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Weather extremes : A spatio-temporal perspectives

L. S. RATHORE, D. R. PATTANAIK and S. C. BHAN

India Meteorological Department, New Delhi – 110 003, India

e mail : lsrathore@gmail.com

सार – एक कृषि प्रधान देश होने के नाते भारत की अर्थव्यवस्था और वृद्धि मुख्यत: मौसम के मिजाज पर निर्भर करती है, विशेष रूप से मौसम की चरम घटनाओं के समय/विलक्षण जलवायु प्रणाली वाली भारत की भूमि पर विशिष्ट प्रकार की अनेक विशेषताएं देखने को मिलती है ये विशेषताएं है: (*i*) मॉनसून की दो ऋतुएं (दक्षिण पश्चिमी और उत्तरपूर्वी), जिनकी वजह से सूखा और बाढ़ की स्थितियॉ उत्पन्न होती हैं, मानसून चक्र में व्यवधान उत्पन्न होता है और भारी वर्षा होने के कारण अकस्मात बाढ़ आ जाती है और भूस्खलन होता है। (*ii*) चक्रवात के दो मौसम (पूर्व मानसून और मानसूनोत्तर चक्रवात का मौसम) (*iii*) गर्मियों का मौसम जिसमें गर्ज भरे तूफान, धूलभरी ऑंधी ओर लू चलती है। (*iv*) हिमालयी क्षेत्रों में प्रचंड बर्फीले तूफान से शीतृऋतु, शीतलहर और कोहरा। जनसंख्या में भारी मात्रा में बढोतरी और शहरीकरण की वजह से बाढ़, सूखा, भारी वर्षा, चक्रवात, ओलावृष्टि, गर्जभरे तूफान, लू और शीतलहर जैसी मौसम की चरम घटनाएं सामाजिक आर्थिक व्यवस्था को प्रभावित करती है जिससे संवेदनशीलता बढी। भारत में मौसम की इन चरम घटनाओं के स्थानिक और कालिक विश्लेषण से संवेदनशीलता की संभावना को समझने और पूर्वानुमान करने के कौशल में सुधार लाने में अत्यंत सहायता मिलेगी और इन पूर्वानुमानों के उपयोग से मौसम की चरम घटनाओं के प्रतिकूल प्रभावों को कम किया जा सकता है।

ABSTRACT. Being mainly an agricultural country the economy of India and its growth mainly depends on the vagaries of the weather and in particular the extreme weather events. India with a land of unique climatic regime due to several characteristic features, including (*i*) two monsoon seasons (south-west and north-east) leading to drought & flood condition, active and break cycle of monsoon and also heavy rainfall leading to flash flood and landslides, (*ii*) two cyclone seasons (pre and post-monsoon cyclone seasons), (*iii*) hot weather season characterized by severe thunderstorms, dust storms and heat waves, (*iv*) cold weather season characterized by violent snow storms in the Himalayan regions, cold waves and fog. The socio-economic impacts of the extreme weather events such as floods, droughts, heavy rainfall, cyclones, hail storm, thunderstorm, heat and cold waves have been increasing due to large growth of population and urbanizations, which has led to greater vulnerability. A spatio-temporal analysis of these weather extremes over India will be very helpful to understand the vulnerability potential and to improve the forecast skill and use these forecasts in minimizing the adverse impacts of such weather extremes.

Key words – Extreme weathers, Droughts and floods, Heavy rainfall, Cyclone, Heat wave, Cold wave, Thunderstorm and hailstorm.

