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Decadal trends in climate over India

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सार — सन् 1901 से 1986 ई० की अवधि के लिए मौसम-विज्ञान प्राचलों नामतः तापमान (सतह वायु, अधिकतम तापमान, न्यूनतम तापमान तथा मध्य क्षोभ मंडल तक उपरितन वायु), स्टेशन स्तर दाब और मौसमी तथा वार्षिक वर्षा के दशकीय विचलनों का अध्ययन किया गया है (1951 से आगे के लिए उपरितन वायु आंकड़े उपलब्ध हैं)। आंकड़ा शृंखला में अनुप्रयुक्त सार्थकता परीक्षण यह दर्शाता है कि देश के करीब-करीब सभी उत्तरी भागों (23° उ० अ० के उत्तर) में तापमान घटने की प्रवृत्ति तथा दक्षिणी भागों (23° उ० अ० के दक्षिण) में बढ़ने की प्रवृत्ति दिखा रहा है। फिर भी समूचे देश में अल्प उष्णता प्रवृत्ति है। वायुमंडलीय दाब द्वितीय तथा तृतीय दशकों के मध्य गिरावट दर्शाता है, किन्तु सन् 1930 ई० के बाद इसने कोई महत्वपूर्ण परिवर्तन नहीं दर्शाया। मौसमी (जून-सितम्बर) तथा वार्षिक वर्षा का दशकीय विश्लेषण यह दर्शाता है कि वर्षा में विविधता सांख्यिकीय सीमाओं के अंतर्गत है।

ABSTRACT. Decadal variations of meteorological parameters, *vig*. temperature (surface air, maximum temperature, minimum temperature and upper air up to middle troposphere), station level pressure and seasonal and annual rainfall are studied for the period 1901 to 1986 (upper air data available from 1951 onwards). Tests of significance applied to data series (stationwise as well as country as a whole) show that the temperatures are showing a decreasing trend in almost all the northern parts of the country (north of 23° N) and a rising trend in southern parts (south of 23°N). For the country as a whole, however, there is a small warming trend. Atmospheric pressure shows a fall between second and third decades but does not indicate any significant change after 1930. Decadal analysis of seasonal (Jun-Sep) and annual rainfall indicates that the variations in rainfall are within the statistical limits.

Key Words — Global warming, Climatic change, Inter-annual variability, Green house effect.

1. Introduction

In recent years, considerable scientific discussion is taking place about global warming and its impact on climatic change. Better understanding of physical systems, increased number of parameters with better time resolutions and availability of better documentation and long data series provide a new thrust to climate research. Although long-term climatic changes have a more lasting effect, floods, droughts, failure of monsoons and other dynamic systems may modulate the climatic trend. While interannual variability of southwest monsoon and other changes in shorter time scale have been extensively studied (Shukla 1984), little work has been done in the Indian region which would throw light on climate change on decadal scale which are manifested through anthropogenic effects besides natural causes.

In this paper an attempt has been made to study the decadal variations of the meteorological elements— mean surface air temperature, maximum and minimum temperatures, upper air temperatures (up to the middle troposphere), seasonal and annual rainfall and atmospheric pressure and to discuss these variations with reference to global changes reported so far. All available data between 1901 and 1986 have been considered.

2. Data and methodology

The National Data Centre, Pune of the India Meteorological Department is the custodian of meteorological data pertaining to the Indian region. These data are collected regularly from several hundreds of observatories spread all over the country (India). Before transfer on to magnetic tapes for permanent archival and supply, in digital form, these data are cleaned, electronically processed and several checks applied to ensure homogeneity and acceptability. Though for some meteorological elements, the data are available prior to 1900, the number of stations is meagre and hence not considered. Thus, for the present study, in order to consider the maximum number of stations with long data sets for surface meteorological elements, the period from 1901 to 1986 has been chosen. Adequate care has been taken regarding the homogeneity of the data. Around 1926, when IMD decided to install the thermometers in the standard Stevenson screen replacing the old type 'Thatched Sheds', necessary corrections were applied to the earlier set of readings due to changed exposure conditions of the thermometers (Pramanik and Jagannathan 1954). While data for surface weather parameters are available from 1901 to 1986 for a large number of stations, upper air data for 31 stations only are available from 1951 onwards.

TABLE 1

No. of stations showing significant variation (F-test)

Period of data (years)	No. of stns.	Surface mean air temp.		Max. temp.		Min. temp.		Pressure		No. of stns.	Rainfall: Seasonal		Rainfall: Annual		No. of stns.	Upper air temp.	
		95%	99%	95%	99%	95%	99%	95%	99%		95%	99%	95%	99%		95	99%
30-39	249	60	36	63	32	64	41	43	22	—	—	—	—	—	31	16	09
40-49	48	20	15	19	13	21	19	16	13	10	01	00	01	00			
50-59	28	11	09	14	08	12	07	12	10	15	01	00	00	00			
60-69	16	09	07	07	05	09	09	12	10	15	03	01	03	01			
70-79	21	26	23	14	11	09	08	18	17	13	03	01	03	01			
80-86	113	63	57	81	74	75	73	97	91	243	41	38	59	57			
Total	475	189	147	188	143	190	157	198	163	296	49	40	66	59	31	16	09

From the daily values, monthly, seasonal and annual means are computed. Based on annual mean values decadal means are calculated for all the elements *viz.* temperature, pressure and rainfall. Only those stations have been considered, for which data availability is more than 30 years in case of surface temperatures and pressure and 40 years in case of rainfall.

The variations in the decadal mean values were analysed using the analysis of variance (single way classification). The statistic tested, using F-test, is the variance ratio, at 95 % level of significance.

$$\text{Variance Ratio (V. R.)} = \frac{S_t^2/(K-1)}{S_E^2/(N-K)} \qquad (1)$$

where, $S_t^2 = \sum_i n_i (\overline{X}_i - \overline{X} \ldots.)^2$

$$S_E^2 = \sum_i \sum_j (X_{ij} - \overline{X}_i)^2$$

$$\overline{X}_i = \text{Mean of the } i_{th} \text{ class} = \frac{\sum_{j=1}^{n_i} X_{ij}}{n_i}$$

$$\overline{X} = \text{Over all mean} = \frac{1}{N} \sum_{i=1}^{K} \sum_{j=1}^{ni} X_{ij}$$

$x_{ij} = j^{th}$ observation in i^{th} decade,

N=Total number of observations

K=Number of decades

and n_i=Number of observations in i^{th} decade.

TABLE 2

Linear trend of meteorological elements

Met. elements	No. of stations	Trend at No. of stations			Trend per 100 years	
		+ve	—ve	zero	All stns.	Only sig. stns.
Surface mean air temp.	475	161	110	204	0.21°C	0.37°C
Max. temp.	475	206	139	130	0.4°C	0.5°C
Min. temp.	475	183	176	116	0.1°C	0.2°C
Upper air temp.	31	—	—	—		
Pressure	475	177	258	40	0.7hPa	2 hPa
Annual rainfall	296	96	193	7		
Seasonal rainfall	296	56	104	136		

3. Results

The number of stations in each 10-year period and the number of stations showing significant variation in decadal means for various met. elements at 95% and 99% levels are shown in Table 1 and the conclusions drawn are not much different. Though the calculations have been made for 99% level of signficance also for greater confidence, the discussions in the paper are based on the results at 95% level of significance only. The trend values (positive, negative and 0) for different met. parameters stationwise and for the country as a whole taking the sign into consideration, are presented in Table 2.

