Acceleration in temperature increase over India :
An application of two-phase regression

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सार – इस शोध–पत्र में जलवायु की भिन्नताओं में परिवर्तन की सीमा तक जलवायु परिवर्तनों का अध्ययन किया गया है। ये परिवर्तन मानव–विज्ञान जनित जलवायु परिवर्तन के अनुरूप होते हैं। पूरे देश में तापमान की प्रवृत्तियों में कहीं उल्लेखनीय परिवर्तन तो नहीं हो रहा है इस तथ्य की जाँच करने के लिए इस शोध पत्र में भारत के सतही वायु तापमान के दीर्घकालिक वार्षिक औसत को रिकार्ड करने हेतु एक द्वि–आयामी समाश्रयण निदर्श का अनुप्रयोग करने का प्रयास किया गया है। यह देखा गया है कि अध्ययन के लिए चुने गए अधिकांश केन्द्रों को 1900 के दशक के मध्य में तापमान की प्रवृत्तियों में वृद्धि पाई गई है। यद्यपि विशिष्ट परिवर्तन बिंदु वर्ष के संबंध में काफी भिन्नताएँ देखी गई है तथापि विभिन्न केंद्रों पर भिन्नताओं की एक जैसी अवधियों का पता चला है। दीर्घ अवधि के तापमानों के रिकार्डों का और अधिक विश्लेषण मानव विज्ञान जनित परिवर्तनों अथवा प्राकृतिक भिन्नताओं के परिवर्तनों का पता लगाने में उपयोगी होंगे।

ABSTRACT. A key issue in climate change is the extent to which there are changes in climate variables that may be consistent with anthropogenically induced climate change. In this paper an attempt has been made to apply two-phase regression model to records of long term annual mean surface air temperature over India to examine whether there are any significant changes in the temperature trends across the country. We find that most of the stations selected for the study, show an acceleration in temperature trends during the mid 1900's. Even though a considerable variation with regard to the specific change point year is seen however there appear to be common periods across the different stations. Further analysis of long duration temperature records may be useful in attributing these changes to the anthropogenic forcing or natural variability.

Key words – Temperature change, Two phase regression, Change point analysis, Climate change, Anthropogenic forcing.

1. Introduction

Atmospheric concentrations of greenhouse gases and aerosols such as carbon dioxide and suphate particles have increased significantly over the 20th century. Increase in greenhouse gases and aerosols influence the Earth's energy balance and cause significant change in climate (IPCC - 2001, Kellog, 1991). In the Third Assessment Report, the IPCC concluded that the forcing to date is likely to be responsible for the observed $0.6 \pm 0.2°$ C increase in global surface temperature observed over the last 140 years. It has been noted that this temperature increase is not globally uniform. Regional variations can be much larger and significant spatial and temporal variation may exist between climatically different regions.

Therefore, it is important to assess the temperature trends at regional and local levels and in particular, any changes in these trends.

Several authors have examined the trends and fluctuations in surface air temperature over the Indian subcontinent. The annual mean surface air temperature averaged over the landmass of India has shown warming of about $0.4°$ C in last century (Thapliyal and Kulshreshtha, 1991, Hingane *et al*., 1985). Increase in the mean temperature over India during last century is almost entirely due to the increase in maximum temperature with the minimum temperature remaining trendless (Rupakumar *et al*., 1994). Consequently there is an increase in the diurnal temperature range over India,

contrary to that observed over other parts of the world (Karl *et al*., 1991; Karl *et al*., 1993; Mearns *et al*., 1995; Hansen *et al*., 1995). This long-term trend is not uniform through time. For example, the annual mean temperature showed a 0.15° C cooling from 1900 to 1920 until it became equal to the long-term mean, then falling 0.1° C in the decade of the 1930s. Contrary to the observations of fall in global temperature (Vinnikov *et al*., 1980, Jones *et al*., 1982, Hansen and Lacis, 1990, Jones and Wigley, 1990, Parker *et al*., 1994, Tett *et al*., 1999) the regional temperature shows an increasing trend reaching a maximum in the 1950s. In the later part of 1950s, the temperature showed a decreasing trend and continued till mid seventies. The decades 1971-80 and 1981-90 have shown greater warming rates than other decades (Srivastava *et al*., 1992). A general cooling in north of 22° N and warming in south India has been observed (Hingane *et al*., 1985, Groisman and Kovyneva, 1989, Srivastava *et al*., 1992). A recent study on the climatic fluctuation over Indo-Gangetic Plains Region (IGPR) by Singh and Sontakke (2002) has concluded that over IGPR there has been warming since the late 19th century to 1952 and cooling afterwards. This cooling after 1952 was attributed by Singh & Sontakke (2002) to the combined effect of regional changes such as expansion and intensification of agricultural activities, spreading of irrigation network and global environmental changes *viz*., global warming and its influence on the Indian monsoon circulation.

