# Chapter 15
# Climate Change over the Indian Sub-continent

**D. R. Pattnaik and A. P. Dimri**

**Abstract** The unique geographical locations of India with the Himalaya and vast Asian land mass on the north and the Indian Ocean to the south give rise to unique climatic regimes. The southwest monsoon season from June to September (JJAS) is associated with drought and flood, active and break cycle of monsoon and heavy rainfall over different parts of the country. Similarly, October to December (OND) season is associated with northeast monsoon season over south peninsula and formation of cyclonic storm over North Indian Ocean. The winter season from January to February (JF) brings cold wave, fog and snow fall, whereas the season from March to May (MAM) is associated with heat wave and second peak of cyclonic storms.

Like the increasing trend of global mean temperature during the last 100 years, during 1901–2016, the annual mean temperature over Indian land mass also showed an increasing trend of 0.64 °C/100 years with significant increasing trend in maximum temperature (1.04 °C/100 years) and relatively lower increasing trend (0.25 °C/100 years) in minimum temperature.

During the period from 1901 to 2016, the JJAS monsoon rainfall does not show any significant trend; however, it shows epochal variations. Associated with the observed climate change, it also indicates trend of frequency of heavy rainfall events.

With respect to the climate change projection by IPCC in its Fourth Assessment Report, it indicates warming of the climate system on global as well as on regional scales with most of the observed increase in global average temperatures since the mid-twentieth century very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

**Keywords** Indian monsoon · Extreme weather · Climate variability · Climate change · Drought and flood · Heat wave and cold wave

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## 15.1 Introduction

India is a land with unique climate, a vast country situated roughly between 8°N and 37°N latitude, which occupies a large area of South Asia. The several characteristic features of India include (1) two monsoon seasons (southwest and northeast); (2) two cyclone seasons (pre- and post-monsoon); (3) hot weather season characterized by severe thunderstorms, dust storms and heat waves; and (4) cold weather season characterized by violent snow storms in the Himalayan regions, cold waves and fog. In 1686 Sir Edmund Halley explained the monsoon as resulting from thermal contrasts between continents and oceans due to differential heating. Accordingly, Halley conceived summer and winter monsoons depending upon the season. Besides differential heating, the development of monsoon is influenced by the shape of the continents, orography and the conditions of air circulation in the upper troposphere. In summer the sun shines vertically over the Tropic of Cancer, resulting in high temperature and low pressure in Central Asia, while the pressure is high over the Arabian Sea and Bay of Bengal. This induces air flow from sea to land and brings heavy rainfall to India and her neighbouring countries (Fig. 15.1a). In winter the sun shines vertically over the Tropic of Capricorn. The north-western part of India grows colder than the Arabian Sea and Bay of Bengal, and the flow of monsoon is reversed (Fig. 15.1b). Also, as the agriculture output primarily depends on rainfall (Gadgil et al. 1999), the variability in monsoon rainfall during June to September (JJAS) can have adverse impacts due to crop failures. This occurs over a range of temporal scales from intra-seasonal to inter-decadal, dominated by interannual variations (Pattanaik 2012). The rain producing monsoon systems are important for various sectors, like agriculture, water management and power industry. As India receives about 75–90% of its annual rainfall during the monsoon season JJAS, a failure in monsoon rainfall leads to drought conditions and can affect the economy of the country. One-sixth area of the country is drought-prone, with the western part of the country, including Rajasthan, Gujarat and some parts of Maharashtra, being more vulnerable and hit very frequently by drought condition. In some years with deficient rainfall, the situation spreads into other parts of the country. The other extreme of the monsoon rainfall associated with excess seasonal rainfall during JJAS and heavy rainfall can lead to flood conditions over many parts of the country. About 40 million hectares (mha) of India are prone to floods, and on an average, floods affect an area of around 7.5 mha per year. The plain region of India is affected by floods almost every year during the monsoon season and is associated with heavy rainfall. Thus, the interannual fluctuations in the summer monsoon rainfall over India are sufficiently large to cause devastating floods or severe droughts.

The variability of monsoon characterized by the onset, withdrawal and active and dry spell of monsoon is crucial for the country. Long breaks during growth periods of crops can substantially reduce yield (Gadgil and Rao 2000). Thus, monsoon rainfall prediction in different time scales has important impact on agriculture. The long-range (on seasonal scale) prediction of monsoon is very useful for planners, especially when a large deficient rainfall scenario is foreseen. In the last few decades,

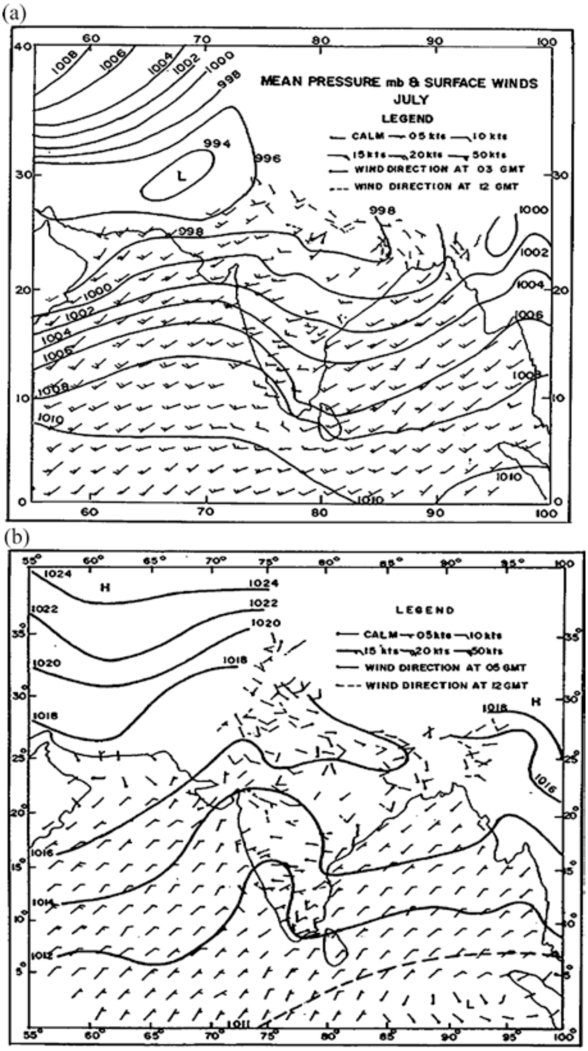


**Fig. 15.1** Mean surface wind and pressure for (**a**) July and (**b**) January. (Source: Rao 1976)

many dynamical models (Palmer et al. 1992; Chen and Yen 1994; Sperber and Palmer 1996; Shukla et al. 2000; Saha et al. 2014; Pattanaik and Kumar 2010, 2014) have been developed for the seasonal prediction of rainfall over India. More importantly, the rainfall forecast on smaller spatial scale of different phases of monsoon (like its onset and advance, active and break cycle of monsoon) on intra-seasonal time scale is crucial for the farming community (Abhilash et al. 2014; Sahai et al. 2013).

In addition to the failure of monsoon during a season that can influence agriculture adversely, there are many other extreme weather conditions, which impact agriculture. The surface air temperature drives crop growth duration and influences milk production in animals and spawning in fish. Temperature and relative humidity both influence pest and disease incidence on crops, livestock and poultry. Thus, for an agro-economic country like India, the variability of surface air temperature on different temporal scales is crucial for policymaking and the national economy. Surface air temperature during the pre-monsoon season also influences soil moisture and hence the performance of the ensuing monsoon (Krishnakumar et al. 1998). Recently, many scientists have studied the different temperature variability patterns over India. Kothawale and Rupa Kumar (2005) indicate that mean maximum temperature (Tmax) increased over India during 1901–1987, and there is a warming trend in annual mean temperature over India mostly due to increasing Tmax that took place during 1901–2003. Associated with high Tmax in summer, most areas in India experience episodes of heat waves causing sunstroke, dehydration and death (De et al. 2005; Pattanaik and Mukhopadhyay 2012). At times, extreme temperatures like heat wave can cause enormous losses of standing crops, livestock and fisheries. Similarly, other extreme temperatures like the cold wave during winter due to frost conditions are also of concern to winter crops (De et al. 2005; Dash and Mamgain 2011).

The current trends of climate change are expected to increase the frequency and intensity of existing hazards, an increased probability of extreme events and vulnerabilities with differential spatial and socio-economic impacts. The Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (AR5; IPCC 2014) has also projected more frequent and intense weather events in the twenty-first century with high confidence levels. This is likely to further degrade the resilience and coping capacities of poor and vulnerable communities. Therefore, it is very desirable to study the observed spatial and temporal variability of rainfall and temperature, as it is linked to weather and climate extremes such as high rainfall/low rainfall/floods/droughts/heat wave/cold wave/cyclone/hail/frost. The objective of this study is to highlight the spatial and temporal variability of rainfall and temperature, along with its projection for the future.

