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Research Article

Statistical Assessment of the Changing Climate of Vadodara City, India During 1969-2006

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Abstract

There is a global change in the climate and cities are looked as the key culprits of this change. India will undergo an immense urbanization in the coming decades, doubling its urban population by 2050. Thus it is very important to understand the dynamics of the changing urban climate of Indian cities. With this background, the present urban climate change study is conducted for the Vadodara city located in the state of Gujarat, India using the hourly Dry Bulb Temperature (DBT) and Wet Bulb Temperature (WBT) available at 00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr for a period of 37 years (1969-2006). The hourly DBT and WBT for the 12 months were bunched on hourly-monthly basis (thereby having 192 specific bunches) for the study period which were then analyzed using the Mann-Kendall trend test at different confidence limits (90%, 95% and 99%). The findings reveal that there is an overall increase in the temperature of the city as for 78% of the time the DBT had an increasing trend and 52% of the time WBT had an increasing trend. For the first half of the day (03-hr to 12-hr) both the DBT and WBT had an overall increasing trend while in the second half of the day (15-hr to 0-hr) DBT had an overall increasing trend and WBT had an overall decreasing trend. This contrasting behavior of the DBT and WBT was specifically seen in the months of May-July which are largely the monsoon months. For both DBT and WBT, the month of February had the overall maximum increasing trend while the month of August had the overall maximum decreasing trend. The present study statistically quantifies the changing urban climate of Vadodara city and these findings would not only add to the pool of knowledge to understand the dynamics of the changing urban climate but will be of ready reference for the policy makers to initiate appropriate measures for mitigation and adaptation.

Keywords: Dry Bulb Temperature, Wet Bulb Temperature, Mann-Kendall Trend Test, Vadodara, Urban Climate, Global Warming.

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1. Introduction

Climate change is referred to as large variation in climate averages which exist for decades or even longer periods (Gocic & Trajkovic, 2013). Although climate change occurs at a global scale, its impact varies from region to region (Trajkovic and Kolakovic, 2009). The combined effects of global climate change and the urban heat island phenomenon are responsible for specific climatic characteristics observed in urban areas representing a well-documented example of climatic modification due to human activities (Cleugh & Grimmond, 2012). This over-heating of urban areas increase the extreme climatic phenomena such as heat waves and the future projections indicate that the frequency and severity of such heat waves will increase (Perkins et al., 2012; Meehl and Tebaldi, 2004) which will increase the thermal risks in the cities and the vulnerability of the urban populations (Founda and Santamouris, 2017). The overheating of urban areas reduces the liveability of the cities as it has significant negatives impacts on energy, economy, environment and health of the citizens (Livada et al., 2019, Mohan and Kandya, 2015). Thus it is very important to have detailed information of the changing climate at all scales like global, regional and city level so that appropriate measures can be initiated for mitigation and adaptation.

In the recent year many studies have been done for detecting the climatic trends and changes across the world, however most of these studies have focused on trends in the maximum, minimum and mean temperatures (Livada et al., 2019; Karaburun et al., 2011; Mohan et al., 2011; ElNesr et al., 2010; Yunling and Yiping, 2005; Gadgil and Dhorde, 2005; Kadioglu, 1997; Rupakumar and Hingane, 1988; Cayan and Douglas, 1984; Colacino and Rovelli, 1983; Colacino and Lavagini, 1982). Most of these studies have inferred an increase in the temperature and reduction in the precipitation. Numerous studies have used the Mann-Kendall Trend test and Sen’s method for detecting the trends in air temperature, rainfall or precipitation, evapotranspiration, wind speed, air quality, etc. (Gocic and Trajkovic, 2013; Karaburun et al., 2011; Pes et al., 2017; Xu et al., 2018; Güçlü, 2020; Salman et al., 2017).

With this background, the present study is planned for the city of Vadodara located in the state of Gujarat, India which adopts the popular approach of using Mann-Kendall trend test for trend deduction however supersedes the previous studies which used only maximum, minimum and mean temperatures by using hourly Dry Bulb Temperatures (DBT) and Wet Bulb Temperatures (WBT) available at 00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr for a period of 37 years (1969-2006) which would bring forth the detailed aspects regarding the changing urban climate. The findings of the present study would add to the pool of knowledge to understand the dynamics of the changing urban climate which would help to initiate appropriate measures for mitigation and adaptation.

1.2 Study area

The study area of the present research work is Vadodara city located in the state of Gujarat, India on the banks of the Vishwamitri River. It is the state’s 3rd largest city after Ahmedabad and Surat having a geographical area of 235 km^2. It lies on 39m above sea level and features a semi-arid climate (BSh) under Köppen's Climate classification having hot, sometimes extremely hot, summers and warm to cool winters. The population of the city is around 2.2 million. It is a rapidly developing city with increasing urbanization and industrialization, which has resulted in a substantial loss of agricultural land and vegetation cover (Nandkeolyar & Garge, 2019).

2. Data and Methodology

2.1 Data

The present study uses the hourly DBT and WBT available at 00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr for a period of 37 years (1969-2006) for Vadodara city. The weather station was located at the Vadodara airport which was managed by the Indian Meteorological Department. The time-series historic data was provided by the Indian Meteorological Department, Meteorological Centre, Ahmedabad.

2.2 Methodology

Fig. 1 displays the methodology flowchart adopted for the present study showing the steps involved for analyzing the temperature trends. The entire time series data of DBT and WBT was sliced on a monthly-hourly basis which was then used for detecting the trends using the Mann-Kendall Trend Test. For this test 03 confidence limits were used i.e. 90%, 95% and 99%. The trends were analyzed not only for DBT and WBT individually but in combination too which brings out a detailed scenario of the changing climate of the city.