1. Introduction

India is a land with a unique climatic regime, being a vast country situated roughly between 8° N and 37° N latitude, occupies a large area of South Asia. This is due to several characteristic features, including (*i*) two monsoon seasons (south-west and north-east), (*ii*) two cyclone seasons (pre- and post-monsoon cyclone seasons), (*iii*) hot weather season characterized by severe thunderstorms, dust storms and heat waves, (*iv*) cold weather season characterized by violent snow storms in the Himalayan regions, cold waves and fog. Also as the Agriculture output primarily depends on rainfall (Gadgil *et al*., 1999) the variability in monsoon rainfall during June to September (JJAS) that occurs over a range of temporal scales from intra-seasonal to inter-decadal, dominated by interannual variations (Pattanaik, 2012) can have adverse impacts due to crop failures. The rain producing monsoon systems like monsoon depressions and lows and the monsoon rainfall pattern in different time scales is important for various sectors, like agriculture, water management, power industry etc. As India receives about 75 to 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. The western part of the country, including Rajasthan, Gujarat and some parts of Maharashtra are hit very frequently by drought situation. If monsoon worsens the situation spreads in other parts of the country too. The other extreme of the monsoon rainfall associated with excess seasonal rainfall during JJAS and heavy rainfall during the season can lead to flood conditions over many parts of the country. About 40 million hectares (mha) of India are prone to floods and on average, floods affect an area of around 7.5 million hectares per year. The plain region of India is affected by floods almost every year during the monsoon season associated with heavy rainfall. Thus, the inter-annual fluctuations in the summer monsoon rainfall over India are sufficiently large to cause devastating floods or serious droughts.

The variability of monsoon rainfall within a season like the onset, withdrawal and active and dry spell of monsoon is also very crucial for the country like India. Long breaks at the time of growth periods of agricultural crops can substantially reduce yield (Gadgil and Rao, 2000). Thus, monsoon rainfall prediction in different time-scale has different implication 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, 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 precipitation over India. More importantly, the rainfall forecast on smaller spatial scale of different phases of monsoon (like its onset & advance, active and break cycle of monsoon) on intra-seasonal time scale is also very crucial for the farming community (Abhilash *et al*., 2014a; Sahai *et al*., 2013; Borah *et al*., 2013; Pattanaik, 2014).

It is not only the failure of monsoon during a season which influences adversely on Agriculture, but there are many other extreme weather conditions, which impact Agriculture. The surface air temperature drives crop growth, duration; influences milk production in animals and spawning in fish. Temperature in conjunction with relative humidity can influence pest and diseases incidence on crops, livestock and poultry. Thus, for agro-economic country like India the variability of surface air temperature on different temporal scales also very 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). Many studies have analysed different temperature variability patterns over India. Kothawale and Rupa Kumar (2005) indicate that mean maximum temperature (*T*max) increased over India during 1901-1987 and there is a significant warming trend in annual mean temperature over India which appears to be mostly due to increasing *T*max during the period 1901-2003. Associated with high *T*max in summer, most areas in India experience episodes of heat waves causing sunstroke, dehydration and death (De *et al*., 2005; Pattanaik & Mukhopadhyay, 2012. At times, the extreme temperatures like heat wave can also cause enormous losses of standing crops, live stock and fisheries. Similarly, the other temperature extreme like the cold wave during winter associated with frost conditions is also very sensitive to winter crops (De *et al*., 2005; Dash and Mamgain, 2011).

