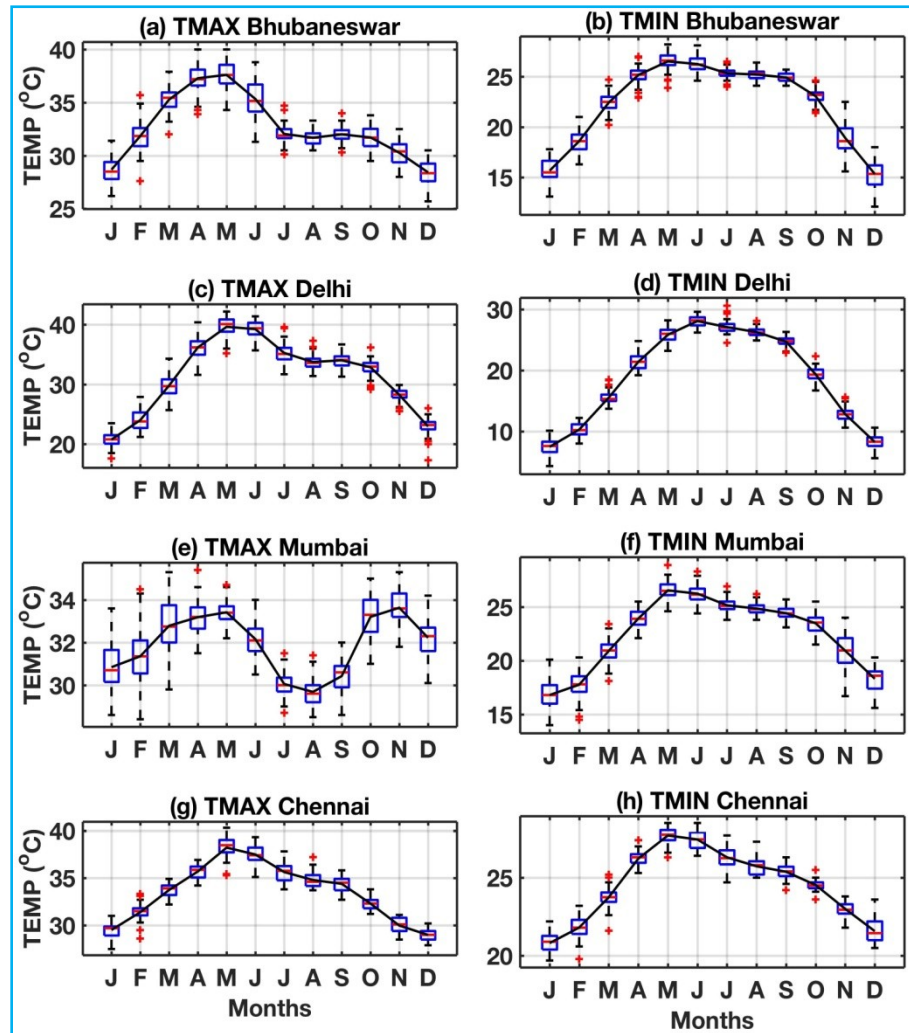
The distribution of modes for monthly TMAX and TMIN [Figs. 2(a&b)] showed that Bhubaneswar city experienced maximum temperature in May (38 years) followed by April (20 years) and the minimum



Figs. 2(a-h). Mode of monthly maximum temperature (left panel), minimum temperature (right panel) in Bhubaneswar, Delhi, Mumbai and Chennai (row wise) for the duration 1951 to 2015 (for Chennai 1980-2015) from IMD observations

temperature occurred in December (36 years) followed by January (28 years). Whereas, in Delhi, the maximum temperature occurred in June (52 years) followed by May and the minimum temperature in January (44 years) followed by December [Figs. 2(c&d)]. In Chennai, the maximum temperature occurred in May (25 years) followed by June and minimum temperature occurred in January (24 years) followed by December [Figs. 2(g&h)]. But Mumbai experienced maximum temperature in November (18 years) followed by May (13 years) and minimum temperature in January (44 years) [Figs. 2(e&f)]. TMAX at Mumbai showed an exceptional variation with the highest peak in November, which is generally different from that of other stations. The box plots [Figs. 3(a-h)] describe the range of the temperature variations for every month with a median. It is important to note that the range of temperature variation (black dotted line) is more for TMAX than TMIN, especially in

