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Some evidence of climate change in twentieth-century India

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Abstract The study of climate changes in India and search for robust evidences are issues of concern specially when it is known that poor people are very vulnerable to climate changes. Due to the vast size of India and its complex geography, climate in this part of the globe has large spatial and temporal variations. Important weather events affecting India are floods and droughts, monsoon depressions and cyclones, heat waves, cold waves, prolonged fog and snowfall. Results of this comprehensive study based on observed data and model reanalyzed fields indicate that in the last century, the atmospheric surface temperature in India has enhanced by about 1 and 1.1°C during winter and post-monsoon months respectively. Also decrease in the minimum temperature during summer monsoon and its increase during post-monsoon months have created a large difference of about 0.8°C in the seasonal temperature anomalies which may bring about seasonal asymmetry and hence changes in atmospheric circulation. Opposite phases of increase and decrease in the minimum temperatures in the southern and northern regions of India respectively have been noticed in the interannual variability. In north India, the minimum temperature shows sharp decrease of its magnitude between 1955 and 1972 and then sharp increase till date. But in south India, the minimum temperature has a steady increase. The sea surface temperatures (SST) of Arabian Sea and Bay of Bengal also show increasing trend. Observations indicate occurrence of more extreme temperature events in the east coast of India in the recent past. During summer monsoon months, there is a decreasing (increasing) trend in the frequency of depressions (low pressure areas). In the last century the frequency of occurrence of cyclonic storms shows increasing trend in the month of November. In addition there is increase in the number of severe cyclonic storms crossing Indian Coast. Analysis of rainfall

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amount during different seasons indicate decreasing tendency in the summer monsoon rainfall over Indian landmass and increasing trend in the rainfall during pre-monsoon and post-monsoon months.

1 Introduction

As per Köppen's classification (Oliver and Wilson 1987) India mainly experiences four types of climate. The climate of the whole of peninsula is Tropical Savana and that of the West Coast is basically Tropical Rain Forest. On the other hand, the climate of the northern part of India is Warm with Dry winds and that of western India is Dry Steppe. During the 4 months from June to September, the southwest summer monsoon is predominant and during October to December, the northeast winter monsoon controls the weather of the country in general. Due to the large extensions of India both along north-south and west-east, different parts of the country experience different ranges of temperature and rainfall even during the same month or season. The mountains in the country add to the wide variation in the climate of places located in the same latitudinal and longitudinal belts. The ecosystems in the coastal belts, the rich biodiversity in the mountainous regions, and the tropical rain forests form the life line of the climate of India. Farmers mostly depend on the performance of monsoon rain and the others living in rural tribal areas look for the forests and ecosystems for their daily needs. Thus the study of climate change in India and search for robust evidences are important issues of concern especially when it is acknowledged that poor people are very vulnerable to climate changes.

The most important weather events affecting India are heat waves, cold waves and fog, snowfall, floods and droughts, monsoon depressions and cyclones. Peoples' perception is in favour of changes in the frequency of occurrence of these weather phenomena. It is very essential to examine the observed data very carefully in order to categorize those as scientific evidences. In the recent past, studies have been conducted by several meteorologists (Srivastava et al. 1992; De 2001; Rupa Kumar et al. 2002; Dash and Rao 2003; Prakasa Rao et al. 2004; Kothawale and Rupa Kumar 2005) using the observed data as well as model results. Earlier, Paramanik and Jagannathan (1954) had analysed surface temperature data series over India. Based on these earlier studies, it may be inferred that the rise in annual mean temperature over India is comparable with the reported rise of global surface temperature by 0.6°C (Jones et al. 1999). Prakasa Rao et al. (2004) examined the effect of urbanization on the meteorological parameters at fifteen Indian cities and found that radiation values, bright sunshine hours, wind speeds and total cloud amounts have a decreasing tendency during the last 40–50 years whereas relative humidity and rainfall amounts show increasing tendency in some cities. It may be noted that increasing amounts of aerosols in the atmosphere can cut the amount of sun-light reaching the ground and hence lead to decrease in bright sunshine hours. Past results, in general, indicate warming during the post-monsoon (October–December) and winter (January–February) and no change in the temperatures during the monsoon season (June–September). Maximum temperatures show positive trends over most parts of the country whereas minimum temperatures show very little trend. It may be noted that there are some differences in the inferences obtained by different researchers because of variations in the length of data record and also regions of study. Considering the socio-economic importance of climate changes in India, which has diversities of climate and topography, it is essential to reexamine different aspects of climate change based on past recorded measurements and data obtained from integration of numerical models. In this study emphasis has been given on the notable spatial (across different regions) as well as temporal (across different seasons) changes in the last century and their possible influence on the atmospheric circulation patterns. Evidences of different phases of changes in climatic parameters at different regions and in different seasons may eventually be utilized to design numerical experiments to understand the underlying physical mechanism in the long run.

It is well known that Atmospheric General Circulation Models (AGCMs) are suitable tools which can be used to forecast the future states of the atmosphere, specially in the context of global warming. Before the AGCMs are actually used for generating future climate scenarios, those need to be verified based on the changes occurring in the spatial as well as temporal variations of some important weather parameters such as temperature and rainfall. Lal and Aggarwal (2000), Lal (2003) had analysed the skills of seven state-of-the-art coupled atmosphere–ocean global climate models in simulating the key characteristics of the Asian Summer Monsoon. Outputs from such models have inferred strong possibility of more intense monsoon rainfall events over the central Indian plains in future. In this study, we intend to examine the changes in the characteristics of temperature and rainfall over different regions of India during winter, pre-monsoon, monsoon and post-monsoon months using both recorded data series and model output. Also indications of heat waves, increase in summer and winter rainfall, trends in the occurrence of Low Pressure Areas (LOPARS), depressions and cyclones are some of the issues which are examined in this paper based on existing data.

Observed monthly maximum and minimum temperatures for the period 1901–2003 and rainfall for the period 1871–2002 used in this study are obtained from http://www.tropmet.res.in whereas monthly mean temperature values are obtained from http://www.ncdc.noaa.gov/oa/climate/online/doe/doe.html. In addition Reynold's Sea Surface Temperature (SST) values from National Climatic Data Centre (NCDC) for the period 1901–2003 are used. Further, data related to cyclonic disturbances and heat wave conditions are obtained from India Meteorological Department (IMD) archive.

Rise in temperature is the most important factor in support of the global warming. Section 2 in this paper deals with the indications of warming in different regions of India in different seasons. Summer monsoon rainfall is the lifeline for the Indian farmers. Section 3 discusses the indications of changes in the seasonal rainfall in India during the last century. Synoptic systems such as LOPARS, monsoon depressions and cyclonic storms determine the weather of several places in India, especially the coastal and peninsular India to a large extent. Section 4 elaborates on the changes in the frequency of occurrences of these cyclonic disturbances. Apart from the extreme weather events occurring in the atmosphere, there are also drastic changes observed in our environment, which include the forests, biodiversity, ecosystems, water bodies, land etc. All these components of the environment are region specific with characteristics widely different from place to place. Changes observed in all such environmental factors may or may not contribute significantly to the changes in the important weather parameters such as temperature and rainfall. Similarly, changes in all these environmental elements might not have occurred due to global warming. Nevertheless, as per IPCC (2001) large scale deforestation and changes in land-use patterns and their direct and indirect impacts on climate have been the focus of several field campaigns and modeling studies. Relationships between human activities and environmental changes can be obtained after careful examination which in turn will benefit all concerned with the prediction and mitigation of climate changes. This paper does not go into the details of these environmental issues visa-vis climate changes. However, for the sake of completeness, Section 5 summarizes the changes in the environment observed in India during the past several years.

2 Indications of warming

Figure 1a–c show the annual temperature anomalies in the mean, maximum, and minimum temperatures averaged over India during the last century. The anomalies in each category of temperature (such as mean, maximum and minimum) have been calculated first by taking the average of 388 available station observations (http://www.tropmet.res.in) over India