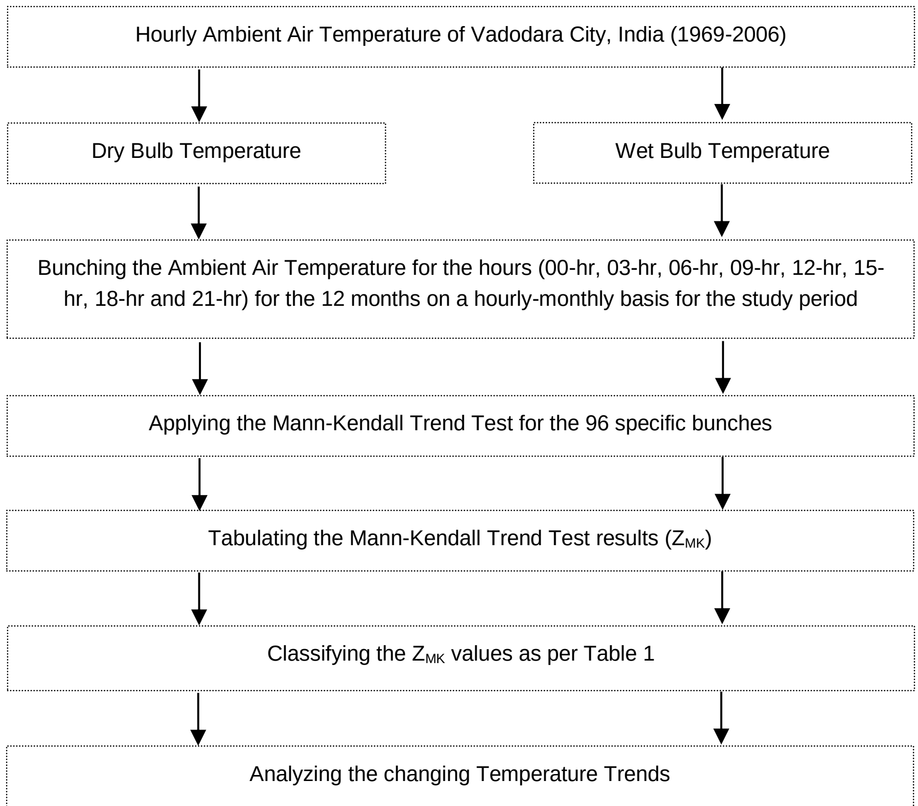

Figure 1: Methodology flowchart of the present study.

2.3 Mann-Kendall Trend Test

The Mann–Kendall nonparametric test (Mann, 1945; Kendall 1975) has been suggested by the World Meteorological Organization to assess the trend in environmental time series data (Yu et al., 2002; Silva et al., 2010). This test consists of comparing each data point of a time series with the remaining data in a sequential order. The number of times that the remaining terms are greater than that under analysis is counted. This test is based on the statistic S which is defined as below:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(x_i - x_j)$$

Here x_j are the sequential data values, n is the length of the time series, and sign $(x_i - x_j)$ is -1 for $(x_i - x_j) < 0$, 0 for $(x_i - x_j) = 0$ and 1 for $(x_i - x_j) > 0$. The mean E [S] and variance V[S] of the statistic S is given as below:

E[S] = 0

$$Var[S] = \frac{n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)}{18}$$

Here t_p is the number of ties for the p^{th} value and q is the number of tied values. The second term represents an adjustment for tied and censored data. The standardized test statistic Z_{MK}

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases}$$

The presence of a statistically significant trend is evaluated using the Z_{MK} value. The statistic is used to test the null hypothesis that no trend exists. A positive Z_{MK} value indicates an increasing trend, while a negative one indicates a decreasing trend. To test for either increasing or decreasing monotonic trend at p significance level, the null hypothesis is rejected if the absolute value of Z_{MK} is great than $Z_{1-p/2}$ which is obtained from the standard normal cumulative distribution table (Modarres and Silva, 2007). In the present study, the significance levels of p = 0.10, 0.05 and 0.01 were applied. Table 1 displays the Z_{MK} value range along with the respective trend type.

Table 1: Interpretation of the Mann-Kendall Trend Test Results (Z_{MK}).

Range of Z_{MK}	**Interpretation of the Temperature Trend** (in terms of Z_{MK} range)	**Trend Code** (for the present study)
> 2.576	Increasing Trend significant at 99% confidence level	+4
> 1.96 & ≤ 2.576	Increasing Trend significant at 95% confidence level	+3
> 1.654 & ≤ 1.96	Increasing Trend significant at 90% confidence level	+2
> 0 & ≤ 1.654	Increasing Trend not significant	+1
0	No Trend	0
≥ -1.654 & < 0	Decreasing Trend not significant	-1
≥ -1.96 & < -1.654	Decreasing Trend significant at 90% confidence level	-2
≥ 2.576 & < -1.96	Decreasing Trend significant at 95% confidence level	-3
< -2.576	Decreasing Trend significant at 99% confidence level	-4

3. Results and discussion

Fig. 2-9 displays the hourly ambient DBT of Vadodara city at 00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr during 1969-2006 while Table 2(a-b) and Table 3(a-b) contains the Mann-Kendall trend test results (Z_{MK} values) for the DBT and WBT during 1969-2006 for the different hours in Vadodara city respectively.

From the Fig. 2-9, Table 2 (a-b) and Table 3(a-b) it can be inferred that during 1969-2006 there was an overall increase in the temperature of Vadodara city as for 78% of the time the DBT had an increasing trend (56% of the time it had an increasing trend significant at 90% or 95% or 99% confidence levels while 22% of the time the increasing trend was not significant) and 22% of the time DBT had a decreasing trend (14% of the time it had a decreasing trend significant at 90% or 95% or 99% confidence levels while 08% of the time the decreasing trend was not significant). However the trend analysis of DBT of every month for the different hours (00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr) along with that of the WBT brings out the detailed scenario of the changing climate of the city which would give the closer insights useful for understanding the urban climate change dynamics. Following are the salient results for the trends of the DBT and WBT both individually and in combination.

3.1 Trend of Dry Bulb Temperature (DBT)

i. All hours of the day (00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr) had an overall increasing trend
ii. The 09-hr had the overall maximum increasing trend while the 0-hr had the overall minimum increasing trend
iii. Arranging the hours in the descending order as per the overall increasing trend, the sequence is 09-hr followed by 15-hr, 18-hr, 12-hr, 21-hr, 06-hr, 03-hr and 0-hr
iv. Except for the month of August and October, the remaining 10 months had an overall increasing trend
v. The month of February had the overall maximum increasing trend while the month of August had the overall maximum decreasing trend.

vi. Arranging the months in the descending order as per the overall increasing trend, the sequence is February followed by December, September, April, June, May, March, November, January and July
vii. Arranging the months in the descending order as per the overall decreasing trend, the sequence is August followed by October.

3.2 Trend of Wet Bulb Temperature (WBT)

i. In the first half of the day (03-hr to 12-hr) there was an overall increasing trend while in the second half of the day (15-hr to 0-hr) there was an overall decreasing trend.
ii. The 12-hr had the overall maximum increasing trend while the 9-hr had the overall minimum increasing trend
iii. Arranging the hours in the descending order as per the overall increasing trend, the sequence is 12-hr followed by 6-hr, 3-hr and 9-hr.
iv. The 0-hr had the overall maximum decreasing trend while the 15-hr had the overall minimum decreasing trend.
v. Arranging the hours in the descending order as per the overall decreasing trend, the sequence is 0-hr followed by 21-hr, 18-hr and 15-hr.
vi. The month of January, February, March, April, September, November and December had an overall increasing trend while the month of May, June, July, August and October had an overall decreasing trend.
vii. The month of February had the overall maximum increasing trend while the month of August had the overall maximum decreasing trend.
viii. Arranging the months in the descending order as per the overall increasing trend, the sequence is February followed by December, March, September, April, November and January.
ix. Arranging the months in the descending order as per the overall decreasing trend, the sequence is August followed by June, July, May and October.