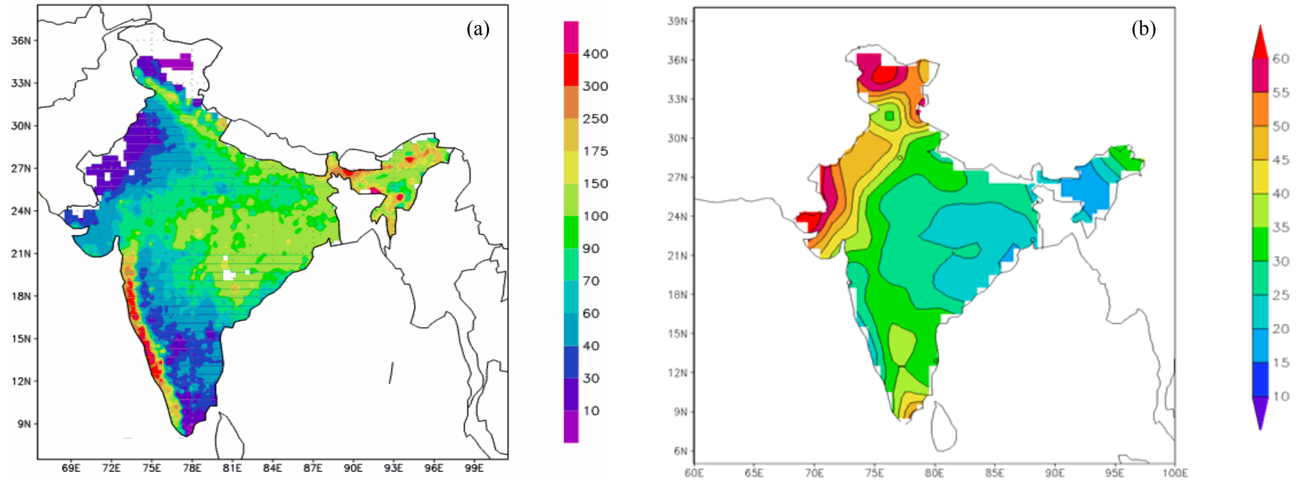
In addition to the hydro-meteorological disasters discussed above such as droughts, floods, dry spells, heat waves, cold waves, the country also frequently affected by other extreme weather and climate events such as tropical cyclones, severe thunderstorms/lightning, hailstorms, dust storms, cloud burst, etc. The major natural disaster that affects the coastal regions of India is cyclone and as India has a coastline of about 7516 kms, it is exposed to nearly 10 per cent of the world's tropical cyclones. About 71 per cent of this area is in ten states (Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Puducherry, Andhra Pradesh, Odisha and West Bengal). The islands of Andaman, Nicobar and Lakshadweep are also prone to cyclones. On an average, about five or six tropical cyclones form in the Bay of Bengal and Arabian Sea and hit the coast every year. Out of these, two or three are severe. Because of the high population density over this part of the world the risk arises due to these adverse climatic conditions are also very high.

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 (AR4; IPCC, 2007) 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. Thus, the extreme events (*e.g.*, high rainfall/floods/heat wave/cold wave/cyclone /hail/frost etc.) cause enormous losses of standing crops, live stock and fisheries. Thus, it is very desirable to study the observed spatial and temporal variability of weather and climate extremes such as : high rainfall/low rainfall/ floods/droughts/heat wave/cold wave/cyclone /hail/frost etc. The objective of the present study is to highlights the spatial and temporal variability of extreme weather over India.

2. Variability of different weather extremes over India

2.1. *Droughts and floods*

India being predominantly an agriculture country, is dependent on the monsoon (JJAS) rainfall. For the



Figs. 1(a&b). (a) Mean all India summer monsoon rainfall during June to September (1951-2003) and (b) Mean co-efficient of variability (%)

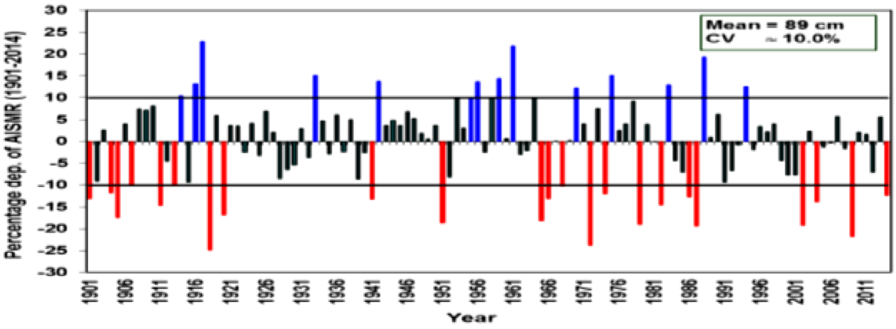


Fig. 2. Mean All India Summer Monsoon Rainfall (AISMR) departure (%) during 1901 to 2014

millions inhabiting monsoonal regions (particularly the Indian sub-continent), the seasonal variation of the rainfall associated with the monsoon system is of far greater importance than the seasonal variation of wind. It is a general perception that life in India revolves around the monsoons. Prior to the onset of monsoon, the Indian monsoon zone is characterized by the presence of a heat low centred near the central Pakistan and adjoining northwestern parts of India. Onset of monsoon over the southern tip of India (Kerala Coast) marked as the beginning of the monsoon season. Once the monsoon cover the entire country, a tropical convergence zone (commonly known as the monsoon trough) gets established over the region. Indian summer monsoon exhibits large spatial variability with regions of high rainfall (the West Coast of the peninsula and over the north-eastern regions) are associated with lowest variability and the regions of lowest rainfall (northwestern parts of India) having highest variability as seen from the mean and coefficient of variability (CV) of JJAS rainfall shown in Figs. 1(a&b) respectively.