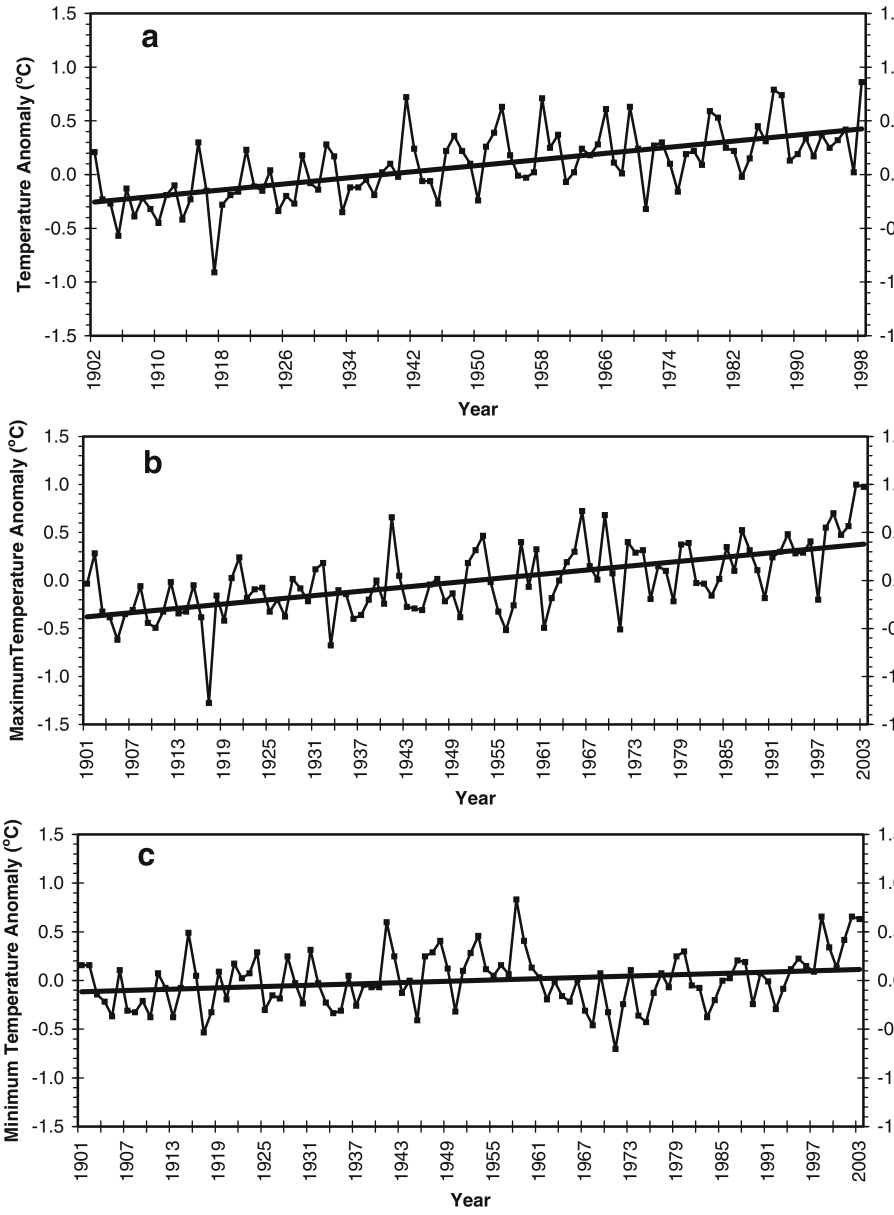


Fig. 1 Time series of annual temperature anomalies (°C) over India **a** average **b** maximum **c** minimum

spreading over all the 102 years of study and then deducting the 102 years mean values from the mean value of each year. The trend lines indicate that the annual mean temperature over India has increased by about 0.7°C (Fig. 1a) and the maximum temperature has increased by about 0.8°C (Fig. 1b). On the other hand the annual minimum temperature over India does not show any appreciable (Fig. 1c) enhancement.

In order to examine the temperature trend over India during different seasons, in this study, the entire year has been divided into four seasons namely, winter (January and February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to December). The time series of mean, maximum and minimum temperatures over India during these four seasons in the last century are shown in Fig. 2a–f. Figure 2a shows that in the last century, the winter-time increase in the mean temperature over India is about 1.0°C whereas during pre-monsoon months there has been a rise of about 0.3°C. During monsoon an increase of mean temperature by about 0.4°C has been observed, whereas during post-monsoon months, the temperature enhancement is maximum at 1.1°C. It may be noted that the temperature rise is highest in post-monsoon months followed by winter. Also, during winter and post-monsoon months the temperature enhancement is more than double of that in pre-monsoon and monsoon months. Such large difference in the temperature rise between the two halves of the year may lead to changes in spatial position of heating sources over the Indian region and adjoining area and hence in the atmospheric circulation patterns. Figure 2c shows an increase of 1.0 and 0.6°C in the maximum temperature during winter and pre-monsoon months respectively. Similar increase during monsoon and post-monsoon are about 0.4 and 1.1°C respectively. On the other hand, the minimum temperatures during winter and pre-monsoon months have negligible changes (Fig. 2e) in the last century. Figure 2f shows decrease in the minimum temperature during summer monsoon months by about 0.2°C and increase of about 0.6°C during post-monsoon months of October to December.

The impact of climate change may differ from one region to the other, specially for a geographically complex country like India. Hence, India has been divided into seven zones as shown in Fig. 3 in order to examine the changes in maximum and minimum temperatures over these regions. The seven zones are north-west, western Himalaya, north central, north-east, interior peninsula, east coast and west coast. Figure 4a and b indicate that the maximum temperature has been increasing during the last century over all the regions of India. However, the increase in magnitude is not the same everywhere. West coast shows maximum increase in the maximum temperature by about 1.2°C. Next to the west coast, maximum temperature has increased by 1°C in the north-east, 0.9°C in the western Himalaya, 0.8°C in the north central, 0.6°C in the north-west, 0.6°C in the east coast and by the least amount of 0.5°C in the interior peninsula. Similarly, Fig. 4c and d show the changes in the minimum temperature over the seven regions of India in the last century. Unlike the maximum temperature, the minimum temperature in the four northern regions of India show some peculiar changes. Figure 4c shows that there is sharp decrease in the minimum temperature by 1.9°C in the western Himalaya, 1.4°C in the north-east, 1.1°C in the north central and 0.7°C in the north-west India during 1955–1972 and then equally sharp rise over the past three to four decades. The minimum temperatures in southern regions such as interior peninsula, east coast and west coast show almost equal enhancement (Fig. 4d) during the last century. Trend lines indicate that interior peninsula shows maximum increase in the minimum temperature by about 0.5°C. Next to the interior peninsula, minimum temperature increased by 0.4°C in the east coast and by the least amount of 0.2°C in the west coast of India. Comparison of Fig. 4c and d indicates that the change in minimum temperatures in the northern and southern regions of India are almost

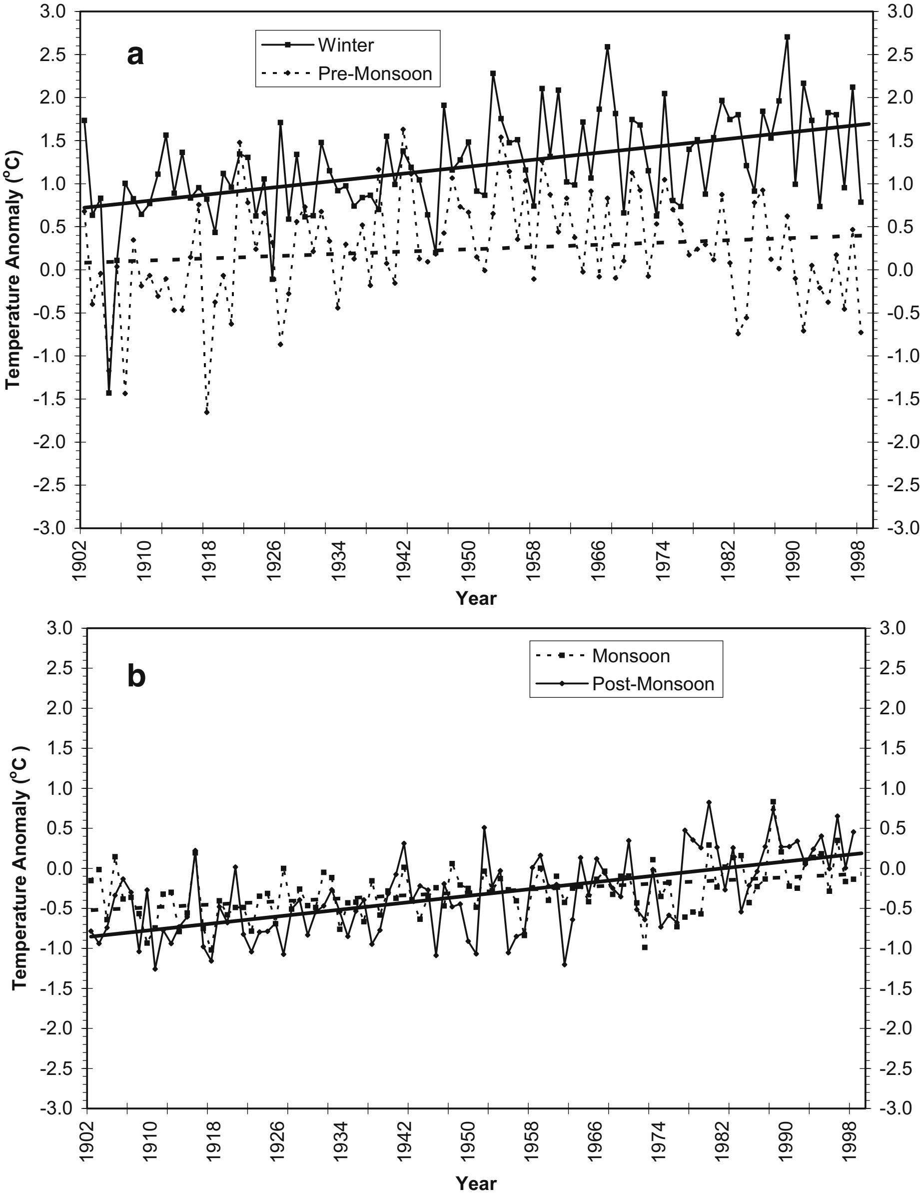
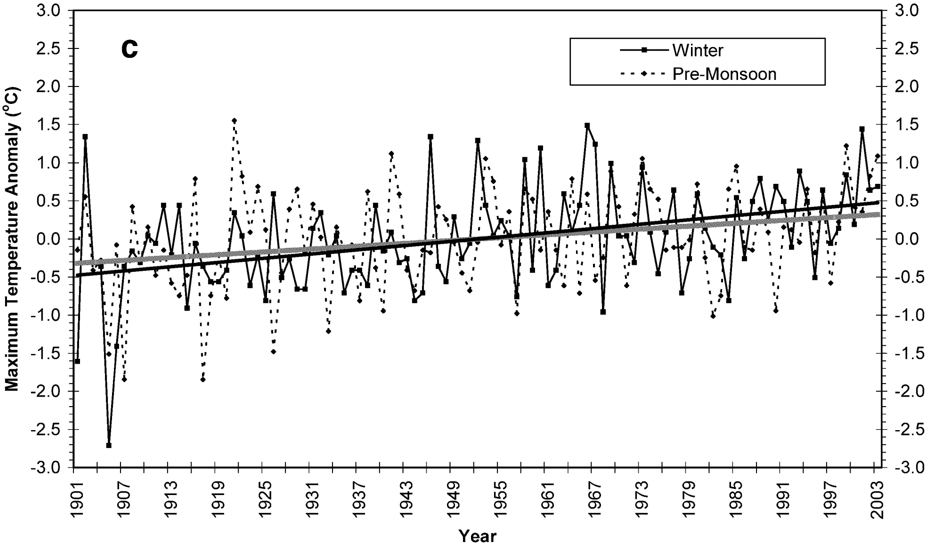


Fig. 2 **a** and **b**: Time series of anomalies in the mean temperatures during **a** winter and pre-monsoon and **b** monsoon and post-monsoon months. **c** and **d** same as **a** and **b** except for maximum temperature. **e** and **f** same as **a** and **b** except for minimum temperature

in opposite phases although the magnitudes of fluctuation in the northern India are large during last four to five decades.