3.3 Composite trend of Dry Bulb and Wet Bulb Temperatures

Fig. 10 displays the various aspects of the combined trend behavior of the DBT and WBT in terms of increasing and decreasing trend during 1969-2006. From the Fig. 10 it can be deduced that:

i. 43% of the time both DBT and WBT had an increasing trend, 35% of the time DBT had an increasing trend while WBT had a decreasing trend, 10% of the time DBT had a decreasing trend while WBT had an increasing trend and 12% of the time both DBT and WBT had a decreasing trend.
ii. The 0-hr had the prominence of the overall decreasing trend for both DBT and WBT while the decreasing trend of DBT and increasing trend of WBT was seen mainly at 03-hr and 12-hr.

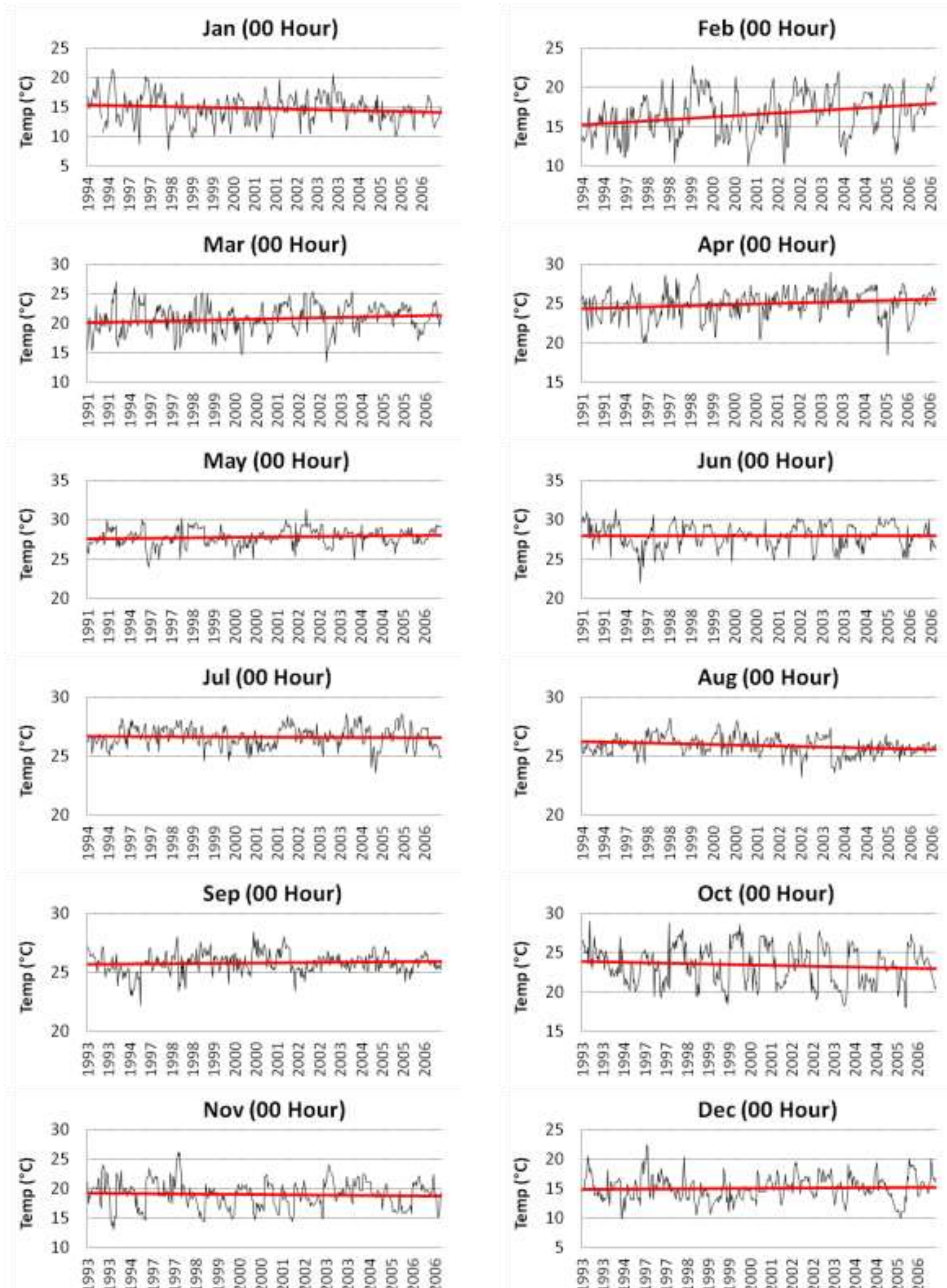

Figure 2: Ambient Dry Bulb Temperature at 00 Hours during 1991-2006.