While many of these studies have focused on trends and variability, it is also necessary to examine the changes in secular behaviour; as such changes may be useful in establishing the link between anthropogenic forcing, other environmental changes and climate change. For this reason, the present study explores the use of two-phase regression model for the identification and analysis of changes in the behaviour of long duration records of temperature. Since the focus of the study is on changes in the secular behaviour such as trends, two-phase regression is particularly useful, as it leads to the identification of change-points; *i.e*., times when there is a change in slope associated with the underlying trend in the data. Further, by examining the data for a number of stations, we can explore the possibility whether these changes are coherent over large regions and thus whether they are due to non-homogeneity in the data or is a signal of change in the natural variability of the climate regime. The non-homogeneities in time series usually occur as a gradual trend, such as in the case of urban warming or as an abrupt discontinuity (jump) of the time series. Such kinds of discontinuities occur for a number of reasons, for example : station displacements, instrumental changes, methodological changes in computations of means (Alexandersson and Moberg, 1997).

The next section in the paper describes the data used in the study and methodology adapted for the change-point analysis. Subsequent section deals with the results and interpretation and the final section summarizes the findings of the study.

2.   Methodology and data

Two-phase regression model (Solow, 1987; Dunnigan *et al*., 1997) provides valuable insight into the existence, timing and significance of changes in the data. The technique is an extension of linear regression wherein change points are identified as locations where the regression line changes. For each subset of data-from the beginning of the data set to the change point and from the change point to the end of the data set, a linear regression is then calculated. Two-phase regression mandates that the two best-fit lines be joined at the change point; there is always, then, a difference in slope between the two new data sets. The model is estimated by fixing change-point, obtaining the ordinary least square estimates of the regression line parameters given change point and computing the residual sum of squares, which depends on the change point. The value of the change point, which minimizes the residual sum of squares, is the change point of our interest (absolute change point). Two-sided confidence interval for the change-point at 95% significance level is calculated using F distribution. This is relevant to examine whether we have a common change point across the different stations. It will give insight about whether there is an overlap in terms of the confidence intervals of the change-point. This makes it possible to discuss the extent to which the acceleration or deceleration in trend appears to be coherent across different stations. Another reason to look at the confidence intervals is that change points that happen towards either end of a record are normally not considered, because the confidence interval for the change point will include the end of the record.

Two-phase regression has been applied to study climate change. For example, Hanson *et al*. (1989) employed two-phase regression to test for constancy of mean in precipitation and temperature data averaged for the contiguous U.S. and the northern plains region of the U.S. An analysis of long-term temperature record for eastern Minnesota has been done using two-phase regression by Skaggs and Baker (1989).

The monthly mean temperature data for Indian stations used in the study have been downloaded from the Global Historical Climatology Network (GHCN) version 2 website (http://lwf.ncdc.noaa.gov/oa/pub/data/ghcn/v2/ghcnftp.html). The Global Historical Climatology Network (GHCN) is a comprehensive global surface

TABLE 1

Results of change-point analysis of the temperature data at stations across India