Since the east and west coasts of India showed rise in temperature during the last century, it is logical to examine the SST of the Arabian Sea (AS) and the Bay of Bengal (BoB). Reynold's SST anomalies over the northern (16–24°N and 63.8–73.1°E) and



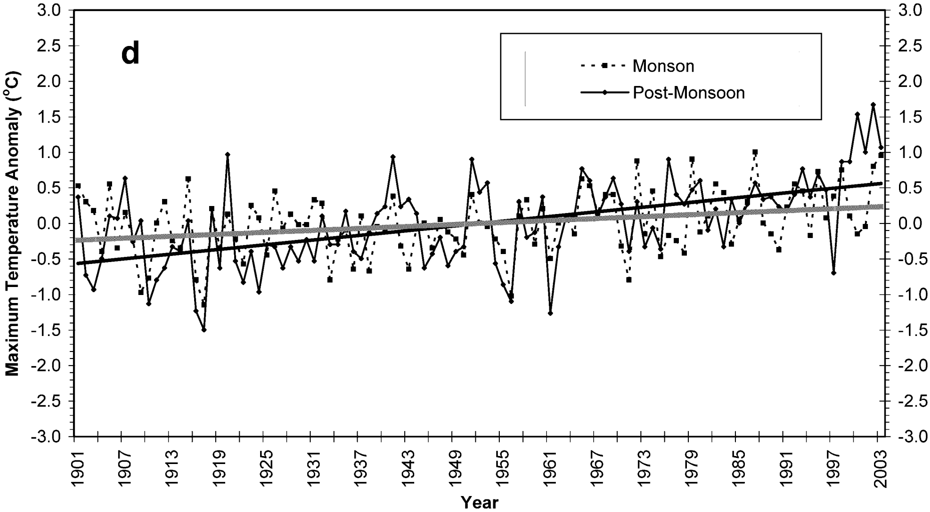
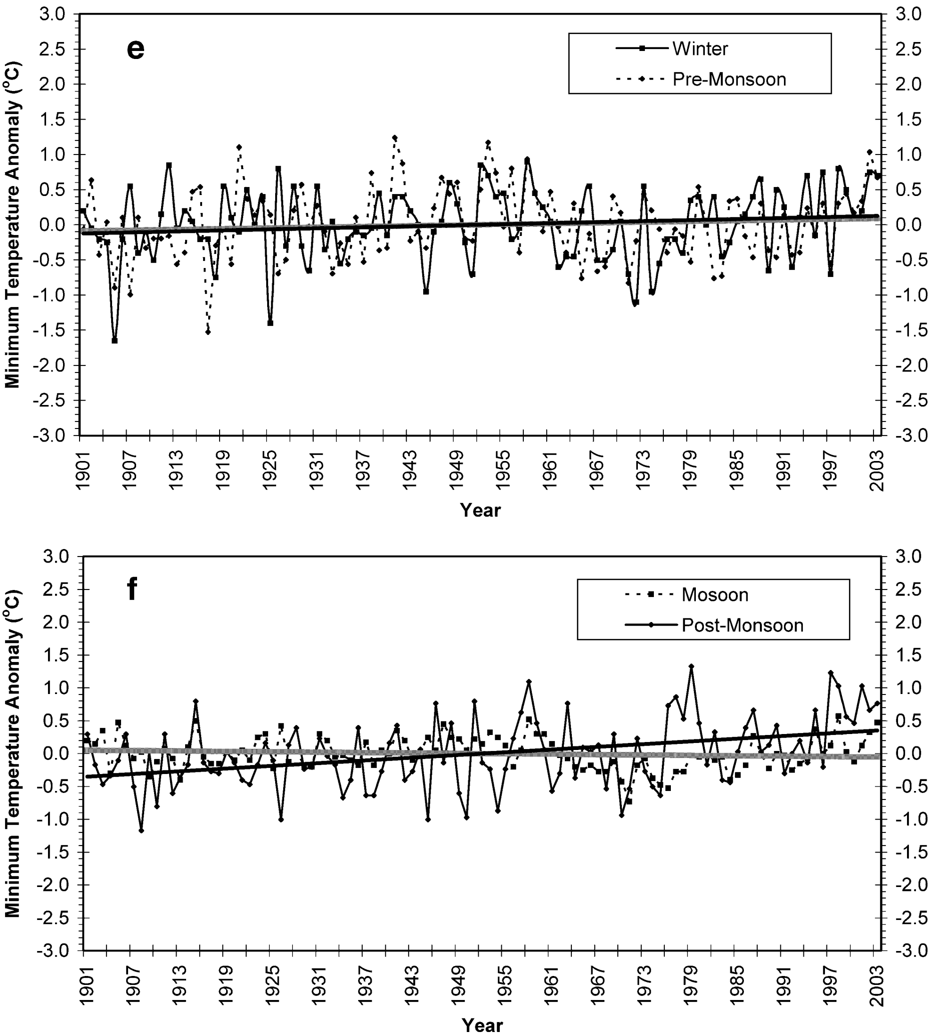


Fig. 2 (continued)

southern (7–16°N and 63.8–75°E) AS and northern (14–21°N and 84.4–91.9°E) and southern (7–14°N and 78.8–90°E) BoB have been depicted in Fig. 5a and b respectively. Figure 5a shows that during the last 100 years, northern and southern sectors of the AS have experienced rise in SST by 0.9 and 1.0°C respectively. Similarly, Fig. 5b depicts rise of SST over northern and southern sectors of BoB by 0.8 and 1.0°C respectively. The rise in SSTs of AS and BoB is in line with the global SST enhancement as studied in detail by Webster et al. (2005). The rise in temperatures of the southern India and those of AS and BoB are of the same order of magnitude. However, the large fluctuations in the minimum temperatures of the regions in the north India need further study in the context of the role of the land-use pattern changes occurring in the Himalayan range and the heat exchanges in the numerous slopes of the Himalayas.



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From the global warming point of view, only the temperature trends may not indicate the severity of climate change. People are usually concerned with the excesses in heating and cooling. It is also essential to examine such extreme heating/cooling events. In 1998, during the period 18 May to 6 June heat wave to severe heat wave conditions prevailed over Orissa. After 5 years, in 2003, similar heat wave conditions were observed during 16 May to 11 June in neighboring Andhra Pradesh. Based on the maximum temperature observed by IMD at different observatories all over the country, it is found that during the heat wave conditions in 2003, the highest maximum temperature in the country was confined to seven stations in the Andhra Pradesh and Orissa (Fig. 6). During this heat wave period of 23 days, the highest maximum temperature varied between 45 and 50°C. As shown in Fig. 7, the maximum temperature at stations Ongole, Hanamkonda, Machillipatnam and Gannavaram were 47, 48, 48.2 and 49°C respectively against their respective climatological highest

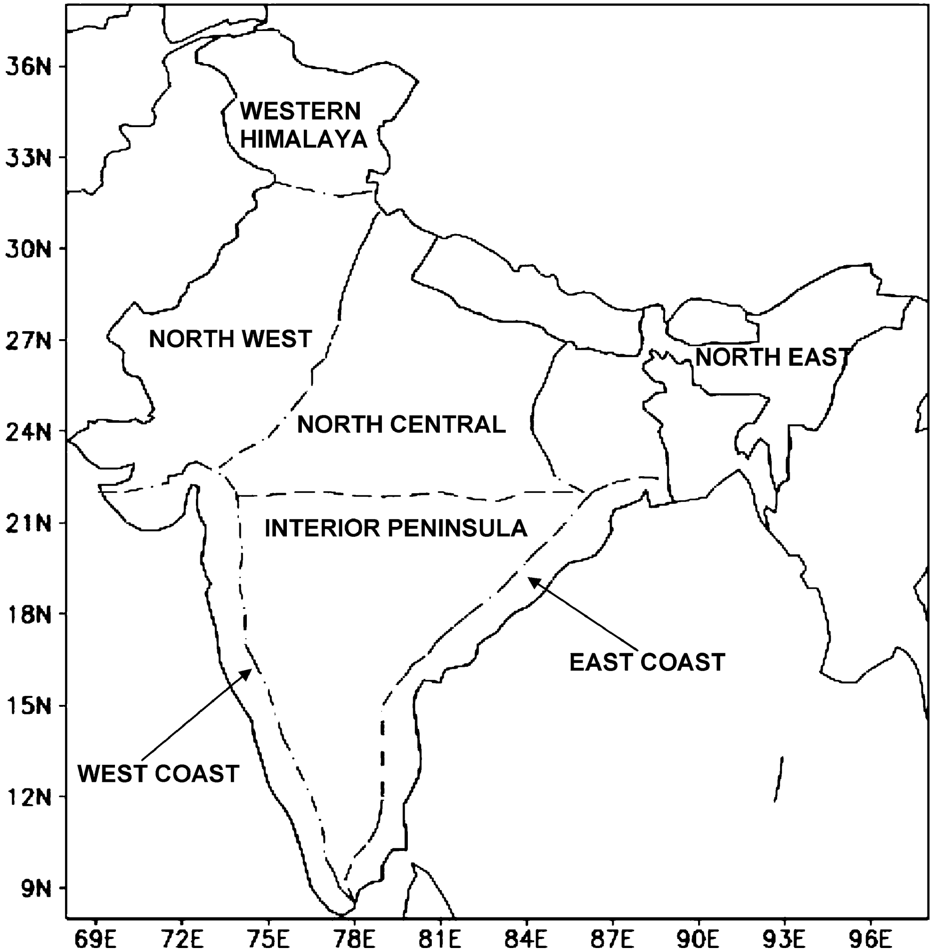


Fig. 3 Map for seven homogeneous regions of India (source IITM) used for examining temperature trends

values 46.7, 46.7, 47.8 and 48°C in the last 100 years. In May–June 2003, about 2,033 people lost their lives in Andhra Pradesh due to such extreme temperature conditions there. Figure 8 shows another instance of extreme temperature occurrences at some stations in Orissa in 1998, where about 1,024 people lost their lives. While citing such extreme events, it is important to note that in the time scale of climate, such events may reflect the annual fluctuations only. However, unusually large magnitudes of fluctuation and their persistence for a long time can not be ignored altogether. Even if such events are considered as isolate, one should be alarmed so as to adapt appropriate strategies and mitigation policies, if any, for the minimization of loss of natural resources and life.