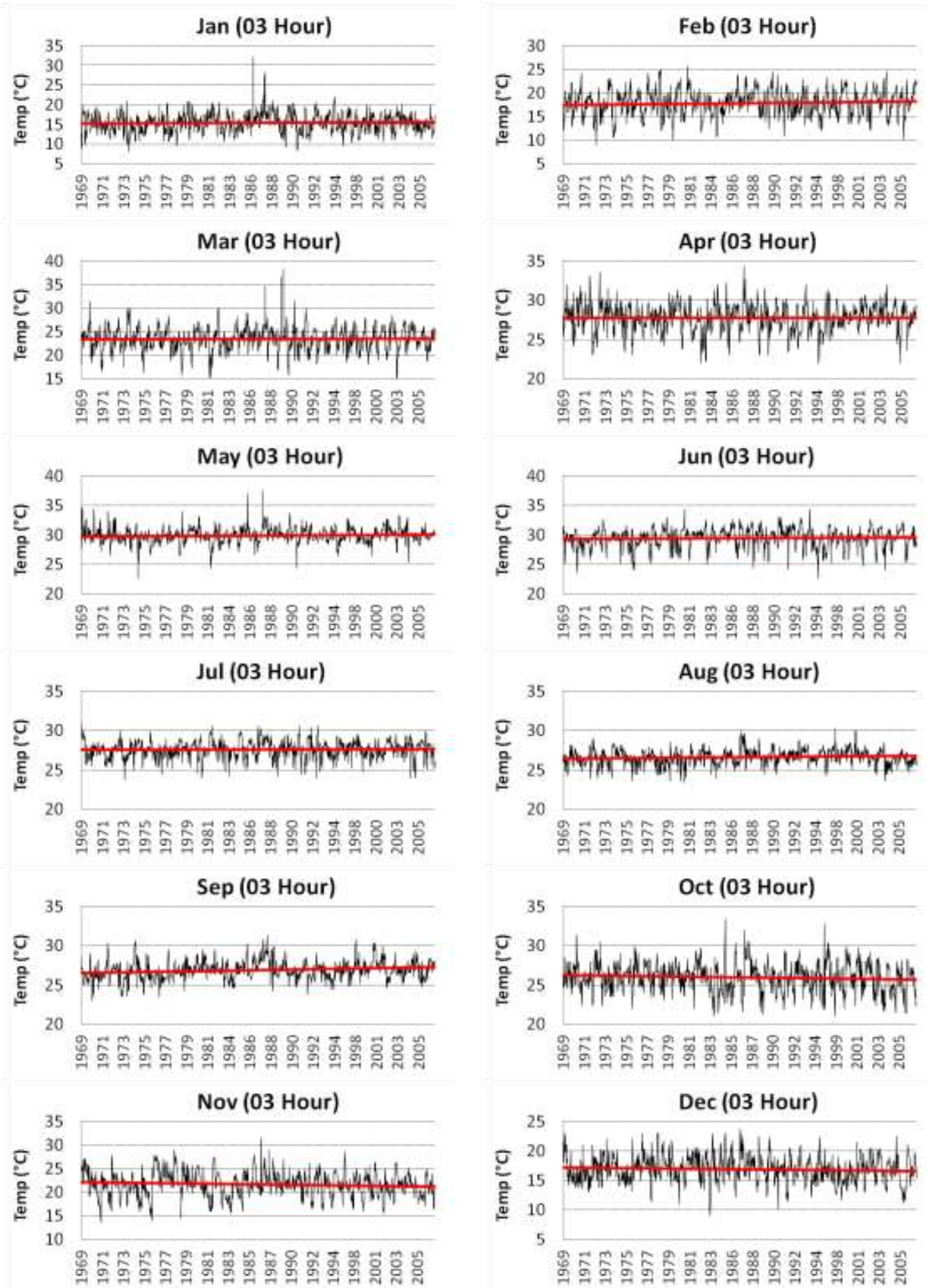

Figure 3: Ambient Dry Bulb Temperature at 03 Hours during 1969-2006.

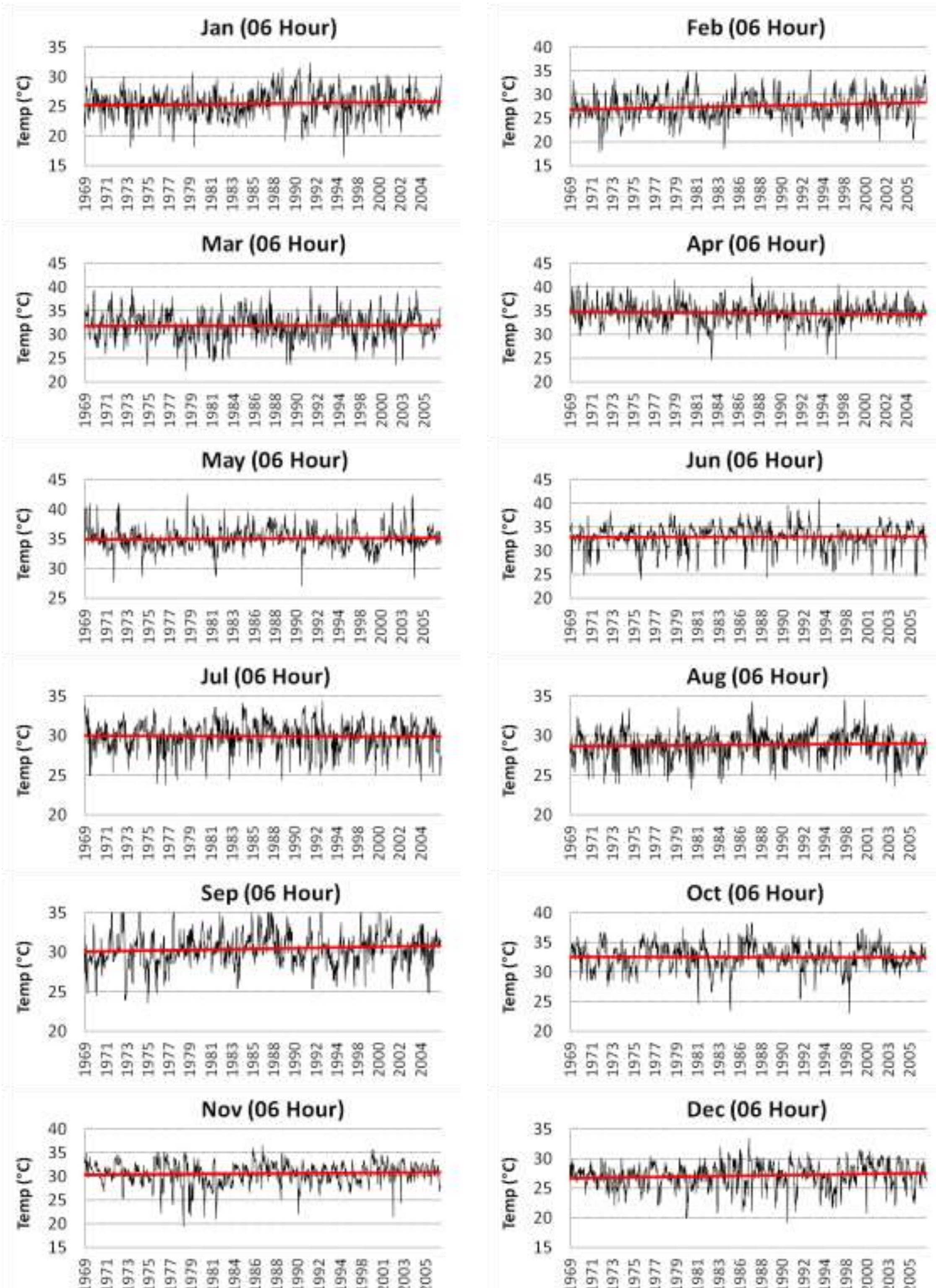

Figure 4: Ambient Dry Bulb Temperature at 06 Hours during 1969-2006.