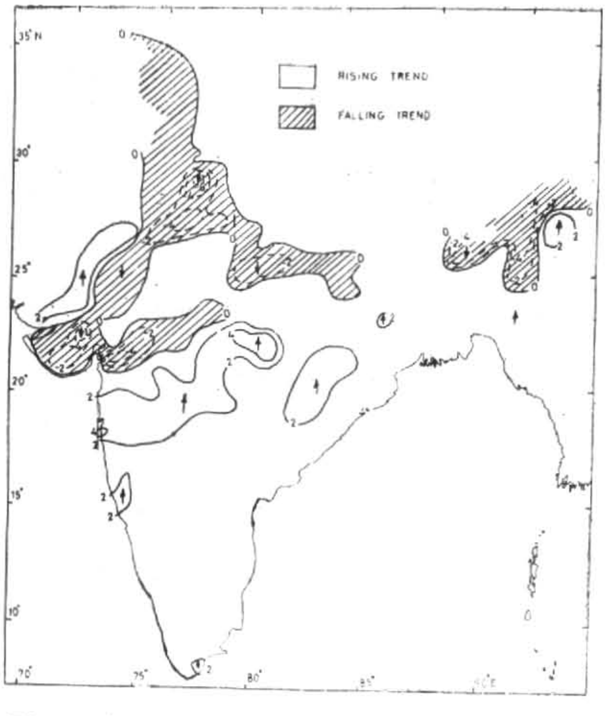

Fig. 1. Linear trend values of surface mean air temperature for 100 years (in °C). Shaded regions indicate falling trend

3.1. *Surface air temperature*

Several studies have reported long-term variation in global mean surface temperature during the past century (Mitchell 1963, Angell and Korshover 1978, Barnett 1978, Hansen *et al.* 1981, Jones *et al.* 1982, 1986; Hansen and Lebedeff 1987, Jones 1988, Parker 1989). However, very few studies have been made on temperature trends in India (Hingane *et al.* 1985).

Surface air temperature data for about 475 stations, spread all over India, have been analysed for significant variation in decadal means by using the analysis of variance (single way classification). Out of these, 189 stations show significant variation in decadal means at 95% level. The linear trend values are calculated for all the 475 stations; 161 stations show positive (increasing) trend, 110 stations negative (falling) trend and 204 stations 'no significant' change. The isolines of trend values are drawn in Fig. 1. Shaded portion indicates cooling trend. From this figure, it is observed that south of 23°N, almost all the stations show positive (increasing) trend whereas stations north of 23°N, especially in northwest and northeast India show negative (decreasing) trend except in extreme NE and NW (Saurashtra and west Rajasthan) areas where a few small pockets show slight increase in trend. The decadal means of surface air temperature are plotted against the grand mean for some representative stations and shown in Fig. 2 (A). Stations north of 23°N namely New Delhi, Shimla, Chandigarh, Abu, Purnea, Patna and a few others are showing a falling (cooling) trend whereas stations south of 23°N, namely, Bombay, Chandrapur, Belgaum, Visakhapatnam, Pamban, Tiruvananthapuram, Madras and others are showing a rising (warming) trend. It may thus be noted that warming trend occurs in south India (south of 23°N) and cooling trend in north central and northeast India (north of 23°N) which is different from the results obtained by Hingane *et al.* (1985), who found the warming trend in the west coast, interior peninsula, north central and northeast regions of India.

Considering the country as a whole, the temperatures are found to be increasing at the rate of 0.21° C per 100 years. This is arrived at by taking the mean of all the trend coefficient values of individual stations (with sign). In view of the fact that the decade has been taken to start from the year 1901, moving average technique has also been applied to get over the bias so as to compare the results by both the methods. Ten-year moving average technique for all the stations gives a trend of 0.2° C per 100 years (Fig. 2B). In this method, the ten-year moving average of each station is first calculated and then the mean value for each year for the country as a whole is calculated. The trend is found by using the least square method. However, considering stations with significant variation only, the trend for the country, taken as whole, works out to 0.37° C/100 years. Thus, on the basis of surface mean air temperature change, a definite warming trend is indicated in the country, *i.e.*, approx. 0.2 to 0.4°C/100 years. This study, however, does not show any cooling around 1940s, as reported by a few workers for northern hemisphere; (Vinnikov *et al.* 1980, Jones *et al.* 1982, Hansen and Lacis 1990) based on global average.

3.2. *Maximum temperature*

Annual mean maximum temperature data for 475 meteorological stations covering period from 1901 to 1986 were analysed as in the previous case. 188 meteorological stations show significant variation at 95% level of confidence. The linear trend values were computed for all the 475 meteorological stations. Out of these, 206 stations show positive (increasing) trend while 139 stations indicate (decreasing) trend. 130 stations show no trend. The trend values are plotted and isolines drawn for significant values at interval of 2° C (per 100 years) as shown in Fig. 3. Shaded portions indicate falling trend. Almost all the stations south of 23°N are showing increasing (warming) trend whereas stations north of 23°N are showing decreasing (cooling) trend. There is a significant cooling in NW and NE India as compared to significant warming in peninsular India. For some meteorological stations, decadal means of maximum temperature are plotted against the grand mean (86 year mean value) and shown in the Fig. 4. In cases of almost all the stations, decreasing trend is found during the beginning years of this century followed by rising trend. Stations north of 23° N are showing decreasing (cooling) trend in the last decade as for example, Jabalpur, New Delhi, Shimla, Purnea, Alipur, Abu and others, whereas stations situated south of 23°N are showing increasing (warming) trend in the last decade, *viz.*, Pune, Tiruvananthapuram, Belgaum, Madras, Mercara, Coimbatore, etc. For the country as a whole, the trend in maximum temperature shows warming by 0.4°C per 100 years based on all the 475 stations. If only those stations are considered whose variation is significant at 95 per cent level, the warming trend increases to 0.5°C/100 years Thus, this corroborates the trend results shown in surface mean air temperature.

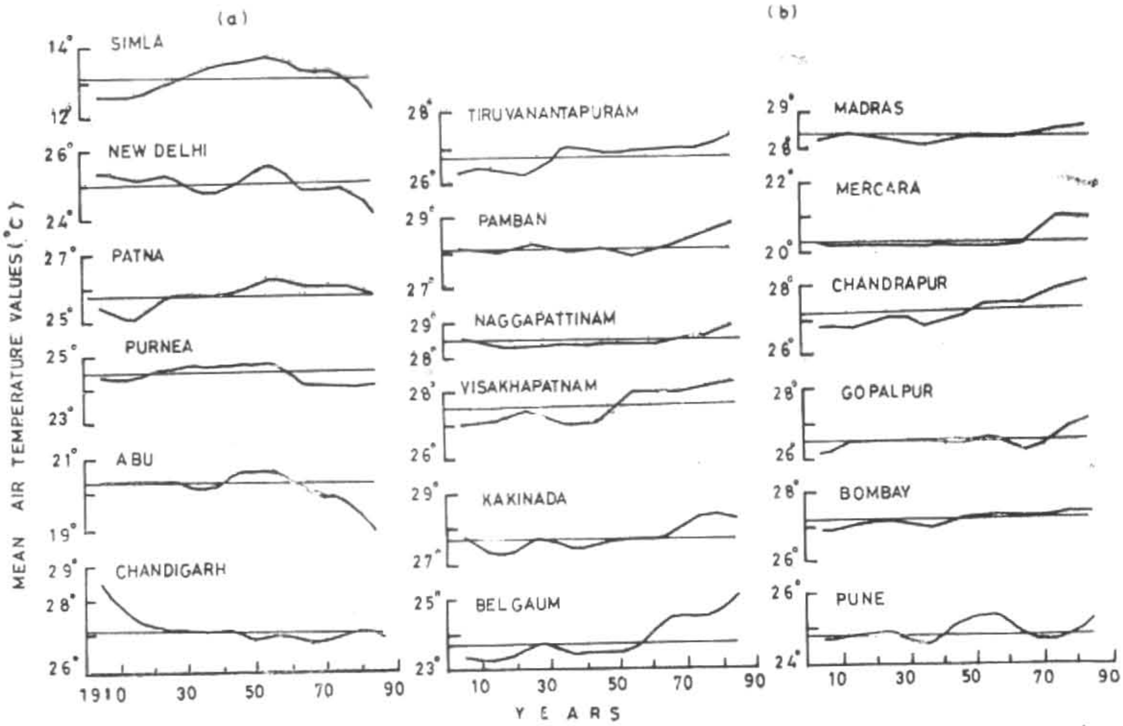

Fig. 2(i). Decadal mean air temperature curves for selected stations over India : (a) Stations showing decreasing trend during last few decades and (b) Stations showing increasing trend during last few decades. Horizontal line indicates grand mean value for that station