## 15.2 Variability of Monsoon Leading to Droughts and Floods

Prior to the onset of monsoon, the Indian monsoon zone is characterized by the presence of a heat low centre near central Pakistan and the adjoining north-western parts of India. Onset of monsoon over the southern tip of India (Kerala coast) is marked as the beginning of the monsoon season. Once the monsoon covers the entire country, a tropical convergence zone (commonly known as the monsoon trough) gets established over the region. Indian summer monsoon (ISM) exhibits large spatial variability with regions of high rainfall (the west coast of the peninsula and over the northeastern regions) that are associated with lowest variability and regions of lowest rainfall (north-western parts of India) having highest variability as seen from the mean and coefficient of variability (CV) of JJAS rainfall shown in Fig. 15.2a, b, respectively.

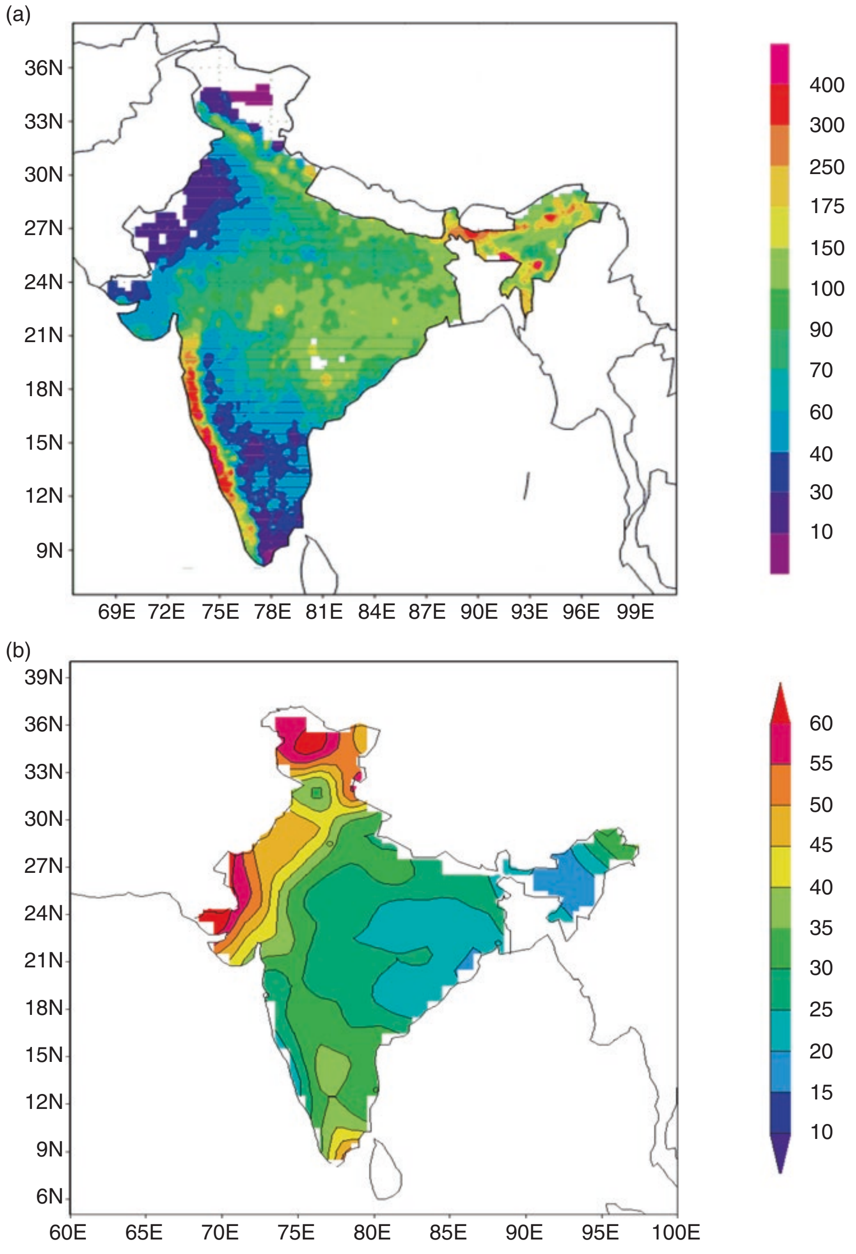


**Fig. 15.2** Mean All India Summer Monsoon Rainfall during (**a**) June to September (1951–2003) and (**b**) mean coefficient of variability (%)

The All India Summer Monsoon Rainfall (AISMR) during JJAS has a unique profile due to its large interannual variability. Long period average (LPA; 1951–2010) of summer monsoon rainfall is found to be about 89 cm with a CV of ≈8.9 cm (10% of LPA). As pointed by many earlier studies, there is a close correspondence between deficit monsoon rainfall and El Niño (Sikka 1980; Pant and Parthasarathy 1981; Rasmusson and Carpenter 1983). However, Krishnakumar et al. (1999) have suggested that the link with El Niño has weakened in the last decade, and in fact the AISMR anomaly was positive in the recent intense warm event of 1997. Many other studies have pointed out various teleconnection patterns other than ENSO to explain the observed interannual variability of AISMR and also the decadal and epochal variability of AISMR (Pattanaik 2012). The interannual variation of AISMR during the 142 years period from 1875 to 2016 is shown in Fig. 15.3. As seen from Fig. 15.3, the period from 1875 to 2016 witnessed many deficient and excess monsoon years. The deficient or excess years are identified based on the rainfall departure of ±1 CV. Large areas are therefore affected if the southwest monsoon plays truant. Most parts of peninsular, central, and northwest India are prone to periodic drought. These regions receive less than 100 cm of rainfall. The droughts of 1965–1967 and 1979–1980 affected relatively high rainfall regions, while the droughts of 1972, 1987, 2002, 2004 and 2009 affected low-rainfall regions, mostly semi-arid and subhumid regions. Recently, India witnessed two consecutive drought years of 2014 and 2015. The interannual variability of AISMR shows more number of deficient years (26 years ≈ 18.3%) compared to the excess years (19 years ≈ 13.4%) during 1875 to 2016. The deficient and excess years are identified from Fig. 15.3 and also given in Table 15.1. As seen from Fig. 15.3, among the drought years, the year 1877

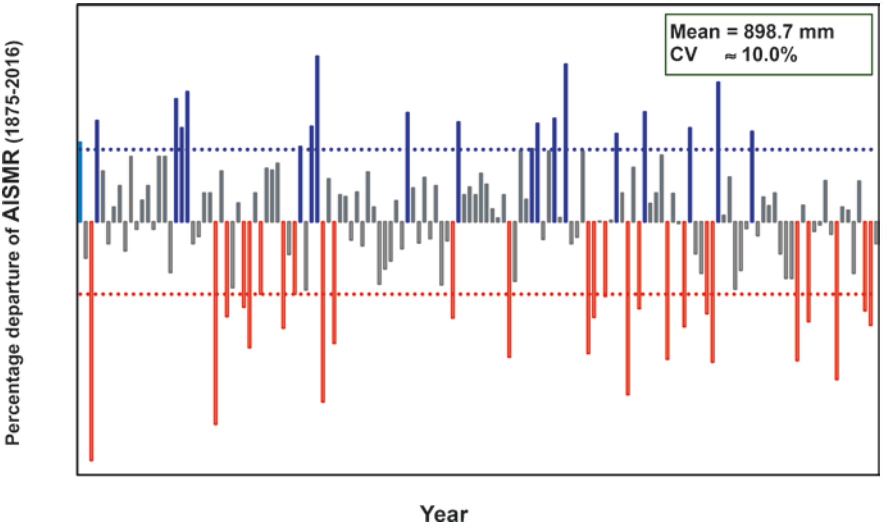


**Fig. 15.3** All India Summer Monsoon Rainfall (AISMR) departure during June to September from 1875 to 2016

received the lowest rainfall (67% of LPA) followed by the years 1918 (75.1% of LPA), 1972 (76.1%) and 2009 (78.2%) with negative departures exceeding 2 SD (≈−20% of LPA) value. Similarly, the excess rainfall ever recorded is found to be in 1917 (122.9% of LPA) followed by 1961 (121.8% of LPA) where the positive departures of seasonal rainfall exceeded 2 SD (≈+20%) value. It may be mentioned here that even in a year of excess (deficient) monsoon on all-India scale, there are pockets of deficient (excess) rainfall over some parts of the country that lead to drought (flood) situations. It is further seen from Fig. 15.3 that there is no excess monsoon year that is reported after 1994.