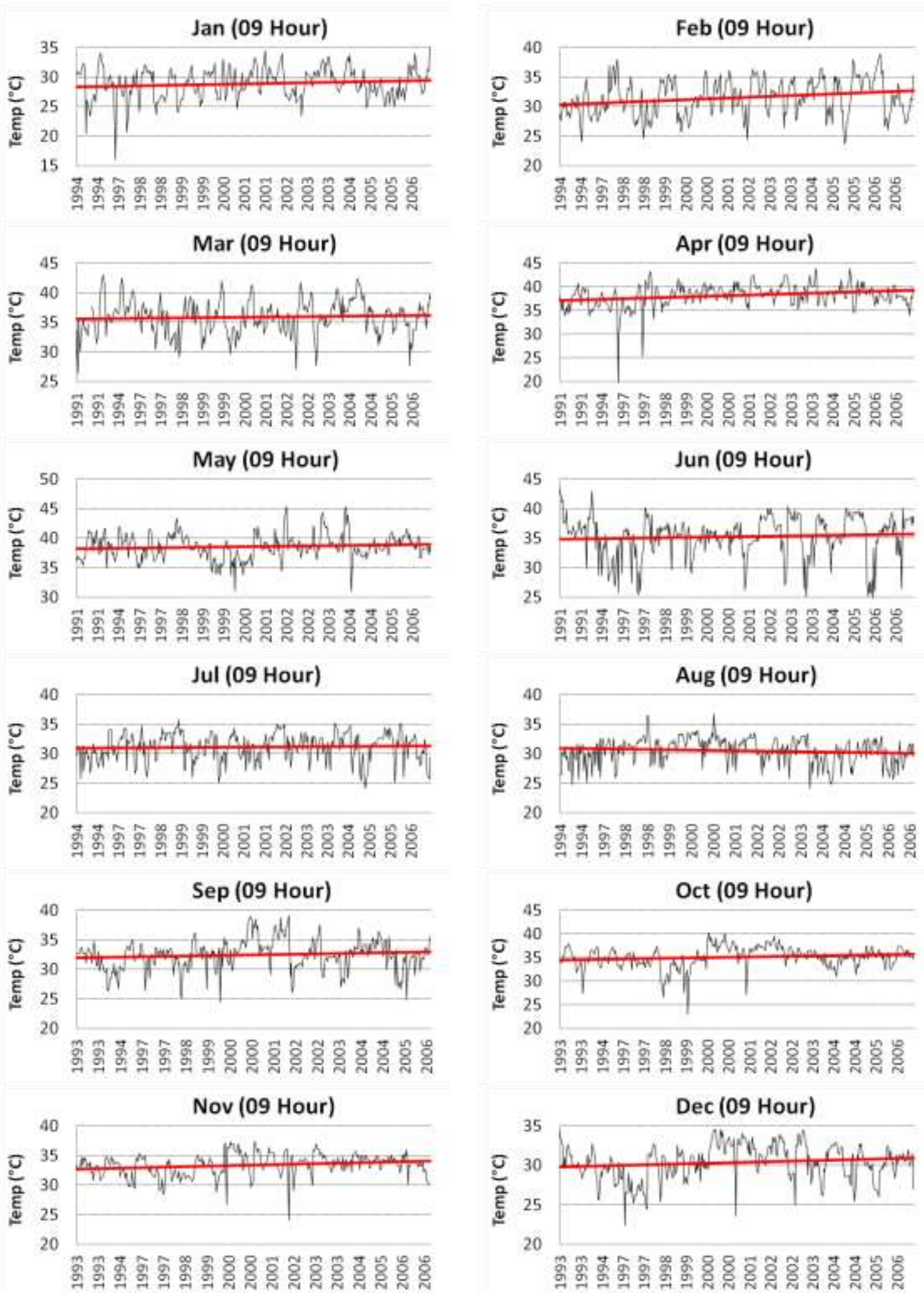

Figure 5: Ambient Dry Bulb Temperature at 09 Hours during 1991-2006.

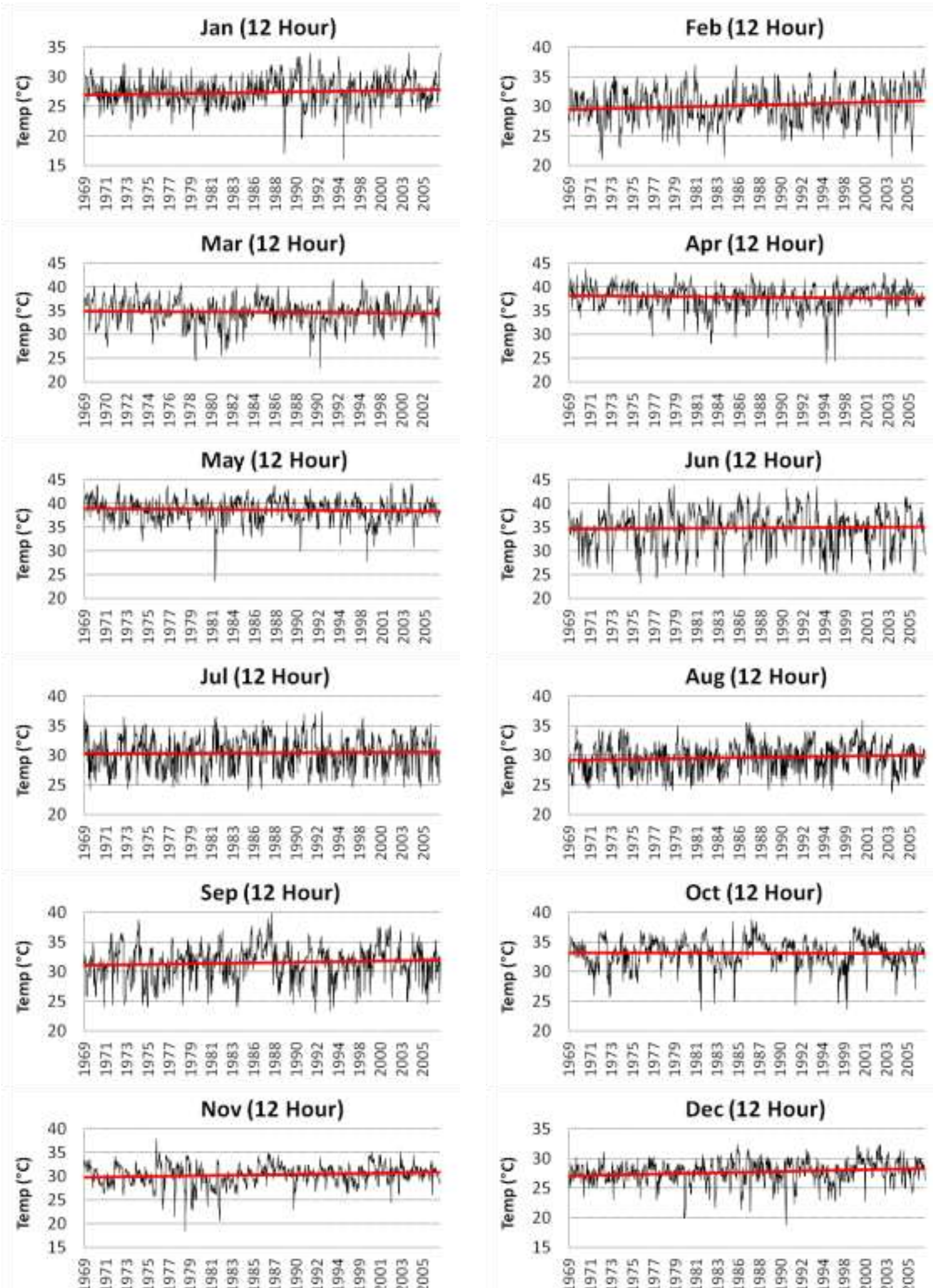

Figure 6: Ambient Dry Bulb Temperature at 12 Hour.