Bhubaneswar and Mumbai. The range of the TMAX at Bhubaneswar varied between 26-40 °C with maximum variation in June, while TMIN varied from 12 °C to 28 °C [Figs. 3(a&b)]. For Delhi city, the range of TMAX and TMIN are 16-42 °C and 4-31 °C respectively [Figs. 3(c&d)]. In Mumbai, ranges for TMAX and TMIN are 28.5-35.5 °C and 14-28 °C respectively during the period of study [Figs. 3(e&f)] whereas, in Chennai the same varied respectively between 28-40 °C and 20-29 °C [Figs. 3(g&h)]. The seasonal pattern of TMAX and TMIN clearly shows the bimodal nature of seasonality with higher air temperature in May except for TMIN at Delhi in June. Moreover, the second peak is observed in September except for TMAX at Mumbai in November. Additionally, more outliers during March-April indicate the highest variability, which can be attributed by the seasonal transition.

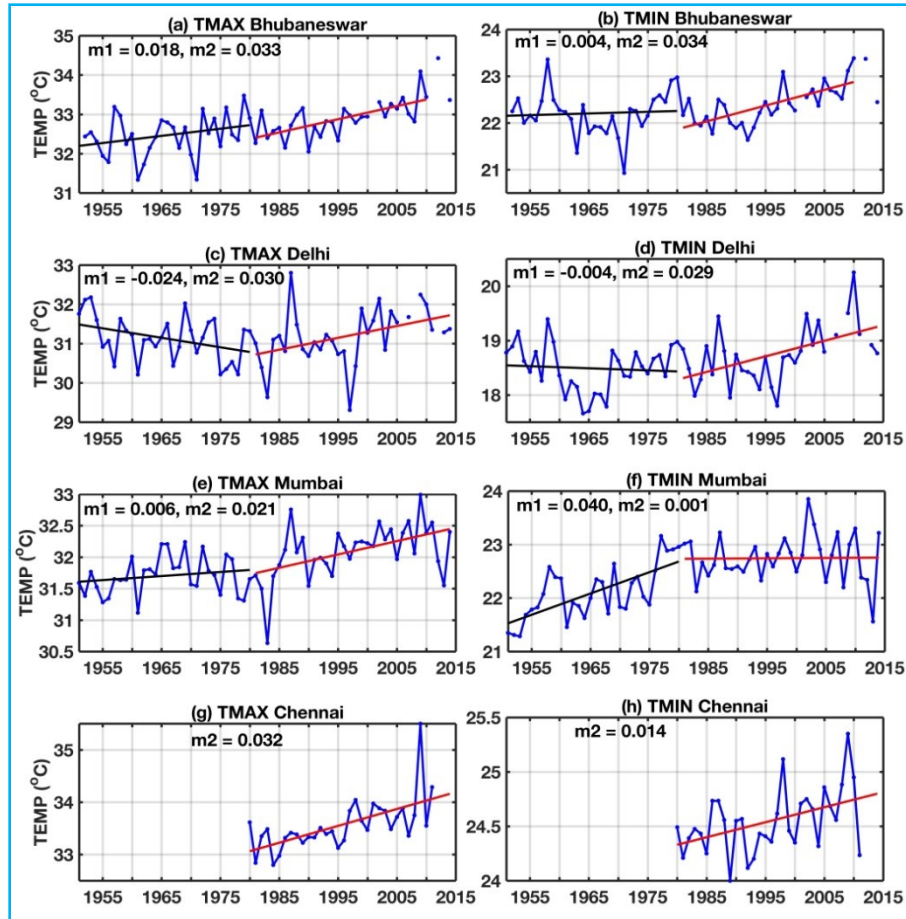


Figs. 3(a-h). Box plot of monthly maximum temperature (left panel), minimum temperature (right panel) in Bhubaneswar, Delhi, Mumbai and Chennai (row wise) for the duration 1951 to 2015 (for Chennai 1980-2015) from IMD observations. The box represents the middle fifty percent of the data. Bottom and top edges of the box represents the 25th percentile & 75th percentile and red line in the box represents the median. 'Plus' symbols indicate the most extreme points those are not considered percentile calculation. The black line indicates the mean temperature of each month

The values of mean and standard deviations (SD) for all cities are tabulated in Table 1. The higher values of SD for Bhubaneswar during the winter season (DJF) indicate more significant variations of TMIN compared to other months. On the other hand, at Mumbai, the SD for TMIN is higher (1.58 °C) with a maximum in November compared to all other cities. Interestingly, the SD for TMIN in Chennai is lesser compared to other cities (Table 1). This increase in the air temperatures may be attributed to the increase in sea surface temperature (SST) over the Indian Ocean and surrounding regions (Rao *et al.*, 2011; Dong *et al.*, 2014; Roxy *et al.*, 2014; Swapna *et al.*, 2014).