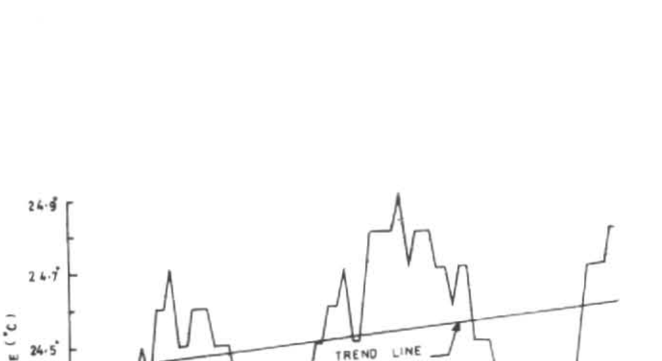

Fig. 2(ii). Mean surface air temperature (10 years moving average)

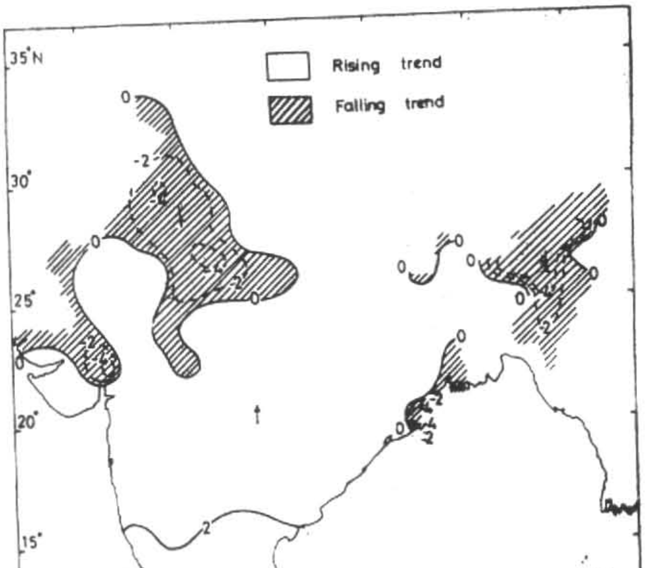

Fig. 3. Linear trend values of mean maximum temperature (in °C) for 100 years. Shaded regions indicate falling trend

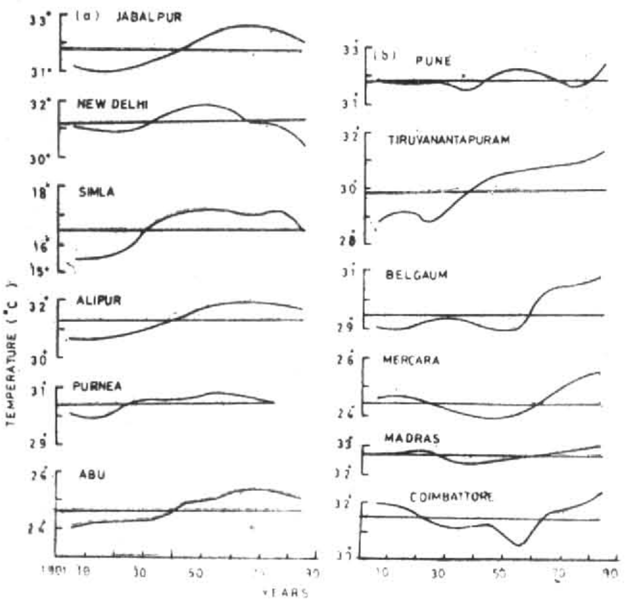

Fig. 4. Decadal mean maximum temperature for selected stations over India : (a) Stations showing decreasing trend during last few decades and (b) stations showing increasing trend during last few decades. Horizontal line indicates grand mean value for that station

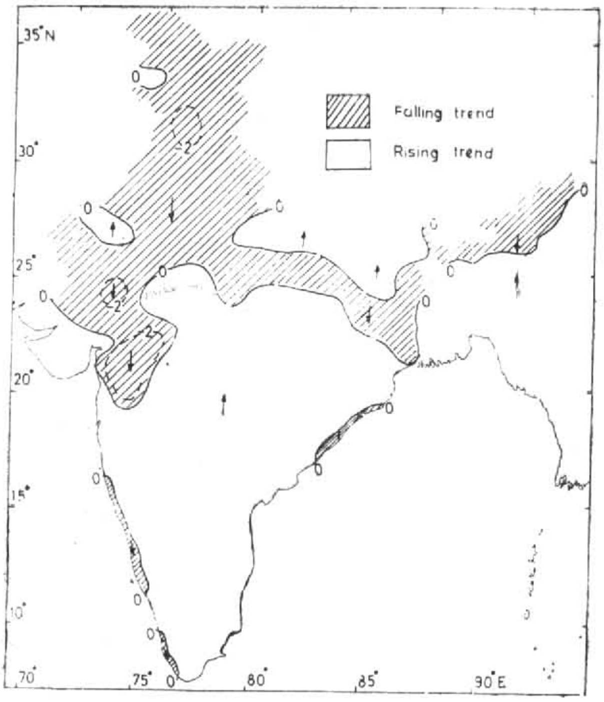

Fig. 5. Linear trend values of surface mean minimum temperature for 100 years (in °C). Shaded regions indicate falling trend

3.3. *Minimum temperature*

Annual mean minimum temperature data for 475 meteorological stations for the period 1901 to 1986 were analysed. While 190 stations show significant variation at 95% level of confidence, linear trend values computed for 475 stations show that 183 stations indicate rising (warming) trend, 176 stations indicate decreasing (cooling) trend and 116 show no trend at all. Fig. 5 represents the isolines drawn for the trend values of 475 stations. Shaded portion indicates falling trend. As it is seen, minimum temperatures are having increasing trend in almost all parts of central and Peninsular India except some pockets in west and east coasts which show nominal falling trend. Some parts of Uttar Pradesh, Bihar, and west Rajasthan also show increasing trend whereas the rest of the country in central and north India show the falling (cooling) trend. The decadal mean values of minimum temperature have been plotted against the grand mean of 86 years for all the stations. For some representative stations, these trends are shown in Fig. 6. Most of the stations south of 20° N and central India, *viz.* Gopalpur, Nagapattinam, Bangalore, Madras, Pamban and others show increasing trend whereas stations in north, northwest and northeast, namely New Delhi, Abu, Shimla, Purnea etc., show falling (cooling) trend.

Considering the country as a whole, the minimum temperature trend indicates an overall increase of 0.1°C/100 years. However, if only those stations (190) are considered which indicate significant variation, the increase in minimum temperature comes out to be 0.2°C/100 years.