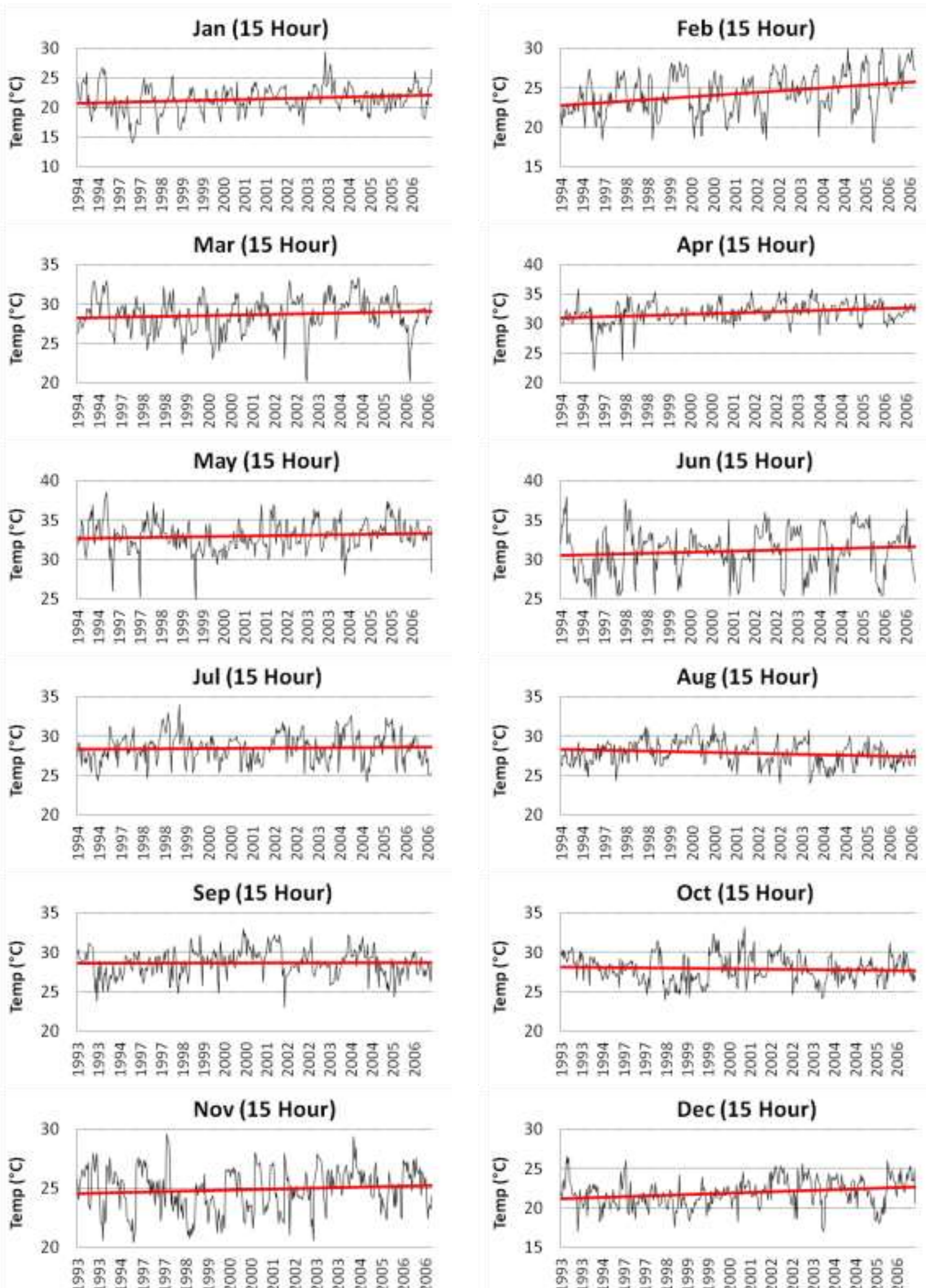

Figure 7: Ambient Dry Bulb Temperature at 15 Hour.

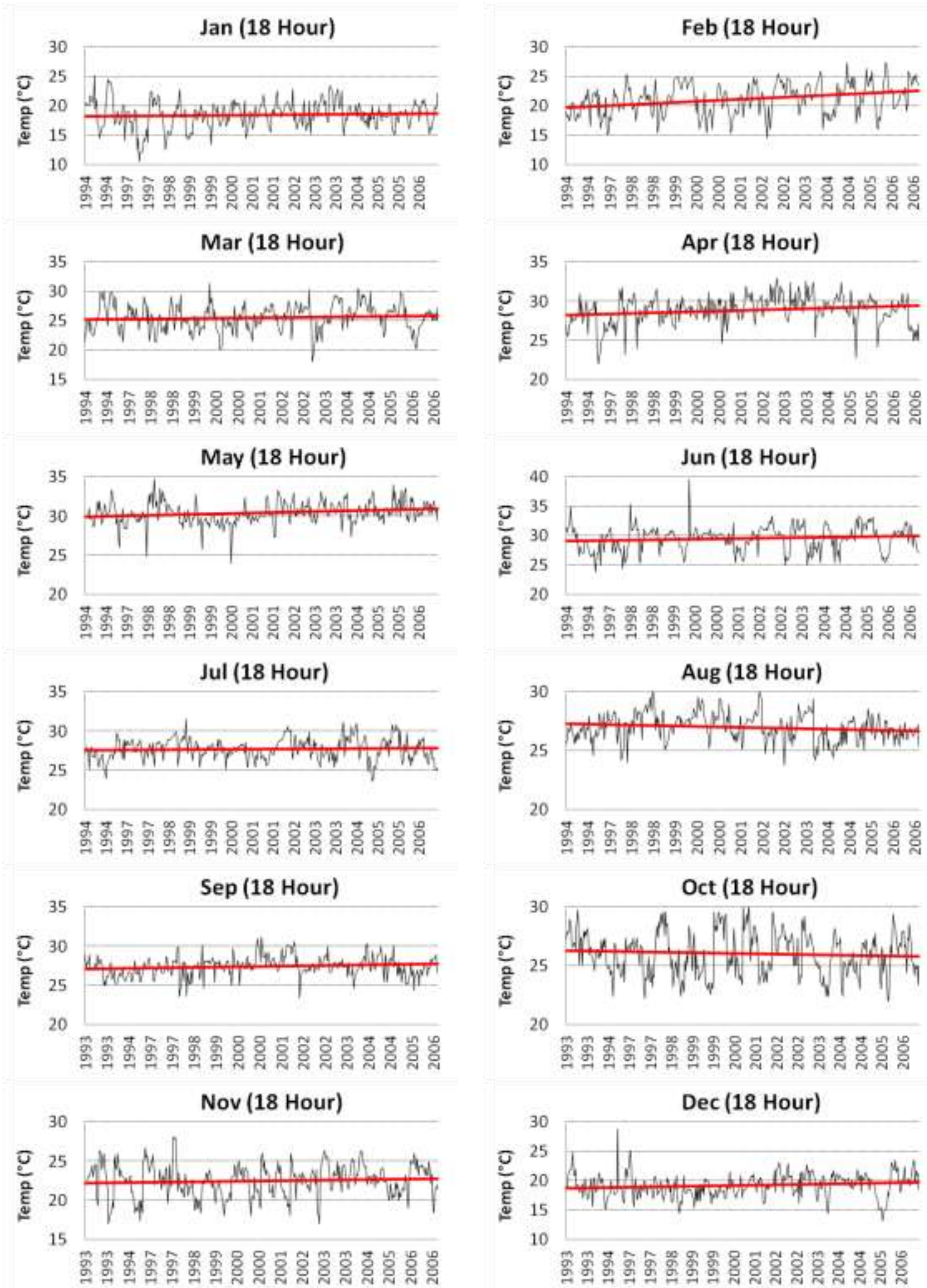

Figure 8: Ambient Dry Bulb Temperature at 18 Hour.