3.2. Trend analysis

Time-series of TMAX and TMIN with associated trends are analyzed with a 90% significance level using the Mann Kendall rank test. Two distinguishable trends are found from the time series of all cities before and after 1980. Therefore, we divided the whole duration in two halves; first half (P1: 1951-1980) and the second half (P2: 1981-2015) for the trend analysis [Figs. 4(a-h)]. A more increasing trend is observed during the time period P2 than P1 possibly due to more industrial growth in that time (Momaya *et al.*, 2017). In P1, TMAX at Bhubaneswar (Delhi) showed higher increasing



Figs. 4(a-h). Temporal variation of maximum temperature (left panel), minimum temperature (right panel) in Bhubaneswar, Delhi, Mumbai and Chennai (row wise) for the duration 1951 to 2015 (for Chennai 1980-2015) from IMD observations. Black and red lines determined the trend during the period 1951-1980 and 1981-2015 respectively. The values of m1 and m2 indicate the trend in °C/year

(decreasing) trend than TMIN but, in P2, TMAX and TMIN showed similar trend ~ 0.033 (0.030) °C/year and ~ 0.034 (0.029) °C/year in Bhubaneswar (Delhi) respectively [Figs. 4(a-d)]. The TMAX at Mumbai showed an increasing trend in both P1 and P2 period with the rate of 0.006 and 0.021 °C/year [Fig. 4(e)]. On the other hand, TMIN at Mumbai experienced the highest (least) increasing trend of 0.040 (0.001) °C/year during P1 (P2) in comparison with other cities (Fig 4f). In the case of Chennai, TMAX (TMIN) exhibited approximately increasing trend of 0.032 (0.014) °C/year during P2. To identify the contributions of monthly and seasonal trends on the overall value, the monthly trends are calculated.

Figs. 5(a&b) represents month wise trends in each city during both the periods P1 (dashed line) and P2 (solid line) for TMAX (upper panel) and TMIN (lower panel). During the winter season (January-February) of P1 (dashed lines), TMAX [Fig. 5(a)], as well as

TMIN [Fig. 5(b)], experienced decreasing trend at all cities except TMIN in Mumbai (green line, Table 2). But, a more negative trend in monsoon time contributes the annually negative trend -0.024 °C/year for TMAX and -0.004 °C/year for TMIN in Delhi (Table 2). More increasing trend in almost every month of TMIN in Mumbai, especially in post-monsoon and winter months, leads the highest increasing trend (0.040 °C/year) in Mumbai compare to other cities [Table 2 and Fig. 4(f)] during P1. More substantial variation in trends of TMIN is observed at Delhi (Red dashed line) during P1 time, although, the maximum trend is observed at Bhubaneswar (blue dashed line) and Mumbai (green dashed line) during November (0.100 °C/year) [Fig. 5(b)].

In the case of P2, the higher increasing trend is observed during winter and pre-monsoon months than monsoon months [Solid lines, Figs. 5(a&b)]. In this period, monthly variation of a trend for TMAX at Chennai (solid

TABLE 1

Monthly mean (°C) and standard deviation (°C) for TMAX and TMIN in Bhubaneswar, Delhi, Mumbai and Chennai

