Vol. 2: 215-223, 1993 | CLIMATE RESEARCH Clim. Res. | Published July 27

Climatic changes and trends over a major river basin in India

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ABSTRACT: Long-term changes of seasonal and annual surface air temperatures and precipitation of the Mahanadi river basin in India are presented. The long-term trends in these 2 important climatic elements were evaluated by linear trend analysis. The results indicate that there is a highly significant warming trend in the mean maximum, mean minimum and average mean temperatures of the basin based on data from 7 stations for the period 1901–80. Results of the trend analysis of surface air temperatures of individual stations are also presented and discussed. Increase in greenhouse gases in the atmosphere over India, recent land-use pattern changes and agricultural practices in the region appear to have a bearing on the observed warming trend. For rainfall, monsoon and annual series were subjected to trend analysis. Basin rainfall series based on data from 125 stations for the period 1901–80 did not show any significant trend. Moreover, none of 10 selected stations in the basin was characterised by a significant increasing or decreasing tendency in either monsoon or annual rainfall.

INTRODUCTION

The Mahanadi river basin, one of the major river basins in India, is located between longitudes 80° 25' and 87° E, and latitudes 19° 15' and 23° 35' N (Fig. 1). The total basin area is about 141 600 km^2 with mean annual river flow of 66 640 million m^3. The entire flow is only due to rainfall in the region since there is no contribution from either snowfall or snowmelt. The normal annual rainfall of the basin is 1360 mm (16% coefficient of variation, CV) of which about 86%, i.e. 1170 mm, occurs during the monsoon season (15% CV) from June to September.

In recent times, atmospheric General Circulation Model (GCM) experiments have indicated that increased concentrations of CO_2 and other trace gases could cause a global warming of 1.5 to 4.5 °C by the middle of the next century (USNRC 1982, WMO 1988). The water resources administrative sector, which is most sensitive to the climatic variations (Chen & Parry 1987, WMO 1987), could be forced to respond in many regions. In view of this an attempt has been made in the present study to determine any climatic change in a major river basin in India.

Climatic change has been defined by Landsberg (1975) as a shift of climatic conditions to a new equilibrium position with values of climatic elements changing significantly. On the other hand, climatic fluctuation has been defined by Landsberg (1975) as a situation of temporary deflection which can revert to earlier conditions or which can be followed by changes in the opposite direction.

Recently, Hingane et al. (1985) studied the long-term trends of surface air temperatures of India. Their analysis showed that the mean annual temperature in India has increased by 0.4 °C during the past century. Rupakumar & Hingane (1988) have reported the results of the analysis of long-term trends of surface air temperatures of 6 industrial cities in India. They concluded that 3 cities (Calcutta, Bombay and Bangalore) showed a significant warming trend, 2 cities (Madras and Pune) did not show any significant trend and 1 city (Delhi) showed a significant cooling trend (Fig. 1).

Considerable work on long-term changes and periodicities of Indian rainfall for various meteorological subdivisions and some stations has been undertaken by many scientists. These studies were summarised by

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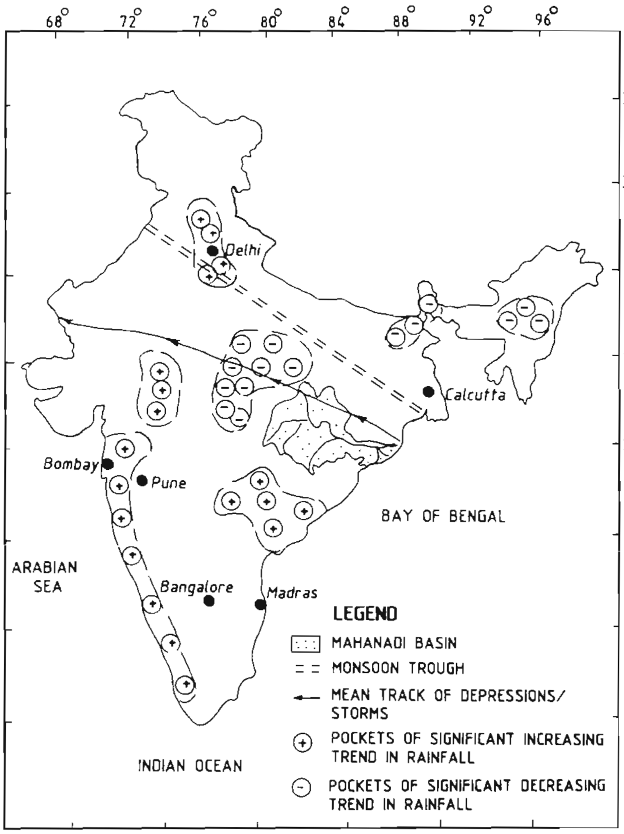

Fig. 1. Map of India showing the Mahanadi Basin, pockets of significant trends in rainfall, monsoon trough and mean track of storms

Parthasarathy & Dhar (1975, 1976a) for annual and different seasonal rainfall for the period 1901–60 and Mooley & Parthasarathy (1979, 1984) for the monsoon rainfall for the period 1871–1978. Meteorological subdivisional rainfall (for 31 subdivisions) was studied extensively by Parthasarathy & Dhar (1974, 1976b) and Parthasarathy (1984) for the period 1871–1978 for 29 subdivisions. The noteworthy findings from these studies were 11 yr solar cycles, Quasi Biennial Oscillations (QBO) of 2 to 3 yr duration and periodicities of very low frequencies (trends) in the rainfall at some stations, subdivisions and regions of India. Pockets where significant positive and negative trends have been reported in the Indian monsoon rainfall are marked in Fig. 1 (DST 1993).

For the present study, a specific region in India, the Mahanadi river basin, was selected for analysis. The reason for selecting this basin is its location with respect to the normal position of the monsoon trough and the mean track of monsoon depressions and storms originating in the Bay of Bengal (Fig. 1), enabling a good case study of a river basin representative of the Asian monsoon region.