S. No.	Station	Period of data		CP with Confidence interval			p-value	Trend (°C/100 Years)		Difference (b-a)
		From	To	Min. - CP	CP-year	Max. - CP		Pre-CP (a)	Post-CP (b)	
1.	Chennai	1875	2002	**1940**	**1971**	**1997**	0.007	0.226	1.677	1.451
2.	Kolkata	1878	2002	**1930**	**1953**	**1966**	0	1.714	0.079	-1.636
3.	Thiruvananthapuram	1890	2002	1891	1895	2001	0.344	8.466	1.121	-7.345
4.	Mumbai	1878	2002	**1886**	**1920**	**1975**	0.043	1.513	0.455	-1.058
5.	Port Blair	1868	2002	**1873**	**1880**	**1903**	0	9.860	-1.347	11.207
6.	Sagar	1875	2002	**1916**	**1997**	**2001**	0.044	0.284	15.310	15.026
7.	Nagpur	1875	2002	1876	1962	2001	0.453	-0.129	0.680	0.809
8.	Akola	1875	2002	1876	1899	2001	0.097	3.033	0.555	-2.477
9.	Bangalore	1875	2002	**1944**	**1975**	**2001**	0.031	0.391	2.089	1.699
10.	Darbhanga	1876	1980	1877	1960	1979	0.069	0.542	-1.867	-2.409
11.	Allahabad	1876	2002	1877	1991	2001	0.078	0.243	6.598	6.355
12.	Pune	1876	2002	**1929**	**1957**	**1982**	0.028	0.038	-1.249	-1.288
13.	Bikaner	1878	2002	**1944**	**1957**	**1968**	0	-1.909	2.501	4.410
14.	Indore	1878	2002	**1928**	**1956**	**1990**	0.007	0.119	1.790	1.672
15.	Agra	1876	1987	**1923**	**1935**	**1971**	0.003	-1.908	0.956	2.864
16.	Dhubri	1881	1981	1882	1904	1980	0.16	-1.019	0.666	1.685
17.	Vishakhapatnam	1889	2002	**1924**	**1935**	**1948**	0	-0.358	1.957	2.315
18.	Veraval	1890	2002	**1987**	**1991**	**1995**	0	0.608	8.297	7.690
19.	Pamban	1891	2002	**1955**	**1968**	**1974**	0	-0.045	3.448	3.493
20.	Srinagar	1893	2002	**1922**	**1996**	**2000**	0.05	0.518	18.640	18.122
21.	Daltonganj	1893	2002	1894	1979	2001	0.336	0.343	1.971	1.627
22.	Hyderabad	1893	2002	**1953**	**1963**	**1974**	0	-1.315	1.957	3.272
23.	Jodhpur	1897	2002	1898	1908	2001	0.101	-9.678	0.226	9.904
24.	Dibrugarh	1901	2002	1902	1941	2001	0.106	1.463	0.119	-1.344
25.	Guwahati	1902	2002	1903	1942	2001	0.104	1.295	-0.089	-1.384
26.	Shimla	1876	1980	**1895**	**1905**	**1913**	0	-6.681	1.176	7.857

Note : Bold values of change point year are significant at 5% level.

baseline climate data set designed for monitoring and detecting climate change. Comprised of surface station observations of temperature, precipitation and pressure, all GHCN data are on a monthly basis. GHCN is produced jointly by the National Climatic Data Center, Arizona State University and Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory. (Details and overview of GHCN version 2 temperature data and metadata can be found at (http://lwf.ncdc.noaa.gov/oa/climate/research/ghcn/ghcnoverview.html).