The southwest monsoon has a stranglehold on agriculture, the Indian economy and consequently, the livelihoods of a vast majority of the rural populace. An overwhelming majority of cropped area in India (around 68%) falls within the medium and low rainfall ranges regions. The All India Summer Monsoon Rainfall (AISMR) during JJAS has a unique identity due to its large interannual variability with the long period average (LPA; 1951-2000) 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 Ni˜no (Sikka, 1980; Pant & Parthasarathy, 1981; Rasmusson & Carpenter, 1983). However, Kumar *et al.*, 1999) have suggested that the link with El Ni˜no 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 also lined various teleconnection patterns other than ENSO to explain the observed interannual variability of AISMR and also on decadal and epochal variability of

TABLE 1

Excess (14) and deficient (23) categories of years based on seasonal rainfall year based on the departure of 1 SD

AISMR (1901-2014)	Excess	1914, 1916, 1917, 1933, 1942, 1955, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994 (14 years)
	Deficient	1901, 1904, 1905, 1907, 1911, 1913, 1918, 1920, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1986, 1987, 2002, 2004, 2009, 2014 (23Years)

AISMR (Pattanaik, 2012). The inter-annual variation of AISMR during 1901-2014 is shown in Fig. 2. As seen from Fig. 2 the period from 1901 to 2014 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 regions are most prone to periodic drought. These regions receive less than 100 cm of rainfall. The drought of 1965-67 and 1979-80 affected relatively high rainfall regions, while the drought of 1972, 1987, 2002, 2004, and 2009 affected low-rainfall regions, mostly semi-arid and sub-humid regions. The interannual variability of AISMR shows more number of drought years (23 years ≈20.2%) compared to the flood years (14 years ≈ 12.2%) during the period 1901 to 2014. The deficient and excess years are identified from Fig. 2 is also given in Table 1. As seen from Fig. 2 among the drought years, the year 1918 received the lowest rainfall (75.1% of LPA) followed by the years, 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 exceeds 2 SD (≈ +20%) value. It may be mentioned here that even in a year of excess (deficient) year on all India scale there are pockets of deficient (excess) rainfall over some parts of the country leading to drought (flood) situations.

Drought poses many problems. Irrigation facilities available in country are limited and therefore, when drought occurs, they cause partial or complete crop failure. If failures occur in consecutive years, it becomes a national calamity, putting great strain on the economy of the country. 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. The three recent worst drought years are 1987, 2002 and 2009. Drought of 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%.

2.2. *Active and break cycles of monsoon*

Analysis of seasonal monsoon rainfall shows intra seasonal variations with active and break phase of monsoon, which is very important for the agriculture sectors and water management. The convective activity over the monsoon trough region and that over the equatorial south Indian ocean oscillates with sea-saw relation with one active and other inactive and *vice versa*. These influence the monsoon activity over Indian region (Gadgil, 2000; Pattanaik, 2007) on intra-seasonal scale. The phenomenon of `break monsoon' is of great interest because long intense breaks are often associated with poor monsoon seasons. Such breaks have distinct circulation characteristics (heat trough type circulation) and have a large impact on rainfed Agriculture. Anomalous southward intrusion of troughs in the mid-latitude westerlies into the Indo-Pak region in the middle and upper troposphere (Ramaswamy, 1962) are often associated with break in monsoon condition. The long dry spell of July 2002 was associated with more number of typhoon activities over the northwest Pacific and its northerly tracks (Pattanaik & Rajeevan, 2007). Although interruption of the monsoon rainfall is considered to be the most important feature of the break monsoon, traditionally breaks have been identified on the basis of the surface pressure and wind patterns over the Indian region. In Ramamurthy's (1969) comprehensive study of breaks during 1888-1967, a break situation was defined as one in which the surface trough (the 'monsoon trough') is located close to the foothills, easterly winds disappear from the sea level and 850 hPa charts, provided the condition persisted for at least two days. However, Ramamurthy (1969) did not propose any criteria for identifying active spells. Subsequent to the classic work of Ramamurthy's (1969), De *et al.* (1998) have identified the breaks during 1968-1997 using the same criteria.