3 Seasonal rainfall

Figure 9a–c depict the time series of Indian rainfall during the four seasons mentioned in Section 2. Figure 9a shows that during pre-monsoon and post-monsoon months there is

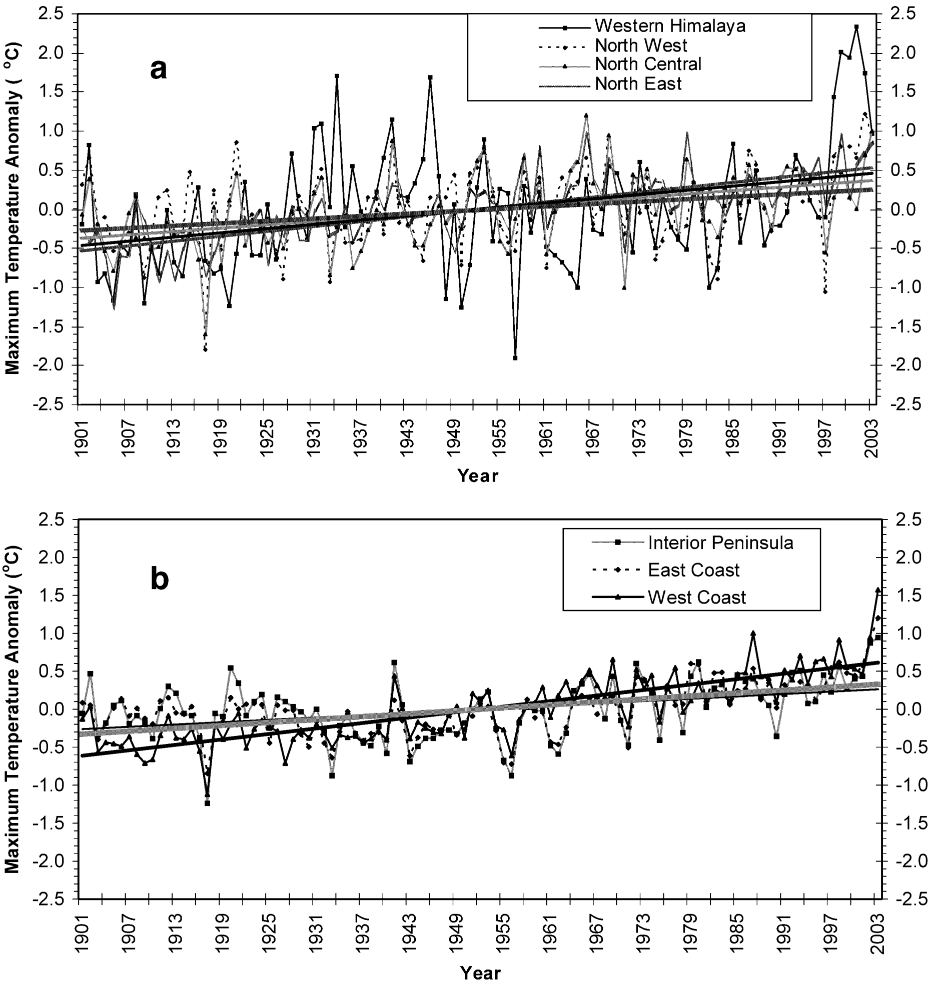
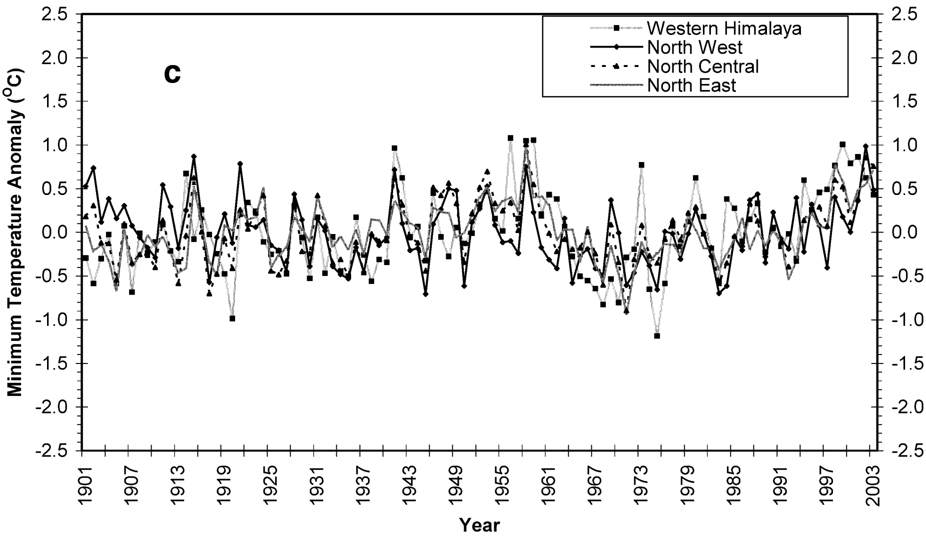
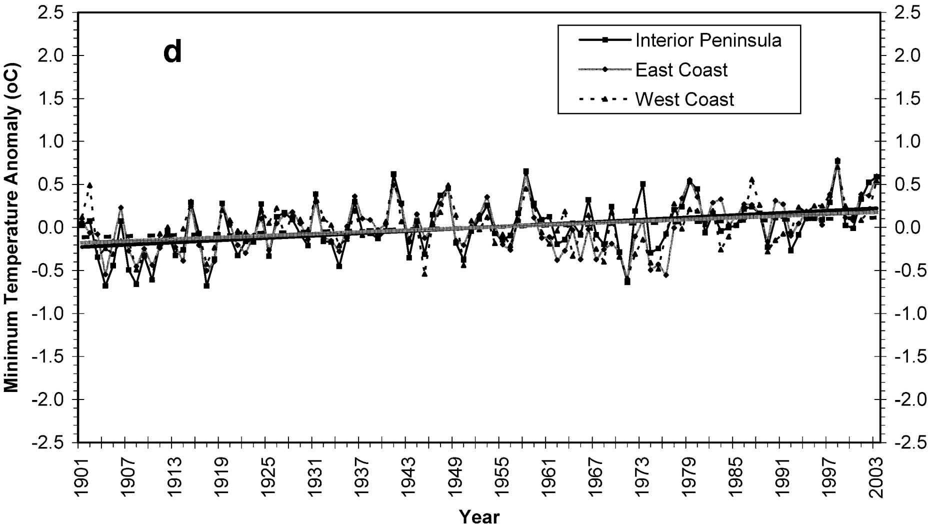


Fig. 4 **a** and **b**: Time series of anomalies in the maximum temperatures over **a** western Himalaya, north-west India, north-central India and north-east India, **b** Interior peninsula, east coast India and west coast India. **c** and **d**: Time series of anomalies in the minimum temperatures over **c** western Himalaya, north-west India, north-central India and north-east India, **d** Interior peninsula, east coast India and west coast India

increasing tendency in rainfall although the magnitudes (0.4 and 1 cm respectively) are small. Figure 9b indicates that the rainfall in winter months has remained more or less constant in the last century. Figure 9c shows that Indian Summer Monsoon Rainfall (ISMR) has decreased by about 1.6 cm during 1871–2002 in addition to the fact that there is about 30-year time scale in fluctuation. The decrease in ISMR is about 2% of its long term average value of 86 cm whereas the increase in rainfall in pre-monsoon and post-monsoon months are 4.3 and 8.3% of their long term average values of 9.2 and 12 cm respectively. These percentages hint at changes in seasonal rainfall amounts.