DATA AND ANALYSIS

Data. ***Temperature:*** There are only 6 optimally distributed stations, viz. Jabalpur (JBP), Raipur (RPR), Sambalpur (SMB), Kanker (KNK), Cuttack (CTK) and Jagdalpur (JDP), over the basin whose surface air temperature data are available for a long-term period, i.e. 1901–80. After having observed no significant tendency at SMB, which is adjacent to a body of water (Hirakud Dam), an additional station, Puri (PRI), located on the coast, was considered for the study. Therefore, in all, 7 stations (marked as rectangles in Fig. 2) were considered in temperature analysis.

The mean monthly maximum, minimum and average mean temperatures were computed from the daily maximum, daily minimum and daily mean temperatures. Mean daily temperatures are based on the arithmetic average of daily maximum and minimum temperatures. Values of mean maximum, mean minimum and average mean temperatures for 4 seasons, winter (December to February), premonsoon (March to May), monsoon (June to September) and postmonsoon (October and November) as well as annual values were computed for all 7 stations for the period 1901–80. In order to obtain a basin temperature series, average values for all 7 stations were taken.

Rainfall: For computing areal rainfall of the Mahanadi Basin, data from a sufficient number of rain gauge stations from 1901 onwards are available. Before 1901, the station network was sparse. Taking this into account, 125 rain gauge stations were considered over the period 1901–80 (marked by small circles in Fig. 2). However, for some important stations (mostly district headquarters), rainfall data are available from 1871. Therefore, for computing long-term

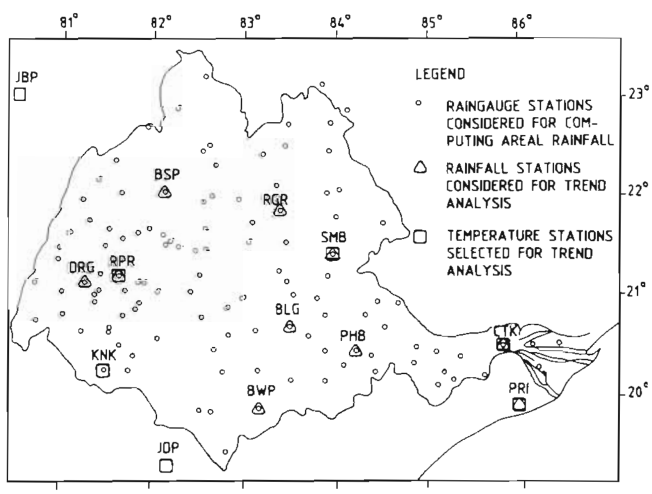

Fig. 2. Station network used for areal rainfall and trend analysis of temperature and rainfall

trends at individual stations, 10 important stations (marked as triangles in Fig 2), viz. Bilaspur (BSP), Raigarh (RGR), Durg (DRG), Raipur (RPR), Sambalpur (SMB), Bolangir (BLG), Phulbani (PHB), Bhavanipatna (BWP), Cuttack (CTK) and Puri (PRI), which are optimally distributed over the basin, were considered (Fig. 2). In the case of rainfall, since 86% of the annual rainfall of the basin occurs in the monsoon season, the analysis has been confined to monsoon season and annual only.

Data quality and length: For studies pertaining to trend analysis, the data length should be at least 80 yr (Mitchell et al. 1966). Taking this into account, these analyses were made only for stations whose data series are available for 80 or more yr. Proper care was taken regarding the homogeneity of the data. There was a change in the exposure of thermometers in 1926, when the India Meteorological Department decided to install the thermometers in the 'standard Stevenson screen' instead of the old 'thatched sheds'. Comparative observations of the temperature readings in 'sheds' and 'screens' were made for at least 2 yr at all stations and corrections derived from the comparative study were applied to the data recorded prior to 1926 (Pramanik & Jagannathan 1954).

Missing observations in the temperature and rainfall data were interpolated by the ratio method suggested by Rainbird (1967). However, when applying this method, temperature/rainfall data of neighbouring stations were used. These have the highest correlation coefficient with the station series where there are gaps in data. After interpolation of missing values, means and standard deviations of the concerned series were computed both with and without interpolated values. The differences in all these means and standard deviations were found to be statistically insignificant.

Analysis. In order to estimate trends in temperature and rainfall series, simple regression analysis with time as the independent variable was used. When testing statistical significance of the linear trends, the effect of autocorrelation in the series was taken into account by increasing the variance by a factor given by Wigley & Jones (1981):

$$f^2(\mathrm{N}, r) = \frac{1+r}{1-r} - \frac{2r(1-r^{\mathrm{N}})}{\mathrm{N}(1-r)^2}$$

where r is lag-1 autocorrelation; and N is number of data points. Linear trends as changes per 100 yr were given for better visualisation. A 9-point Gaussian low-pass filter was used to give a smoothed curve as was used earlier in Indian studies by Hingane et al. (1985) and Rupakumar & Hingane (1988). The smoothed curve is drawn as the time series in addition to the trend line.

The long-term trends are generally tested using the Mann-Kendall rank test and the linear trend. The Mann-Kendall rank test, based on the run test of a ranked time series, is sensitive to non-linear trends as shown by Mitchell et al. (1966). However, it indicates only the direction and the significance of the trend and cannot quantify the trend. On the other hand, the linear trend has the advantage of giving magnitude and direction as well as statistical significance. The linear trend, which is the slope of the simple least-squares regression line with time as the independent variable, was tested for statistical significances by F-ratio, giving due consideration to the autocorrelation of the series. Statistical significances of the regression coefficient (a) are given in Table 2.