TABLE 2

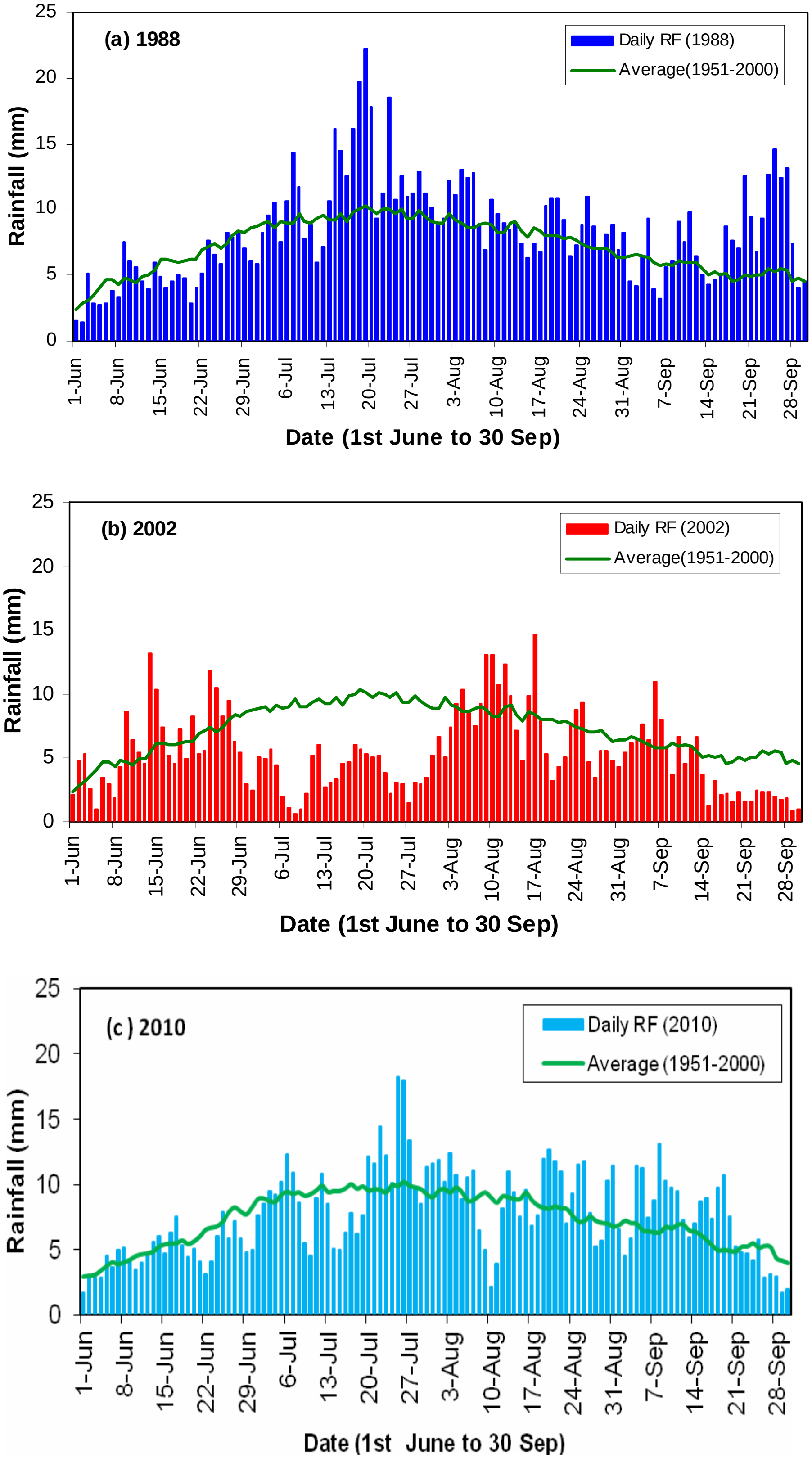
Active and break spells during July and August identified based on rainfall criteria of Rajeevan *et al*. (2010) for the period 1951-2007 along with that identified based on synoptic criteria by Ramamurthy (1969) for 1951-1967 and De *et al*. (1998). The active and break spells by rainfall criteria of Pai *et al*. (2013b), which is almost identical with that of Rajeevan *et al*. (2010) is also given for recent years from 2008 to 2014