3.4. *Upper air temperature*

Several experiments with general circulation models indicate that increased concentration of greenhouse gases in the atmosphere will result in increased temperatures in the troposphere and decreased temperatures in the stratosphere (Karoly 1989, Schlesinger and Mitchell 1987, Parker 1989). However, for the Indian region, Rupa Kumar *et al.* (1987) have studied the temperature changes based on limited data. The present study includes radiosonde temperature data from 31 stations spread all over the country for the period 1951-1986 to investigate temperature trends in the lower and middle troposphere over India. Data at pressure levels from surface to 500 hPa at 50 hPa intervals (wherever available) were used both for 00 and 12 UTC and tested for significant variation, if any. Out of 31 stations, temperature variations have been found to be significant for 16 stations, namely, Srinagar, New Delhi, Jodhpur, Lucknow, Guwahati, Calcutta, Nagpur, Burdwan, Bombay, Visakhapatnam, Madras, Mangalore, Bangalore, Port Blair, Minicoy and Tiruvananthapuram at different pressure levels for 00 and 12 UTC. The decadal upper air temperature mean values for most of these stations for different pressure levels are plotted for each decade and the grand mean value (mean of all observations available for a pressure level) is shown by a straight line (Fig. 7 a,b). As can be seen from the figure, a declining (cooling) trend is seen for the stations north of 20° N, namely, New Delhi, Jodhpur, Guwahati, Calcutta, etc., whereas stations south of 20°N, *e.g.*, Tiruvananthapuram, Port Blair, Visakhapatnam, Madras etc. initially show a cooling trend followed by a warming trend.

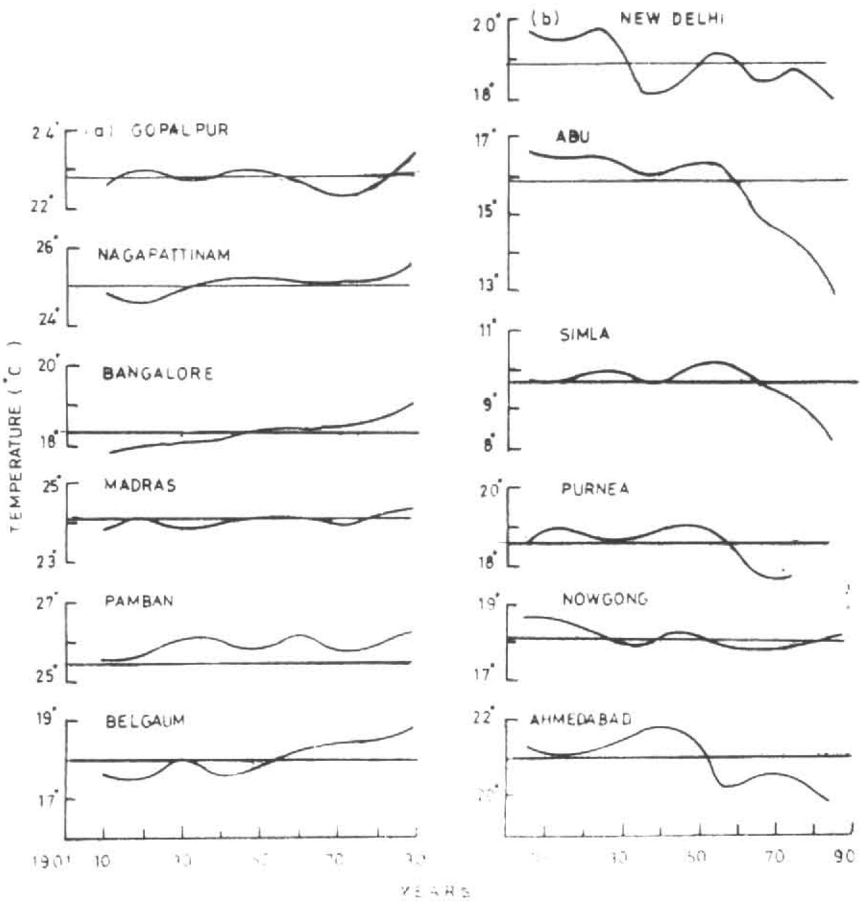

Fig. 6. Decadal mean minimum temperature for selected stations over India : (a) Stations showing increasing trend during last few decades, and (b) Stations showing decreasing trend during last few decades. Horizontal line indicate grand mean value for the station

Similar to surface air temperature, maximum and minimum temperatures trend, the upper air temperature (up to middle troposphere) also indicates warming in southern India while cooling in northern India. It can, therefore, be inferred that a general cooling trend exists in the north India and a warming trend in the south India up to the middle troposphere.

3.5. *Mean air temperature over the country as a whole*

To consider the variability and trend in surface air temperature from a different angle, the decadal means of air temperature for the country as a whole, considering only those stations where surface air temperature variations are significant (95% level), are plotted for each decade and is shown as 'B' in Fig. 8. The mean value of 30 years (1931-60) for country as a whole is shown by a straight line while overall trend is indicated by the dotted line 'C'. A grand mean of 30 years has been considered in this case (instead of 86 years mean in other cases) so as to compare our results with that of Jones *et al.* (1986) who have, in their study of global mean temperatures also taken the reference period of 30 years 1950-79. A part of the curve by Jones *et al.* (1986) from 1900 to 1984 has been reproduced in the same figure.

To study the variability of the temperature, pressure and rainfall series, the mean, weighted mean, T_w, standard deviation σ and weighted standard deviation σ_w are calculated for these elements (Fig. 9) as follows :

$$\text{Weighted mean, } T_w = \frac{\sum_{i=1}^{n} \sigma_i T_i}{\sum_{i=1}^{n} \sigma_i}$$

Weighted standard error,

$$\sigma_w = \left[\sum_{i=1}^{n} \sigma_i (T_i - T_w)^2 / \sum_{i=1}^{n} \sigma_i \right]^{\frac{1}{2}}$$

where, T_i = Mean of i^{th} decade

σ_i = standard deviation of i^{th} decade

3.6. *Atmospheric pressure*

The work on long term pressure changes over India is meagre, as available in the published literature. Pramanik and Jagannathan (1955) have studied the mean sea level annual pressure data of 25 stations for over 80 years but they could not find any definite trend in