Month	Bhubaneswar				Delhi				Mumbai				Chennai			
	TMAX		TMIN		TMAX		TMIN		TMAX		TMIN		TMAX		TMIN	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Jan	28.68	1.19	15.67	1.16	20.76	1.25	7.46	1.18	30.84	0.97	16.80	1.24	29.55	0.75	20.83	0.62
Feb	31.85	1.45	18.60	0.94	24.02	1.56	10.28	1.12	31.35	1.15	17.77	1.17	31.37	0.88	21.79	0.77
Mar	35.28	1.15	22.43	0.87	29.80	1.78	15.53	1.03	32.79	1.16	20.91	0.98	33.72	0.74	23.73	0.68
Apr	37.29	1.19	25.17	0.81	36.18	1.59	21.39	1.24	33.19	0.74	23.92	0.84	35.69	0.66	26.23	0.47
May	37.61	1.24	26.52	0.81	38.50	1.66	22.13	1.36	33.42	0.58	26.55	0.78	38.26	1.30	27.72	0.53
Jun	35.34	1.61	26.25	0.77	39.26	1.36	28.08	0.90	32.16	0.75	26.24	0.80	37.52	1.01	27.46	0.62
Jul	32.05	0.84	25.34	0.50	35.28	1.53	27.10	0.94	30.06	0.55	25.16	0.59	35.58	1.08	26.27	0.74
Aug	31.69	0.65	25.21	0.47	33.75	1.17	26.28	0.67	29.68	0.59	24.85	0.51	34.76	0.83	25.71	0.56
Sep	32.01	0.68	24.92	0.40	34.04	1.22	24.72	0.78	30.43	0.68	24.42	0.56	34.36	0.82	25.36	0.46
Oct	31.72	0.99	23.06	0.69	32.87	1.26	19.34	1.07	33.20	1.01	23.48	0.81	32.33	0.64	24.53	0.33
Nov	30.28	1.11	18.92	1.45	28.26	0.89	12.82	1.09	33.63	0.80	20.92	1.58	30.01	0.77	23.01	0.51
Dec	28.43	1.04	15.34	1.33	22.96	1.30	8.25	1.09	32.22	0.83	18.32	1.19	29.00	0.63	21.56	0.69

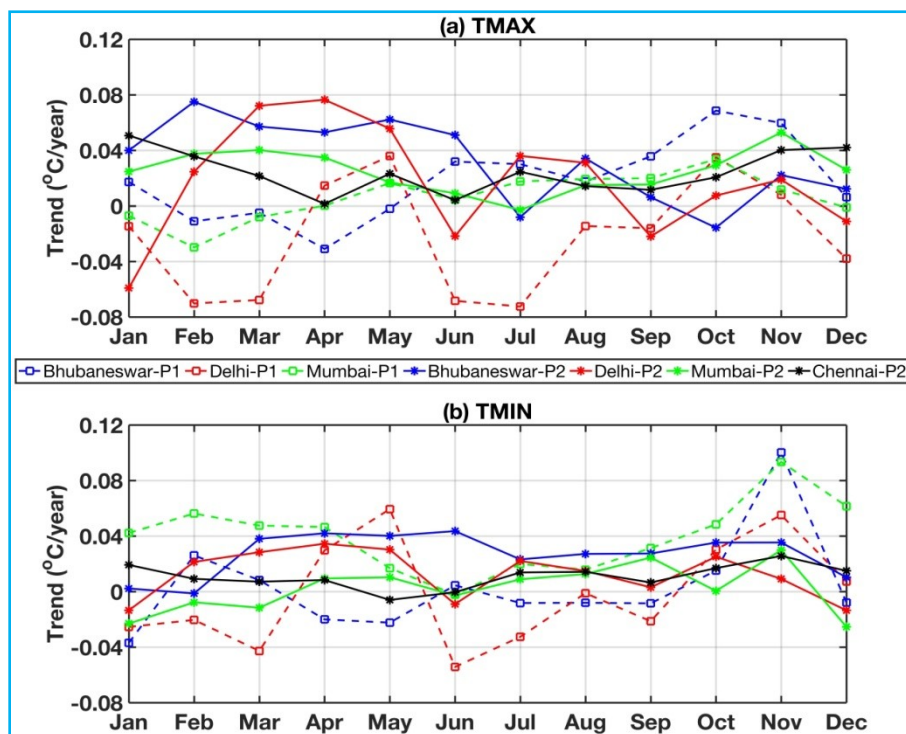
TABLE 2

Monthly and annual trend in °C/year for TMAX and TMIN in Bhubaneswar, Delhi and Mumbai during the period P1 (1951-1980)