Like the interannual variability of AISMR, the interannual variability of monthly rainfall during June to September from 1901 to 2010 for the country as a whole also shows large interannual variability. The mean, coefficient of variability (CV) and the monthly percentage contribution to the total seasonal rainfall are shown in Table 15.2. As shown from Table 15.2, the contribution of peak monsoon months of July and August to the seasonal total rainfall is found to be about 33% and 29%, respectively, whereas the contribution of June rainfall and September rainfall to the seasonal total is found to be about 18.6% and 19.4%, respectively. Unlike the CV of AISMR, which is close to 10%, the CV of monthly rainfall is high particularly during the withdrawal and onset phases of monsoon; during September (23%) and June (22%), respectively. During the peak monsoon months of July and August, the CVs are about 14% and 15%, respectively. Thus, the onset and withdrawal phases of monsoon are more variable compared to that of peak monsoon months of July and August.

Meteorological drought happens when the actual rainfall in an area is significantly less than the climatological mean of that area. Drought has both direct and indirect impacts on the economic, social and environmental fabric of the country. The immediate visible impact of monsoon failure leading to drought is felt by the agricultural sector. The impact passes on to other sectors, including industry.

**Table 15.1** Excess (19) and deficient (26) categories of years based on seasonal rainfall year based on the departure of 1 SD

| | | |
|---|---|---|
| AISMR (1875–2016) | Excess (19 years) | 1875, 1878, 1892, 1893, 1894, 1914, 1916, 1917, 1933, 1942, 1955, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994 |
| | Deficient (26 years) | 1877, 1899, 1901, 1904, 1905, 1907, 1911, 1913, 1918, 1920, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1986, 1987, 2002, 2004, 2009, 2014, 2015 |

**Table 15.2** The mean, coefficient of variability (CV) and the monthly % contribution to the total seasonal rainfall

| Rainfall | June | July | August | September | JJAS (June–September) |
|---|---|---|---|---|---|
| Mean (mm) | 167.4 | 295.6 | 261.8 | 173.9 | 898.7 |
| Coefficient of variability (CV) | 22.1% | 14.2% | 15.1% | 23.1% | 10% |
| Contribution to seasonal total (JJAS) | 18.6% | 32.9% | 29.1% | 19.4% | 100% |

The five recent worst drought years are 1987, 2002, 2009, 2014 and 2015. Drought during the year 2002 caused reduction in food grain production to the tune of 13% in India (Gadgil and Rao 2000). In the year 2009, the percentage area affected by moderate drought (when rainfall is 26–50% below normal) was 59.2%. Due to this drought condition, there was a fall in gross domestic product (GDP) by about 0.5%.

## 15.3 Decadal and Epochal Variability of AISMR

Although the Indian monsoon rainfall for the country as a whole does not show any trend, it is however seen that the Indian Summer Monsoon Rainfall (ISMR) displays multi-decadal variations in which there is clustering of wet or dry anomalies. The decadal mean departure of AISMR during last 13 decades from 1875 to 2016 is shown in Fig. 15.4, which indicates an alternating sequence of multi-decadal periods having frequent droughts and flood years. The first and last decades are not consisting of 6 years from 1875 to 1880 and 2011 to 2016 and the remaining 11 decades are from 1901 to 1910, 1911 to 1920 and so on till 2001 to 2010. As seen from Fig. 15.4, we can delineate (1) 1901–1930 dry period (2) 1931–1960 wet period and (3) 1961–1990 also a dry period. Earlier studies by Pant and Rupa Kumar (1997) using the data series of Parthasarathy et al. (1994) also found similar results of 30 years of alternating sequences of dry and wet

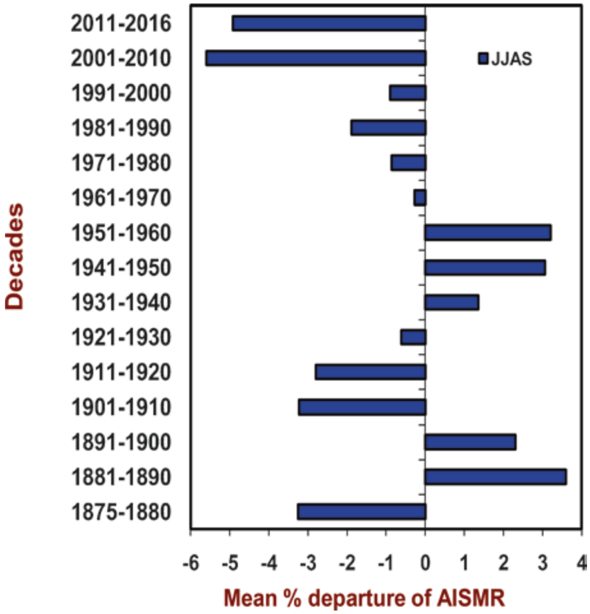


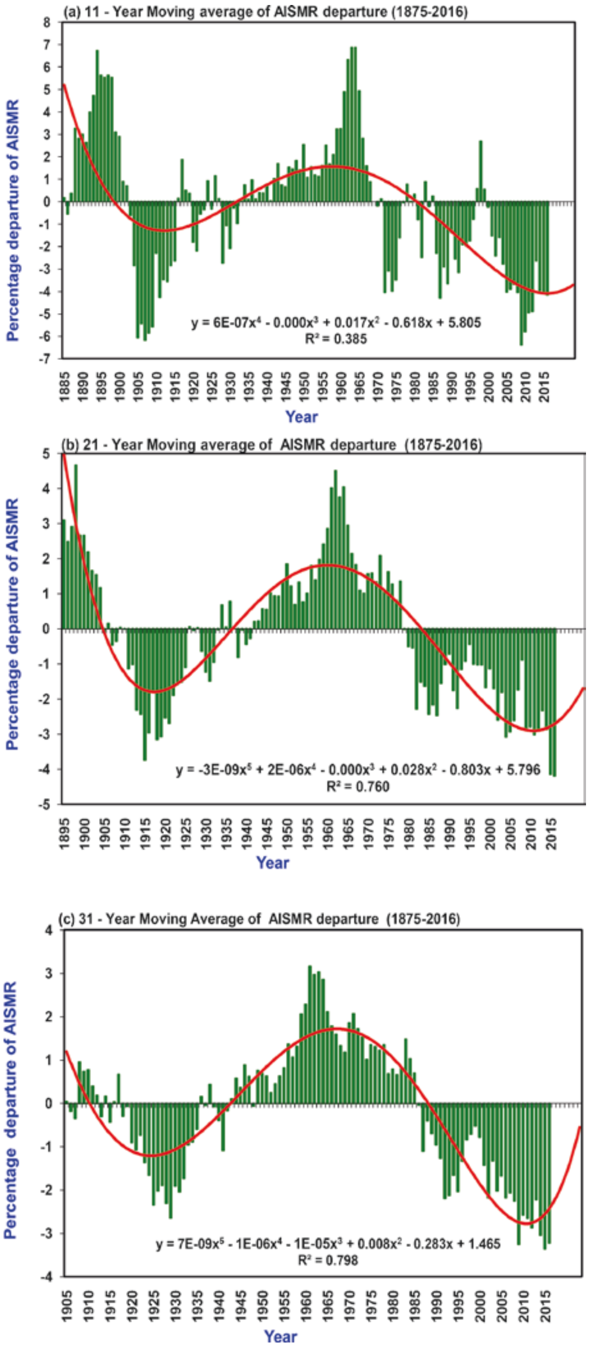
**Fig. 15.4** Decadal variability of AISMR during 1875 to 2016

period. As also seen from Table 15.1, during the first decade of 1901–1910, there are four deficient years but no excess year. In the decade 1911–1920, there are four deficient and three excess years, and during the decade 1921–1930, there is no deficient year and no excess year. Thus, during the dry period of 1901–1930, we observe eight deficient years and three excess years. During the next three decades of wet period (1931–1960), we observe two deficient years and five excess years. In the dry period of 1961–1990, there were nine deficient years and five excess years. The recent two decades also witness negative composite anomalies with three deficient years from decade 2001 to 2010 and two deficient years observed during the last 6 years from 2011 to 2016. Thus, it is seen that the ISMR displays multi-decadal variations in which there is clustering of wet or dry anomalies. Many other studies also indicated a highly variable but reduced trend of the ISMR with a prominent epochal nature of variability (Thapliyal and Kulshreshtha 1991; Pant and Rupa Kumar 1997; Hingane et al. 1985; Rupa Kumar et al. 1992; Rajeevan et al. 2006). The monsoon rainfall shows epochal behaviour with alternating epochs of above and below normal rainfall. Thapliyal and Kulshreshtha (1991) also analysed the climate change and the epochal variations of monsoon rainfall over India and found no systematic climate change or trend over India. Kripalani and Kulkarni (1997) examined the epochal variation of monsoon rainfall and its association with the ENSO-AISMR relationship and showed that the impact of El Niño on the AISMR was more severe during the below normal epochs than during the above normal epochs. To examine the epochs of above and below normal rainfall, 11 years, 21 years and 31 years running means of AISMR were calculated to isolate low-frequency behaviour. These epochs of above and below normal rainfall are shown in Fig. 15.5a–c. The epochal behaviour as shown in Fig. 15.5b, c indicates the AISMR is in the negative epoch and entering into the above normal epoch. A recent study found that the existence of the multi-decadal epochal variability of rainfall is clearly established in the all-India monsoon rainfall, as well as monsoon rainfall over the four homogenous regions. However, over different homogenous regions, the phases of multi-decadal variability are found to be different.