RESULTS

Temperature

Mean temperature conditions and its variability for all 7 stations and the basin are given in Table 1. The surface air temperatures showed lower variability during the monsoon season and higher variability during winter and premonsoon periods. Magnitudes of linear trends for annual and seasonal values of mean maximum, mean minimum and average means at all 7 stations and for the basin are given in Table 2. The mean annual maximum, annual minimum and average mean temperature for all 7 stations and for the basin, along with the 9-point Gaussian low-pass filter and trend line, are presented in Figs. 3 to 10. The following important aspects emerge:

(1) Mean maximum, mean minimum and average mean surface temperatures of the basin on an annual basis show significant increasing tendencies at 0.1, 1 and 0.1% levels respectively. The current rate of increase in the annual average surface air temperature of the basin is 1.1°C per 100 yr.

(2) All stations except Sambalpur and Puri showed significant increasing tendencies (at 0.1 to 5% levels). It may be recalled that Sambalpur is close to Hirakud reservoir and in view of this, we took an additional station close to the sea (Puri) which is also characterised by no trend in annual air temperatures.

(3) Higher magnitudes of linear trends are observed in the mean maximum temperatures than in the mean minimum temperatures. (Possible physical mechanisms are suggested in the 'Discussion'.)

(4) The annual mean maximum temperatures of the basin and all stations except Sambalpur and Puri show significant increasing tendencies (at 0.1 to 5% levels) with a maximum increase of 2.2°C per 100 yr at Jabalpur, about 7% of the average maximum temperature.

Table 1. Seasonal and annual temperatures (mean ± SD) in the Mahanadi Basin

	Temperature (°C)		
	Maximum	Minimum	Mean
Annual			
Jabalpur	31.8 ± 0.8	18.4 ± 0.6	25.0 ± 0.7
Raipur	32.5 ± 0.6	20.9 ± 0.6	26.7 ± 0.5
Sambalpur	32.6 ± 0.7	20.7 ± 0.5	26.6 ± 0.4
Kanker	31.7 ± 0.5	19.9 ± 0.6	25.8 ± 0.5
Cuttack	32.8 ± 0.6	22.4 ± 0.5	27.6 ± 0.4
Jagdalpur	31.1 ± 0.5	18.9 ± 0.5	24.7 ± 0.5
Puri	30.1 ± 0.4	23.7 ± 0.5	26.9 ± 0.3
Mahanadi Basin	31.8 ± 0.5	20.7 ± 0.4	26.2 ± 0.4
Winter			
Jabalpur	26.7 ± 1.1	10.1 ± 0.9	18.2 ± 0.9
Raipur	28.2 ± 0.7	14.0 ± 0.9	21.1 ± 0.7
Sambalpur	28.3 ± 1.0	13.2 ± 1.1	20.7 ± 0.7
Kanker	28.4 ± 0.7	12.8 ± 1.1	20.6 ± 0.7
Cuttack	29.2 ± 1.0	16.4 ± 1.0	22.8 ± 0.8
Jagdalpur	28.6 ± 0.9	12.3 ± 1.2	20.0 ± 1.0
Puri	27.4 ± 0.5	18.3 ± 1.0	22.9 ± 0.6
Mahanadi Basin	28.1 ± 0.7	13.9 ± 0.8	20.9 ± 0.7
Premonsoon			
Jabalpur	37.8 ± 1.2	20.9 ± 1.0	29.2 ± 1.1
Raipur	38.7 ± 1.3	24.4 ± 1.0	31.5 ± 1.0
Sambalpur	38.6 ± 1.3	23.2 ± 0.8	30.9 ± 0.9
Kanker	37.5 ± 1.0	23.3 ± 1.0	30.4 ± 0.9
Cuttack	37.5 ± 0.9	24.7 ± 0.6	31.1 ± 0.7
Jagdalpur	36.6 ± 1.0	21.6 ± 0.8	29.0 ± 0.8
Puri	31.0 ± 0.5	25.9 ± 0.7	28.4 ± 0.4
Mahanadi Basin	36.8 ± 0.8	23.4 ± 0.6	30.1 ± 0.7
Monsoon			
Jabalpur	32.1 ± 0.9	24.2 ± 0.4	28.1 ± 0.6
Raipur	32.2 ± 0.8	24.5 ± 0.5	28.3 ± 0.6
Sambalpur	32.5 ± 1.0	25.2 ± 0.6	28.9 ± 0.6
Kanker	30.9 ± 0.7	24.0 ± 0.5	27.5 ± 0.5
Cuttack	32.9 ± 0.7	25.8 ± 0.4	29.4 ± 0.5
Jagdalpur	29.9 ± 0.6	22.5 ± 0.3	26.6 ± 0.5
Puri	31.3 ± 0.4	26.6 ± 0.6	28.9 ± 0.3
Mahanadi Basin	31.7 ± 0.6	24.7 ± 0.3	28.2 ± 0.4
Postmonsoon			
Jabalpur	30.1 ± 1.3	15.4 ± 1.4	22.6 ± 1.1
Raipur	30.3 ± 1.1	18.7 ± 1.1	24.5 ± 0.8
Sambalpur	30.4 ± 1.1	19.0 ± 1.3	24.7 ± 0.9
Kanker	29.5 ± 1.0	17.1 ± 1.4	23.3 ± 0.9
Cuttack	31.0 ± 1.0	21.3 ± 0.9	26.2 ± 0.8
Jagdalpur	28.8 ± 0.9	17.3 ± 1.2	22.7 ± 0.9
Puri	30.4 ± 0.7	22.8 ± 0.8	26.6 ± 0.6
Mahanadi Basin	30.1 ± 0.9	18.8 ± 1.0	24.4 ± 0.7

(5) For annual mean minimum temperatures, all stations except Sambalpur and Puri and the basin as a whole also showed significant warming trends (0.1 to 5% levels).

