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Climatic change and variability

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1. Introduction

It is fresh in our memories that in recent years the adverse climatic events have frequently disrupted the human societies. The severity of Sahelian drought, 1968-73, has caught the public attention. More recently the drought has occurred with double intensity and its disastrous effects have now spread over Ethiopia, Sudan and other neighbouring African countries. In the 1970s, the adverse climate became a major destabilizing factor in the national economies and the food production of the world. The year 1972 saw a worldwide epidemic of costly climatic episodes, including drought in India and Soviet Union. Flood years like one in 1974 in Bangladesh have frequently put heavy demand on international support and rescue to alleviate the disastrous consequences. In 1975, cold waves in Brazil badly damaged coffee crops, while in 1976 drought in Europe caused widespread economic problems. The occurrence of extremely pronounced *El-Nino* in 1982/83 is another climate related event during which cold nutrient-rich upwelling water off the coasts of Peru, Ecuador and Colombia was replaced by warm water from the equatorial Pacific with disastrous consequences on fisheries, and excessive and destructive rainfall along those coasts. Simultaneously, major climatic events like droughts over Australia have occurred over several parts of the world. Such extreme climatic events during past two decades have demonstrated the sensitivity of human welfare and international relations to climatic events.

The study of past records shows that climatic aberrations occurred recently are not unusual and similar calamities have occurrred in the past also. Evidences gathered from the past remains, preserved in the earth suggest that earth's climate has changed over time scale ranging from a few thousand years to million of years.

In this article, an attempt has been made to summarize the climate-change and variability. The problem has been discussed, in detail, with particular reference to the analysis, made by using Indian rainfall and temperature data for recent hundred years. In addition, the effect of natural and man-made causes on climatic change; the model studies for assessing the impact of increasing carbon-dioxide on future global warming and the simulation of past climate by general circulation models have also been briefly discussed.

2. Global perspective of climatic change

Climate, from geological epoch has been changing with time and it is reasonable to assume that it will certainly continue to do so in future also (Lamb 1977). The fascinating climatic history of past few million years is extracted from ecological interpretations of palaeobiological materials which are mainly the macro-and-micro remains of plants and animals buried in geological remains. The synoptic picture of a climatic pattern into long past may be obtained from the evidence derived from radio-carbon dating, dendochronology, tree rings, oxygen-isotope ratio of oceanic sediment-cores, insect studies and adaptability to different climates by human beings and animals.

The history of our global climate shows that climatic conditions that prevailed over last few hundred million years (Fig. 2) differed markedly from that of the present, with higher overall temperatures and also fewer differences in temperatures in the lower and higher latitudes (Morner and Karlen 1984). These higher latitudes began to cool sharply about 70 million years ago leading to polar glaciation about a million years ago. The glaciation in the Northern Hemisphere has fluctuated considerably since then and the most dramatic climatic changes have been the ice-ages which have occurred approximately every 0.1 million years (Hare 1979). Ancient climates of 20 million years BP (Before Present) are believed to have been generally warmer by 5° to 10° C than today. There have been at least 3 ice-ages, the oldest proven being 650 million years BP (Hare 1979). The past 2 million years (the

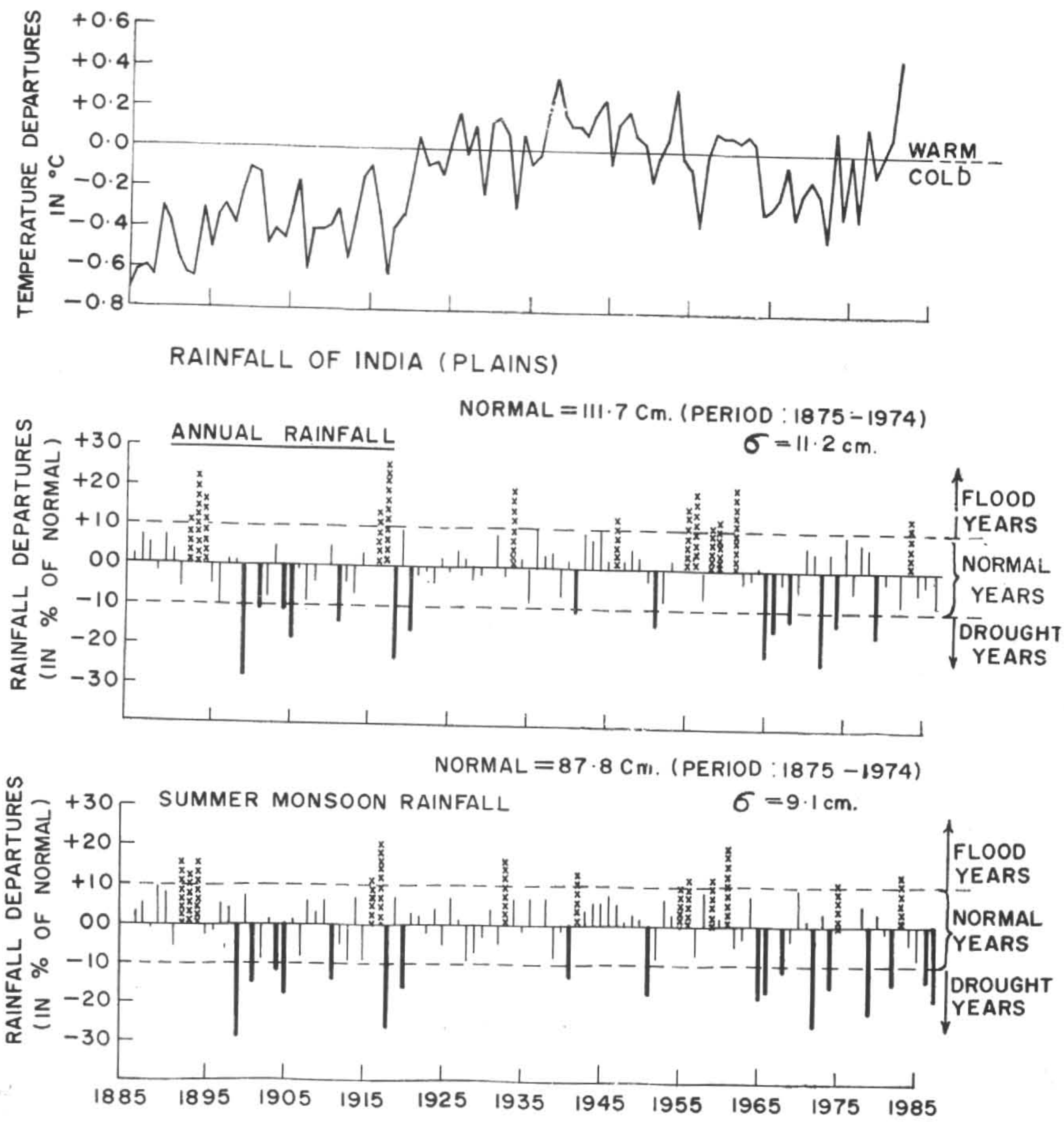

Fig. 1. Northern Hemispheric temperature, droughts and floods over India (*After* Jones *et al.* 1982)

quarternary period) have been a sequence of glacial epochs with extensive ice sheets covering much of North America and Eurasia at about 0.1 mllion years interval. The coming of a new interglacial epoch during our own times was, as usual, quite sudden. The early holocene (10,000 years B.P.) was accompanied in many parts of the world by some increase in precipitation, especially in the sub-tropical deserts of Northern Hemisphere, (*e.g.*, Flohn 1979 and Gerasimov 1979). Thereafter, beginning a little before 5,000 years ago, a series of changes ensued that led for the most part towards less favourable conditions. A significant cooling began about a millennium later across much of Eurasia (Fig. 3).