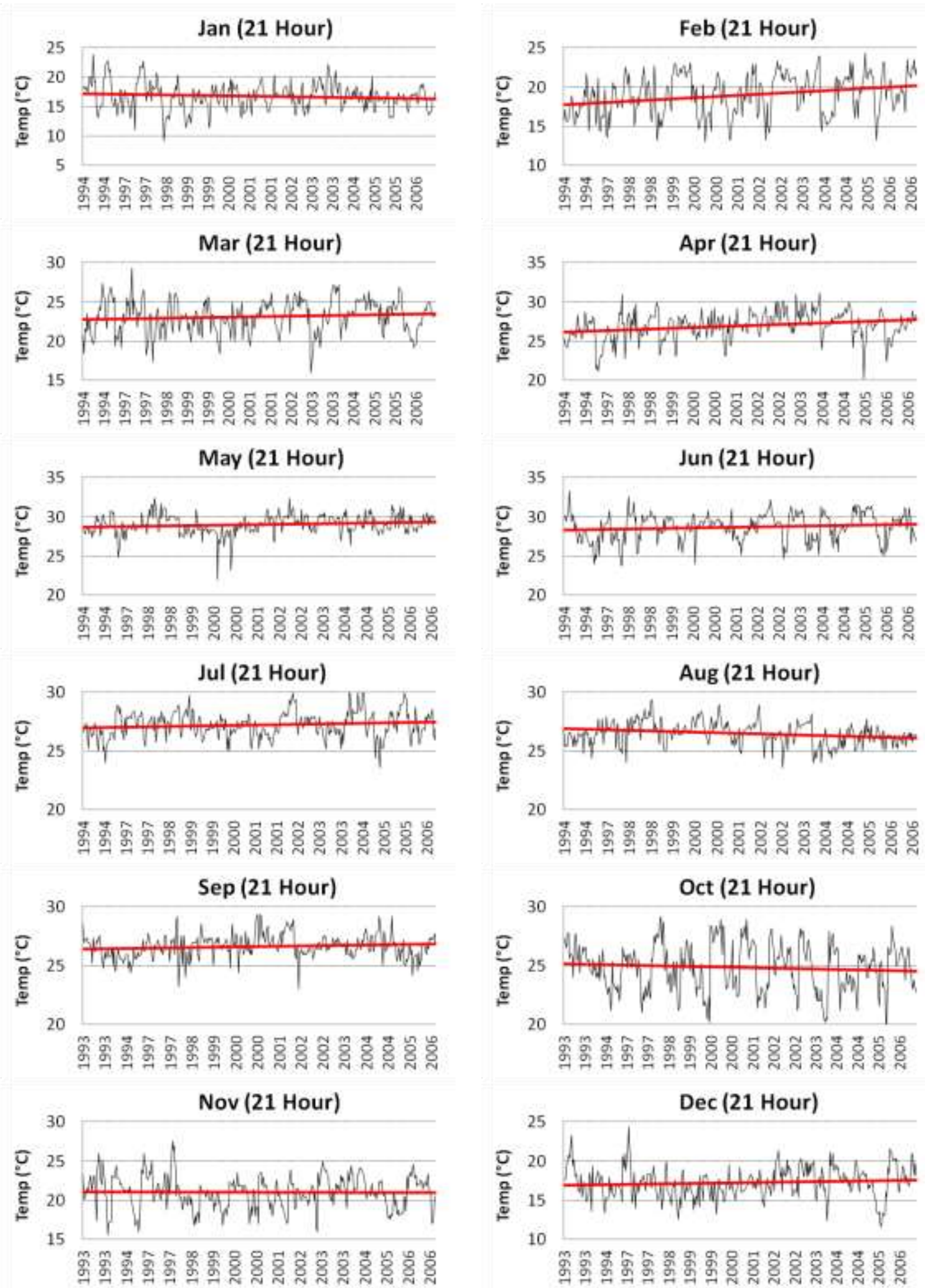

Figure 9: Ambient Dry Bulb Temperature at 21 Hour.

Table 2(a): Mann-Kendall Trend Test Results (Z_{MK} values) for the Dry Bulb Temperature in Vadodara city during 1969-2006 for the different hours.

Months	0 hr	3 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr
	Z_{MK}							
January	-2.921	1.524	2.469	1.469	3.479	3.165	1.032	-1.816
February	5.301	2.646	4.424	6.757	5.289	5.090	5.583	4.182
March	2.934	1.035	0.411	0.845	-0.024	2.540	2.141	2.532
April	4.682	-0.077	-3.927	5.185	-2.101	5.413	5.689	4.810
May	3.017	2.920	1.697	2.249	-2.715	2.315	4.411	3.555
June	1.974	2.279	1.383	3.324	1.517	2.465	2.619	2.620
July	-0.463	2.239	-0.036	1.535	0.870	1.205	0.941	0.759
August	-4.249	3.377	2.315	-1.981	3.323	-2.715	-2.985	-4.381
September	1.729	6.316	4.528	3.221	3.202	0.567	1.967	1.536
October	-0.500	-2.526	-1.419	1.866	-0.985	0.465	0.314	0.162
November	-0.900	-3.540	1.446	3.589	4.307	2.703	1.845	0.238
December	2.077	-2.399	0.853	3.068	7.139	6.971	5.490	4.272

Table 2(b): Trend type for the Dry Bulb Temperature.

Months	0 hr	3 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr
	Trend Type							
January	-4	+1	+3	+1	+4	+4	+1	-2
February	+4	+4	+4	+4	+4	+4	+4	+4
March	+4	+1	+1	+1	-1	+3	+3	+3
April	+4	-1	-4	+4	-3	+4	+4	+4
May	+4	+4	+2	+3	-4	+3	+4	+4
June	+3	+3	+1	+4	+1	+3	+4	+4
July	-1	+3	-1	+1	+1	+1	+1	+1
August	-4	+4	+3	-3	+4	-4	-4	-4
September	+2	+4	+4	+4	+4	+1	+3	+1
October	-1	-3	-1	+2	-1	+1	+1	+1
November	-1	-4	+1	+4	+4	+4	+2	+1
December	+3	-3	+1	+4	+4	+4	+4	+4

Table 3(a): Mann-Kendall Trend Test Results (Z_{MK} values) for the Wet Bulb Temperature in Vadodara city during 1969-2006 for the different hours.