Winter

During this season, the basin's average temperature exhibited a significant increasing trend (at 1% level). In case of individual stations, 5 stations, excepting Sambalpur and Puri, showed significant warming trends (at 0.1% level) with a maximum increase of 2.7 °C per 100 yr at Jabalpur. It is seen that the major contribution to increasing trend in average temperatures is by the mean maximum temperatures in this season.

Premonsoon

In this season Sambalpur, Cuttack and Puri did not show any significant trend. Increasing trend in the average mean temperature was highest at Jabalpur (2.9 °C for 100 yr) which is significant at 0.1% level. In the mean maximum temperatures, only Jabalpur showed a significant rising trend (at 0.1% level). In the case of minimum temperatures, the whole basin (at 5% level), Jabalpur (at 1% level), Raipur and Kanker (at 5% levels) exhibit significant warming trends for this season.

Monsoon

During this season the basin as a whole and 3 stations, namely Jabalpur, Kanker and Jagdalpur, showed significant warming trends in the average mean temperatures. In the mean maximum temperatures, 2 stations adjacent to water bodies, i.e. Cuttack and Puri, were characterised by significant warming trends (at 5% levels) in addition to a rising trend at Jabalpur (at 1% level). Jabalpur and Kanker are the only 2 stations that showed rising trends in the mean minimum temperatures at 1 and 5% levels respectively in this season.

Postmonsoon

Except Puri, all stations and the basin as a whole showed significant increasing trends in the average mean temperatures. The largest trend of 3.3 °C per 100 yr, which is highly significant at the 0.1% level was observed at Jabalpur. In the mean minimum and mean maximum temperatures, all stations except Sambalpur and Puri exhibited significant warming trends (0.1 to 5% levels).

The analysis further reveals that the major contribution to the warming trend in the region is the mean maximum temperatures. Our analysis also shows that the post-monsoon and winter seasons dominate in the increase of annual mean surface air temperatures in the region. (Explanations for these observations are suggested in the 'Discussion'.)

Rainfall

The analysis of rainfall series of the basin and as well as 10 selected stations revealed the following: (1) The rainfall series of the basin based on the arithmetic average of 125 stations did not show any significant trend either in the monsoon season or on an annual basis. (2) Amongst the 10 selected stations no station showed any significant decreasing or increasing tendency. The actual rainfall series along with 9-point Gaussian low-pass filter and a trend line for the basin is depicted in Fig. 11

Table 2. Linear trends (°C per 100 yr) of seasonal and annual surface air temperatures in the Mahanadi Basin. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

	Winter (Dec–Feb)	Premonsoon (Mar–May)	Monsoon (Jun–Sep)	Postmonsoon (Oct–Nov)	Annual
Average mean					
Jabalpur	2.7***	2.9***	1.1***	3.3***	2.3***
Raipur	1.3***	1.1*	0.4	1.3*	1.0**
Sambalpur	0.6	−0.4	0.3	1.0*	0.3
Kanker	1.1***	0.9*	0.6*	1.5**	0.9***
Cuttack	2.1***	0.3	0.4	1.5**	1.0**
Jagdalpur	3.0***	0.9*	0.9*	2.3**	1.6***
Puri	0.5	0.1	0.1	0.2	0.2
Mahanadi Basin	1.6***	0.8*	0.5**	1.6***	1.1***
Mean maximum					
Jabalpur	2.6***	2.5***	1.2**	2.9***	2.2***
Raipur	1.4***	1.1	0.6	1.2*	1.1**
Sambalpur	0.6	−0.3	1.0*	0.6	0.5
Kanker	1.1	0.6	0.6	1.2*	0.9**
Cuttack	2.6***	0.1	0.8*	1.9**	1.2***
Jagdalpur	1.6**	0.3	0.2	1.3**	0.8*
Puri	0.9*	0.2	0.7*	0.7*	0.6
Mahanadi Basin	1.5***	0.6	0.7*	1.4*	1.0**
Mean minimum					
Jabalpur	1.4**	1.9**	0.5*	2.5**	1.4***
Raipur	1.2*	1.4*	0.2	1.5*	0.9*
Sambalpur	0 3	−0.6	−0.6**	0.9	−0.2
Kanker	1.1*	1.2*	0.6*	1.7*	1.0***
Cuttack	1.6**	0.5	0.1	1.0*	0.7*
Jagdalpur	0.8	0.8	0.3	1.4*	0.7*
Puri	−0.1	−0.1	−0.7**	−0.2	−0.3
Mahanadi Basin	0.9*	0.7*	0.0	1.3*	0.6*

DISCUSSION

An attempt has been made to explore possible reasons for the observed increase of temperatures in the region. The causes are thought to be mostly anthropogenic. Several studies on impact on climate and man-induced input on latent and sensible heat and possible climatic changes were reported earlier (SMIC 1971, Flohn 1977, Kellog 1977, 1978). The increase in population is also related to urbanization and other development activities in the region which have many interactions and interventions on the local environment (Lockwood 1979). The human population of the region has been steadily increasing, similar to the other major parts of India. Like other major parts of the globe, the chemical composition of the atmosphere over India has been changing for the past few decades (Mitra 1992), initially as a result of agriculture, more recently of industrial activities. As a consequence, the atmosphere volume mixing ratio of CO_2 has increased. The annual per capita CO_2 emission has increased gradually in India from 0.06 to 0.20 metric tons from 1950 to 1988 (Mitra 1992). Results also showed that 67% of the carbon released in the atmosphere over India is due to shifting cultivation and accidental fires. In addition, the atmospheric concentrations of several other trace gases are increasing. Although CO_2 is the single most important amongst them, the combined greenhouse forcing of CH_4, $CFCl_3$, CF_2Cl_2, N_2O and some others together is almost equal to that of CO_2. In the study area, CH_4 is an important greenhouse gas since large pockets of forests have been cut and converted into agriculture for meeting the food demands of the increasing population in the region, and rice is the major crop in the study area (Saha et al. 1989). Considerable work has been reported in the literature on methane emissions vis-a-vis temperature changes (Rasmussen & Khalil 1984, Ramanathan et al. 1985, Parashar et al. 1992). Due to construction of the Hirakud Dam in 1957 in the basin near Sambalpur, with a storage capacity of 5822 million m^3 of water and