For the present study, we selected 26 stations, which have more than 100 years of data. In addition, we selected seven stations [New Delhi (1931 to 2002), Dwarka (1901 to 1978), Kochi (1875 to 1973), Cuttack (1878 to 1972), Ludhiana (1875 to 1973), Jaipur (1881 to 1960) and Kota (1898 to 1973)] corresponding to large cities, which had at least 70 years of data. The mean annual values of surface air temperatures at various stations across India were calculated with the help of monthly mean values from the actual datasets. The missing monthly temperature values were filled in by linear interpolation. If the data for consecutive two years or more were missing, the series was broken into two parts and the missing years were omitted, the longer data subsets have been taken for analysis.
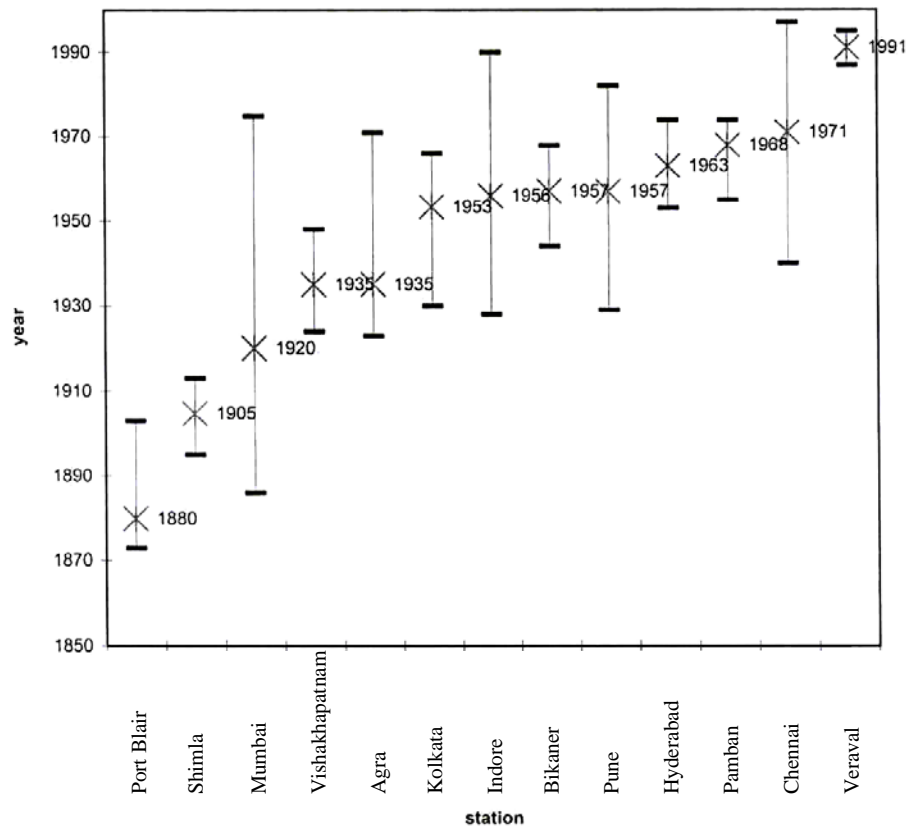
Fig. 1. Significant change-points with confidence intervals at selected stations in India

3.   Results and interpretation

The results of applying two-phase regression to the annual mean surface air temperature data at various stations across India are shown in Table 1. From Table 1, it is clear that most of the stations selected for the study show a significant change point, which represents either an acceleration, a deceleration or a change in direction of temperature trend. It is also evident that most of the stations depict acceleration in the temperature after the shift points. Deceleration in the temperature after the significant change point has been observed in the case of Mumbai (earlier Bombay) and Kolkata (Calcutta). Pune and Port-Blair show a decreasing trend in the temperature after the significant change point, while a reverse trend is noticed at Veraval and Shimla. Fig. 1 shows the pictorial representation of the significant change point at 5% confidence interval at stations across India. From the confidence interval of the change points at stations Bangalore, Srinagar, Allahabad and Sagar it is evident that the maximum limit of the interval goes very close to the end of dataset which reflects the artifact of the model and therefore the change points at these stations might not be very reliable for drawing conclusions about a change in behaviour of the series. Consequently, these stations are not included in further analysis.