Year	Active spells by rainfall criteria of Rajeevan *et al*. (2010) and Pai *et al*. (2013b)	Break spells by rainfall criteria of Rajeevan *et al*. (2010) and Pai *et al*. (2013b)	Break by synoptic criteria used by Ramamurthy (1969) and De *et al*. (1998)
1951	25–27J	24–29A	1–3J, 11–13J, 15–17J, 24–29A
1952	23–31J	9–13J.28–30A	9–12J
1953	3–5A, 12–19A	–	24-26J
1954	9–12A	22–28A	18–29J, 21–25A
1955	29–31A	24–26J	22–29J
1956	2–8J, 11–14J,1–5A	–	23–26A
1957	20–23A	–	27–31J, 5–7A
1958	8–11J	–	10–14A
1959	12–14J, 26–29J	–	16–18A
1960	1–4J, 15–17A	18-23J	16–21J
1961	6–10J, 16–18J, 24–26A	–	–
1962	16–18J, 12–14A	27-29J	18–22A
1963	10–12A	13-19J, 21-23J	10–13J, 17–21J
1964	5–7J, 15–17A, 23–25A	29J-4A	14–18J, 28J–3A
1965	26–29J, 24–26A	6-11J, 1-14A	6–8J, 4–15A
1966	–	2–12J, 21–31A	2–11J, 23–27A
1967	1–3J, 24–29J	7-14J	7–10J
1968	5–10J, 29-31J, 4–6A	25-31A	25–29A
1969	29J–1A	–	17–20A, 25–27A
1970	1–3J, 17–20A, 27–29A	13-19J	12-25J
1971	19–21J, 26–31A	8-10J, 5-7A, 17-20A	17-20A
1972	5–7J	18J-3A	17J-3A
1973	7–9J, 13–15J, 12–14A, 18–20A, 26–31A	24-26J, 31J-2A	23J–1A
1974	17–20A	29-31A	30–31A
1975	13–16J, 12–15A	–	24–28J
1976	16–18J, 28–31A	–	–
1977	5–7J	15-20A	15–18A
1978	7–10J, 15–17A, 24–30A	–	16–21J
1979	3–5A, 7–12A	2–6J, 14–29A	17–23J, 15–31A
1980	1–3J	17–20J, 13–15A	17–20J
1981	7–10J	24–27A	26–30J, 23–27A
1982	12–14A, 17–23A	1-8J	–
1983	18–21J, 18–20A	23–25A	22–25A
1984	3–6A, 9–11A, 15–19A	27–29J	20–24J
1985	15–17J, 30J–3A, 6–9A	23-25A	22–25A
1986	21–24J, 13–15A	22-31A	23–26A, 29–31A

TABLE 2 (*Contd.*)

Year	Active spells by rainfall criteria of Rajeevan *et al*. (2010) and Pai *et al*. (2013b)	Break spells by rainfall criteria of Rajeevan *et al*. (2010) and Pai *et al*. (2013b)	Break by synoptic criteria used by Ramamurthy (1969) and De *et al*. (1998)
1987	24–29A	23–25J, 30J–4A, 8–13A, 16–18A	28J–1A
1988	26–28J	14-17A	5–8J, 13–15A
1989	–	18–20J, 30J–3A	10–12J, 29–31J
1990	21–24A, 29–31A	–	8-10J, 27-31J
1991	29–31J	–	–
1992	26–29J, 16–18A	4-11J	–
1993	7–9J, 15–18J	20–23J, 7–13A, 22–28A	19-21J
1994	2–4J, 9–17J, 18–20A, 25–27A	–	–
1995	18–25J	3–7J, 11–16A	12-15A
1996	24–28J, 19–22A	10–12A	1-5J
1997	30J–1A, 20–26A	11–15J, 9–14A	–
1998	3–6J	20–26J, 16–21A	–
1999	–	1–5J, 12–16A, 22–25A	–
2000	12–15J, 17–20J	1-9A	–
2001	9–12J	31J–2A, 26–30A	–
2002	–	4–17J, 21–31J	–
2003	26–28J	–	–
2004	30J–1A	10–13J, 19–21J, 26–31A	–
2005	1–4J, 27J–1A	7–14A, 24–31A	–
2006	3–6J, 28J–2A, 5–7A, 13–22A	–	–
2007	1–4J, 6–9J, 6–9A	18–22J, 15–17A	–
2008	10-12A	16-21J, 21-24A, 28-30A	–
2009	13-16J, 20-23J	29J-9A, 17-19A	–
2010	–	-	–
2011	25-27A	1-3J	–
2012	11-13A	–	–
2013	19-22A	–	–
2014	21-23J, 4-6A	15-21A	–