From constructions of many workers (*e.g.*, Singh 1971, Flohn 1979), it is clear that much of the sub-tropical dry belt, from West Africa to Rajasthan, was wetter between 12,000 and 4,000 years ago than today, with some less humid phases. According to Singh (1971), arid and semi-arid regions over Rajasthan and neighbourhood had humid climate between 4,000 and 8,000 years BP (Fig. 3). By 7,000 BP, temperatures were a little higher than today, as has been concluded from the analysis of pollen deposits in bogs and lakes sediments. The sub-tropical and warm temperate belt of Northern Hemisphere, which had seen extensive deserts during the glacial epoch, became generally more moist. It is seen

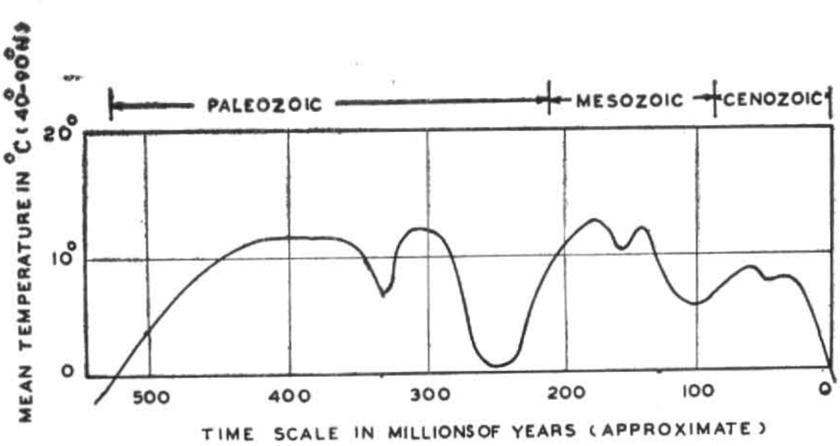

Fig. 2. Variation of temperature during geological time as estimated from fossils evidence (*After* Brooks 1951)

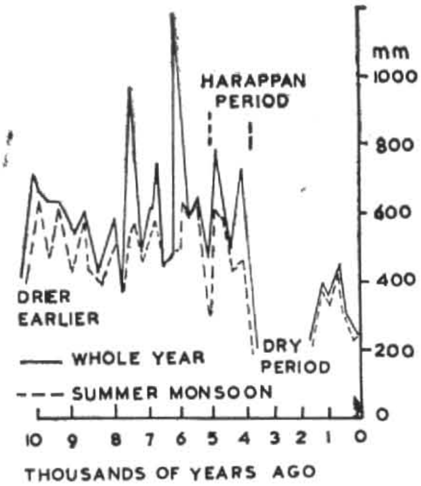

Fig. 3. Rainfall over Rajasthan region for past 10,000 yr (*After* Singh 1971)

In Fig. 3 values of rainfall over the Rajasthan region for the past 10,000 years are estimated from lake levels and botanical evidence based on pollen analysis. The cities of Harappa and Mohenjodaro in the Indus valley flourished in what are now deserts, during 2,500 and 1,700 B.P. when the mean rainfall was between 500 and 800 mm per year.

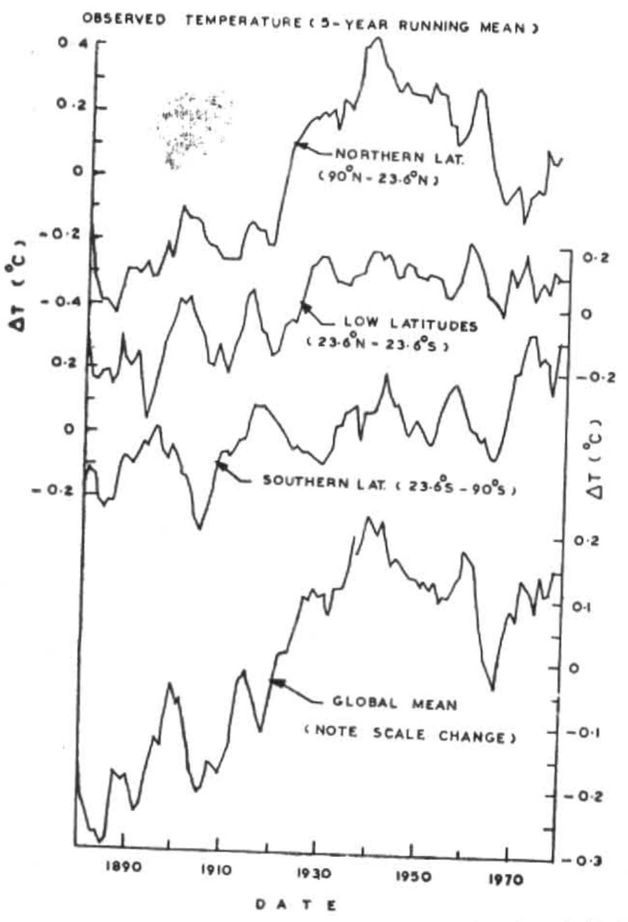

Fig. 4. Observed surface air temperature trends for three-latitude bands and the entire globe. Temperature scales for low latitudes and global mean are on the right (*After* Hansen *et al.* 1981)

from Fig. 3 that Rajasthan and Indus valley precipitation was at times more than its present value. The rise of North Africa, Middle Eastern and Indus valley (Harappan) cultures was favoured by the climate.

In the past 40,000 years drop in temperature began in many phases. Desiccation occurred over many sub-tropical areas and great deserts started assuming their modern aridity. Fig. 3 shows the dramatic effects in Rajasthan desert. The desiccation eclipsed the Indus civilizations. In the past 1,000 years when climate has been fairly stable, the noteworthy variations were : (*i*) an early medieval warm phase (800-1200 AD) and (*ii*) the Little Ice Age between 1550 and 1850 AD, a sharply cooler period by about 1.5° C. During latter period Arctic ice expanded affecting Greenland and Iceland and injuring European economies.

Climatic fluctuations have continued in this century also with a warm-up trend having occurred during the 1920s and 1930s, followed by a cooling trend which seems to be reversing since late 1960s (Budyko and Vinnikov 1976, Wallen 1984). It is interesting to note from Fig. 1 that during the warm epoch of 1930-1960 the droughts over India were considerably less frequent when compared to the preceding and the succeeding cold epochs.

3. Global climatic fluctuations during the period of instrumental record

Although some instrumental observations of weather date back to the seventeenth century, the effective observation of surface climatic elements really began little more than a century ago. At sea the coverage was largely confined to main navigational lanes. Since mid-1950s, a reasonable density of upper air observational network is available.