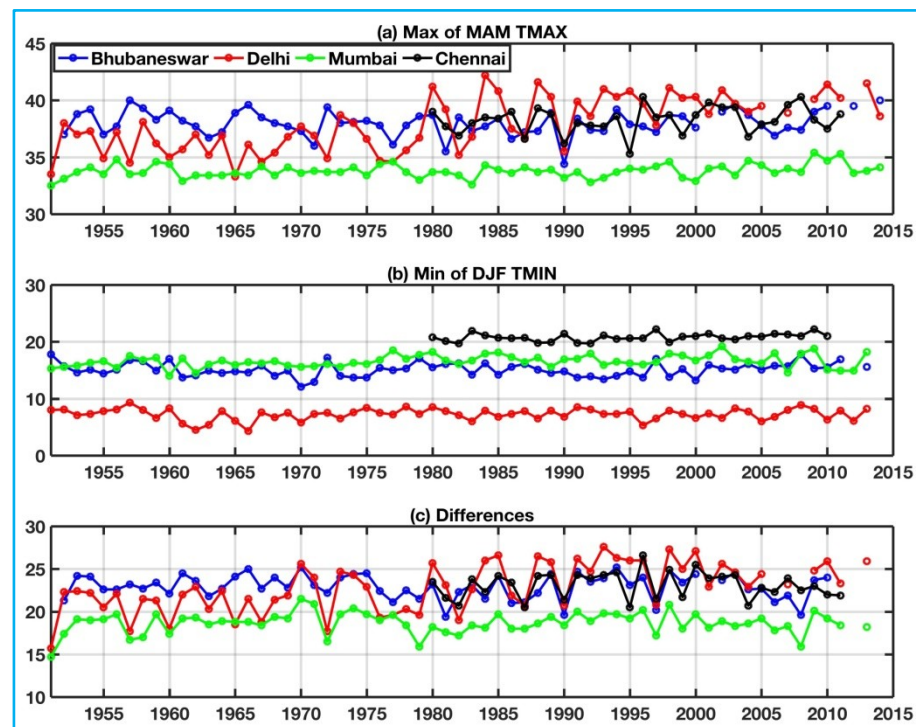
Month	Bhubaneswar		Delhi		Mumbai	
	TMAX	TMIN	TMAX	TMIN	TMAX	TMIN
Jan	0.017	-0.037	-0.015	-0.025	-0.007	0.042
Feb	-0.011	0.026	-0.070	-0.020	-0.030	0.056
Mar	-0.005	0.008	-0.068	-0.043	-0.008	0.048
Apr	-0.031	-0.020	0.015	0.030	0.000	0.046
May	-0.002	-0.022	0.036	0.059	0.016	0.017
Jun	0.032	0.005	-0.068	-0.054	0.004	-0.002
Jul	0.030	-0.008	-0.072	-0.033	0.018	0.020
Aug	0.018	-0.008	-0.014	-0.001	0.019	0.016
Sep	0.036	-0.008	-0.016	-0.021	0.020	0.031
Oct	0.069	0.015	0.035	0.030	0.034	0.048
Nov	0.060	0.100	0.008	0.055	0.012	0.093
Dec	0.006	-0.008	-0.038	0.007	-0.001	0.062
Annual	0.018	0.004	-0.024	-0.004	0.006	0.04

black) and Mumbai (solid green) showed a similar pattern with the maximum trend in November (~ 0.040 °C/year) [Fig. 5(a)]. Also, the monthly variation of trends is more in TMAX at Delhi (solid red) during P2 varying between -0.060 °C/year in January and 0.080 °C/year in April [Fig. 5(a)]. In the case of TMIN, monthly variation of trend is consistent during P2 time at all location [Fig. 5(b)]. Among four cities, Bhubaneswar experienced the highest trend for TMIN (0.044 °C/year) in June and for TMAX (0.075 °C/year) in February during P2. The month wise trends are tabulated in table 2 for P1 and Table 3 for P2.

Also, we have analyzed the trend of the highest TMAX during March-May (MAM), lowest TMIN during December-February (DJF) by considering a year starting from June to May and trend of the differences during 1951-2015 for each city (Fig. 6). Time series of the highest TMAX in Delhi during MAM showed the maximum temperature in P2 time in comparison to all other cities with highest increasing trend 0.091 °C/year. However, during P1 time Bhubaneswar city showed the maximum temperature with less increasing trend 0.003 °C/year (Table 4).



Figs. 5(a&b). Monthly temperature trend for maximum temperature (upper panel) and minimum temperature (lower panel) in Bhubaneswar (blue), Delhi (red), Mumbai (green) and Chennai (black) for the duration P1 (1951 – 1980, dashed lines) and P2 (1981-2015, solid lines) from IMD observations



Figs. 6(a-c). Time series of (a) largest TMAX during March-May, (b) lowest TMIN during December-February and (c) their differences in Bhubaneswar (blue line), Delhi (red line) and Mumbai (green line) during 1951-2015 and Chennai (black line) during 1980-2015

TABLE 3

Monthly and annual trend in °C/year for TMAX and TMIN in Bhubaneswar, Delhi, Mumbai and Chennai during the period P2 (1980-2015)