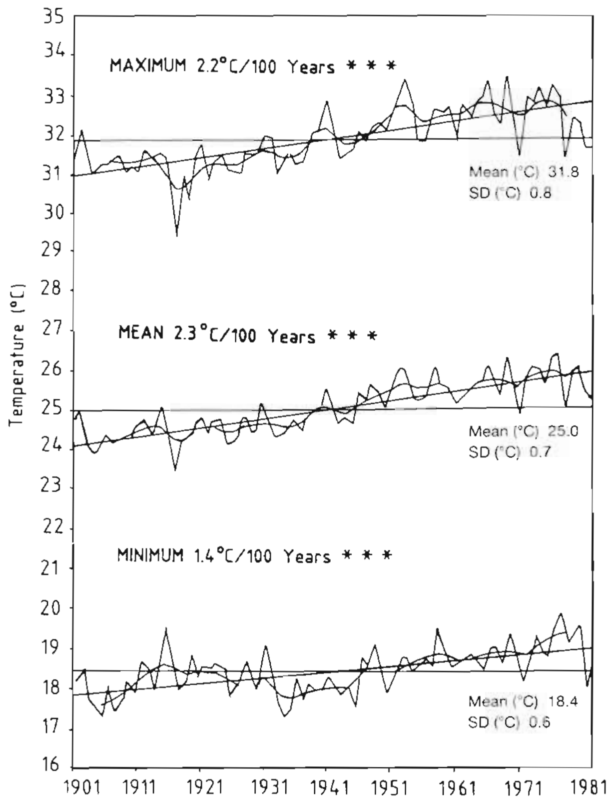

Fig. 3. Trend analysis of surface air temperature (°C) at Jabalpur

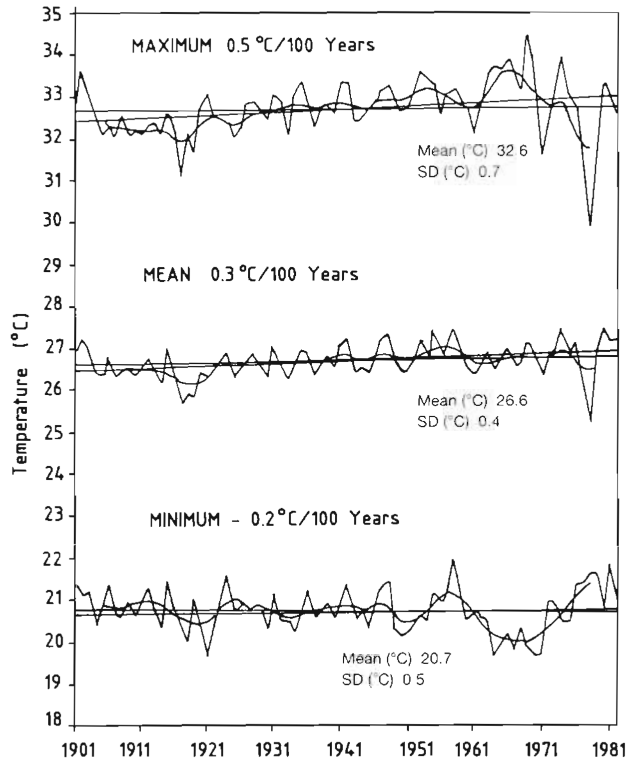

Fig. 5. Trend analysis of surface air temperature (°C) at Sambalpur

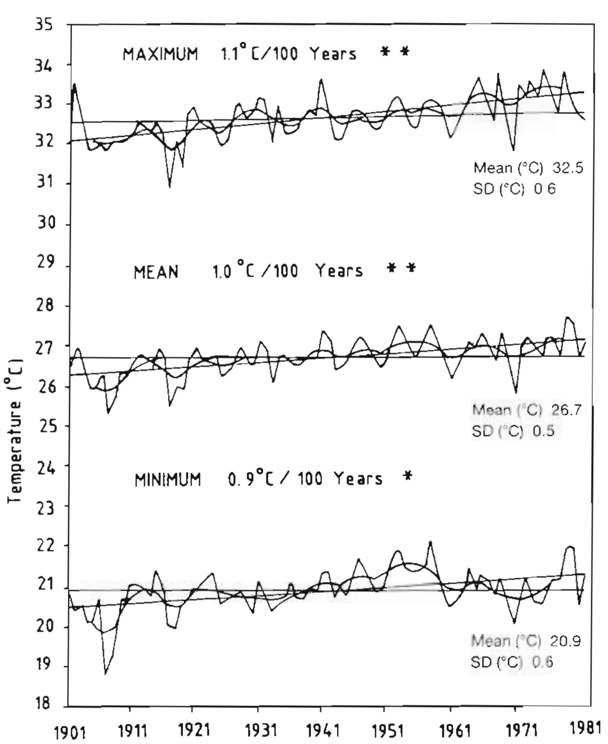

Fig. 4. Trend analysis of surface air temperature (°C) at Raipur

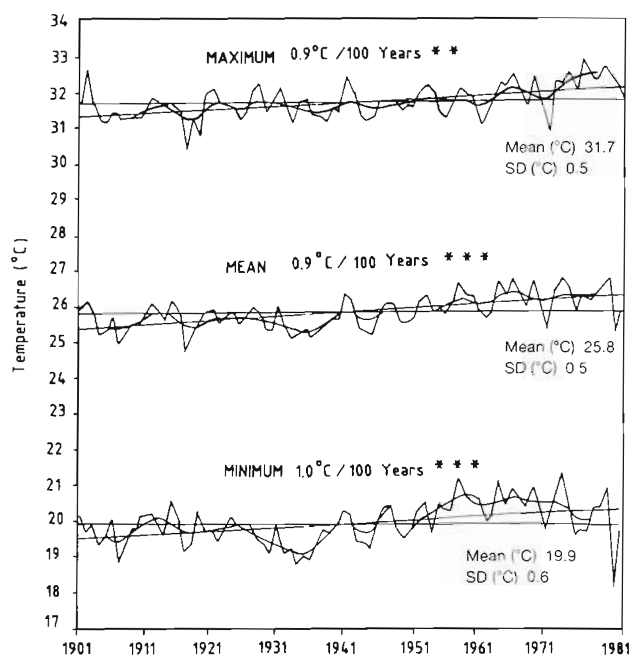

Fig. 6. Trend analysis of surface air temperature (°C) at Kanker

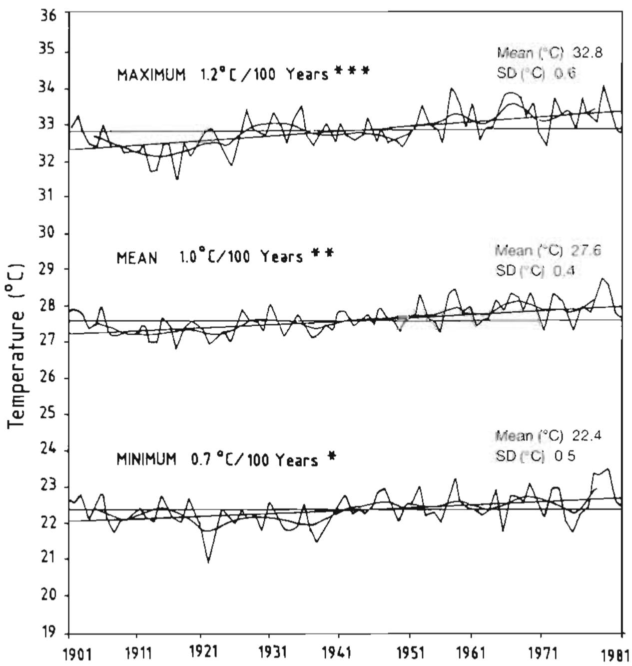

Fig. 7. Trend analysis of surface air temperature (°C) at Cuttack

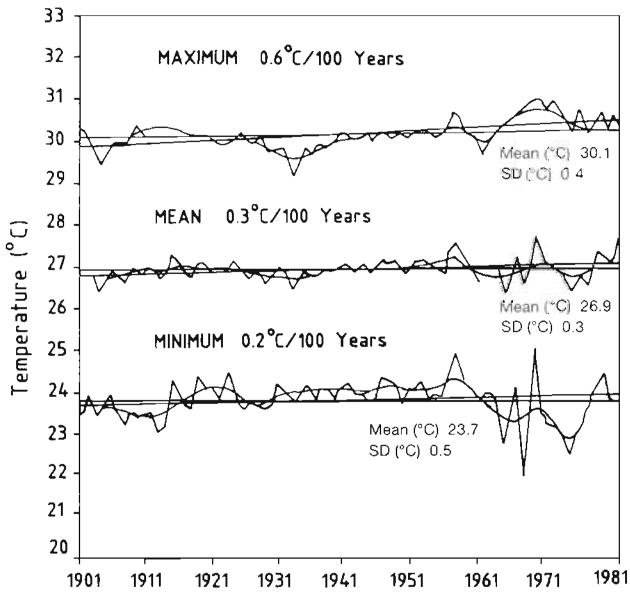

Fig. 9. Trend analysis of surface air temperature (°C) at Puri

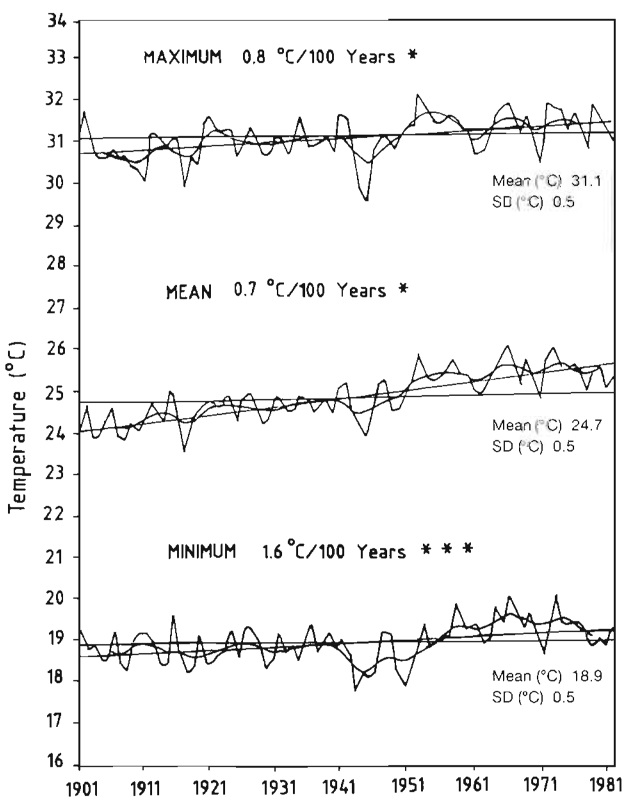

Fig. 8. Trend analysis of surface air temperature (°C) at Jagdalpur

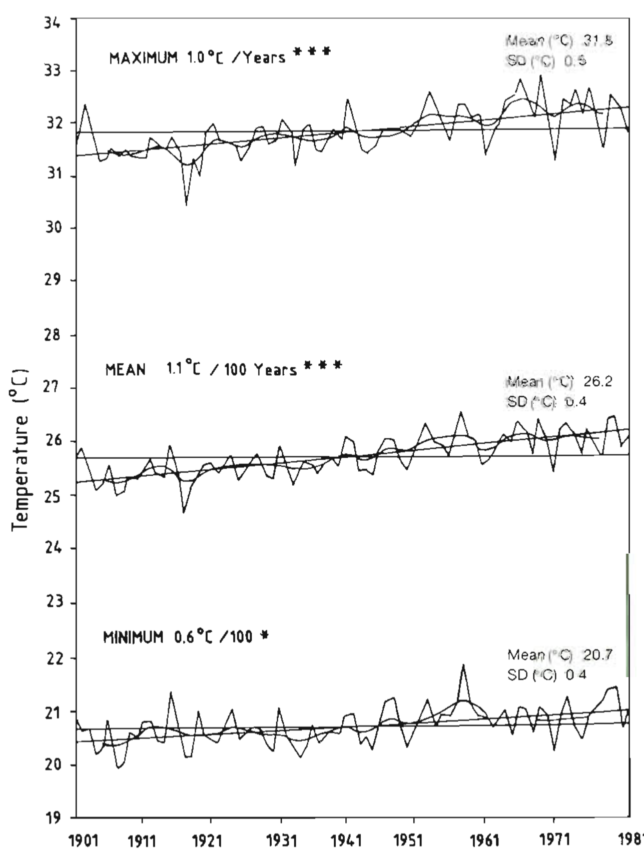

Fig. 10. Trend analysis of surface air temperature (°C) in the Mahanadi Basin

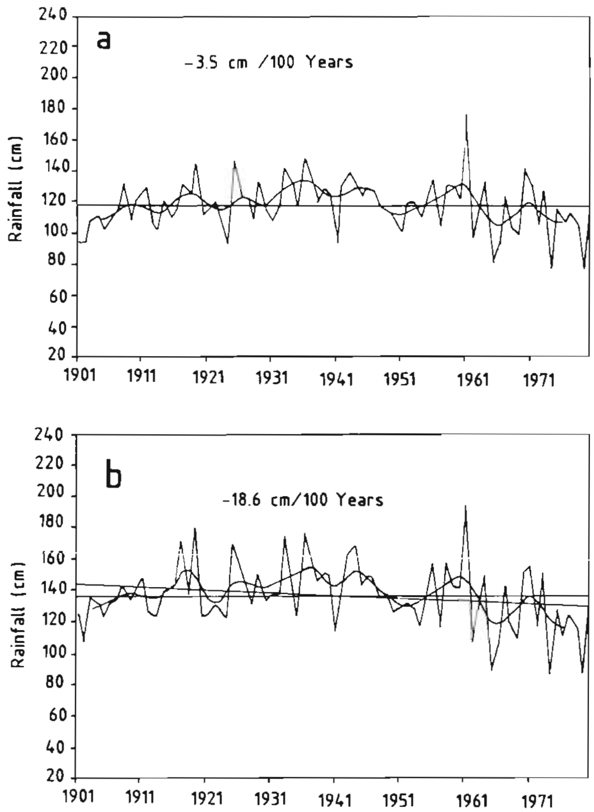

Fig. 11. Trend analysis of (a) monsoon and (b) annual rainfall (cm) of Mahanadi Basin

having an irrigation potential of 253 750 ha, the emission of CH_4 has definitely increased. Quantitative data on methane flux in India are available only from the methane campaign year of 1991.