3.1. *Trend of mean temperature since* 1880

Recently many attempts have been made to construct global temperature history from the past observations made over land (Diaz *et al.* 1980, Jones *et al.* 1982, Vinnikov *et al.* 1980) and oceans (Follard *et al.* 1984). Hansen *et al.* (1981) have divided each hemisphere in 40 equal area boxes and obtained

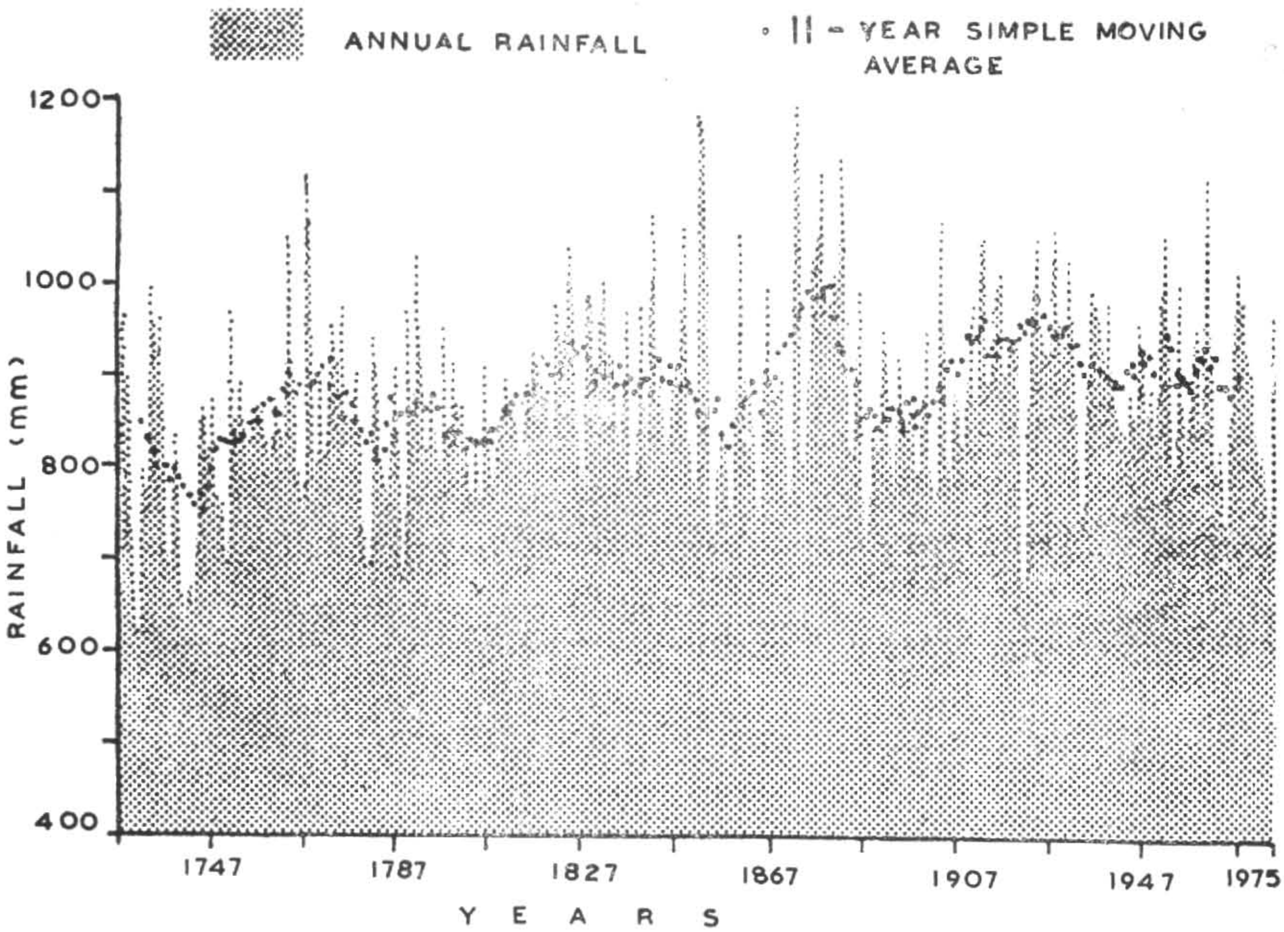

Fig. 5. Estimated mean annual precipitation over England and Wales since 1727 (*After* Rodda and Sheckley 1978)

Fig. 6. Variation of mean annual precipitation at Toronto, Canada, since 1946, by 10-year moving means, showing apparent decline in late nineteenth century and a decade of drought in the 1920s and 1930s

(*After* Hare and Thomas 1979)

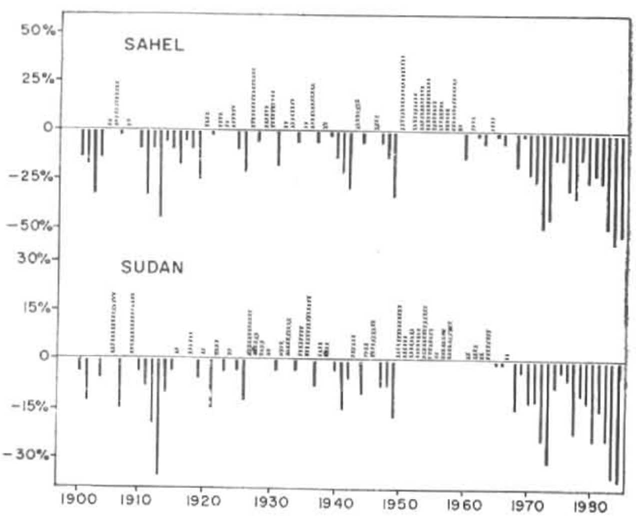

Fig. 7. Variation of annual rainfall in two environmental zones in north and west Africa. The scales are per cent deviation from normal (*After* Nicholson 1985)

temperature trend in a particular box area by combining the observed trends of all the stations which lie within the box. Subsequently, the trends for boxes in a latitude zone were combined with each box weighted equally, and the global trends have been obtained by area weighting the trends for all latitude zones. They found that meaningful results began in 1880s. The temperature trends in Fig. 4 are smoothed with a 5-year running mean to make the trend readily visible. It is seen from the figure that northern latitudes warmed by 0.8° C between 1880s and 1940, then cooled by 0.5° C between 1940 and 1970. Low latitudes warmed by 0.3° C between 1880 and 1930, with little change thereafter. Southern latitudes warmed by 0.4° C in the past century. The global mean temperature increased by 0.5° C between 1885 and 1940 with slight cooling thereafter. The global temperature is high today as it was in 1940. The common conception that the world is cooling is based on Northern Hemisphere experiences to 1970 (Jones *et al.* 1982, Vinnikov *et al.* 1980). It may be mentioned that the global surface temperature rise by 0.4° C in the past century is roughly consistent with calculated carbon-dioxide warming (Hansen *et al.* 1981). The striking feature, however, is that the inter-annual variability of world temperature is much larger than the trend. Especially in high latitudes the year to year differences of temperatures are striking.