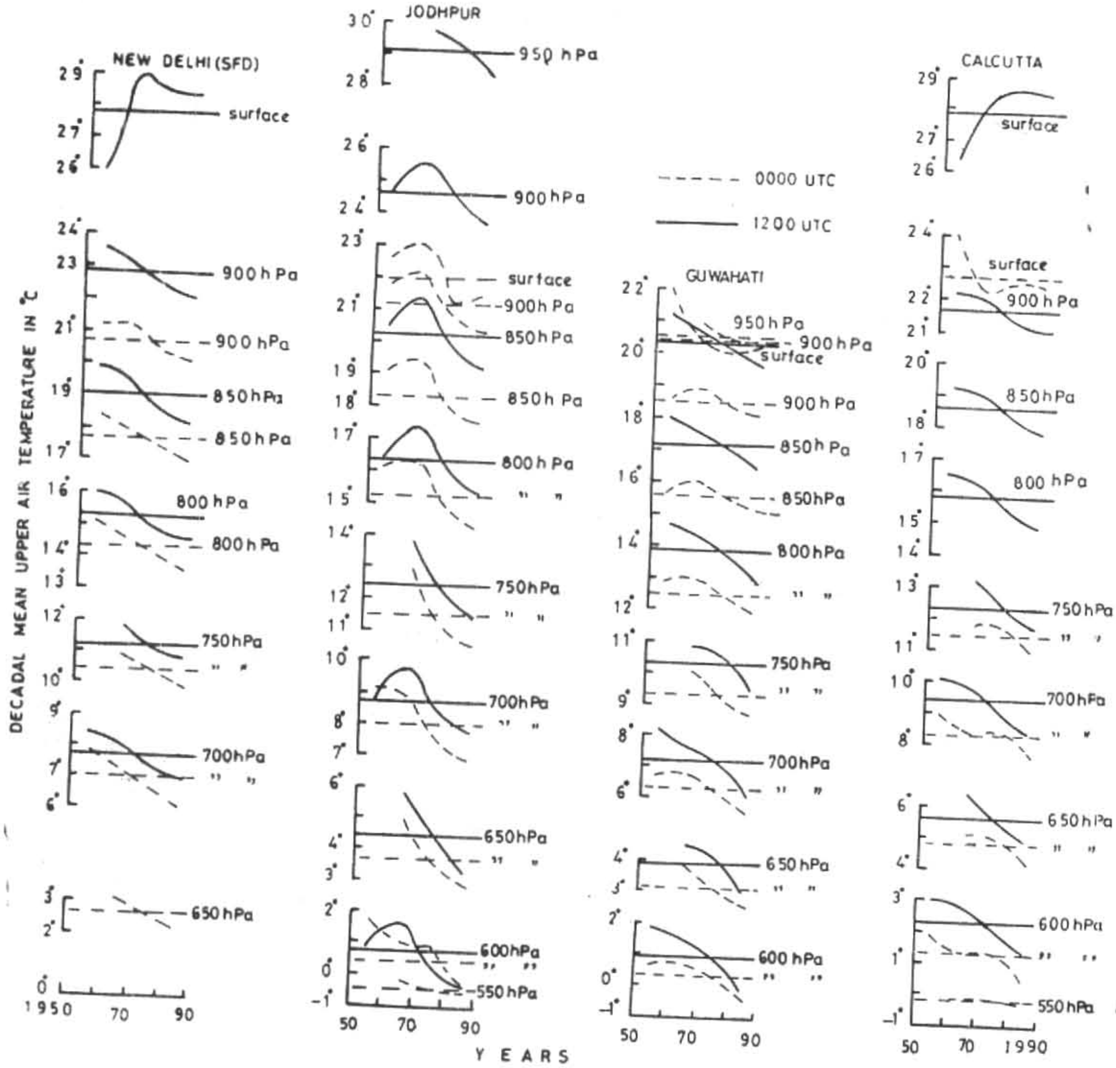

Fig. 7(a). Decadal upper air mean temperatures (- - - 00UTC, ——— 12UTC)

pressure data of these stations. To have a fresh look at this aspect, station level pressure data for 475 meteorological stations, spread all over the country, is considered for the period 1901-1986. These pressure data are analysed using analysis of variance, F-test (single way classification) for any significant variation. 198 stations show significant variation at 95% level of confidence. The decadal linear trend calculated for all the 475 stations shows negative (falling) trend for 258 stations, positive (increasing) trend in case of 177 stations and 40 stations show uniform (no) trend. Stationwise decadal mean values for some representative stations are plotted for each decade and the grand mean (mean value for all the stations for 86 years) is shown by a straight line (Fig. 10). Almost all the stations show falling trend. The decrease is quite significant ($\sim$2 hPa) in the third decade (1920-30) for all the stations. Thereafter, the variation is rather small. The decadal mean values for the country as a whole only for stations showing significant variation according to F-ratio test and the trend line, are shown in Fig. 11 (a). The overall trend value is decreasing at about 2 hPa/100 years. However, the trend value for the country as a whole, taking all 475 station,

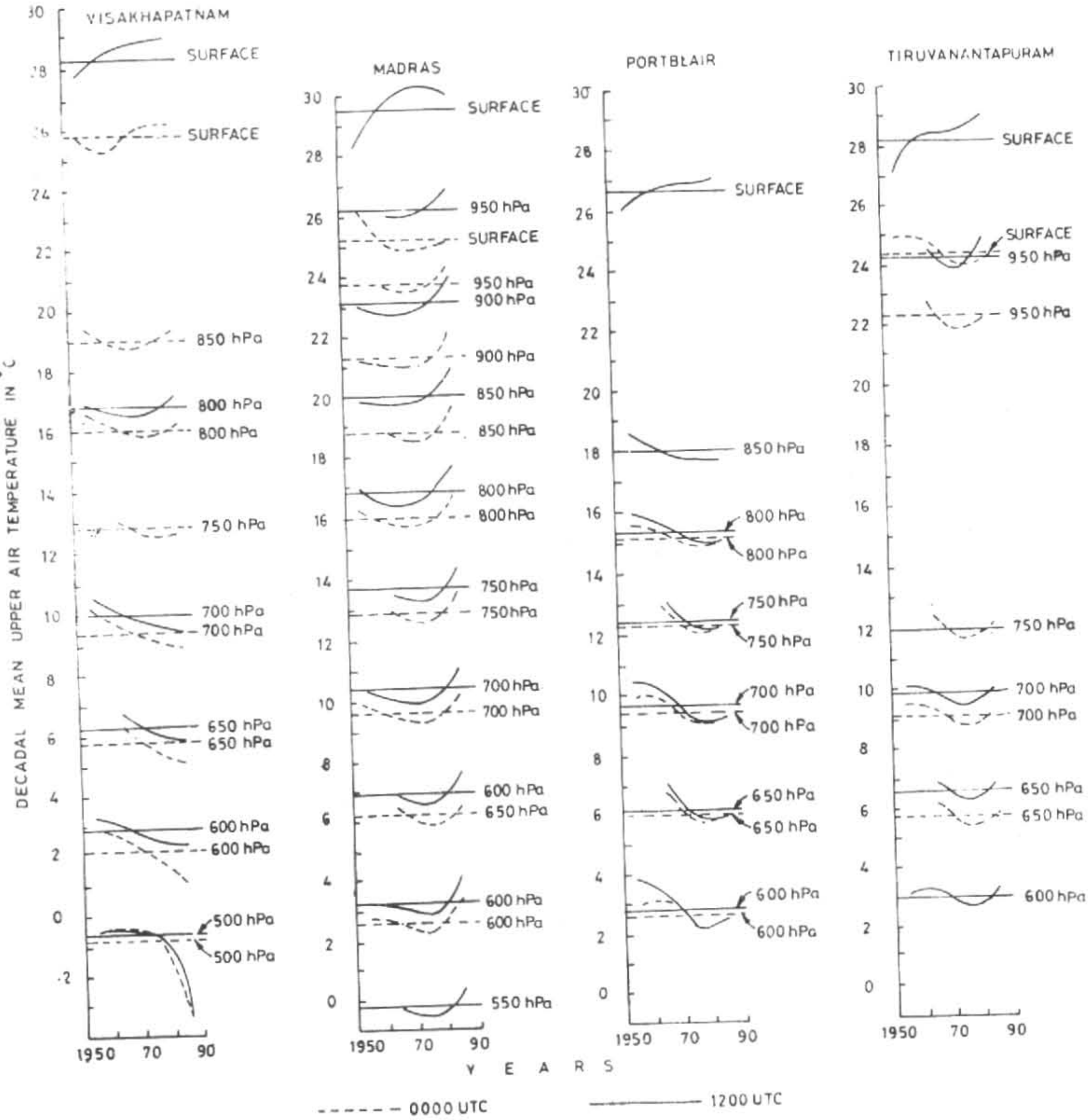

Fig. 7(b). Decadal upper air mean temperatures

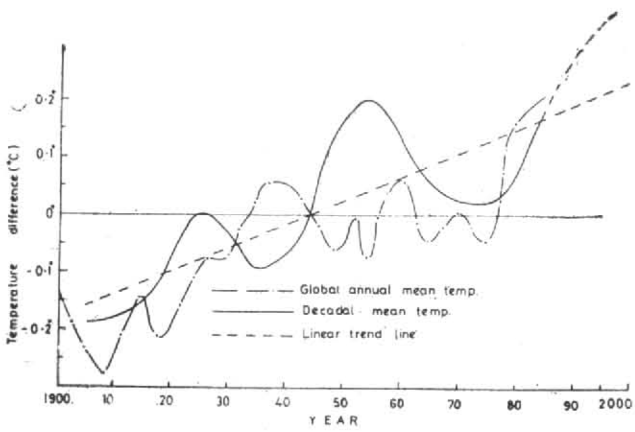

Fig. 8. Mean air temperature, (A) Global annual mean temp., (B) Decadal mean temp. and (C) Linear trend line