## 15.4 Sub-division-Wise Trend of Monsoon Rainfall

Although Fig. 15.2 indicates large variability of AISMR, it does not show any significant linear trend. However, there exists trend in the sub-divisional rainfall (Guhathakurta and Rajeevan 2007). As shown by these authors and also indicated here (Fig. 15.6) during the season as a whole, three sub-divisions, viz. Jharkhand, Chattisgarh and Kerala, show significant decreasing trend, and eight subdivisions, viz. Gangetic West Bengal, West Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalaseema, Coastal Andhra Pradesh and North Interior Karnataka, show significant increasing trends.

**Fig. 15.5** Epochal variability of (**a**) 11-year, (**b**) 21-year and (**c**) 31-year moving average of AISMR



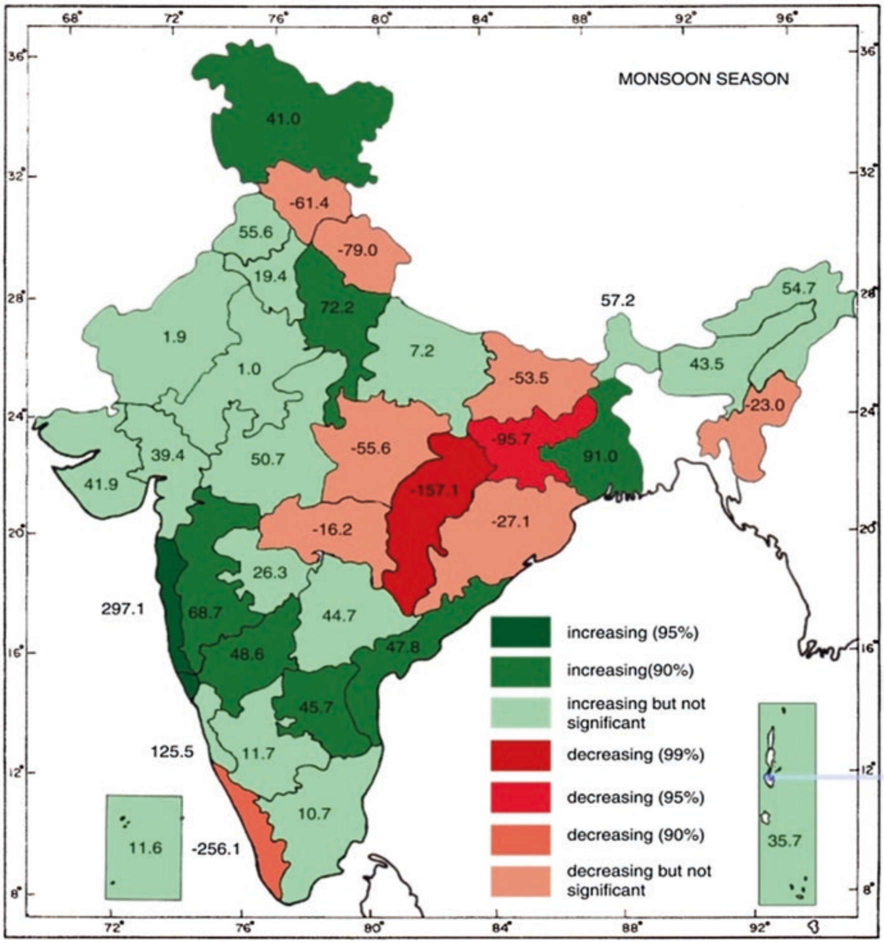


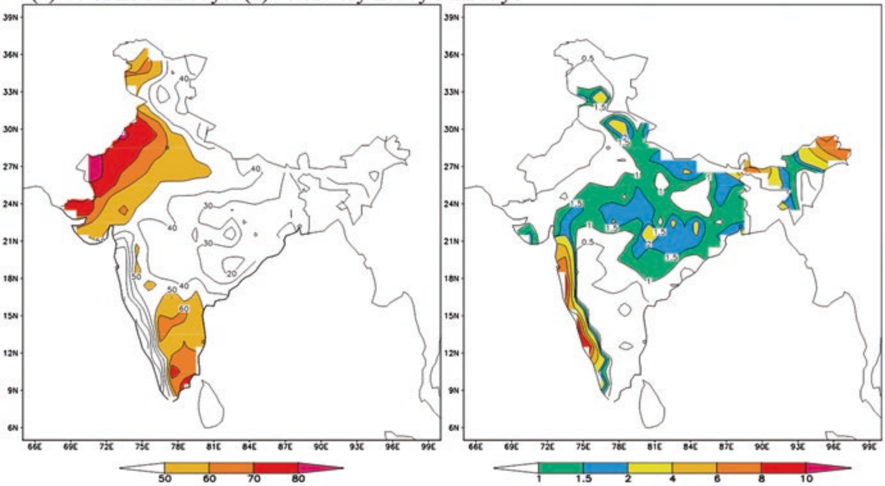
**Fig. 15.6** Increase/decrease in seasonal rainfall in mm during 100 year for each of 36 meteorological subdivisions for the southwest monsoon season during June to September. Different levels of significance for increasing and decreasing trend are shaded with colours. (Source: Guhathakurta and Rajeevan 2007)

## 15.5 Extreme Rainfall and Its Variability

During the southwest monsoon season JJAS, many parts of India, including the west coast of the peninsula and northeast and central region of the country, receive heavy to very heavy rainfall during active spells of the summer monsoon. However, within the season, spells with heavy rainfall alternate with spells of little or no rainfall. On occasion, the rainfall is exceptionally heavy at some stations associated with active monsoon trough and passage of low pressure areas and depressions. The high rainfall over the west coast of India and the heavier rainfall over the Western Ghats are generally attributed to forced ascent over the orography of the Western Ghats (Francis and Gadgil 2006). The orographic features over the west coast and Northeast India and the movement of synoptic-scale systems from the Bay of Bengal region to the central parts of India (Rao 1976; Soman and Kumar 1990; Gadgil 2000; Sikka 2006; Pattanaik 2007) also contribute to heavy rainfall events over different parts of India. These heavy rainfall events with daily rainfall, of the order of 10 cm or more at some stations over the west coast and other parts of India, cause extensive damage to life and property every year during JJAS through landslides and flash floods. There are many past instances of Indian stations having recorded as much as half of their annual mean rainfall, and sometimes more than that, in one single day (Dhar and Mandal 1981). The exceptionally heavy rainfall of 944 mm over Mumbai (Santacruz) on 26–27 July 2005 was very unprecedented in nature, which led to large-scale urban flooding (Jenamani et al. 2006; Sahany et al. 2010).

Climate change studies have indicated increasing frequency of extreme weather events including the frequency of heavy rainfall over the globe. Many modelling studies indicate that changes in intense rainfall are more likely as global temperature increases (Kharin and Zwiers 2000; Allen and Ingram 2002; Semenov and Bengtsson 2002). Over the Indian region, there have been some studies (Goswami et al. 2006; Rupa Kumar et al. 2006; Guhathakurta and Rajeevan 2007; Rajeevan et al. 2008; Dash et al. 2009; Pattanaik and Rajeevan 2010) highlighting different aspects of mean and extreme rainfall events during the southwest monsoon season. Dash et al. (2009) have shown significant increase in short and dry rain spells and decrease in long rain spells. By providing empirical evidence of changes in the frequency of these extreme events, a better basis for impact assessments of the consequences of these changes, including landslides, floods and soil erosion, can be provided. Pattanaik and Rajeevan (2010) have studied the details about the trend and frequency of heavy rainfall events over India and its contribution to total rainfall during the southwest monsoon season for a period of 55 years from 1951 to 2005 using the daily gridded (1 × 1) rainfall. Based on the classification by IMD of rainfall amount in a single day, three categories of rainfall '$R$' are considered by them to study the variability of frequency of heavy rainfall events such as (1) light to rather heavy rainfall ($0 < R \leq 64.4$ mm), (2) heavy rainfall ($64.4 < R \leq 124.4$ mm) and (3) very heavy to exceptionally heavy rainfall ($R > 124.4$ mm) using 55 years of data from 1951 to 2005. In this study, the last categories with $R > 124.4$ mm are referred hereafter as extreme rainfall events. In order to see the dominating regions of heavy rainfall events and no rain days, the mean frequency in terms of the % days of the whole season JJAS of 122 days for no rain days and three categories of rainy days are shown in Fig. 15.7a–d. The no rain days as shown in Fig. 15.7a gradually increases towards northwest parts of India where the number of rainy days in a season JJAS is less, whereas Fig. 15.7b shows the highest frequency of Category-1 rainfall days (more than 70%) over the west coast and eastern and northeast regions, gradually decreasing towards the northwest of India. The average frequency of Category-2 and Category-3 rainfall as shown in Fig. 15.7c, d, respectively, is very small compared to the frequency of Category-1 rainfall over almost the entire