Month	Bhubaneswar		Delhi		Mumbai		Chennai	
	TMAX	TMIN	TMAX	TMIN	TMAX	TMIN	TMAX	TMIN
Jan	0.040	0.002	-0.059	-0.013	0.025	-0.023	0.051	0.019
Feb	0.075	-0.001	0.025	0.021	0.038	-0.008	0.036	0.009
Mar	0.057	0.038	0.072	0.028	0.040	-0.012	0.022	0.007
Apr	0.053	0.042	0.076	0.034	0.035	0.009	0.001	0.008
May	0.062	0.040	0.056	0.030	0.017	0.010	0.023	-0.006
Jun	0.051	0.044	-0.022	-0.009	0.009	-0.003	0.004	0.000
Jul	-0.008	0.023	0.036	0.022	-0.003	0.009	0.025	0.014
Aug	0.034	0.027	0.031	0.015	0.015	0.013	0.014	0.014
Sep	0.006	0.027	-0.022	0.003	0.015	0.025	0.012	0.007
Oct	-0.016	0.035	0.007	0.025	0.029	0.000	0.021	0.017
Nov	0.022	0.035	0.019	0.009	0.053	0.030	0.040	0.026
Dec	0.012	0.010	-0.011	-0.014	0.026	-0.025	0.042	0.015
Annual	0.033	0.034	0.030	0.029	0.021	0.001	0.032	0.014

In Mumbai, the largest TMAX during MAM showed almost constant (varying in between 33 to 35 °C) with comparatively less increasing trend 0.009 °C/year. Chennai experienced higher temperature variation with trend 0.026 °C/year during P2 time. Lowest TMIN during DJF showed less variation than the maximum temperature in each city. Delhi exhibited lesser temperature (~5-10 °C) with an increasing trend of 0.003 °C/year, whereas, Chennai exhibited higher temperature (~20-22 °C) with an increasing trend of 0.028 °C/year. The lowest TMIN during DJF in Bhubaneswar and Mumbai experienced similar temperature with increasing temperature of 0.004 and 0.016 °C/year respectively. The time series of the difference between the largest TMAX during MAM and lowest TMIN during DJF showed higher variation (~15-27 °C) with highest increasing trend 0.085 °C/year in Delhi. However, Mumbai showed less variation with a decreasing trend of 0.009 °C/year, due to higher increasing trend in TMIN than TMAX. Also, these time series for Bhubaneswar exhibited a decreasing trend of 0.002 °C/year during 1951-2015 and Chennai exhibited increasing trend of 0.006 °C/year during 1980-2015. To investigate long-term variability in TMAX and TMIN, we have performed wavelet analysis and discussed in the following section.

3.3. Wavelet analysis

Wavelet analysis provides a consistent and unbiased estimation of the real wavelet power spectrum of the time series and hence, it is a humble and vigorous way to