Rajeevan *et al*. (2010) suggested criteria for the identification of active and break spells on the basis of recently derived daily gridded rainfall dataset (Rajeevan *et al*., 2006). The criteria were carefully chosen so that they can be used on real-time applications during the monsoon using operational daily rainfall analysis. In the method active and break events were identified by averaging the daily rainfall over the core monsoon zone and standardizing the daily rainfall time series by subtracting from its long term normal (1951-2000) and by dividing with its daily standard deviation. The core region is roughly from 18.0° N to 28.0° N and 65.0° E to 88.0° E. The active and break spells during July and August identified by Rajeevan *et al*. (2010) using this method from 1951 to 2007 (Table 2) is compared with break days with those defined by Ramamurthy (1969) from 1901 to 1967 and De *et al*. (1998) from 1968-1996. As seen from Table 2 for smaller duration break there is a very large overlap and the break spells for the period 1951-2007 using the criteria of Rajeevan *et al*. (2010) found to be mostly comparable with those identified by Ramamurthy (1969) and De *et al*. (1998). Later, Pai *et al*. (2013b) with the high resolution gridded rainfall data (0.25 × 0.25) and used the criteria suggested by Rajeevan *et al*. (2010) to



Figs. 3(a-c). All India area weighted daily rainfall (mm) during the monsoon season of (a) excess year 1988, (b) deficient year 2002 and (c) normal year 2010

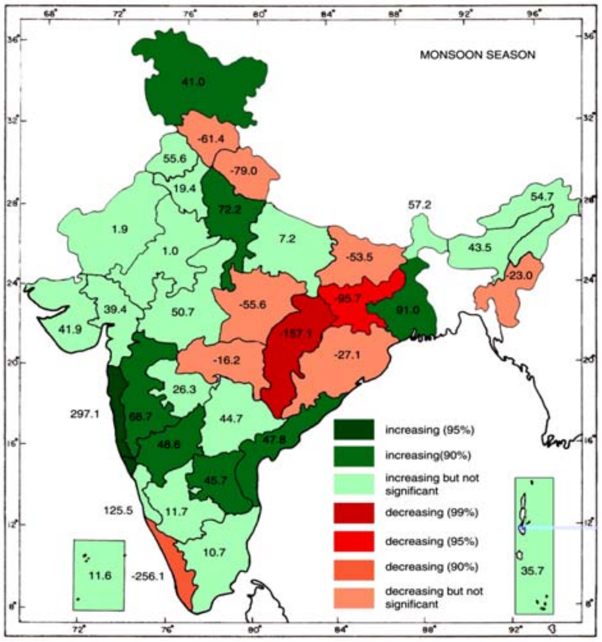


Fig. 4. Increase/Decrease in seasonal rainfall in mm during 100 year for each of 36 meteorological subdivisions for the south-west monsoon season during June to September. Different levels of significance for increasing and decreasing trend are shaded with colours (*Source* : Guhathakurta and Rajeevan, 2007)

identify the break and active spells for the entire data period of 1901-2010. As discussed by them the break and active spells identified by them are comparable and nearly consistent with that identified by Rajeevan *et al*. (2010) for the common period of 1951-2007 except for the year 1956, when there was no break identified by Rajeevan *et al*. (2010) but the Pai *et al*. (2013b) identified the break from 25-29 August. Thus, the active and break spells based on Pai *et al*. (2013b) is included in the Table 2 from 2008 to 2010 and from the IMD's monsoon report from the period 2011-2014, which followed the same criteria as used by Pai *et al*. (2013b).