ISMR data (http://www.tropmet.res.in) for 29 meteorological subdivisions (out of a total of 35 in India) are available to us for analysis. In order to save space, the trends in ISMR in all the meteorological sub-divisions are not shown in this paper. Figure 10 shows selected





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three subdivisions with maximum decreasing trends (Fig. 10a–c) and three subdivisions with maximum increasing trends (Fig. 10d–f) in terms of magnitudes. Figure 10a–c show that in the last century, there has been maximum decrease in summer monsoon rainfall to the extent of 16 cm in South Assam followed by 15 cm in East Madhya Pradesh and 6 cm in Orissa. On the other hand Fig. 10d–f indicate that maximum increase in summer monsoon rainfall is equal to 30 cm in coastal Karnataka followed by 25 cm in Konkan and Goa and 12 cm in Punjab. Ten meteorological sub-divisions namely South Assam, East Madhya Pradesh, Orissa, Vidarbha, Kerala, Gujarat, West Uttar Pradesh, Saurashtra, Bihar Plain and Marathwada show decreasing trend, while increasing trend is observed in twelve sub-divisions such as Coastal Karnataka, Kankan & Goa, Punjab, Telengana, Gangetic West Bengal, Haryana, Coastal Andhra Pradesh, Rayalaseema, North Interior Karnataka,

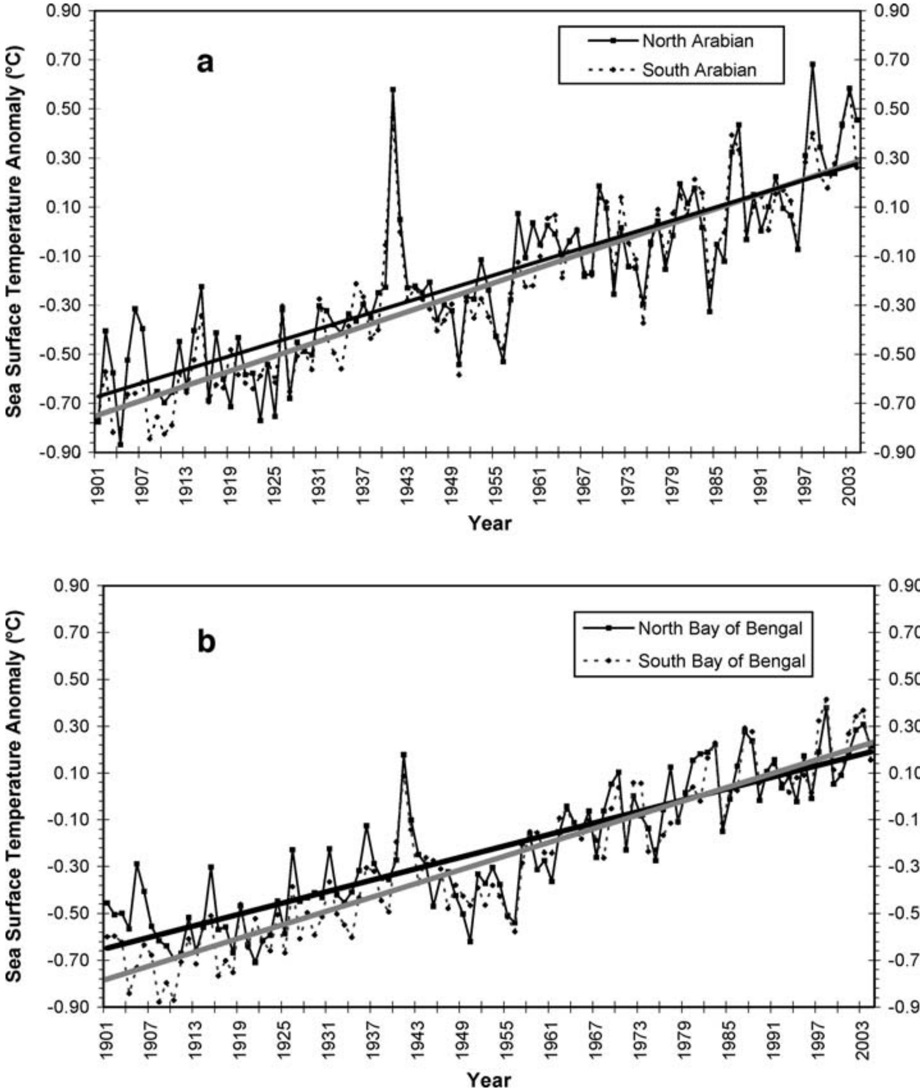

Fig. 5 Time series of Sea Surface Temperature (°C) over **a** Arabian Sea and **b** Bay of Bengal

West Rajasthan, South Interior Karnataka and Sub-Himalayan West Bengal. Seven sub-divisions such as Tamil Nadu, Madhya Maharashtra, West Madhya Pradesh, East Rajasthan, Bihar Plateau, East Uttar Pradesh and North Assam do not show any trend in ISMR. Rainfall data of six meteorological sub-divisions such as Jammu and Kashmir, Uttaranchal, Lakshadweep, Himachal Pradesh, Andaman and Nicobar Islands and Arunachal Pradesh are not analysed here.

As per the practice in IMD, heavy rainfall events are those when there is greater than or equal to 7 cm of rainfall in 24 h. Frequency of such events during summer monsoon shows increasing trend over certain parts of the country namely Andaman and Nicobar Islands, Lakshdweep, west coast and some pockets in central and north-west India, while most of

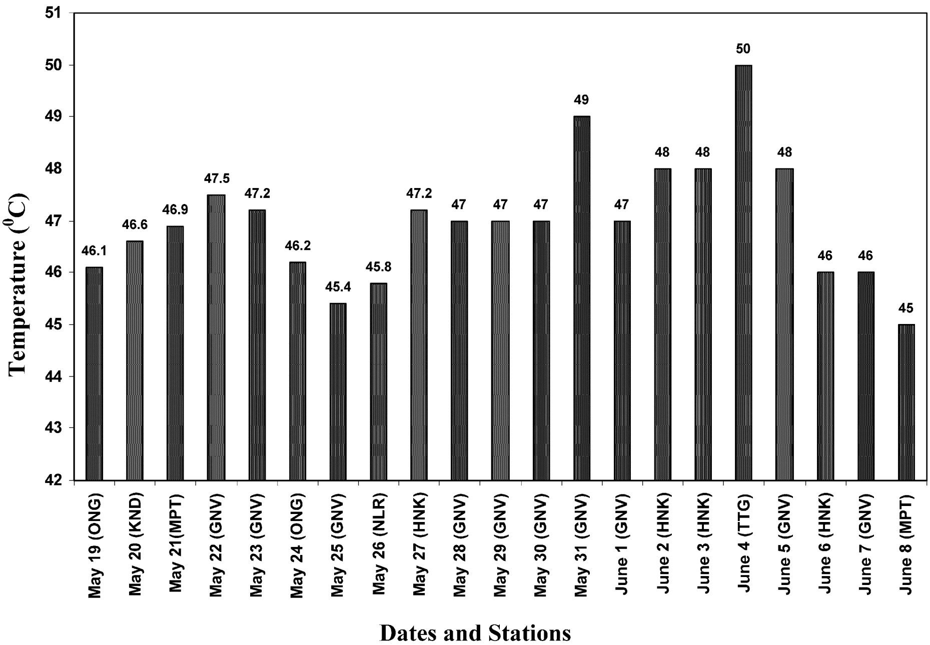

Fig. 6 Highest maximum temperature recorded at some stations of Andhra Pradesh and Orissa during heat wave (May 19–June 10, 2003). Stations considered are Ongole – (*ONG*), Kakinada – (*KND*), Machillipatanam (*MPT*), Gannavaram – (*GNV*), Nellore – (*NLR*), Titlagarh – (*TTG*), Hanamkonda – (*HNK*)

other areas have decreasing trend. However, decreasing trends in heavy rainfall incidents in winter, pre-monsoon and post-monsoon season are noticed over most parts of the country. Decreasing trend of drought has also been noted in affected areas such as northwest India, parts of central peninsula and southern parts of Indian peninsula. Figure 11 shows the percentage of the total area of India affected by drought from 1877 to 2002 where the solid

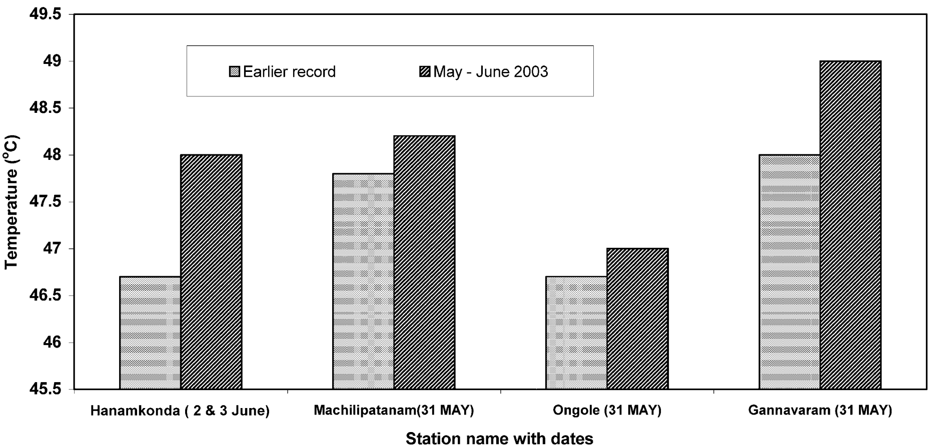

Fig. 7 Highest maximum temperature recorded at some stations during heat wave of Andhra Pradesh in May and June 2003 and the earlier recorded highest maximum temperature

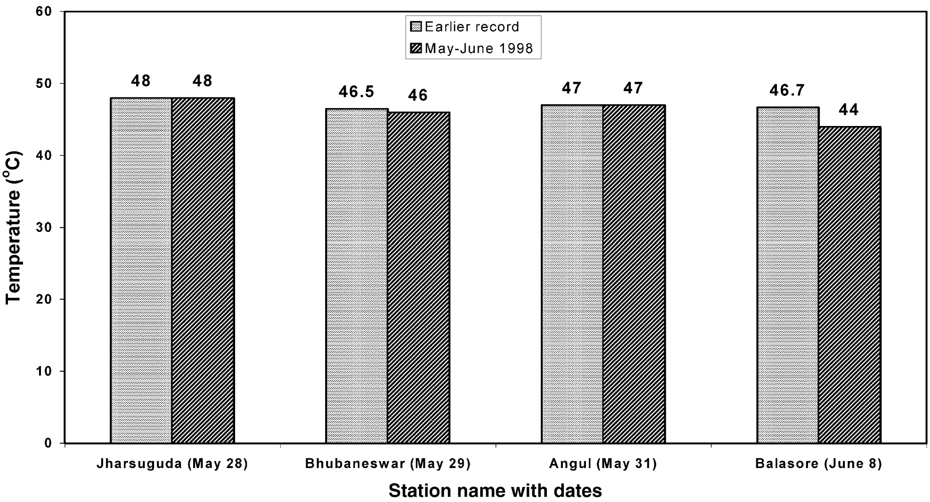

Fig. 8 Highest maximum temperature recorded at some stations during heat wave of Orissa in May and June 1998 and the earlier recorded highest maximum temperature

line indicates a decreasing trend in the area affected by drought. It may be mentioned that as practiced in IMD, when the rainfall is 26–50% below normal it is called moderate meteorological drought. Similarly, when the rainfall is less than or equal to 50% below normal it is termed as severe meteorological drought. In Fig. 11 the total percentage of geographical area of the country affected by both moderate and severe drought conditions are considered (Mooley and Pant 1981).