Months	0 hr	3 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr
	Z_{MK}							
January	-3.600	5.231	4.829	-0.903	8.454	-1.322	-0.869	-2.617
February	2.762	6.993	7.088	6.002	11.301	3.925	3.371	3.161
March	2.756	5.397	5.668	1.232	10.148	-1.835	-0.546	0.094
April	-1.135	2.403	5.947	1.994	9.029	-0.662	-1.747	-1.496
May	-5.410	-0.717	2.164	3.992	1.282	-1.872	-2.856	-4.262
June	-4.372	-3.086	-1.266	3.088	-0.725	-0.867	-3.439	-4.412
July	-4.043	-1.067	-1.124	1.895	0.279	-1.071	-2.734	-4.726
August	-6.948	0.483	0.782	-1.796	2.097	-4.489	-5.819	-6.105
September	-3.619	4.613	6.430	4.446	8.047	1.015	-0.721	-2.792
October	-2.994	0.178	2.086	0.025	5.060	-2.004	-2.266	-2.369
November	-2.245	1.763	4.201	-0.209	7.572	-0.771	0.027	-0.977
December	-0.840	1.824	5.799	1.899	9.880	3.885	4.223	3.256

Table 3(b): Trend type for the Wet Bulb Temperature.

Months	0 hr	3 hr	6 hr	9 hr	12 hr	15 hr	18 hr	21 hr
	Trend Type							
January	-4	+4	+4	-1	+4	-1	-1	-4
February	+4	+4	+4	+4	+4	+4	+4	+4
March	+4	+4	+4	+1	+4	-2	-1	+1
April	-1	+3	+4	+3	+4	-1	-2	-1
May	-4	-1	+3	+4	+1	-2	-4	-4
June	-4	-4	-1	+4	-1	-1	-4	-4
July	-4	-1	-1	+2	+1	-1	-4	-4
August	-4	+1	+1	-2	+3	-4	-4	-4
September	-4	+4	+4	+4	+4	+1	-1	-4
October	-4	+1	+3	+1	+4	-3	-3	-3
November	-3	+2	+4	-1	+4	-1	+1	-1
December	-1	+2	+4	+2	+4	+4	+4	+4

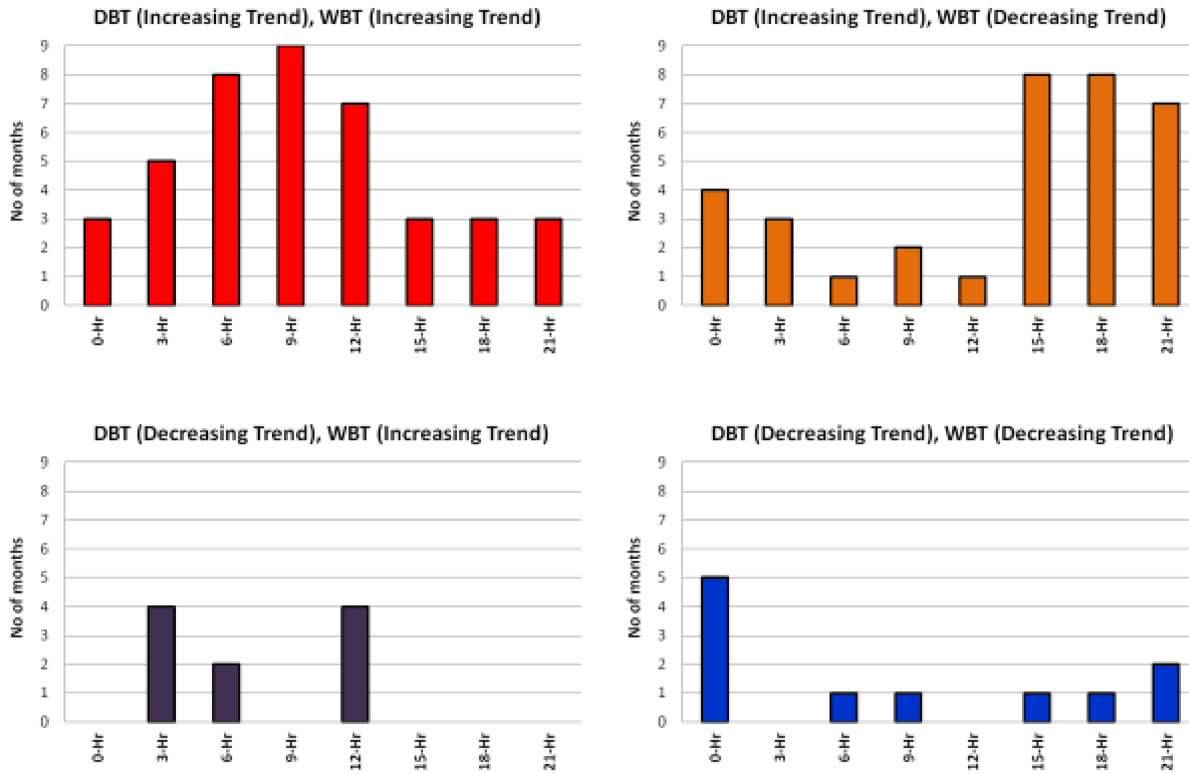

Figure 10: Composite trend behavior of the DBT and WBT during 1969-2006.

4. Conclusion

The salient conclusions of the present urban climate change study done over the city of Vadodara located in the state of Gujarat, India using the hourly DBT and WBT available at 00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr for a period of 37 years (1969-2006) are as follows:

i. There was an overall increase in the temperature of Vadodara city as for 78% of the time the DBT had an increasing trend (56% of the time it had an increasing trend significant at 90% or 95% or 99% confidence levels while 22% of the time the increasing trend was not significant) and 52% of the time WBT had an increasing trend (41% of the time it had an increasing trend significant at 90% or 95% or 99% confidence levels while 11% of the time the increasing trend was not significant)
ii. For the DBT, all hours of the day (00-hr, 03-hr, 06-hr, 09-hr, 12-hr, 15-hr, 18-hr and 21-hr) had an overall increasing trend while for the WBT in the first half of the day (03-hr to 12-hr) there was an overall increasing trend while in the second half of the day (15-hr to 0-hr) there was an overall decreasing trend.
iii. In the period May-July, WBT had a decreasing trend while DBT had an increasing trend which infers a reduction in the relative humidity. Incidentally much of this period is of monsoon inferring alteration in the precipitation.
iv. For the DBT, except for the month of August and October, the remaining 10 months had an overall increasing trend while for the WBT the increasing trend was seen in November – April and September.
v. For both DBT and WBT, the month of February had the overall maximum increasing trend while the month of August had the overall maximum decreasing trend.

The present study statistically quantifies the changing urban climate of Vadodara city and the findings would add to the pool of knowledge to understand the dynamics of the changing urban climate which would help to initiate appropriate measure for mitigation and adaptation.

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