shows a decreasing (falling) trend of 0.7 hPa/100yr during the period. If however, the conspicuous, fall prior to 1930 is excluded, there is no significant trend [Fig. 11(b)].

3.7. *Rainfall*

Considerable amount of work has been reported by several workers on the variability of seasonal and annual rainfall over India during the last 100 years (Walker 1910, Pramanik and Jagannathan 1953, Koteswaram and Alvi 1969, 1970, Raghavendra 1973, 1974, 1980, Parthasarathy and Dhar 1974, Parthasarathy and Mooley 1978, 1981, Mooley and Parthasarathy 1984, Pant *et al.* 1988, Sarker and Thapliyal 1988, Parthasarathy *et al.* 1990). The present study has adopted a somewhat different approach through the analysis of variance for every decade based on the data of 296 well distributed stations.

The decadal means of annual rainfall were plotted against the grand mean [Fig. 9(d)]. As can be seen from the figure, there is a steep rise in annual rainfall up to 5th decade. Though increase in rainfall is seen right from the first decade, it was only during the third decade that annual rainfall (decadal mean) crosses above the normal value (1130 mm) and goes on increasing till 5th decade. In the nineteen fifties, the curve starts showing falling trend which continues till 7th decade. During 1950-60, the value of mean rainfall falls below the mean average and continues to be below the mean value till end of 9th decade even though there was a small increase in the rainfall in 8th decade but the value still remained below the grand mean value (1130 mm).

Almost similar results have been obtained for the seasonal rainfall variations Fig. 9(c).

It was observed that for most of the hill stations, there is a slight decrease in rainfall particularly during the last 2 to 3 decades. The decadal mean values both for annual as well as monsoon season rainfall for a few representative hill-stations have been shown in Fig. 12. This result lends support to the general feeling that deforestation on a large scale could have contributed towards the lowering of rainfall amount in the recent past.

4. Discussions

The stationwise analysis of temperature parameters show that there is a warming trend in the northern parts of the country (north of 22°-23°N), whereas there is a cooling trend in south, both at the surface as well as lower and middle tropospheric levels (Figs. 2 & 7). Similar results (cooling in the north and warming in south India) has also been reported by Hingane *et al.* (1985) and Groisman and Kovyneva (1989) for surface air temparature and by Rupa Kumar *et al.* (1987) for upper air temperature. Though a general cooling trend is observed in the northern parts of the country, in some regions *viz.*, Saurashtra, parts of west Rajasthan and extreme north east rising trend is observed. Rising trend in Saurashtra and west Rajasthan is supported by the studies conducted by Pakistan Meteorological Department in which they find warming trend at lower latitudes (south Pakistan) and cooling trend at higher latitudes (WMO 1990). However, in the case of upper air temperatures, our study shows that almost all stations north of 20°N show a falling trend while stations south of 20°N show an increasing trend. Studies made by Rupa Kumar *et al.* (1987), however, do not show any change in the south Indian stations.

For the country as a whole, the decadal trend in surface air temperature is shown in Fig. 8 considering only those stations where surface air temperature variations are significant. The slope of the trend line gives a small warming trend of about 0.4° C/100 years. Similar indication of warming (0.37° C/100 year) is reflected in stationwise analysis of surface temperature also. Hingane *et al.* (1985), and Pant and Hingane (1988) have arrived at a similar conclusion based on analysis of mean monthly temperature data and all India mean temperature anomalies. Our study, based on decadal mean air temperature for the country as a whole, shows that in the first 5 decades, the decadal mean values are below the grand mean value indicating a cooler regime. There is a warmer regime, however, from the end of 5th decade (1940-50) to the last decade (1980-90).

If we compare the temperature trends over the Indian region with that of global and hemispheric averages