(a) % of no rain days (c) % of very heavy rain days



(b) % of heavy rain days(d) % of exceptional heavy rain days

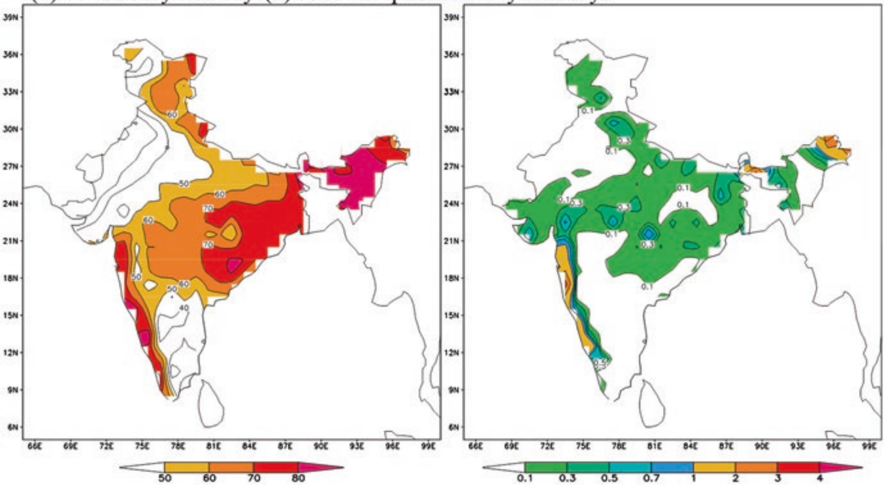


**Fig. 15.7** Average percentage of frequency of no rain days and different categories of rain days identified in Table 15.1 during the monsoon season (June to September) from 1951 to 2005. (**a**) % of no-rain days, (**b**) % of Category 1 rainfall days, (**c**) % of Category 2 rainfall days and (**d**) % % of Category 3 rainfall days. Shaded regions are more than 50% in (**a**) and (**b**), more than 1% in (**c**) and more than 0.1% in (**d**). (Source: Pattanaik and Rajeevan 2010)

country, with the highest frequency over the west coast of India (more than 10% for Category-2 and more than 3% for Category-3), northeast parts of India and also some isolated pockets over central parts of India. Thus, it is seen that the highest frequency of extreme rainfall event is mainly observed over the west coast region extending up to the Gujarat coast, northeast parts of the country and some parts of Central India. Figure 15.7d also shows higher frequency of extreme rainfall events over some parts of Central India in the belt north of 18°N, which is mainly associated with movement of synoptic-scale systems from the Bay of Bengal. Pattanaik and Rajeevan (2010) also found that the frequency of extreme rainfall (rainfall ≥ 124.4 mm) shows increasing trend over the Indian monsoon region during the southwest monsoon season JJAS and is significant at 98% level. Their study also found that the increasing trend of contribution from extreme rainfall events during JJAS is balanced by a decreasing trend in Category-1 (rainfall ≤ 64.4 mm/day) rainfall events. On monthly scale, the frequency of extreme rainfall events shows significant (95% level) increase during June and July, whereas during August and September, the increasing trend is not significant (data not presented). Like the frequency of extreme rainfall event, the contribution of extreme rainfall to the total rainfall in a season is also showing highly significant increasing trend during the monsoon season JJAS on seasonal scale and during June and July on monthly scale (Pattanaik and Rajeevan 2010).

## 15.6 Temperature Variability and Trends

While commenting on the observed changes in the climate system, the Fifth Assessment Report (AR5) of IPCC (2014) stated that warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. The Fourth Assessment Report (AR4) by IPCC (2007) had also indicated increasing trend of the mean annual global (land + ocean) surface air temperature by about 0.74 °C during the last 100 years (1906–2005) with land temperature increasing at much higher rate than this. This report also indicated significant increasing trend of heat wave (HW) over different parts of the globe. Perkins et al. (2012) based on the data from 1950 to 2011 found increasing global trends in the intensity, frequency and duration in the observed summer time heat waves and annually calculated warm spells. The changes in the frequency or intensity of these extreme events have profound impact on human society and the natural environment (Parker et al. 1994; Easterling et al. 2000; Meehl and Tebaldi 2004; Coumou and Rahmstorf 2012).

Similar increasing trend of global surface air temperature is also reported over India, which can be seen from Fig. 15.8 for the last 116 years from 1901 to 2016, with the linear trend per 100 years in the annual mean land surface air temperature anomalies averaging over India at 0.64 °C (IMD 2017). For the year 2016, the annual mean temperature for the country was +0.87 °C above the 1971–2000 average, thus making the year 2016 as the warmest year on record since 1901. The other nine warmest years on record in order are 2009 (anomaly +0.85 °C), 2010 (0.82), 2015 (0.59), 2006 (0.56), 2002 (0.45), 2007 (0.417), 2014 (0.415), 1998 (0.41) and 1958 (0.37). It may be mentioned that 12 out of the 15 warmest years were from the recent past 16 years (2001–2016). Also, the past decade (2001–2010/2007–2016) was the warmest decade on record with anomalies of

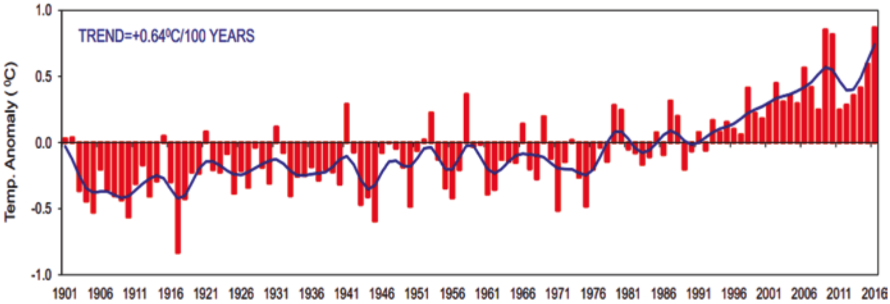


**Fig. 15.8** Annual mean land surface air temperature anomalies averaged over India for the period 1901–2016 (base period of 1971–2000). The dotted line indicates the linear trend in the time series. The solid blue curve represents the sub-decadal time scale variation smoothed with a binomial filter. (Source: Annual Climate Summary, IMD 2017)

0.46 °C/0.51 °C above average. During 1901–2016, the annual mean temperature showed an increasing trend of 0.64 °C/100 years with significant increasing trend in maximum temperature (1.04 °C/100 years) and relatively lower increasing trend (0.25 °C/100 years) in minimum temperature.

Time series and trend in mean temperature anomalies for different seasons, viz. winter (January to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to December) for the period 1901–2016 are shown in Fig. 15.9a–d, respectively (IMD 2017). The mean temperature for the winter season (with anomaly +1.36 °C above average) 2016 was the third highest since 1901. The five warmest winter years in order were 2006 (with anomaly +1.76 °C), 2009 (1.45), 2016 (1.36), 2010 (0.83) and 1966 (0.79). January month (with anomaly +0.93 °C) was the fourth warmest, and February (with anomaly +1.8 °C) this year was the second warmest since 1901. The pre-monsoon season (March to May) this year was also significantly warmer. The season this year with anomaly +1.22 °C above average was the second warmest ever since 1901. The five warmest pre-monsoon years in order are 2010 (1.72), 2016 (1.22), 1921 (0.97), 2009 (0.82) and 1953 (0.78). March, April and May months were the third, second and sixth warmest, respectively, since 1901.