Parashar et al. (1991) estimated a maximum release of 0.09×10^{15} g CH_4 yr^{-1} from the rice fields of India which is 6% of the global methane budget. Recent studies in India (Mitra 1991, Parashar et al. 1993) have indicated that emissions of methane are maximum (0.8 to 1.0 mg m^{-2} h^{-1}) from 50 to 70 d after transplanting the rice crop. Diurnal analysis revealed that maximum efflux of 1.5 to 1.7 mg m^{-2} h^{-1} is observed from 12:00 to 15:00 h. These results support the features of the seasonal dominance (postmonsoon and winter) and also the mean maximum temperatures which are observed in the present study. On the other hand, the premonsoon and monsoon seasons are characterised by widespread convective activity over the region which possibly contributes to some extent to the dampening out of the mechanisms causing warming in these seasons, by more mixing of surface layers. Since the region is practically cloud-free during winter and postmonsoon seasons, it may be reasoned that the albedo changes which may have occurred due to changes in land use are probably playing a role in addition to methane emission characteristics. Detailed changes in land use patterns in the Mahanadi Basin were discussed in All India Soil and Landuse Survey (1988) and Rao (1992).

The most important aspect to emerge from this study is a significant warming trend observed in the Mahanadi river basin. The major contribution to the warming trend is by the mean maximum temperatures. Seasonal analysis revealed that postmonsoon and winter seasons are predominant in causing the overall annual rise in the surface air temperatures of the region. Though the steady increase of annual temperatures could not be attributed to any single physical mechanism, the increasing trend in the greenhouse gases in the atmosphere, especially CO_2 and CH_4, and changes in land-use patterns were found to have a bearing on the observed warming trend in the basin.

Acknowledgements. The author is thankful to Dr K. Rupakumar and Mr K. Krishna Kumar of the Indian Institute of Tropical Meteorology, Pune, for useful suggestions. The basic data was provided by the India Meteorological Department, Pune. The author is thankful to the reviewers of the paper for their valuable suggestions and constructive comments. Thanks are also due to Mr V. K. Premkumar and Mr Benjamin Kisku of DST for typing the manuscript and Mrs Gita Dey for tracing the diagrams.