3.2. *Trend of precipitation since the seventeenth century*

Several workers have studied the long period precipitation data of different countries of the world. Rodda and Sheckley (1978) have collected and recalibrated numerous rainfall and snowfall observations over England and Wales. Since 1727, the estimated annual precipitation over the regions are shown in Fig. 5. The data do not show any striking trend or any pronounced peaks which suggests any real periodicities. Similarly, examination of a long record of Indian annual and monsoon rainfall does not show any striking changes over more than a century. The record fails to indicate either a trend, or a tendency towards prolonged episodes as can be seen from Fig. 1.

A record from Toronto, Canada (Fig. 6) shows two effects often at other stations : a single, abrupt decrease of mean precipitation of about 10 per cent in the 1860s and early 1870s and a decade long drought phase in 1920s and 1930s (Hare and Thomas 1978).

Recently, the severe drought conditions have disrupted human societies, like in Africa, where Sahelian drought of 1968-1973 has caught the attention of the world and demonstrated the reality of climatic variability and its significance to the mankind. Severe droughts have affected northeastern Brazil, western China, India, eastern Australia. Many of these episodes have caused great human sufferings. Since last two decades, a period of progressive desiccation is noted (Fig. 7) over Sahel and Sudan. This downward trend of rainfall is not found during any other period within nineteenth century. The available evidence, nevertheless, supports the view that Sahelian drought, though severe and damaging, is an aspect of climatic variability, and not of true variation employing a lasting shift to drier conditions—though there is no sure way of ruling the latter possibility out.

Most of the other long term records from both hemispheres show similar small effects, but no clear trends emerge on a hemisphere or global basis. It can, therefore, be summarised that recent impact of climate on human economy has been largely due to variability, rather than due to lasting climatic change. However, if the present climate, even with its natural fluctuations continue, it would still be necessary to prepare for the type of stress, recently faced by the mankind.

4. Climatic fluctuations in India during the period of instrumental record

In India, accurate climatic data based on instrumental observations are available only for the past hundred years (Choudhury and Ganesan 1981, Prasad and Gadgil 1987). The problem of trend and periodicity in Indian climate has always attracted and continues to attract attention of public and scientists. In India and abroad, several studies have been carried out to establish climatic change over India.

4.1. *Rainfall variability*

Blanford (1886) was the first meteorologist who made extensive studies of Indian rainfall. The analysis of 19-year (1867-1885) annual rainfall data for India as a whole did not reveal any significant oscillation or systematic trend in the rainfall. In addition, the analysis also revealed that year to year fluctuations in rainfall were random in nature. During the period, he noticed that the average annual rainfall over India was about 107 cm and varied from highest value of 124 cm in 1878 to the lowest 90 cm in 1868. The second study on rainfall variation was conducted by Walker (1910), who examined the summer monsoon rainfall over India from 1841 to 1908 and concluded that there was no perceptible climatic change. On detailed analysis he found a tendency for monsoon rainfall over northwest India to increase to a maximum between 1891 & 1894 and to decrease to a minimum upto 1899. Thereafter, the rainfall started showing increasing tendency in subsequent years. For India as a whole, the rainfall was below normal during 1843-60 and 1895-1907, the worst drought years being 1848, 1855, 1877 and 1899. Walker (1910, 1914, 1922) further indicated that the abnormal changes in atmosphere seem to be responsible for deficiency of monsoon rainfall over India. Rao (1936) studied 40 years (1893-1932) annual rainfall data over different districts of Mysore State of India. He found some trend in two districts only. Subsequently, Agarwala (1952) studied the fluctuations in annual rainfall over India and did not find any significant trend and periodicity. In a systematic study Pramanik and Jagannathan (1953) analysed 60 to 100 years rainfall data over 30 Indian stations and concluded that there was no short period cycle in annual rainfall and also in the distribution of rainfall particularly in arid and semi-arid regions of northwest India. In case of semi-arid region of Deccan, they found a tendency for deficient rainfall to be more frequent. In addition, no significant increase or decrease in decadal averages of the annual rainfall was noted by them. Rao and Jagannathan (1963) studied 81 years (1875-1955) rainfall data over 25 sub-divisions of India. The study did not reveal any major climate changes in the rainfall series except for oscillatory/increasing trend in part of the series. This type of trend was noted only in a few sub-divisions of India. Recently, the detailed analysis of rainfall data by several investigators like Koteswaram and Alvi (1969, 1970) for different stations