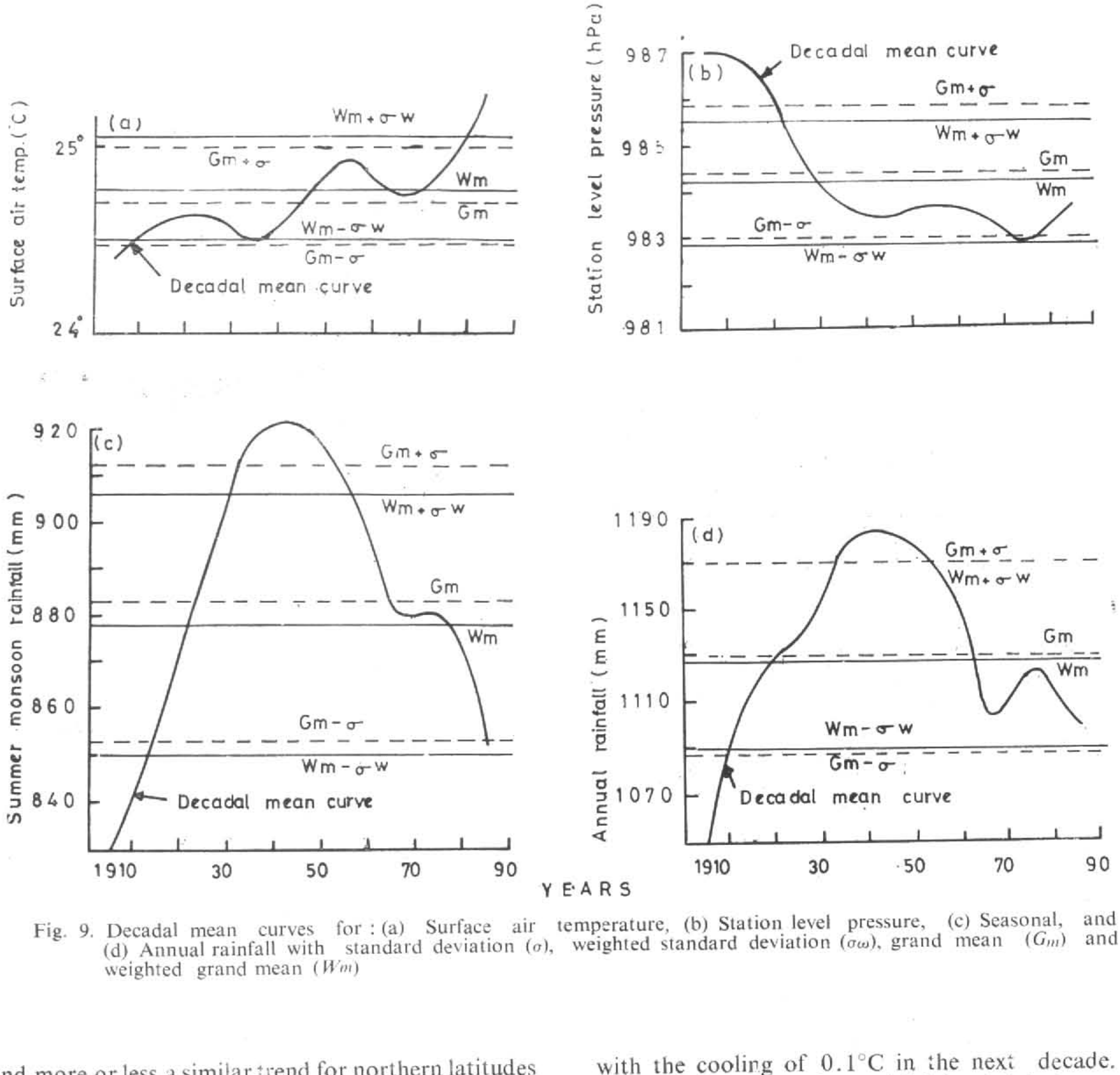

Fig. 9. Decadal mean curves for : (a) Surface air temperature, (b) Station level pressure, (c) Seasonal, and (d) Annual rainfall with standard deviation (σ), weighted standard deviation (σ_ω), grand mean (G_m) and weighted grand mean (W_m)

we find more or less a similar trend for northern latitudes (23° N to 90°N). A warming of about 0.8°C from 1880 to 1940 followed by a cooling of about 0.5°C between 1940 and 1970 has been reported by Hansen *et al.*, (1981), Wigley and Jones (1981) and Borzenkova *et al.* (1976). Similarly, a warming of about 0.3°C to 0.4°C has been reported for lower and southern latitude (23°N to 90°S) and the mean global surface air temperature shows a rising trend of about 0.4°C during the past century (Hansen *et al.* 1981). Our study also shows a similar trend for the Indian region.

For comparison of the regional variation with that of global scenario, the curve showing global annual mean temperature variations (*after* Jones *et al.* 1986) has been reproduced in Fig. 8 (A). Both the curves, for regional as well as global variation, show increasing trends with time. The regional curve (B) shows a cooling of 0.15°C in the decadal mean for first two decades compared to the grand mean. Thereafter, it started rising and equalled the country mean in the third decade (1920-30). It again started falling with the cooling of 0.1°C in the next decade. Contrary to the observations of fall in global temperature the regional temperature shows an increasing trend in the 5th decade and reaches the peak in 6th decade. In the later part of 1950s, the temperature over Indian region shows a falling trend which continued till mid-seventies. The decadal mean temperature again started rising in the late seventies and still continues to do so. The global curve (A) also shows more or less a sinusoidal nature like the curve (B) but with a phase lag. This phase lag may be attributed to fact that the globe covers three-fourth of ocean and the combined variation of land and ocean temperatures to the regional variation can only be compared with this limitation. The wave like nature of the decadal mean temperature curve shows a gradual increase in both amplitude and wavelength with time, suggesting a longer and warmer climate in the near future over India (as shown by dotted line in the Fig. 8). It may be mentioned that annual average air temperature over the southern parts of U.S.A. increased before 1940 and declined afterwards.

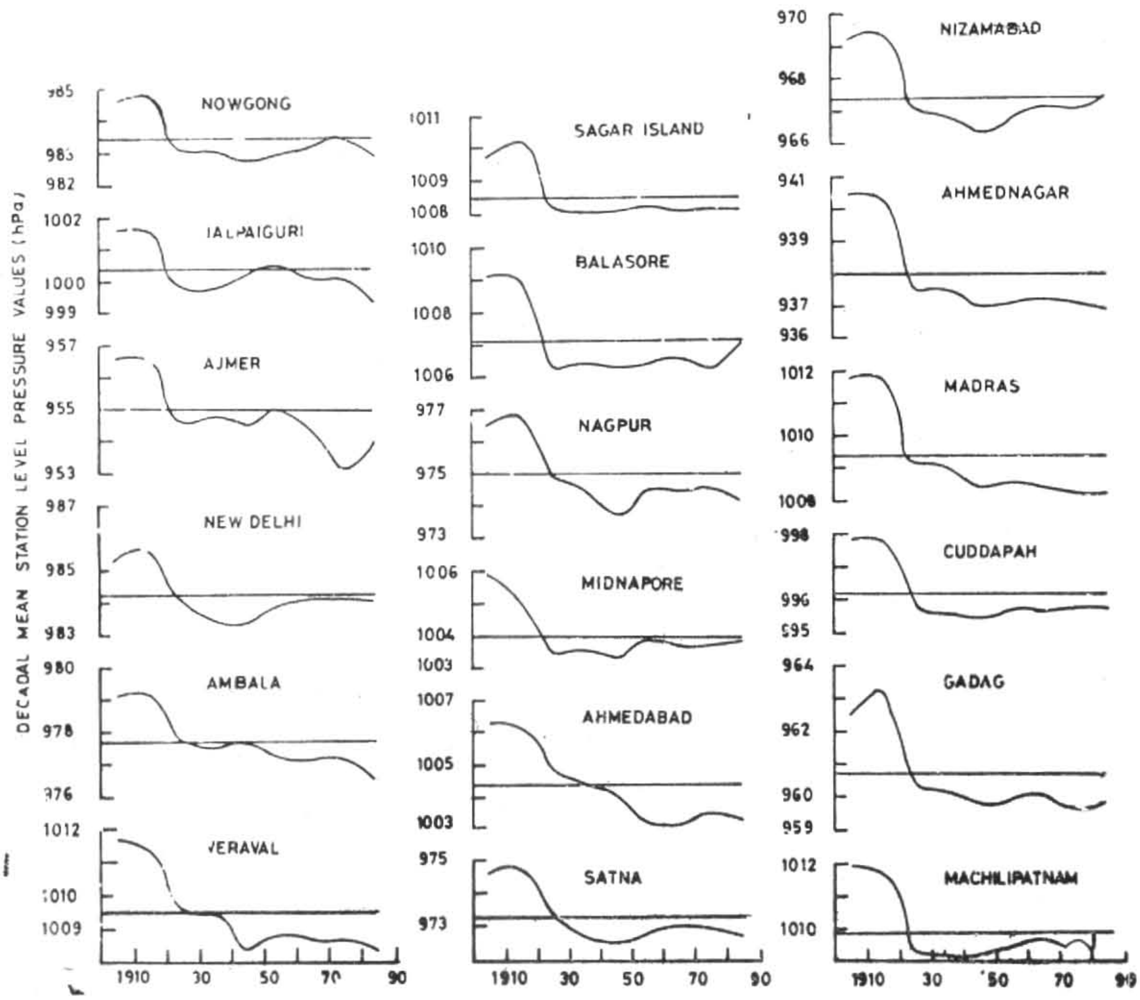

Fig. 10. Decadal mean station level pressure curves for selected stations over India. Horizontal line indicates grand mean value for that station

It may be noted that the temperature mean values over India between the second and eighth decades (Fig. 9) are within limits of $\pm 1\sigma$ values. In the first decades, the temperature mean value is outside the—1σ value indicating larger variability (cooling in that decade). Similarly, in the ninth decade, the value outside the standard deviation value ($+1\sigma$) shows a comparatively warmer period. For most part of the series though the trend of the temperature is increasing, it lies within $\pm 1\sigma$.