There has been found commonality among the stations in terms of change point year and its confidence interval. It is clear that there are two set of stations which are depicting common change points. Vishakhapatnam and Agra have shown change points at 1935 and both stations depict increasing trend in the temperature after the shift point. Bikaner and Pune have depicted a common change point in the year 1957 but they exhibit opposite trends after the shift point. Former has increasing trend in the temperature while latter has decreasing trend. From Fig. 1, it is evident that most of the change points lie in the period 1920-1971. Three stations *viz*., Port Blair (1880), Shimla (1905) and Veraval (1991) are quite different. From Fig. 1 it is seen that the northern stations of India (Shimla, Agra, Bikaner, Indore) encountered the significant change point much earlier than the southern stations (Chennai, Veraval, Hyderabad, Pamban). Thus, there is a gradual lag in the change point years from north to south stations.
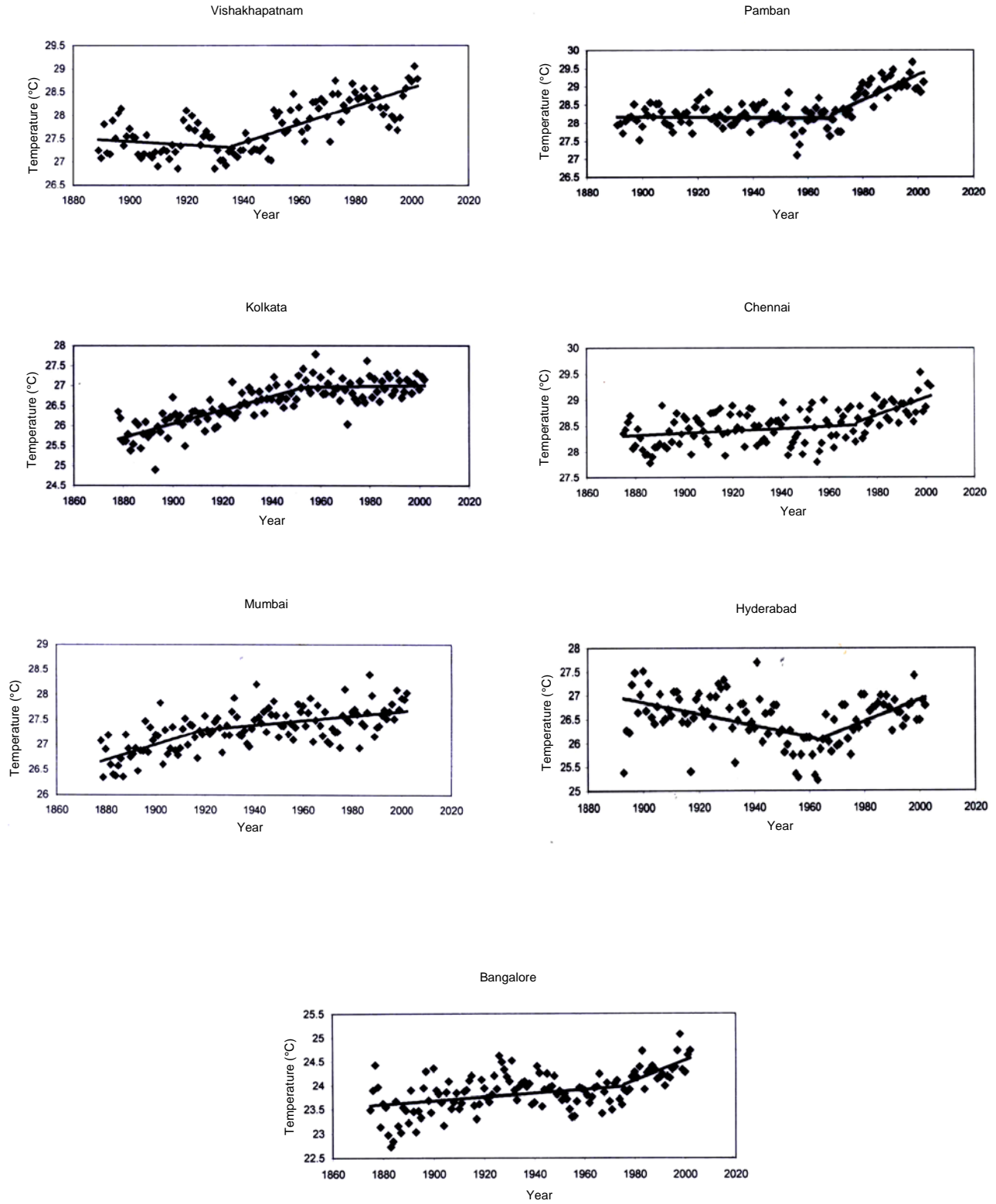
Fig. 2. Plots of mean annual surface air temperature with trend lines using two-phase regression at some stations in India

Fig. 2 depicts the plots of the annual mean temperature with trend lines at some stations selected for the analysis. Chennai (earlier Madras) shows change point in the year 1971, the year divides the series into two significantly different sub-series in respect to their slopes. After 1971 there is increasing trend in the temperature time series. Pamban shows a significant change point in 1968, after this year increase in trend in the temperature series has been observed. A shift point in 1963 has been depicted in the temperature series at Hyderabad and an increasing trend in the series has been revealed thereafter. These stations, Chennai, Pamban and Hyderabad, have shown significant change points and general increasing trend in the temperature after near nineteen seventies. This is in concurrence with the finding that there has been an increasing trend in the surface air temperature over most part of India after nineteen seventies (Srivastava *et al*., 1992).