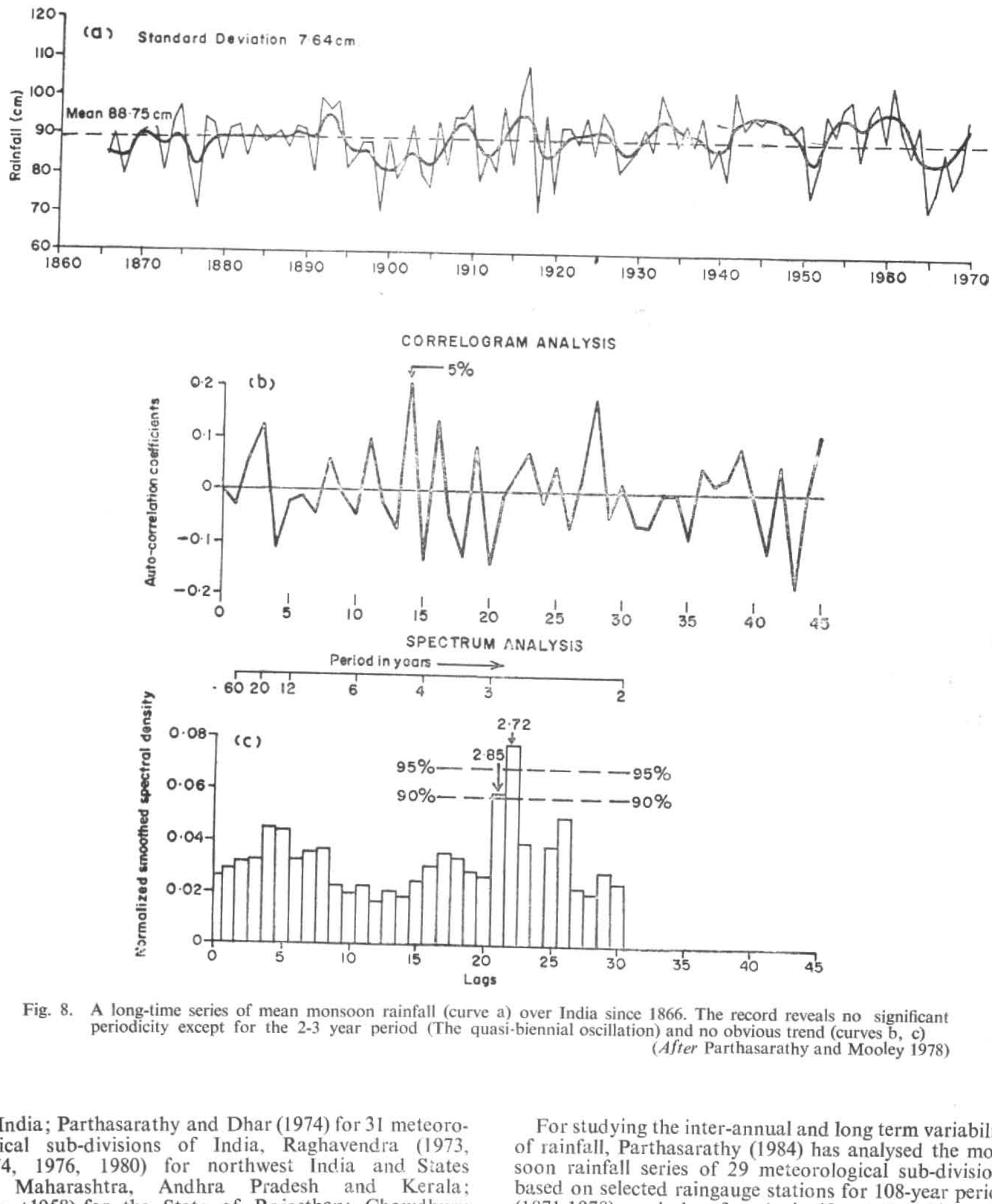

Fig. 8. A long-time series of mean monsoon rainfall (curve a) over India since 1866. The record reveals no significant periodicity except for the 2-3 year period (The quasi-biennial oscillation) and no obvious trend (curves b, c) (*After* Parthasarathy and Mooley 1978)

of India; Parthasarathy and Dhar (1974) for 31 meteorological sub-divisions of India, Raghavendra (1973, 1974, 1976, 1980) for northwest India and States of Maharashtra, Andhra Pradesh and Kerala; Rao (1958) for the State of Rajasthan; Chowdhury and Abhyankar (1979) for Gujarat; Parthasarathy and Mooley (1981) for State of Karnataka and Dhar *et al.* (1982) for State of Tamil Nadu etc have found significant evidence for the presence of different cycles ranging from high frequency to very low frequency in the rainfall series of different regions/sub-divisions of India. However, they have generally not found any long term trend in the rainfall data of different regions of India.

For studying the inter-annual and long term variability of rainfall, Parthasarathy (1984) has analysed the monsoon rainfall series of 29 meteorological sub-divisions based on selected raingauge stations for 108-year period (1871-1978) and has found significant Quasi-Biennial Oscillation in 19 contiguous sub-divisions and a 14-year cycle in 8 sub-divisions. Detailed examination of the series for India as a whole (Mooley & Parathasarathy 1984) indicated the presence of three major climatic rainfall periods, two deficient rainfall periods 1871-1920 and 1965 to 1974, and one good rainfall period 1921 to 1964. The highest (115% of normal) and lowest (71% of normal) rainfall are respectively recorded in 1961 and 1877. The average monsoon rainfall is 85.31 cm

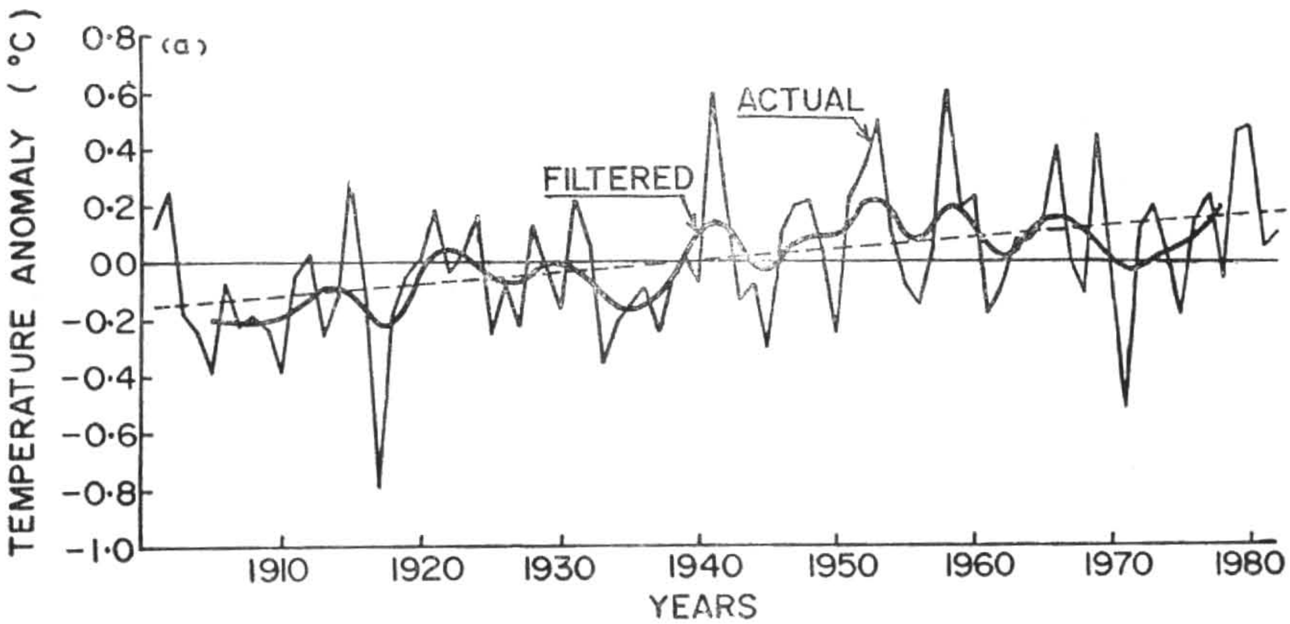

Fig. 9 (a). Actual and filtered (Gaussian lowpass filter) values and the trend line of annual temperature anomalies in India during the period 1901-1982

(*After* Hingane *et al.* 1985)

with coefficient of variance of 9.5%. The study of 100-year (1875-1974) monsoon rainfall data over India (Banerjee and Raman 1976) has revealed that (*i*) there is no persistence, cyclicity, trend or definite pattern in unfavourable monsoon occurrences, (*ii*) the inter annual variability is highest over northwest India and (*iii*) the interval between successive bad years varies widely between 0 & 15 years while between good years it does not exceed four years.

Recently, Rajagopalachari *et al.* (1984) studied the monsoon rainfall over India as a whole and separately over 31 meteorological sub-divisions of the country. The study has revealed the existence of 2.0-3.5 year cycle in the rainfall series of India as a whole, which is significant at 95% level. However, this cycle of 2.0 to 3.5-year period has been found in 14 sub-divisions only. In addition, the rainfall data of 4 meteorological sub-divisions have revealed the existence of 6.0 to 6.5-year cycle at 95 per cent confidence level. Similarly the detailed analysis of record of monsoon rainfall over India (Parthasarathy and Mooley 1978, Mooley and Parthasarathy 1984) shows no striking changes over more than a century and fails to indicate either a trend or a tendency towards prolonged drought episodes (Fig. 8).

Detailed analyses of long period rainfall data over different sub-divisions of India and also over India as a whole do not indicate any long term climatic change, but only indicate year to year random fluctuations during recent 100 years. Some significant cycles whose period *ranges from quasi-biennial to 15* years have been generally noted in some regions. It may, however, be mentioned that these cycles barely explain less than 10 per cent of the variance and cannot be used for prediction.