4 Monsoon depressions and cyclones

Monsoon depressions are important synoptic scale disturbances, which are formed on the mean flow of the Indian summer monsoon by drawing energy from the latter. As per the definition of IMD, in case of depressions, the pressure gradient between the centre and a distance of 250 km from it ranges between 5 and 13 hPa and the surface winds in cyclonic circulations are between 8.5 and 16.5 m/s. Weaker systems with only one closed isobar and with surface wind speeds less than 8.5 m/s are called LOPARS. Cyclonic storms are more intense than depressions with surface wind speeds stronger than 16.5 m/s. Amongst all the monsoonal weather systems, monsoon depressions are recognized as the main rainfall producing synoptic systems over India. Intra-seasonal and inter-annual variations of monsoon depressions and their effect on intra-seasonal and inter-annual variations of ISMR have been discussed by many authors (e.g. Jenamani and Dash 1999). In addition to the inter-annual variation, ISMR exhibits strong interdecadal variations. Characteristics of the monsoon disturbances and their relationship with ISMR in longer time scales such as decadal to 30 years have also been examined. These studies show the existence of dominant interdecadal shifts in the characteristics of monsoon disturbances and their relationship with ISMR (Jenamani and Dash 2001; Dash et al. 2004).

Bhaskar Rao et al. (2001) using the monthly frequency of all the observed cyclonic systems found two significant trends i.e. an increasing trend till the middle of last century followed by a decreasing trend. The frequency of monsoonal cyclonic disturbances above

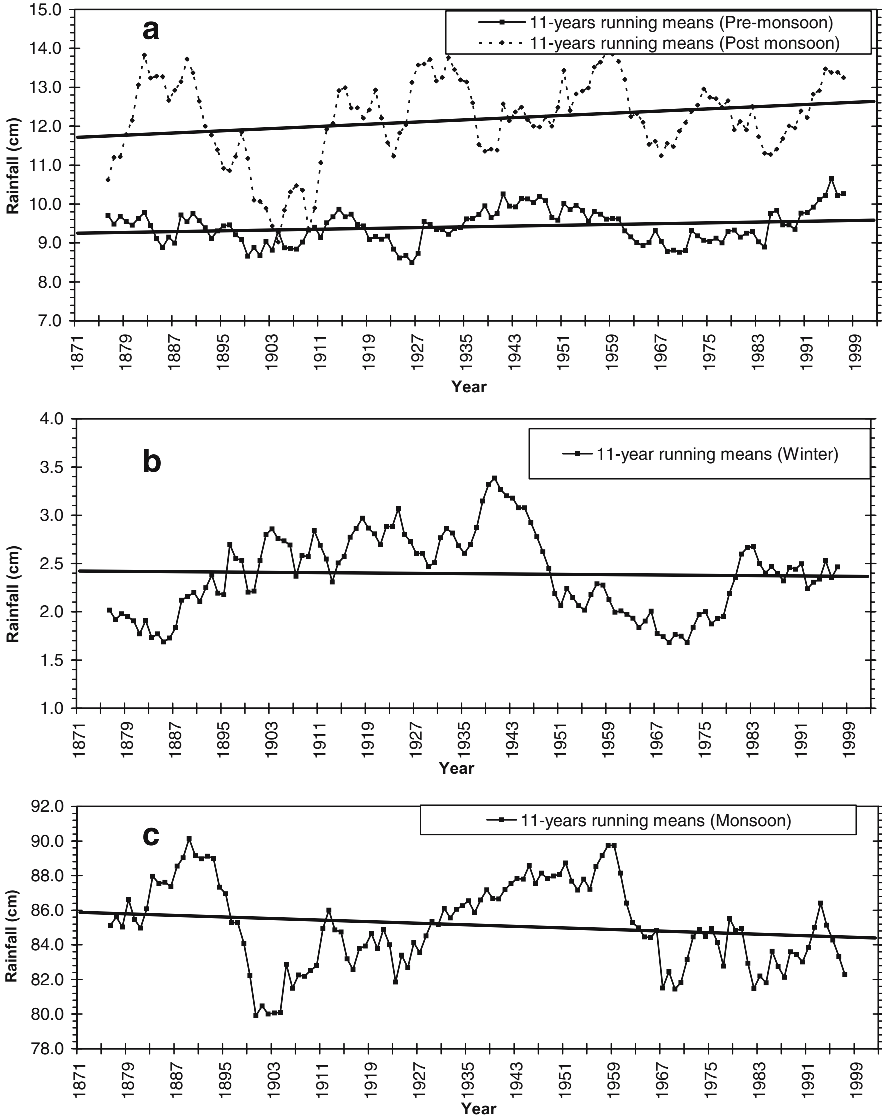

Fig. 9 Time series of rainfall in India during **a** pre-monsoon months of March, April and May and post-monsoon months of October, November and December **b** winter months of January and February **c** monsoon months of June, July, August and September

the intensity of depressions show decadal oscillations with their number fluctuating from as low as 35 for the decade 1981–1990 to as high as 62 during 1971–1980 and 1921–1930. The frequency of monsoonal cyclonic disturbances in the north Indian Ocean has shown a significant decreasing trend during the twentieth century, registering about 50% reduction from beginning to the end of the century. The decreasing trend is more pronounced during recent decades. The maximum number of 72 monsoonal cyclonic disturbances occurred during the decade 1939–1948. This number fell to 25 during the 1990s. Thus the frequency of all types of monsoonal cyclonic disturbances has decreased at the rate of about seven to

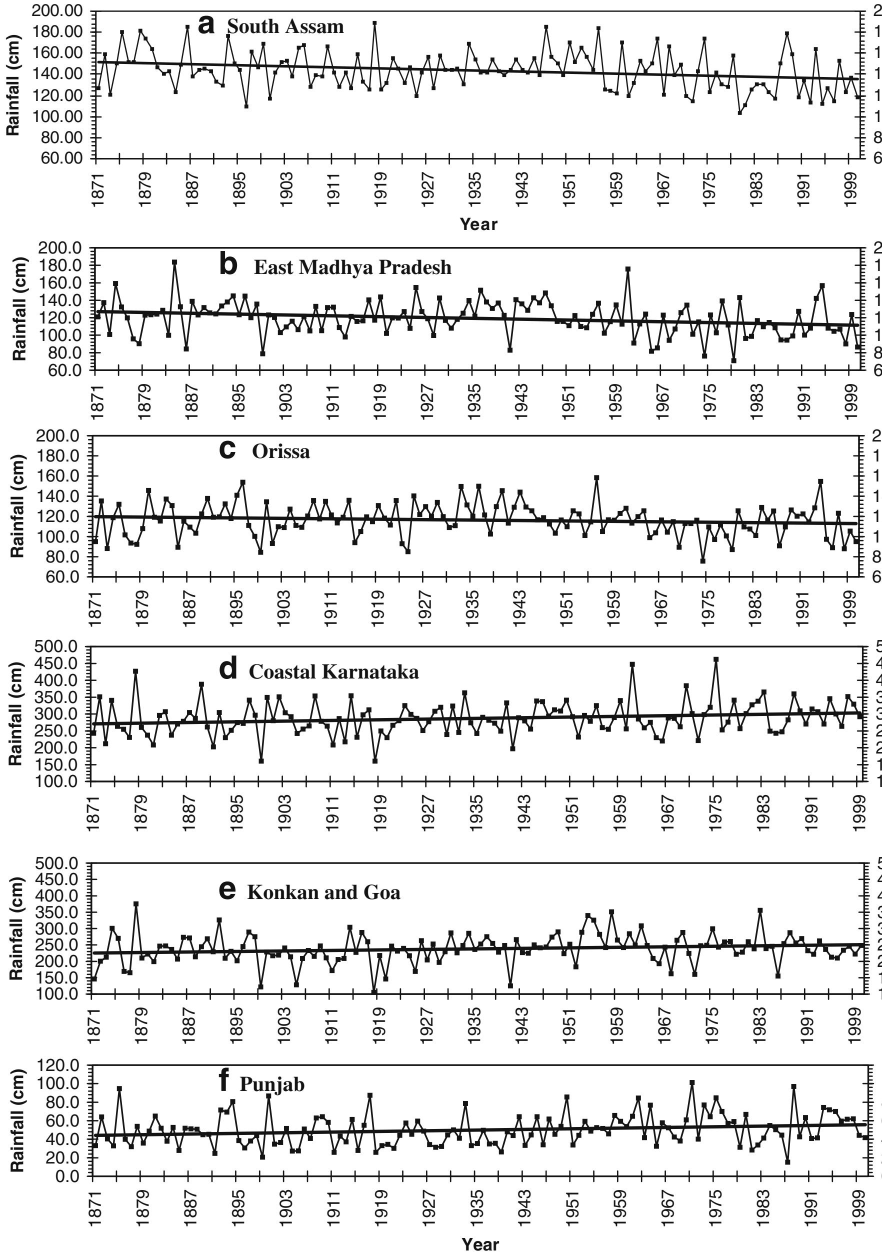

Fig. 10 Time series of summer monsoon rainfall showing significant changes over six meteorological subdivisions of India. Selected three subdivisions with maximum decreasing trends (**a**–**c**) and three subdivisions with maximum increasing trends (**d**–**f**)

eight disturbances per decade. The frequency of cyclonic storms of the monsoon season has decreased at the rate of about two cyclones per decade in hundred years. It is interesting to note that the decrease in the monsoonal cyclonic disturbances is maximum during the last four decades. Also the rate of decrease in the cyclonic activity over the BoB is more