LITERATURE CITED

All India Soil and Landuse Survey (1988). Report of the Ministry of Agriculture, Govt of India, New Delhi

Chen, R. S., Parry, M. L. (eds.) (1987). Policy oriented impact assessment of climatic variations. International Institute for Applied Systems Analysis, RR-87-7, Laxenburg, Austria

Dept of Science & Technology (DST), Govt of India (1993). Geosphere biosphere programme (April, 1993). DST, New Delhi

Flohn, H. (1977). Climate and energy: a scenario to the 21st century. Clim. Change 1: 5–20

Hingane, L. S., Rupakumar, K., Ramana Murthy, Bh. V. (1985). Long-term trends of surface air temperature in India. J. Climatol. 5: 521–528

Kellog, W. W. (1977). Effects of human activities on global climate. WMO Tech. Note No. 156

Kellog, W. W. (1978) Global influences of mankind on the climate. In: Gribbon, J. (ed.) Climate change. Cambridge University Press, Cambridge, 7: 205–227

Landsberg, H. E. (1975). Sahel drought change of climate or part of climate. Arch. Met. Geophy. Bioklim. Ser. B, 23: 193–200

Lockwood, J. G. (1979). Causes of climate. Edward Arnold, London

Mitchell, J. M., Dzerdyeevskii, B., Flohn, H., Hofmeyr, W. L., Lamb, H. H., Rao, K. N., Wallen, C. C. (1966). Climatic change: WMO-195, TP 100. WMO Tech. Note 79

Mitra, A. P. (1991). Greenhouse gas emissions in India – A preliminary report. Scientific report No. 1, June 1991. Council of Scientific & Industrial Research, New Delhi

Mitra, A. P. (1992). Greenhouse gas emission in India – 1992 update, Scientific Report No. 4, Aug. 1992. Council of Scientific and Industrial Research & Ministry of Environment & Forests, New Delhi

Mooley, D. A., Parthasarathy, B. (1979). Poisson distribution and years of bad monsoon over India. Arch. met. Geophys. Bioklim. Ser. B 27: 381–388
Mooley, D. A., Parthasarathy, B. (1984). Fluctuations in all India summer monsoon rainfall during 1871–1978. Clim. Change 6: 287–301
Parashar, D. C (1993). Methane emission studies from paddy fields in India. Preprints of the National Symposium on International Geosphere Biosphere Programme held at Madras (April 21–24, 1993). 1: 9–10
Parashar, D. C., Gupta, Prabhat. K., Rai, J., Sharma, R. C., Singh, N. (1992). Correlation of methane emissions with temperature and other parameters. Proc. Int. Symp. on Global Change held at Waseda Univ., Tokyo (March 27–29, 1992) 1: 184–188
Parashar, D. C., Rai, J., Gupta, Prabhat, K., Singh, N. (1991). Parameters affecting methane emission from paddy fields. Indian J. Radio Space Phys. 120: 12–17
Parthasarathy, B. (1984). Some aspects of large-scale fluctuations in the summer monsoon rainfall over India during 1871–1978. Ph.D. thesis, Poona University, Poona
Parthasarathy, B., Dhar, O. N. (1974). Secular variations of regional rainfall over India. Q. Jl R. met. soc. 100: 245–257
Parthasarathy, B., Dhar, O. N. (1975). Trend analysis of annual Indian rainfall. Hydrol. Sci. Bull. 20: 257–260
Parthasarathy, B., Dhar, O. N. (1976a). A study of trends and periodicities in the seasonal and annual rainfall of India: Indian J. Meteorol. Geophys. 27: 17–22
Parthasarathy, B., Dhar, O. N. (1976b). Studies of trends and periodicities of rainfall over Madhya Pradesh. Proc. Indian natn. Sci. Acad. 42: 73–80 (Part A)
Pramanik, S. K., Jagannathan, P. (1954). Climatic change in India – II. Temperature. Indian J. Meteorol. Geophys. 5: 29–47
Rainbird, A. F. (1967). Methods of estimating areal average precipitation, WMO/IHD Report No. 3. WMO, Geneva
Ramanathan, V., Cicerone, R. J., Singh, H. B., Kiehl, J. T (1985). Trace gas trends and their potential role in climate change. J. geophys. Res. 90: 5547–5566
Rao, P. G. (1992). Some climatological and hydrometeorological aspects of Mahanadi catchment, India. Ph.D. thesis, Indian Institute of Technology, New Delhi
Rasmussen, R. A., Khalil, M. K. (1984). Atmospheric methane in the recent and ancient atmospheres-concentrations, trends and interhemispheric gradient. J. geophys. Res. 99: 11599–11605
Rupakumar, K., Hingane, L. S. (1988). Long-term variations of surface air temperatures at major industrial cities of India. Clim. Change 13: 287–307
Saha, A. K., Rai, J., Raman, V., Sharma, R. C., Parashar, D. C., Sen, S. P., Sarkar, B. (1989). Methane emission from inundated fields in a monsoon region. Ind. J. Radio & Space Phys. 18: 215–217
Study of Man's Impact on Climate (SMIC) Report (1971). Inadvertent modification. MIT Press, Cambridge, MA
USNRC (1982). Carbon dioxide and climate: a second assessment. National Academy Press, Washington, DC
Wigley, T M. L., Jones, P. D. (1981). Detecting CO_2 induced climatic change. Nature 292: 205
World Meteorological Organisation (WMO) (1987). Water resources and climatic change: sensitivity of water resource systems to climatic change and variability. Meeting of the experts on the sensitivity of water resource systems to climate variability, 17–20, Nov. 1987, Norwich, UK, World Climate Applications Programme, WCAP-4 (WMO/TD No. 247), WMO, Geneva
World Meteorological Organisation (WMO) (1988). The changing atmosphere: implications for global security. Conference Proceedings, 27–30 June, 1988. WMO, Geneva

Editor: T Oikawa

Manuscript first received: January 30, 1992
Revised version accepted: July 1, 1993