Different scientists have studied various aspects of variability of extreme temperature over India. Rao et al. (2005) have reported that 80% stations in peninsular India and 40% stations in northern India showed increasing trend in the days with critical extreme maximum temperature. Kothawale et al. (2010) have found widespread increasing trend in the frequency of occurrence of hot days and hot nights and widespread decreasing trend in those of cold days and cold nights in pre-monsoon season. Dash and Mamgain (2011) by using the gridded temperature data examined this aspect over India and its seven homogeneous regions during the period 1969–2005. The results indicate a significant increase in the number of warm days in summer in the interior peninsula. In the entire country and on the east and west coast, the maximum number of warm days during the summer has been noticed in the last decade, 1996–2005. The results broadly suggest warming trends in large

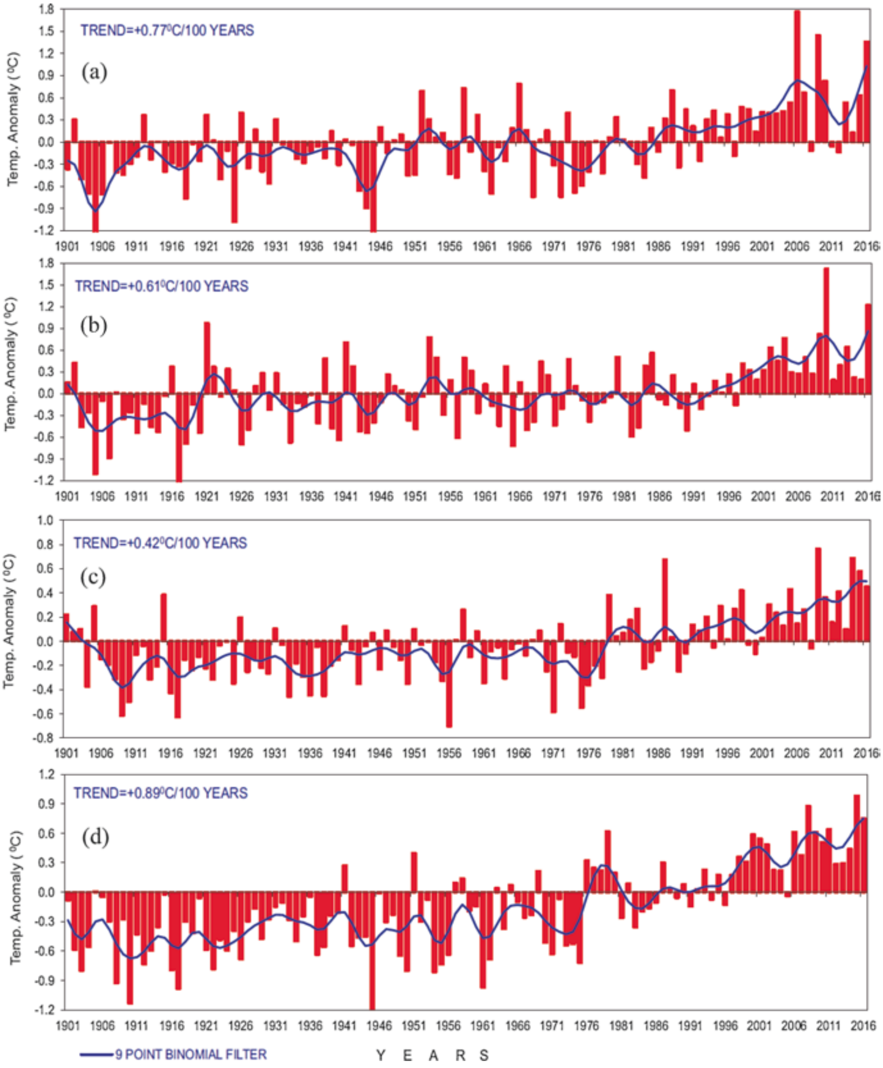


**Fig. 15.9** Annual mean land surface air temperature anomalies averaged over India for the period 1901–2016 (base period of 1971–2000) during (**a**) winter, (**b**) pre-monsoon, (**c**) monsoon and (**d**) post-monsoon. The dotted line indicates the linear trend in the time series. The solid blue curve represents the sub-decadal time scale variation smoothed with a binomial filter. (Source: Annual Climate Summary, IMD 2017)

parts of India. Revadekar et al. (2012) have found widespread warming with increase in intensity and frequency of hot events and decrease in frequency of cold events in India. Jaswal et al. (2014) studied monthly extreme temperatures over India during summer using daily temperature data from 1969 to 2012 by using both the percentile and absolute values simultaneously. On the basis of percentiles and absolute values of daily Tmax over 227 stations during summer months, the three relative/absolute hot events considered by them are hot days (HD) ($D_{max}$ > 90th percentile; $D_{max}$ > 35 °C, respectively), very hot days (VHD) ($D_{max}$ > 95th percentile; $D_{max}$ > 40 °C, respectively) and extremely hot days (EHD) ($D_{max}$ > 98th percentile; $D_{max}$ > 43 °C, respectively). As shown in Fig. 15.10a–f, their study indicates:

- On all-India scale, hot, very hot and extremely hot days are increasing in all summer months suggesting hot days have become more common now.
- Geographical distribution of trends suggests significant increase in hot days in North India in April and South India in March. Also, hot, very hot and extremely hot days are significantly more over west coast of India in summer months.
- There is significant decrease in hot, very hot and extremely hot days over Indo-Gangetic Plains in the month of May (Fig. 15.10a–f).

The season from December to February is winter in almost all of India that experiences cold wave conditions. However, the minimum temperature (Tmin) drops below 8 °C in many parts of northern India during November to February (Pattanaik and Mukhopadhyay 2012). Almost every winter, parts of North India, northwest India and Central India experience cold wave (CW) and severe cold wave (SCW) conditions. Occurrences of extreme low temperature in association with incursion of dry cold winds from north to the sub-continent are known as cold waves. The CWs mainly affect the areas to the north of 20°N, but in association with large amplitude troughs, CW conditions are sometimes reported from Maharashtra and Karnataka. After the passage of western disturbances, the CWs sometimes penetrate almost all the eastern states of India. In the southern part, the temperature difference is not marked due to the moderating effect of the Indian Ocean, the Bay of Bengal and the Arabian Sea. Normally, winters are dry in northern India, although there is rainfall associated with western disturbances. From an agricultural point, Tmin is very important in the protection of plants from frost injury. As plenty of moisture is available in the atmosphere immediately after the passage of western disturbance, and with other favourable regional and synoptic-scale conditions, it can lead to the formation of fog. A recent study by Jenamani (2007) has shown that due to the rapid urbanization in city like Delhi, the fog occurrences have been associated with the rise of pollution causing a fall in Tmax in winter.

Kothawale et al. (2010) have found widespread decreasing trend in cold days and cold nights in pre-monsoon season. Revadekar et al. (2012) also found decrease in frequency of cold events in India. While using the percentile and absolute values of Tmin over India during 1969–2012 simultaneously, Jaswal et al. (2014) defined three relative/absolute cold events as cold nights (CN) ($D_{min}$ > 10th percentile; $D_{min}$ < 10 °C, respectively),very cold nights (VCN) ($D_{min}$ < 5th percentile; $D_{min}$ < 5 °C, respectively) and extremely cold nights (ECN) ($D_{min}$ < 2nd percentile; $D_{min}$ < 2 °C, respectively) as shown in Fig. 15.11a–f. The percentile and absolute value-based data series of CN, VCN and ECN are prepared for all 227 stations for winter months from December to February for the period 1969–2012. Their research indicates the following trends: decreasing trend of cold, very cold and extremely cold nights in December, mixed trend in January, while in February, there is significant decreasing trend in North India and mixed trend in South India.