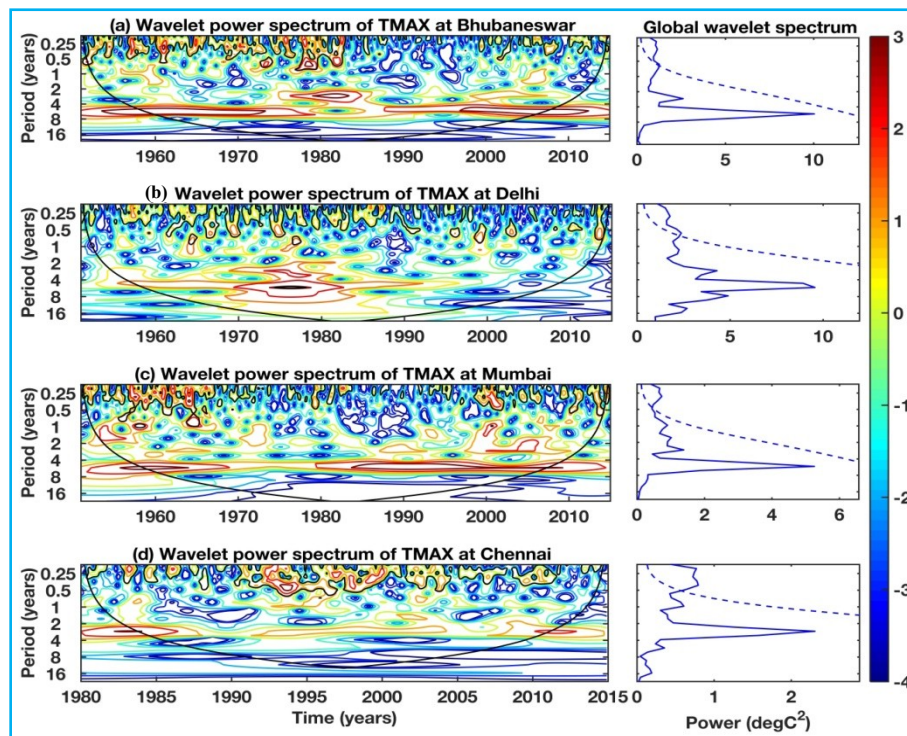
TABLE 4

Trend in °C/year for largest TMAX during March-May, lowest TMIN during December-February and their differences for Bhubaneswar, Delhi, Mumbai and Chennai

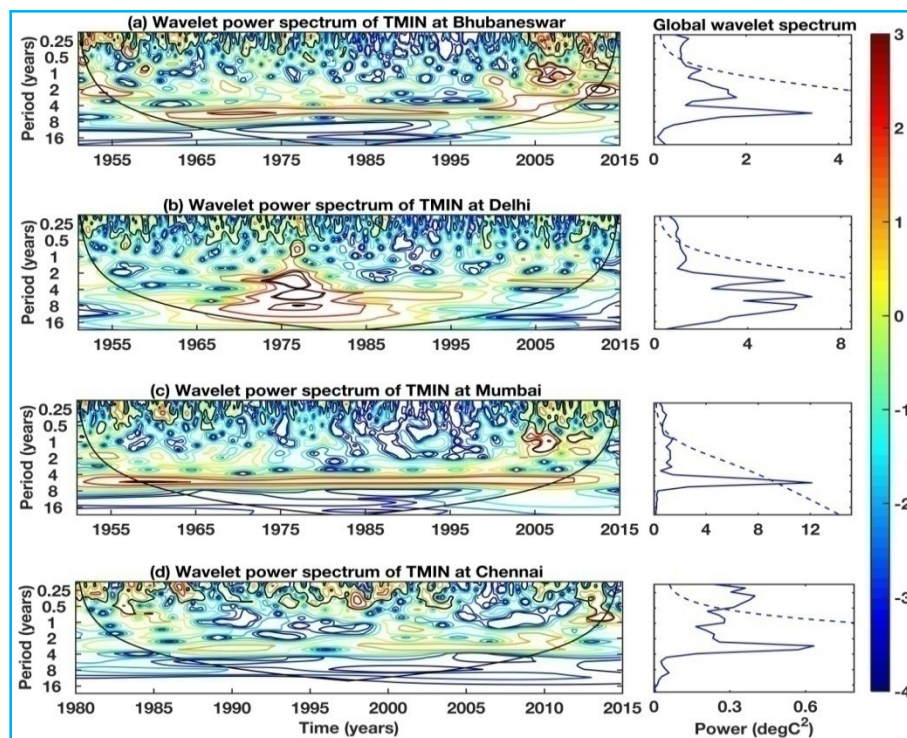
Trends	Bhubaneswar	Delhi	Mumbai	Chennai
Largest TMAX	0.003	0.091	0.009	0.026
Lowest TMIN	0.004	0.003	0.016	0.028
Difference	-0.002	0.085	-0.009	0.006

characterize the variability. With the wavelet analysis, it is confirmed that all the four cities are having an annual and semi-annual signal as shown from the box plot. The semiannual signal in Mumbai (TMAX) dominates the annual signal (Figure not shown). The low-frequency signals are analyzed by removing the monthly climatology for TMAX [Figs. 7(a-d)] and TMIN [Figs. 8(a-d)]. The analysis for TMAX shows that the dominating frequencies of variability [peaks of the blue line and red contours of Figs. 7(a-d)] are three years and five years for all cities except Chennai, where only three years signal dominates.

It is to be noted that five years frequency band is not consistent at Delhi as in Mumbai and Bhubaneswar. It is observed only during 1975-1980. The 3-year signal is dominating during 1978-1984 at Bhubaneswar, 1974-1980 at Delhi and 2000-2006 at Mumbai [Figs. 7(a-c)]. From the global wavelet spectrum, corresponding to 5-year signal, Bhubaneswar and Delhi have more power (10 °C²) in compare to Mumbai (~5 °C²).