4.2. *Temperature variability*

For determining the trend, the annual maximum and minimum temperatures of 30 meteorological observatories situated in India and neighbourhood have been studied by Pramanik and Jagannathan (1954). The detailed analysis has revealed that there is no general tendency of systematic increase or decrease of temperature over these stations. They concluded that small irregular oscillations which are connected with random noise are associated with year to year variation of the temperature. Jagannathan (1963) has analysed the trends in the characteristics of seasonal variation of temperature in the arid and semi-arid regions of the globe which included 8 Indian stations with about 55 to 100 years data. He has not observed systematic increase or decrease in the mean annual temperature of the Indian stations. Jagannathan and Parthasarathy (1972) have analysed the series of the mean annual temperature and characteristic parameters representing seasonal variation of temperature over another set of 8 Indian stations using about 90 years data. They, however, reported increasing trend in the mean annual temperature at 4 stations (Calcutta, Bangalore, Bombay and Allahabad) and decreasing trend at one west coast station (Fort Cochin). Recently, Hingane *et al.* (1985) have made an attempt to study the trends in long series of temperature data of different regions of the country of India as a whole. They have used temperature data of 73 fairly widespread stations, for the period 1901-1982 and have concluded that a slight but definite warming trend in the mean annual Indian temperature has been noted from 1901 to 1982. Different regions of the country namely west coast, interior Peninsula, north central India and northeast India, have shown pronounced warming in the mean annual

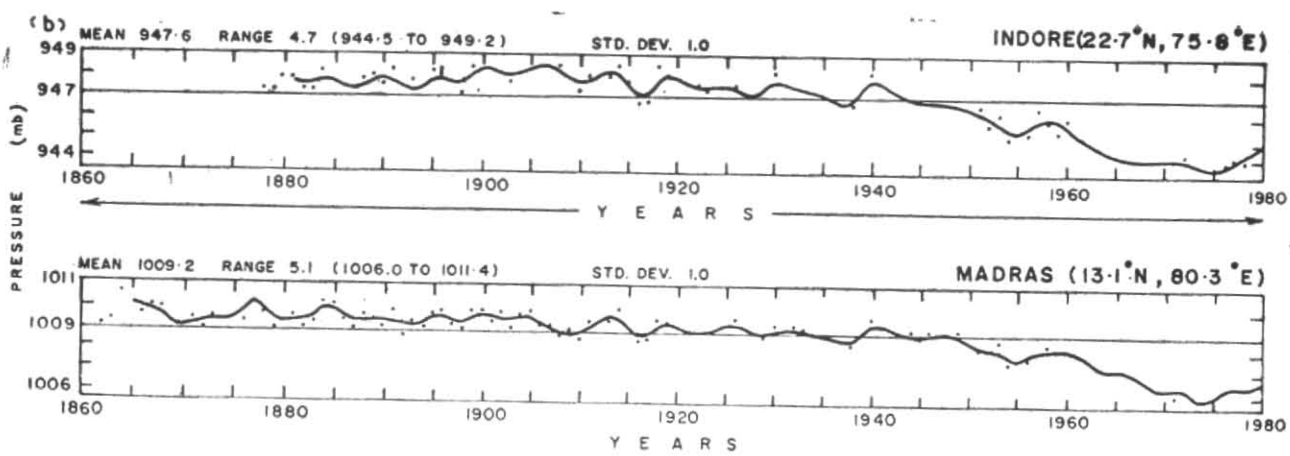

Fig. 9 (b). A long series of annual mean sea level pressure over two Indian stations

temperature. The mean annual temperature for the country, the smooth anomaly obtained by applying 9 point Gaussian filter and a fitted trend line are shown in Fig. 9(a). From the trend line it is seen that about 0.4°C warming has taken place during recent 8 decades. This trend changes from one season to the other : in post monsoon and winter seasons, it is 0.7°C whereas it is 0.4°C during pre-monsoon and slight negative —0.3°C during monsoon season.

In annual temperature significant trend at 95 per cent level has been found over nearly half of the 73 stations. About 41 per cent stations show warming trend, while 8 per cent stations show cooling trend. Significant cooling trends are noted over northwestern region of the country, whereas warming trends are noted in the central and eastern part of the country.

One interesting feature may be noted that Indian mean annual temperature does not show the post 1940 cooling which has been observed for the Northern Hemisphere. On the contrary, the Indian temperatures have shown steadily increasing trends over past 8 decades. It is difficult to interpret above result in terms of cause and effect. It may, however, be noted that during recent one century, considerable increase in the consumption of fossils fuel, deforestation and land use pattern have taken place in the country.

4.3. *Pressure variability*

Very little work on long term pressure changes over India has been reported in the literature. The mean sea level annual pressure over 25 observatories of India have been studied by Pramanik and Jagannathan (1955). On analysing 80 years data they have not found any systematic increasing or decreasing trend in the pressure data of these stations. They noted that year to year variation is rather random except for some cyclic tendency at a few stations. For nearly one century the variation of the annual pressure over two Indian stations Madras and Indore is shown in Fig. 9 (b). It is seen from the figure that the long period pressure data do not suggest any long term climatic change.

It can be concluded that in recent hundred years, the climatic fluctuations over India are generally random and do not show any consistent periodicity particularly in rainfall, temperature and pressure. In recent 8 decades the pressure and rainfall have not shown any systematic trend, however, the temperature has shown slight warming over India.

5. Causes for inducing climatic changes

Recent studies (*e.g.*, Hare 1979, 1985; Gates 1979) have shown that variability is a natural property of climate. In the past geological times, the climate variability was believed to be induced by the natural processes, (Hays *et al.* 1985), while in recent decades the man made causes like increasing carbon dioxide, deforestation and aerosol in the atmosphere are also contributing in the modification of the climate. The important natural cause for climatic change is the variation in the solar radiation arriving at the surface of the earth. The main factors responsible for the variation of insolation are the changes in orbital characteristics of the sun, the variable sun's out-put the volcanic dust, the continental drift etc. A few theories like astronomical (Milankovich), continental drift, volcanic dust etc have been put forward by various scientists for explaining the climatic change. Some of the theories have gained support to varying degrees. In 1930 Milankovich formulated the astronomical theory of climate change, wherein he showed that the dominant periodicities of the oscillations between ice-ages and inter glacials were in excellent agreement with the periodicities of the changes in the three parameters, *viz.*, eccentricity, tilt and precession describing the earth's orbit around the sun. The important changes in these quantities are : the eccentricity has a periodicity of 100,000 years and varies from 0.0001 to 0.054 (current value, 0.017), the tilt has a periodicity of 40000 years and varies from 22.0° to 24.5° (current value, 23.4°), whereas the precession index has periodicity of 23,000 years and varies from —6.9 to +3.7 per cent (the index being defined zero for 1950 A.D.). It is believed that considerable reduction in the incoming solar radiation due to these orbital variations are indeed the triggers of ice-ages. This theory has recently gained support from scientists as the excellent comparison between the earth's orbital variations and the climatic changes inferred from measurements of ratios of oxygen isotopes from deep ocean-core beds, has been found.