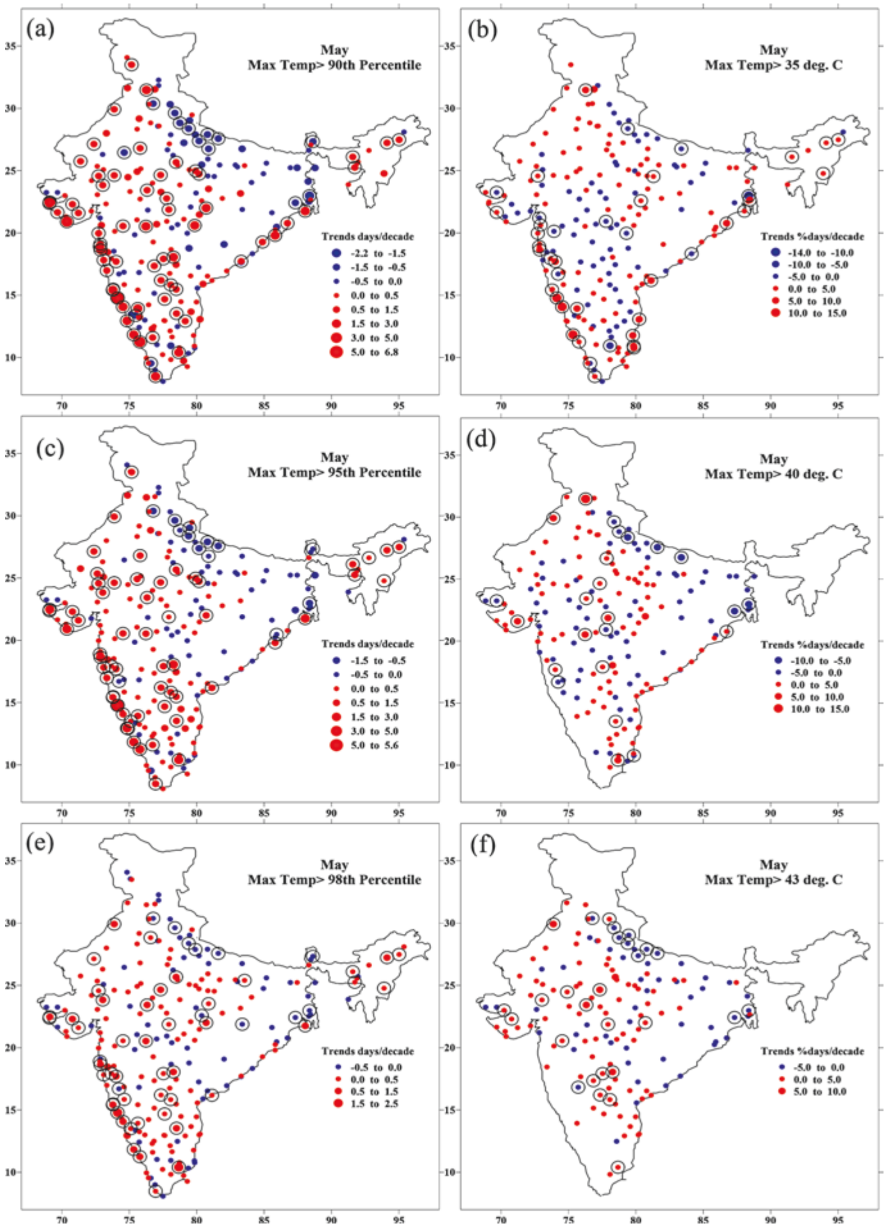


**Fig. 15.10** (**a**–**f**) Spatial distribution of trends in frequencies of daily maximum temperature above 90th, 95th and 98th percentile and daily maximum temperature above 35 °C, 40 °C and 43 °C in the month of May during the period 1969–2012. (Source: Rathore et al. 2016)

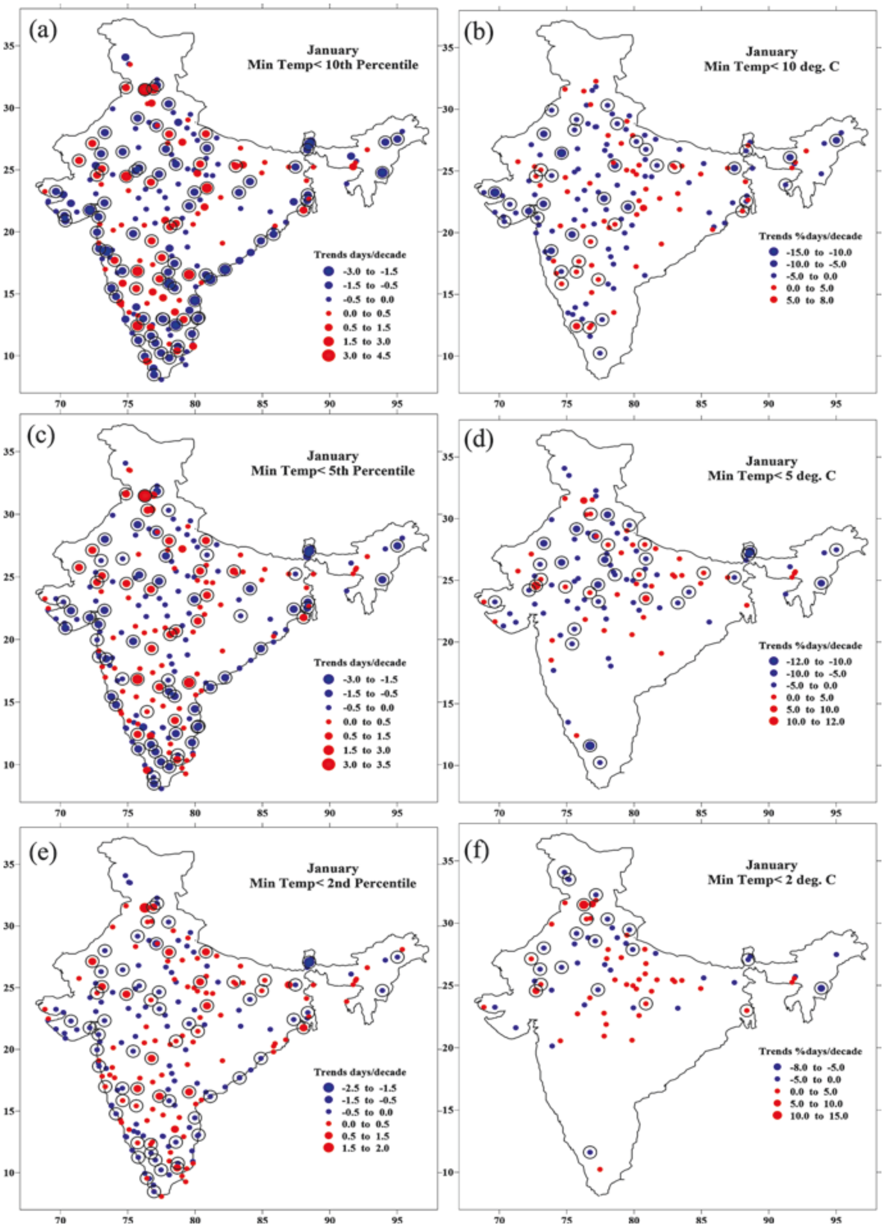


**Fig. 15.11** (**a**–**f**) Spatial distribution of trends in frequencies of daily minimum temperature below 10th, 5th and 2nd percentile and daily minimum temperature below 10 °C, 5 °C and 2 °C in the month of January during the period 1969–2012. (Source: Rathore et al. 2016)

## 15.7 Extreme Temperatures in Terms of Heat Wave (HW) and Cold Wave (CW)

March, April and May are the summer months in India. The average temperature is around 32 °C, but in the western region, the maximum temperature (Tmax) can be far above the average. Hot winds known as 'loo' are the marked feature of summer in northern India. Extremely hot weather is common in India during late spring, preceding the climatological onset of the monsoon season in June. During April, the isotherm line greater than 38 °C covers most large parts of India with a small pocket of Central India with temperature greater than 40 °C. During May, the Tmax increases and exceeds 40 °C over large parts of India covering north-western parts of the country extending towards the Indo-Gangetic Plain. During June, though the monsoon currents cool the southern parts of the country, the Tmax remains more than 40 °C in north-western parts of the country. During summer, most areas of India experience episodes of heat waves (HW definition: when normal Tmax of a station ≤40 °C, 'HW' if Tmax departure is 5–6 °C and severe HW (SHW) if Tmax departure ≥7 °C; when normal Tmax of a station >40 °C, HW if Tmax departure is 4–5 °C and SHW if Tmax departure ≥6 °C) almost during every year causing sunstroke, dehydration and death. The global climate anomalies have indicated that 1998 was the warmest year in the last century (Jones and Briffa 1992) where more than 1000 people died over India due to scorching temperatures over Orissa, Coastal Andhra Pradesh, Rajasthan and Tamil Nadu during May/June. Similarly, in May 2003 the heat wave claimed over 1600 lives throughout the country, while some 1200 individuals died in the state of Andhra Pradesh alone. Like in 2003, during 2005 India was under the grip of severe heat wave towards the third week of June, and about 200 people died in the eastern parts of the country covering the state of Orissa and its neighbourhood (Bhadram et al. 2005). Similarly, during the recent heat wave over eastern coastal states of India (Telengana, Andhra Pradesh, Odisha) during late May and early June 2015, there were more than 2400 deaths (Pattanaik et al. 2016). Along with high temperature, the high humidity compounds the effect of heat wave, and due to this, a quantity Heat Index (HI) is defined, which is a function of both temperature and humidity (Pattanaik et al. 2013).