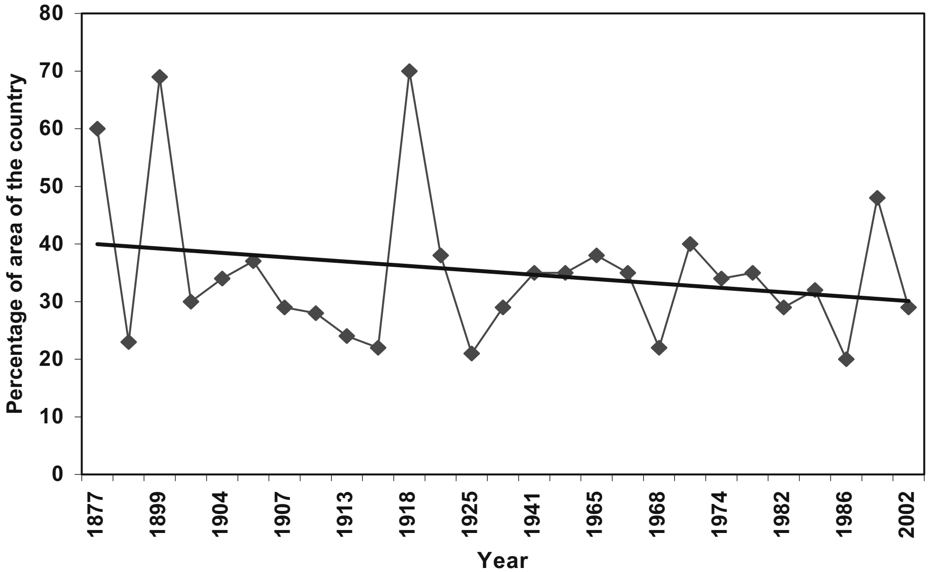

Fig. 11 Percentage of area of the country under moderate and severe drought for the period 1877–2002

compared to that over the AS. Srinivasa Rao et al. (2004) based on reanalyzed data of NCEP/NCAR have concluded that a decrease of the strength of Tropical Easterly Jet (TEJ) leads to a decrease of the number of tropical cyclones over BoB.

Figure 12a shows the total number of annual monsoonal cyclonic disturbances with the minimum intensity of monsoon depressions over the Indian region during 1889–2003. In general, there is a decreasing trend in the total number of depressions, cyclonic storms and systems with higher intensities specifically, the decrease since 1970s is well marked. On the other hand, Fig. 12b shows marked increase in the number of LOPARS. Since the number of LOPARS show increasing tendency whereas that of depressions and cyclonic storms indicate decreasing trend, it has been inferred (Dash et al. 2004) that the dynamical conditions of the atmosphere such as horizontal and vertical wind shears, mean sea level pressure and moisture are not favourable for the intensification of lows into depressions and cyclonic storms. Decadal frequencies of depressions and cyclonic storms have decreasing trend since 1970s. Such decreasing trend in the frequency of occurrence of monsoon depressions over Indian region has been so dominant in recent years that their average seasonal frequency has come down to 2 or 3 in the most recent decade of 1993–2002 from its long period average value of 7 to 8. It may be noted that for the first time in the last 115 years of data available with IMD, not a single depression or cyclonic storm formed over the Indian region including the BoB and AS during the monsoon season of 2002.

Except the high monsoonal cyclogenesis which favours formation of systems up to depression intensity, flow pattern over Indian region during May, October and November are very much favourable for intense cyclone formation (Ramage 1971). Figure 13 shows the significant increasing trend in the frequency of disturbances with the intensity of monsoon depressions and stronger formed in the post-monsoon month of November in contrast to very small decreasing trend in the other post-monsoon month October and no trend found in the pre-monsoon month of May. However, during the last two decades or so, their frequency has increased in May in contrast to decrease in other 2 months. Similarly, Fig. 14 shows the frequency of disturbances with minimum intensity of that of cyclonic

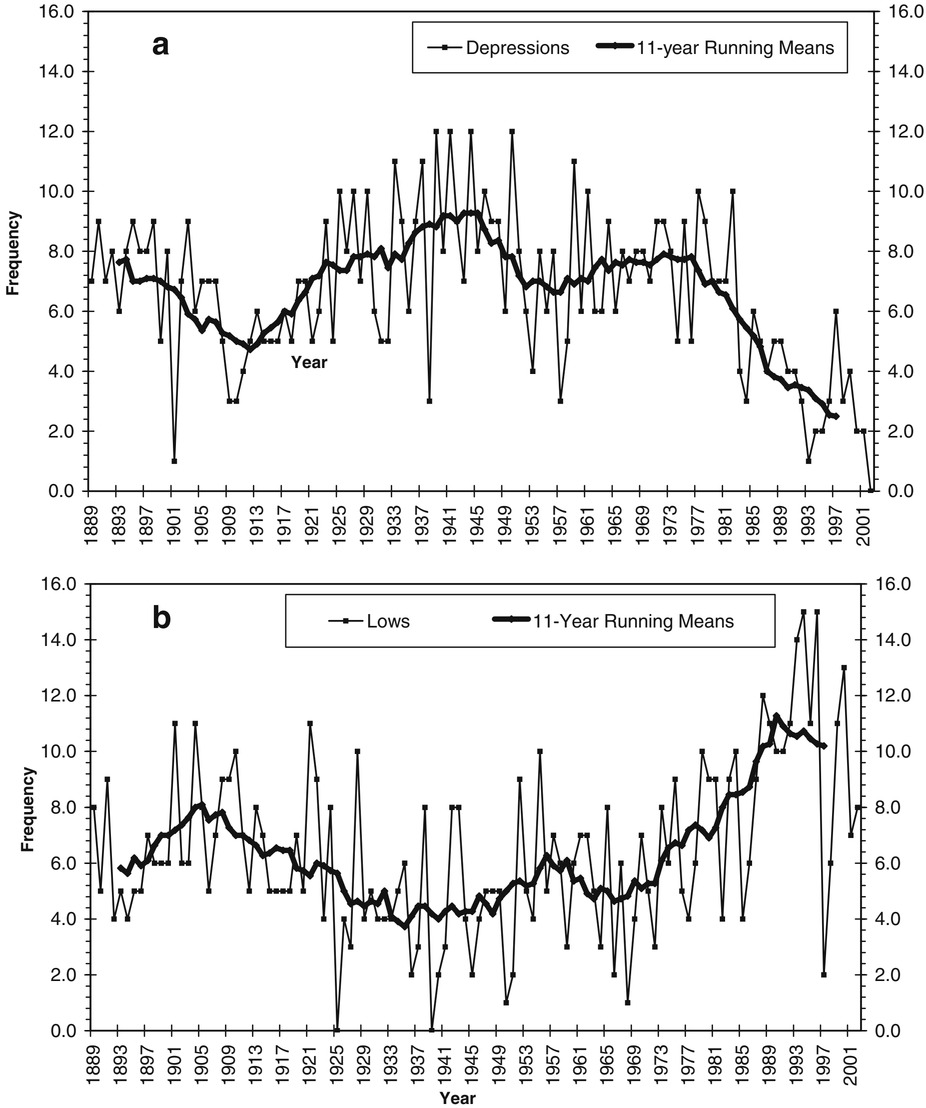

Fig. 12 Eleven-year running means of annual frequency of disturbances with the minimum intensity of **a** monsoon depressions and **b** low pressure areas over the Indian region (1889–2003)

storms formed in May, October and November. It is interesting to note that there is increasing trend in the frequency in all these months. The increasing trend in November is much more than that in May and October. Singh et al. (2000) using 122 years (1877–1998) of data had inferred similar trend. Webster et al. (2005) examined the systems with intensity of cyclones and above over the past 35 years in details and inferred that the number of cyclones and cyclone days has decreased in all basins (except the North Atlantic) during the past decade. However, there has been a large increase in the number and proportion of cyclones reaching more intense categories 4 and 5. The largest increase occurred in the North Pacific, Indian and South west Pacific Oceans.