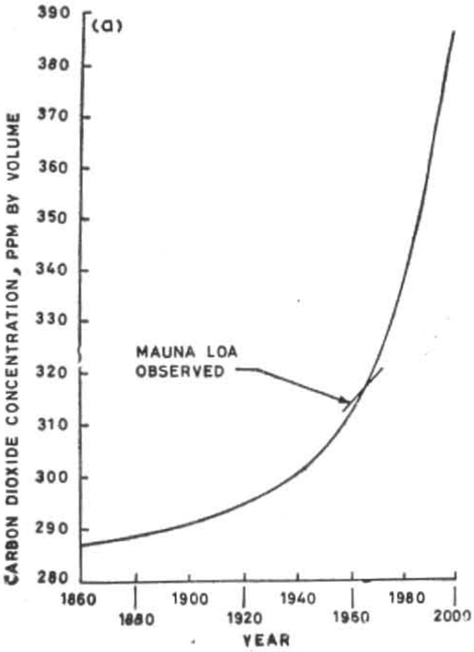

Fig. 10 (a). Changes in atmospheric carbon dioxide resulting from the combution of fossil fuels

(*After* Machta and Telegadas 1974)

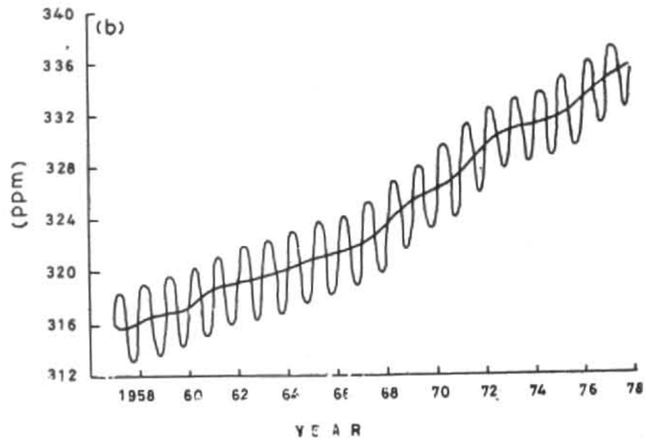

Fig. 10 (b). The carbon dioxide concentrations measurements as made near Mauna Loa in Hawaii. Seasonal fluctuations due to the large uptake of carbon dioxide in summer by plants in the northern hemisphere and oxidation of plant tissues in winter are seen superimposed on steady increase

(*After* Keeling *et al.* 1976)

Climatic changes over shorter time scales of a century or so are attributed to variations in the albedo and the concentrations of important constituents of the atmosphere. When the aerosol content of the atmosphere increases, particularly from volcanic eruptions, more solar radiation is reflected away and cooling of the earth is affected. Recent observations following the eruption of the El-Chichon volcano in 1982 have indicated that a cooling by almost 1° C occurred within days of the eruption. A large scale nuclear war is expected to inject millions of tonnes of particulate matter into the atmosphere and could cause sudden cooling leading to 'Nuclear Winter'.

Increased interest and research in the human activities and their effect on environment have created some evidence that people themselves have or will change the climate, inadvertently. There are three ways in which mankind affects climate (*i*) by changing the composition of the atmosphere, including the changes in the concentration of water, (*ii*) by releasing the heat into atmosphere, and (*iii*) by changing the physical and biological properties of the underlying surfaces. The steady increase in CO_2 (Neftel *et al.* 1985) and dust in the atmosphere are causing concern for effecting changes in the climate. The recent studies have, however, shown that the impact of increasing CO_2 on global climate is considerable and in due course of time, this activity of mankind may inadvertently change the global climate.

6. Climate impact of increasing atmospheric carbon dioxide

Due to burning of fossil fuels, the atmosphere CO_2 has increased from 300 ppm (part per million) in 1880 to 340 ppm in 1980 (Figs. 10a, b). The CO_2 abundance is expected to reach 600 ppm in the next century, even if growth of fossil fuel use is slow (Hansen *et al.* 1981). Carbon dioxide absorbs in the atmospheric 'window' from 7 to 14 micro-metres which transmits thermal radiation emitted by the earth's surface and lower atmosphere. Increased atmospheric CO_2 tends to close this window and causes outgoing radiation to emerge from higher colder levels, thus warming surface and lower atmosphere by so called 'Greenhouse' mechanism (Wang *et al.* 1976). A number of investigators have examined the CO_2 induced effects by one-dimensional (vertical direction only), two-dimensional and three-dimensional climate models. However, despite the range of complexities, the estimates of global warming from different models have been somewhat similar. The most sophisticated models sugget a mean warming of 2 to 3.5°C for doubling the CO_2 concentration from 300 to 600 ppm (Manabe and Stouffer 1980), which is a likely value to be attained by the middle of next century. Many investigators (*e.g.*, Hansen *et al.* 1981), however, feel that the full impact of CO_2 warming may be delayed by several decades due to oceanic processes which substantially control the climate. In addition, the identification of net CO_2 warming in observed climate also depends on the magnitude of climate variability due to other factors like ground albedo alteration, tropospheric aerosols, clouds, infra-red sensitive trace gases etc. By utilizing one-dimensional radiative-convective model (with fixed relative humidity limiting lapse rate 6.5° C/km and fixed cloud, temperature) the effects of various climatic variables mentioned above have been calculated by Hansen *et al.* (1981) and the results are shown in Fig. 11.

The general agreement between modelled and observed temperature trends strongly suggests that CO_2 and volcanic aerosols are responsible for much of the global temperature variation in the past century. The model projections indicate that CO_2 warming should emerge from the noise level of natural climate variability by the end of this century. This suggests a high probability of warming in the 1980s.

Projected global warming for fast energy growth of 3 (present being 4-5) per cent per year, is about 3.0 to 4.5°C at the end of the next century. However, other climate-forcings may counteract or reinforce the CO_2 warming at the end of next century and may be about 2.5°C. This would exceed the temperature during the previous inter-glacial period 125,000 years ago and would approach the warmth of the mesozoic (225 million years BP), *i.e.,* the period of dinosaurs.

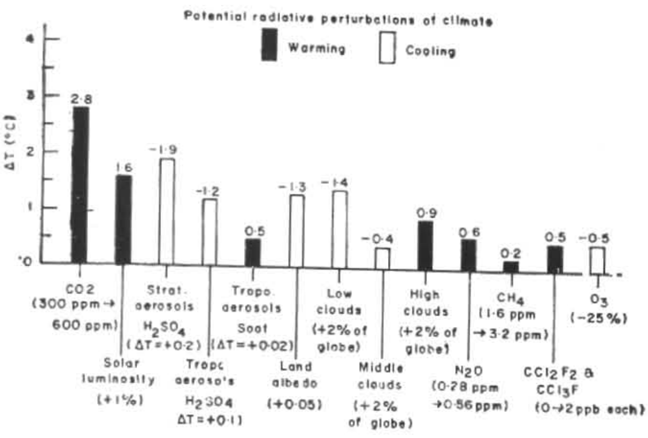

Fig. 11. Surface temperature effect of various global radiative perturbations, based on the 1-D R.C. model. The $\triangle T$ for stratospheric aerosols is representative of a very large volcanic eruption

(*After* Hansen *et al.* 1981)

7. Climate experiments with numerical models

Climate is the synthesis of weather over a period, long enough to establish its statistical characteristics (mean, variance, probabilities of extremes etc) and climate prediction is concerned with how the statistics will change in future. In early stages fairly simple one and two-dimensional models have been used to explore new formulation and parameterizations, but they fail to represent and reproduce many important features of the observed world's climate, especially those that are strongly influenced by regional, geographical and topographical features, such as, monsoons. Sophisticated three-dimensional General Circulation Models (GCMs) have been constructed, developed and tested by several groups like, Geophysical Fluid Dynamics Laboratory, Godard Institute of Space Science, National Centre for Atmospheric Research etc. These GCMs are based on the physical principles governing the changes in mass, momentum, energy and water substance, on the Newtonian (Navier-Stokes) equations of motion applied to a parcel of air, the laws of thermodynamics and the equation of a gas. These models have been used in a wide variety of climate investigations and their results, which have been analysed in considerable detail, appear to be as realistic as any that have been produced. One or two simplified oceanic GCMs, have been coupled to atmospheric GCMs. However, much has not been achieved so far.