As shown by Pai et al. (2013), the spatial variation of seasonal climatology of 'HW' days experienced over the country expressed as average 'HW' days per season during last 50 years from 1961 to 2010 during March to July is shown in Fig. 15.12a, b. It is seen from Fig. 15.12a that except over Northeast India and large parts of the peninsula (south of ~21°N and west of 80°E), most areas of the country have experienced on an average ≥2 HW days. Many areas of West Rajasthan, Punjab, Haryana, northern parts of East Rajasthan, Madhya Pradesh, Chattisgarh, Vidarbha, western Uttaranchal, East Uttar Pradesh, western parts of Jharkhand and Bihar, Gangetic West Bengal, northern parts of Orissa, Telangana, Coastal Andhra Pradesh, eastern parts of Rayalaseema and north Tamil Nadu on an average have experienced ≥8 HW days. Figure 15.12b is the same as Fig. 15.12a but for average 'SHW' days per season. It is seen that average 'SHW' days of 1–3 days were mainly

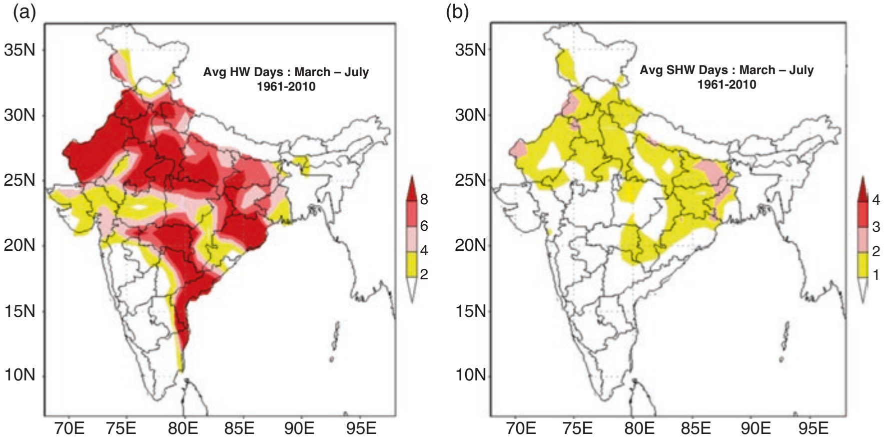


**Fig. 15.12** (**a**) Seasonal climatology map of number of HW days during the hot weather season (March–July) over India. The climatology was computed by averaging the number of HW days for the period (1961–2010) and (**b**) same as (**a**) but for number of SHW days. (Source: Pai et al. 2013)

experienced over northwest, north and eastern parts of the country. As shown by Pattanaik and Hatwar (2006), the 'HW' during the middle of June in 2005 was due to stagnation in monsoon progress over the region.

In addition to the loss of human lives associated with 'HW', the continuous higher temperatures during critical growth stages of rabi crops also reduce the crop yields considerably. Change in the characteristics of extreme temperatures of different intensities and duration has significant impact on sectors like agriculture and health. Heat wave can kill birds in the poultry farm industry. It is estimated that about 2,000,000 birds died in May and June of 2003 with an estimated loss of 27 crore rupees in Andhra Pradesh (Rao 2012). Heat wave can reduce a milk yield by 10–30% in first lactation and 5–20% in second and third lactation periods in cattle and buffaloes; it also effects the growth, puberty and maturity of crossbreed cows and buffaloes.

Cold wave conditions observed in the hilly regions in the north of India and adjoining plains are usually influenced by western disturbances. These systems are transient winter disturbances in the midlatitude westerlies that often have weak frontal characteristics. De et al. (2005), on the basis of observations from various sources, have inferred that the occurrence of cold wave conditions in the last century was at a maximum in the Jammu and Kashmir regions followed by Rajasthan and Uttar Pradesh. Results of Pai et al. (2004) show that cold wave conditions were most often experienced in west Madhya Pradesh in the decade 1971–1980, in Jammu and Kashmir in 1981–1990 and in Punjab in 1991–2000. Study by Dash and Mamgain (2011) indicates a significant decrease in the frequency of occurrence of cold nights in the winter months in India and in its homogeneous regions in the north except in the Western Himalaya. Southern regions show a drastic decrease in the frequency of cold nights relative to the period 1969–1975.

## 15.8 Climate Change Projection over India

The Fifth Assessment Report (AR5) published by IPCC (2014) presents four scenarios, known as Representative Concentration Pathways (RCPs). The scenarios show the result of different levels of emissions of greenhouse gases, from the present day to 2100, on global warming. In all scenarios, carbon dioxide concentrations are higher in 2100 than they are today. The low-emission scenario (RCP2.6) assumes substantial and sustained reductions in greenhouse gas emissions. The high-emission scenario (RCP8.5) assumes continued high rates of emissions. The two intermediate scenarios (RCPs 4.5 and 6.0) assume some stabilization in emissions. The report indicates that regardless of action taken now to reduce emissions, the climate will change until around the middle of this century. In the longer term, in all except the low-emissions scenario, global warming at the end of the twenty-first century is likely to be at least 1.5 °C. In the two higher-emission scenarios, global warming is likely to be 2 °C. In the second lowest-emission scenario, global warming is more likely than not to be 2 °C. Warming will continue beyond 2100 under all emission scenarios except the lowest and will continue to vary between years and between decades. The Fifth Assessment Report provides the strongest scientific evidence of climate change yet.

The Fourth Assessment Report (AR4) of the IPCC (2007) contains the most detailed summary of climate change situation, involving thousands of authors from dozens of countries. The summary includes the following two points.

- Warming of the climate system is unequivocal.
- Most of the observed increase in global average temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

The Special Report on Emissions Scenarios (SRES) scenarios were used for AR4 in 2007 and have been subject to discussion on whether growth in emissions since 2000 makes these scenarios obsolete. The four SRES scenario families of AR4 versus projected global average surface warming until 2100 are given in Table 15.3.

The highlights of the Fifth Assessment Report AR5 reports (IPCC 2014) over Asia region indicate the following.

**Temperature Trends**

- Projections indicate that, compared to the average in the twentieth century, average annual temperatures could rise by more than 2 °C over land in most of South Asia by the mid-twenty-first century and exceed 3 °C, up to more than 6 °C over high latitudes, by the late twenty-first century under a high-emission scenario. Under a low-emission scenario, average temperatures could rise by less than 2 °C in the twenty-first century, except at higher latitudes, which could be up to 3 °C warmer.

**Table 15.3** Four *SRES* scenario families of the Fourth Assessment Report (AR4) by the IPCC versus projected global average surface warming till 2100

| | More economic focus | More environmental focus |
|---|---|---|
| Globalization (homogeneous world) | A1<br>Rapid economic growth (groups: A1T; A1B; A1Fl)<br>1.4–6.4 °C | B1<br>Global environmental sustainability<br>1.1–2.9 °C |
| Regionalization (heterogeneous world) | A2<br>Regionally oriented economic development<br>2.0–5.4 °C | B2<br>Local environmental sustainability<br>1.4–3.8 °C |

*SRES* Special Report on Emissions Scenarios (Source: IPCC fourth Assessment Reports 2007)

- Oceans in subtropical and tropical regions of Asia could warm under all emissions scenarios and would warm most at the surface. The frequency of hot days in South Asia is likely to increase further in the future (high confidence).

**Rainfall Trends**

- Projections indicate that more rainfall will be very likely at higher latitudes by the mid-twenty-first century under a high-emission scenario and over southern areas of Asia by the late twenty-first century. Under a low-emission scenario, more rainfall at higher latitudes is likely by mid-century, but substantial changes in rainfall patterns are not likely at low latitudes. More frequent and heavy rainfall days are projected over parts of South Asia (low confidence).
- An increase in extreme rainfall events related to monsoons will be very likely in the region. More frequent and heavy rainfall days are projected over parts of South Asia (low confidence).

## 15.9 Summary and Conclusions

The observed climate variability and observed climate change is an accepted fact not only on global scale but also on regional scale over Indian region. Like the increasing trend of global mean temperature during the last 100 years, during 1901–2016, the annual mean temperature over Indian land mass also showed an increasing trend of 0.64 °C/100 years with significant increasing trend in maximum temperature (1.04 °C/100 years) and relatively lower increasing trend (0.25 °C/100 years) in minimum temperature. The observed climate variability and change over India also indicates increasing frequency of heat wave/severe heat wave days over India during the hot weather season. Similarly, during the period from 1901 to 2016, the seasonal monsoon rainfall, although, does not show any significant trend; however, there exists a multi-decadal epochal variability of rainfall in the all-India monsoon rainfall, as well as monsoon rainfall over the four homogenous regions. However, over different homogenous regions, the phases of multi-decadal variability are found to be different; it shows epochal variation.

Associated with the observed climate change, it also indicates increasing trend of frequency of heavy rainfall events.

With respect to the projected climate change in the Fifth Assessment Report (AR5) by IPCC over Asian region, it indicates increase of average annual temperatures by more than 2 °C over land in most of South Asia by the mid-twenty-first century under a high-emission scenario. Oceans in subtropical and tropical regions of Asia could warm under all emissions scenarios and would warm most at the surface. The frequency of hot days in South Asia is likely to increase further in the future. It further indicates that an increase in extreme rainfall events related to monsoons will be very likely over the South Asian region. More frequent and heavy rainfall days are projected over parts of South Asia (low confidence).

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