Mumbai (earlier Bombay) has depicted a significant change point at 1920. Before and after the shift point the temperature data revealed trends of 1.51 and 0.45° C / 100 year, respectively. Thus, there is decrease in the increasing trend of the surface air temperature at Mumbai after 1920. Significant change point in the year 1953 has been found in the time series of the temperature at Kolkata. The trend values pre and post change point are 1.7 and 0.08° C / 100 year respectively. A decrease in the increasing trend in the surface air temperature is observed after 1953 at Kolkata. This decrease after the change point at Mumbai and Kolkata may be attributed to the industrial development increasing the concentration of the aerosols in local atmosphere. Thus at Mumbai and Kolkata the role of aerosols dominates over the greenhouse gas global warming after the change point. Pune has shown significant change point in 1957. Before 1957 the temperature series depicted a trend of 0.04° C / 100 year and after trend of -1.3° C / 100 year. Thus, there is cooling after 1957 at Pune. Rupakumar and Hingane (1988) have also found that since 1960s, cities Kolkata and Pune have less warming and cooling respectively. Further using data between 70 and 100 years, the change point analysis has been performed on the temperature series of large Indian cities. It has been observed that Kochi (1875 to 1973) and Jaipur (1881 to 1960) have significant change point in the year 1898 and have cooling after the shift point. Delhi depicts a non-significant change point in 1941 and some cooling trend is observed after that. These cities seem to have been affected by the dominant effect of aerosols due to industrial activities in the local atmosphere after the change point.

Cuttack has shown a significant change point in 1921. Decreasing trend (-1.42° C / 100 year) before change point and an increasing trend (1.32° C / 100 year) has been observed. A significant change point at 1935 has been detected at Agra. Before the shift point the trend in the temperature data is -1.91° C / 100 year and thereafter a trend of 0.96° C / 100 year. Thus, there is increasing trend in the temperature series after 1935. Vishakhapatnam also shows significant change point in 1935. Before the shift point there has been a decreasing trend (-0.36° C / 100 year) and after that an increasing trend (1.96° C / 100 year), therefore there is warming at Vishakhapatnam after 1935. A significant change point in 1905 has been detected at Shimla. Before 1905 the time series of the temperature revealed a trend of -6.68° C / 100 year and thereafter a trend of 1.18° C / 100 year. There has been warming after 1905 at Shimla. At Bikaner, a significant change point is detected in 1957. There has been a decreasing trend in the temperature data before 1957 and an increasing trend thereafter. A warming after 1957 has been observed at Bikaner. Indore depicts a significant change point in 1956. Before the shift point the series possess a trend of 0.12° C / 100 year and thereafter 1.79°C / 100 year. Thus, there has been observed an increasing trend in the temperature at Indore after 1956. These stations Cuttack, Agra, Vishakhapatnam, Shimla, Bikaner and Indore seem to have been affected by global warming and urban heat island effect is dominant over the aerosol effect in the local atmosphere after the change point.

4.   Conclusions

Application of change-point analysis to the long-term annual mean surface air temperature to detect the presence, timing and significance of the shift point at number of stations in India has revealed the following conclusions :

(*i*)   Individual stations depict different change points in the temperature time series. Some of them reveal common change point years and decades. Most of the significant change points are noticed near 1950s and 1970s in the temperature data. An increasing trend is observed after the change point at these stations which is in agreement with the earlier finding that most of the stations in India shows increasing trend after 1970s. There has also been found some instances of only tail overlapping of change point interval *viz*., at Mumbai & Port - Blair, Shimla & Port Blair and Bikaner & Vishakhapatnam.

(*ii*) One interesting observation is that most of the northern stations of India have noticed the significant change point in early years in comparison to the southern stations. Thus, in general, there seems to be a gradual lag in the change point years at southern stations of India as compared to the northern states.

(*iii*) Most of the stations show increasing trend after change point. The increasing trend in temperature was somewhat arrested in case of Kolkata and Mumbai and in contrast to this a high increasing trend was observed in respect of Shimla and Veraval. The trend is reversed for Pune and Port Blair after the change point.

(*iv*) For stations, Kolkata, Bikaner and Indore ; 1950s show significant change points in the temperature data and depict increasing trends after the shift points. Agra and Vishakhapatnam show significant change points in 1930s and depict an increasing trend in the time series of temperature after the shift points. These stations seem to reflect the composite effects of global and regional/local changes in the surface air temperature such as global warming, industrialization and urban heat island effect in the series.

(*v*) Extension of this research can be done regarding the identification of characteristics and configuration of climatic and anthropogenic variables inducing the change point in temperature series in the Indian subcontinent which needs detailed investigation.

Acknowledgements

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