7.1. *Simulation of present global climate*

The GCMs have successfully simulated the major features of global atmospheric circulation and of the present world climate, at least as far as average conditions are concerned. In particular, they have been successful in simulating :

(*i*) the presently observed global patterns of surface pressure, wind, temperature and rainfall and their seasonal changes;

(*ii*) the various components of the global heat, momentum and hydrological balances and the contributions made to these balances by various modes of transport;

(*iii*) the observed net surface fluxes of heat, momentum and moisture;

(*iv*) the seasonal shifts of circulation and rainfall including important regional changes like monsoons.

In seeking possible natural causes of major climatic fluctuations one may contemplate changes in the external forces or agencies acting on the atmosphere, internal changes within the atmosphere-ocean system itself and interactive combination of both. It is likely that global climate could be modified by changes in the incoming solar radiation, the atmospheric composition (*e.g.,* CO_2, dust, ozone, water vapour etc); the cloudiness, the albedo of earth's surface through changes in soil moisture, vegetation, ice and snow cover, and the oceanic circulation leading to changes in sea-surface temperature and the transport of heat and moisture.

7.2. *Simulation of past climate*

The GCM experiments (*e.g.,* Wetherald and Manabe 1975) indicate that a 2 per cent increase in the solar constant would produce a rise of 3° C in the mean global surface temperature, but a decrease of 2 per cent would produce an average temperature drop of 4.3° C. The induced changes are calculated to be much greater near the poles than at the equator because of marked changes in albedo and snow cover. Mason (1976) and Hays *et al.,* (1976) have shown that seasonal effects are much greater than annual. They have conducted simulation experiments for solar radiation greater than the present value by 4 per cent (a conditior existed 10,000 years B.P.) and 2 per cent (a condition existed 25,000 years B.P.), and have demonstrated that these variations in the incoming solar radiation coincided quite well with the major advances and recessions of the ice sheets in the Northern Hemisphere during the last half million years.

Manabe and Hahn (1977) have simulated atmospheric circulation in GFDL-11 layer model using present and ice-age (18,000 B.P.) boundary conditions. They found that total global rainfall was 10 per cent lower in the ice-age simulation; the reduction over land being 31 per cent but only one per cent over the ocean. The global average temperature fell by 5.4°C: the average drop over land being 7.7°C but only 4.4°C over oceans.

Manabe and Wetherald (1975) have demonstrated that doubling of CO_2 raises the temperature of the model troposphere and cools the stratosphere. The increase in the average global surface temperature is 3°C — with maximum of 10°C in polar regions caused partly by the retreat of the highly reflecting ice and snow surfaces and partly by the general thermal stability of the lower troposphere limiting convective heat transfer to the lowest layers. In the tropic this warming is spread throughout the entire troposphere by intense moist convection and so the temperature rise is smaller. Doubling the CO_2 also increases the intensity of the model's hydrological cycles, the average annual evaporation and precipitation both being increased by about 7 per cent.

A number of experiments with GCM have been performed by several scientists. However, more sophisticated coupled ocean-atmosphere GCMs are required to be developed for tackling the problem of climate prediction satisfactorily.

8. Climate predictability

Presently, no deterministic models are available for predicting climatic change. In the present state of GCMs, even the best model is not yet able to predict the change of the climate over the next year, decade or century. This is partly due to lack of model capacity to reproduce non-linear interactions among ocean and atmospheric processes. Prediction of climatic variations induced by changes in the external forcing factors like the incoming solar radiation, the slow changing boundary conditions of the climatic system or by man's activities assumes that these stimuli can be predicted accurately in advance. Thus, the prediction of future climatic changes pose a formidable scientific problem. In both future diagnostic and modelling research, the development of sophisticated coupled atmosphere-ocean models is a basic requirement for achieving capability to predict the changes in climate.

9. Concluding remarks

In recent hundred years the fluctuations in climate dominate in time and space; the amplitude of time fluctuations is much larger than any systematic trend in the behaviour of climate. Especially in high latitudes the year to year differences of temperature are striking. Analysis of data from both the hemispheres shows similar year to year fluctuations with no significant trend. During recent century the climatic fluctuations in India are generally random. While the pressure and rainfall show no trend, the temperature shows slight warming trend during recent 8 decades over India. However, if the present climate with its natural fluctuations continues it would still be necessary to prepare for the type of stress recently faced bythe mankind.

Though the variability of climate on all time scales has been proved, so has also been proved the atmosphere's ability to return to a state not very different from its long term condition. However, the fact of variability around this stable condition remains mainly reflecting the internal instabilities of the system. In addition, there have been external forcing mechanisms like change in earth's orbital parameters, continental drift etc, at work to increase this variability. In recent years, man's activity in changing the composition of the atmosphere has also added to the variability of the climate. Evidence is gathering that local and regional climates can be modified by man's activities. There is, however, no experimental evidence to demonstrate that global climate change has been affected by human activities, although modification may conceivably exist—remaining undetected because of the great natural variability of climate.

The experience of last few years, which have brought unusual year to year fluctuation of climate in many parts of the world including India seems to be sufficient to convince most people (and their governments) that even a temporary fluctuation of climate had profound impact on agricultural production and on use of energy and water resources. Like all other phenomena in nature, the climate and its changes are presumably governed by physical laws and discernment of those laws is the goal of modern climate research. Although the prediction of climate through GCM is a formidable problem, the present climate models with their usual approximations provide some guess about the future climate. The potential effects of model projected warming on climate in 21st century include the creation of drought-prone regions in North America and central Asia as part of shifting of climatic zones, erosion of the west Antarctic ice sheet with a consequent worldwide rise in sea level. Paleoclimatic evidence suggests that surface warming at high latitudes will be 2 to 5 times the global mean warming (*e.g.*, Lamb 1977). Climate models suggest that large regional climate variations will accompany global warming. A major regional change in doubled CO_2 experiment with three dimensional general circulation model, was the creation of hot, dry conditions in much of the western two thirds of the United States, and Canada and in large part of central Asia (*e.g.*, Manabe and Stouffer 1979). However, there are some beneficial effects of CO_2 warming also. The warming will include the increased length of the growing season and less consumption of heat energy in higher latitudes. It may, however, be mentioned that the magnitude of warming cannot be accurately predicted now, because it depends strongly on the climate processes, the energy growth rate, the choice of fuels for the next century, the variation of natural climate forces in future etc. It is hoped that a partial answer of this formidable problem may emerge after the sophisticated ocean-atmosphere general circulation models are developed.

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