Figs. 7(a-d). Climatology removed wavelet power spectrum (in left) and global wavelet power spectrum (in right) of monthly maximum temperature in (a) Bhubaneswar, (b) Delhi, (c) Mumbai and (d) Chennai for the duration 1951-2015 (for Chennai 1980-2015). The inverted cone region is the cone of influence, where zero padding has reduced the variance. Black contour denote the 95% significance level. The right panel represents the global wavelet power spectrum (blue line) with 95% confidence level (blue dotted line)



Figs. 8(a-d). Same as Figs 7, but for minimum temperature

In case of TMIN, climatology removed wavelet power spectrum at Mumbai [Fig. 8(c)] depict only one consistent signal of 5-year with higher power ($12\text{ }^{\circ}\text{C}^2$) throughout the duration whereas, the other cities have multiple signals with less power. In Bhubaneswar, 5-year signal is dominating during 1962-1995 and a 3-year signal is dominating during 1952-1954 and 2013-2014. Similarly, in Delhi, both 5-year and 3-year signals are dominating during 1973-1978. But in Chennai 3-year signal has the least power ($0.6\text{ }^{\circ}\text{C}^2$) compared to all other cities. The 3-5 years signal associated with the TMAX and TMIN may be attributed to the El-Niño Southern Oscillation (ENSO) and changes in the atmospheric circulation through Walker circulation. Moreover, the 2-3 years signals are due to the Quasi-Bilinear Oscillation (Baldwin *et al.*, 2001). The wave spectrum and dominant frequency of air temperature motivate us to carry out the research to find the relation with climate events like Indian Ocean Dipole (IOD) and ENSO in the nearby future.

4. Conclusions

This study is conducted on the statistical analysis of TMAX and TMIN over four urban cities Bhubaneswar, Chennai, Mumbai and Delhi in India using long-term (65-years: 1951-2015) IMD observations to address the variability in different time scales and to identify the dominant signals. The modes of monthly temperature indicate that Bhubaneswar city experienced maximum temperature in May followed by April and the minimum temperature in December followed by January. The results are similar for Delhi and Chennai. But for Mumbai, it experienced maximum temperature in November followed by May. The seasonal pattern and its variance showed that Delhi experiences more temperature contrast annually with TMIN extending from $4\text{ }^{\circ}\text{C}$ to TMAX of $42\text{ }^{\circ}\text{C}$, which is more significant as compared to the other three locations. Although, the rate of an increasing trend for both TMAX and TMIN at Delhi is least. On the other hand, in terms of SD, TMIN at Delhi showed the highest variability of $1.78\text{ }^{\circ}\text{C}$ during March but, TMIN at Chennai showed less variability in compared to other cities. A bimodal nature is observed in the seasonal variation of TMAX and TMIN with higher temperature variation in May except at Delhi in June and second temperature peak in September except for TMAX at Mumbai in November. The trend analysis for two separates periods (P1: 1951-1980) and (P2: 1981-2015) indicates the faster increase of TMAX and TMIN in all cities except Mumbai for TMIN. TMIN in Mumbai showed the highest increasing trend ($0.040\text{ }^{\circ}\text{C}/\text{year}$) during P1 time and least increasing trend ($0.001\text{ }^{\circ}\text{C}/\text{year}$) during P2 time. Month-wise trend analysis indicates the significant increase in the temperature in all months except the monsoon months (June to September) both for TMAX and TMIN. During

P1, the highest trends for TMAX and TMIN are observed at Bhubaneswar in October and November respectively. Similarly, during P2, the above trends are also noted at Bhubaneswar during February and June.

The long-term signals with a periodicity of 3 and 5-year are found in all cities except at Chennai where only the 3-year signal observed. Climatology removed wavelet spectrum for TMIN indicate that most of the power is concentrated in a 5-year band for Mumbai, whereas the same is distributed in a 3-year and 5-year band in Bhubaneswar and Delhi respectively. In the case of TMAX, a consistent 5-year signal is observed at Bhubaneswar and Mumbai with the power 10 and $5\text{ }^{\circ}\text{C}^2$ respectively. The above study on the long term observed temperatures over the four urban stations helps to get a better understanding of the regional characteristics and short-term and long-term variabilities of air temperature. The study will be extended for the gridded data recently prepared by IMD. The investigation of reasons for different variability will be carried out using other global events IOD and ENSO indices in the future (Rohini *et al.*, 2016; Srivastava *et al.*, 2017).

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