The trend line for the decadal mean station level pressure values for the country as a whole (considering only those stations where the pressure variations are significant) shows a falling trend of about 2 hPa/100 yrs (Fig. 11). While analysing the pressure values, the hill station values have not been considered in order to avoid the altitude effect. Similar to stationwise studies (Fig. 10), the decadal mean curve for the country as a whole also shows a sharp fall of about 2 hPa in the 2nd and 3rd decade (1911-1930). The pressure values continue to show very gradual fall till 5th decade after which there is a slight increase till 8th decade. Thereafter there is again a falling trend in the 9th (1980-1990) decade. A very small falling trend, though not so conspicuous as in the present study, is also reported by Groisman and Kovyneva (1989) while Sarker and Thapliyal (1988) did not find any significant change in sea level pressure over the Indian region during the last century. The difference in results, in the present study, may be attributed to the inclusion of a longer period data for a large number of stations spread all over the country. The decadal mean curve shows variations which are within the statistical limits of $\pm 1\sigma$ Fig. 9(b) except in the first two decades (1901-1920).

The decadal means of seasonal and annual rainfall for the country as a whole are shown in Figs. 9 (c, d). The seasonal rainfall curve shows steep rise till 5th decade and gradual fall thereafter. In the first two decades of the present century, the rainfall though increasing, was below the normal value (833 mm). During the third decade, it crosses the mean value and reaches the peak value (922 mm) in the 5th decade. From 6th decade onwards there is a gradual fall and during the 8th decade, the decadal seasonal mean rainfall value falls below the normal mean and continues to be below it in the 9th decade as well. However, the values are well within the statistical limits of $\pm 1\sigma$ during the same period.

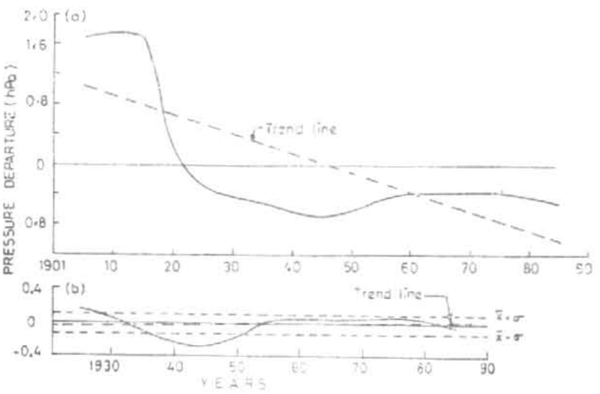

Fig. 11. Decadal mean station level pressure over India

Following a similar trend, the decadal annual mean rainfall curve also shows a continuous increase in rainfall right from 1st decade (1050 mm) to 5th decade (1183 mm). During the 3rd decade, the decadal mean value crosses the all India average of annual rainfall (1130 mm). In this case the value falls below the normal value for the 7th decade itself, whereas in the case of seasonal rainfall it occurred during the 9th decade. During the eighth decade, there is a marked increase in annual rainfall (from 1105 mm to 1125 mm) but the value remains below the country's normal value. Again during the 9th decade, there is a decrease in rainfall. The values, however, are within the statistical limits of $\pm$ 1σ. Mooley and Parthasarathy (1984), while studying the interannual and long term variability have examined the rainfall series for India as a whole and have indicated the presence of three major climatic rainfall periods, a good rainfall period from 1921 to 1964 and two deficient rainfall periods during 1871-1920 and 1965-1974. However, the present analysis based on decadal mean value shows two deficient rainfall periods 1901-1920, 1965-1987 and one good period from 1921-1964, which can be attributed to the longer data series used in the present study.

Combining the results of variations in decadal means of surface air temperature, pressure and rainfall indicate some interesting features. In the first three decades, the decadal mean surface air temperature and rainfall show increasing trend while the pressure values show a decreasing trend which is the usual hydrostatic balance. In the 4th decade though there is a decrease in decadal mean surface temperature value, the pressure and rainfall mean values continue to show fall and rise respectively. In the 5th and 6th decades while the decadal mean values of temperature show an increase, the pressure values do not show any significant change but the rainfall curve shows maxima in the 5th decade and thereafter a decrease in rainfall.

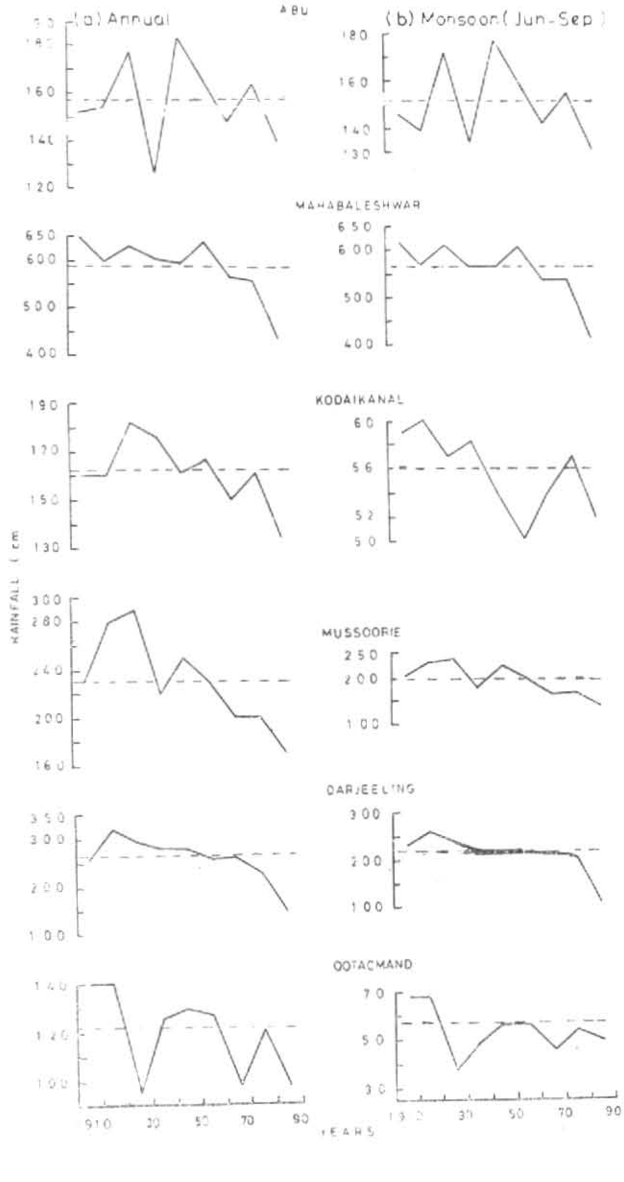

Fig. 12. Decadal mean rainfall (cm) curves for some representative hill stations : (a) Annual and (b) Monsoon (Jun-Sep)

In the 7th decade, all the three parameters show decreasing trend in their values. In the last two decades the decadal mean surface air temperature curve shows an increasing trend whereas decadal mean pressure curve shows first a little decrease followed by a slight rising trend. Corresponding decadal mean annual rainfall curve shows slight increase in the 8th decade and a falling trend thereafter. It would thus be noted that in the Indian region, all the three parameters namely temperature, pressure and rainfall do not show variations in the same phase.

5. Conclusions

The decadal study of various meteorological parameters for the period 1901-1986 brings out the following conclusions :

(*i*) The stationwise study shows that the temperatures are decreasing in almost all parts of the country north of 23°N while the southern parts of the country are, perhaps, getting slightly warmer. This trend is seen right from the surface to middle troposphere.

(*ii*) For country as a whole, there is a small warming (0.2° C to 0.4°C/100 years) trend.

(*iii*) Stationwise, as well as for country as a whole, the pressure values indicate a falling trend since 1915. However, there is no significant trend if the data prior to 1925 is excluded.

(*iv*) The decadal variation in the seasonal and annual rainfall are within the statistical limits of $\pm 1\sigma$.

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