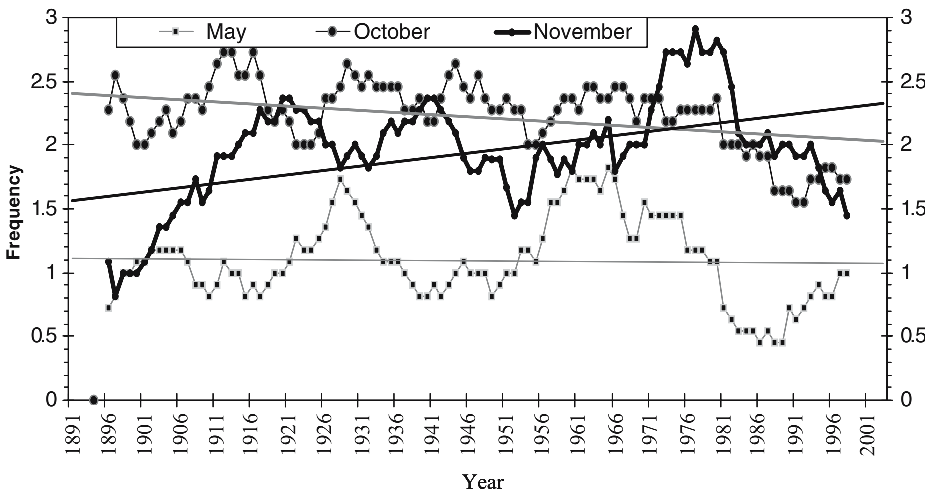

Fig. 13 Eleven year running means of frequency of disturbances with the intensity of depression and above formed in the months May, October and November during 1891–2003

Based on the observed data for the period 1891–2000, it may be inferred that the number of cyclonic storms crossing the east and west coasts of India has decreased during the last century whereas the number of severe cyclonic storms crossing both the coasts has increasing tendency. In the decade 1891–1900, nearly 36 cyclonic storms formed in the BoB and crossed the east coast. This number decreased in subsequent decade and became the least at 13 in the last decade 1991–2000. Dhar and Nandargi (2001) have inferred that due to the reduction in cyclonic disturbances and also the number of cyclonic disturbances that crossed the Indian coast, there has been reduction in rainstorm activities during the recent decades. On the contrary, number of severe cyclonic storms crossing the east coast in the decade 1891–1900 was 10 which increased to 19 in the decade 1971–1980 and became 13 in the last decade 1991–2000. The scenario at the west coast of India was similar for the cyclonic storms and severe cyclonic storms formed over the AS. In the decade 1891–2000, number of cyclonic storms crossing the west coast was 6. This number reduced to 3 in the decade 1991–2000. On the other hand, there was no severe cyclonic storm crossing the west coast in 1981–1900. This number became 4 in the decade 1941–1950. In the last decade 1991–2000, two severe cyclonic storms crossed the west coast of India. Thus there is increasing trend of number of severe cyclonic storms crossing Indian coasts. Webster et al. (2005) have also found similar increasing trend in case of Atlantic Hurricanes.

5 Other parameters

The global mean sea level is expected to rise as a result of the thermal expansion of the oceans, and the melting of glaciers and polar ice sheets, which occur due to global warming. The analysis of tide gauge records shows a global sea level rise by about 10–25 cm over the last 100 years (Gabriele et al. 2001). However, vertical land movements cause the main uncertainty of results from tide-gauges. Some sectors of world coastlines have been subsiding in recent decades, as indicated by the evidence of tectonic movements. Methods may be adopted for filtering out the effects of long-term vertical land movements and also

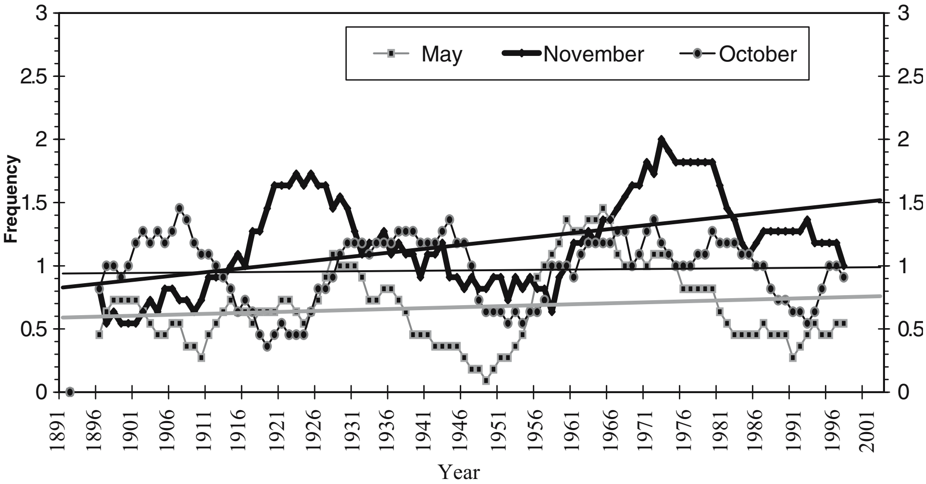

Fig. 14 Eleven year running means of frequency of disturbances with the minimum intensity of cyclonic storms formed in the months of May, October and November during 1891–2003

long period tide-gauge records should be examined for estimating trends in the sea level rise due to climate change. No extensive study has been conducted so far to examine whether there is any indication of sea level rise on both the coast lines in India. Das and Radhakrisnan (1991, 1993) reported a rising trend in sea levels at Mumbai and Chennai for a limited period. No significant influence on global warming on the sea level at Mumbai and Chennai has been reported so far. The vast amount of tide gauge data at other ports need to be examined critically with due consideration to the seismic activities on the eastern boundary of the Indian plate, high sedimentation rate near the head BoB, local subsidence and other regional factors.

Storm surges in the BoB are the major cause of coastal flooding along the East Coast of India and Bangladesh. The projected rise in the sea level due to greenhouse warming may affect the storm surges and consequently the coastal flooding in the BoB. The combined effect of sea level rise and storm surges is extremely dangerous to the population in Ganga–Brahmaputra–Meghna delta region of Bangladesh.

Global changes will affect the regional water sources very much. Climate change may either increase or decrease water availability through precipitation, temperature, cloudiness and humidity, increasing the level of uncertainty. The timing and magnitude of surface runoffs will also be the main concern.

The coastal regions of India including Andaman and Nicobar Islands are rich in diverse ecosystems and mangrove wetlands. The mangroves act as barriers against cyclones, avoid coastal erosion and serve as habitat of a number of aquatic lives specially fish, prawns and crabs. These ecosystems are influenced by geomorphology of the coast, climate, tidal amplitude and duration, and quantity of fresh water inflow. Climate changes will disturb the delicate balance of the ecosystems and hence can bring out visible changes in them.

Desertification is a slow process and it occurs due to persistent events such as droughts, accelerated soil erosion by wind and water, increasing salinization of soils and near-surface groundwater supplies, reduction in soil moisture retention, an increase in surface runoff and streamflow variability, reduction in species diversity and plant biomass, reduction in the overall productivity in dryland ecosystems etc. The combined effect of climatic stress and dryland degradation can become very dangerous leading to extreme social disruption, migrations, and famine.

It is well known that in most of the cities in India, the air and water pollution problems are alarming due to more vehicles, power plants, textile mills and other industries. The pollutants are mainly lead, SPM, Carbon Monoxide (CO), Polycyclic Aromatic Hydrocarbons (PAHs), Sulphur Dioxide (SO2), benzene and oxides of nitrogen. Apart from affecting the chemical reactions in the atmosphere, these pollutants are responsible for adversely affecting the health of the people.

6 Conclusions

Detailed analysis of observed data clearly indicate that the maximum temperature has been increasing during the last century over all the regions of India. However, the magnitude of increase is not the same everywhere. West coast shows maximum increase in its maximum temperature by about 1.2°C followed by 1°C in the north east, 0.9°C in the western Himalaya, 0.8°C in the north central, 0.6°C in the north west, 0.6°C in the east coast and the least amount of 0.5°C in the interior peninsula. The characteristics of change in the minimum temperature of the last century is found to be different in the regions in the north and south India. There is a sharp reduction in the minimum temperature in north India during 1955 to 1972 and then equally sharp rise over the past three to four decades in the last century. Such large fluctuation is not noticed in the south. The increase in the temperatures in the southern Indian regions goes well with the rise in SSTs of BoB and AS. However, the large fluctuation in the minimum temperature in the north India needs further examination in the context of changes in land-use and vegetation patterns in the Himalayan range and the exchange of heat on the numerous slopes of the Himalayas.

Results of this comprehensive study also show that in the last century, the enhancement in the mean atmospheric surface temperature in India is about 1 and 1.1°C during winter and post-monsoon months respectively. During these two seasons, the maximum temperatures also indicate rise by about same magnitudes respectively. On the other hand during monsoon (post-monsoon) months the minimum temperature has decreased (increased). During pre-monsoon and monsoon months the mean temperatures have increased by about 0.3 and 0.4°C respectively. The decrease in the minimum temperature during summer monsoon and its increase during post-monsoon months create a large difference of about 0.8°C in the seasonal temperature anomalies which may eventually alter the distribution of heating sources and hence atmospheric circulation pattern.

Extreme temperature events have increased in the recent past. During the heat wave period from 19 May up to 10 June 2003, the highest daily maximum temperature in the country was observed in Andhra Pradesh instead of in the north west and central plains of India where it used to occur normally. During the heat wave period of 23 days, the highest maximum temperature varied between 45 and 50°C at four stations in the east coast. These stations broke their 100 years record in maximum temperatures. Similar type of unusual severe heat waves had occurred in Orissa during May–June 1998.

Rainfall pattern during different seasons indicate small increase during winter months of January and February, pre-monsoon months of March, April and May and post-monsoon months of October, November and December. In contrast ISMR shows small decreasing trend.

There is a decreasing trend in the frequency of the total number of depressions, cyclonic storms and systems with higher intensities observed during the months June to September.

On the other hand there is increase in the number of low pressure areas during these monsoon months. The total number of cyclonic disturbances crossing the east coast of India shows decreasing trend, while number of severe cyclonic storms crossing east coast shows increasing trend.

No attempt has been made in this study to establish whether the changes observed are due to manmade activities or due to natural climate changes. It is very difficult to arrive at such conclusions, unless consolidated modelling studies are undertaken in future. Numerical experiments are being designed to understand the physical mechanism leading to the inhomogeneity in climatic changes in space and time. In addition to the global effect of Greenhouse Gases (GHGs), it is very important to examine the regional features which modulate the global effects of warming.

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