The coupled convective phenomenon like the phase and magnitude of Madden Julian Oscillation (MJO) has direct influence on intra-seasonal oscillation of monsoon rainfall over India (Pai *et al*., 2009). The excess (deficient) rainfall years are mainly associated with more active (break) spells of monsoon. The prolonged break during July for the deficient year 2002 (AISMR 81% of LPA) and the very active cycle of monsoon during the excess year 1988 (AISMR 119% of LPA) are shown in Figs. 3(a&b) respectively. Even the normal seasonal monsoon year like 2010 (AISMR 102% of LPA) also have intra-seasonal variation with active and weak phases of monsoon [Fig. 3(c)]. Like in case of inter-annual variability the intra-seasonal variability of monsoon rainfall over India as a whole as shown in Figs. 3(a-c) can be different over smaller spatial domains like a state or meteorological sub-division, where it can experience long break (active) spells of monsoon in spite of all India rainfall on active (break) phase.

2.3. *Sub-division-wise trend of monsoon rainfall*

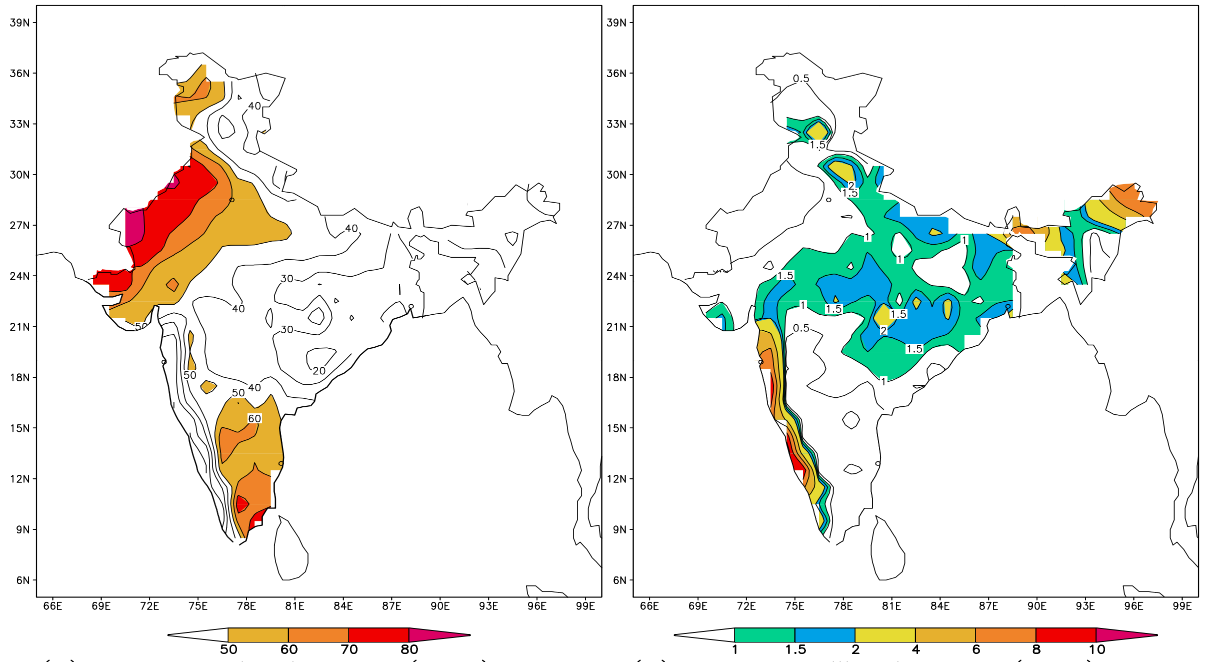
Although the Fig. 2 indicates large variability of AISMR and monthly rainfall respectively it does not show any significant linear trend. However, there exists trend in the sub-divisional rainfall (Guhathakurta and Rajeevan, 2007). As shown by them and also indicated here (Fig. 4) during the season as a whole, three sub-divisions, *viz*., Jharkhand, Chattisgarh, Kerala show significant decreasing trend and eight subdivisions, *viz*., Gangetic West Bengal, West Uttar Pradesh, Jammu & Kashmir, Konkan & Goa, Madhya Maharashtra, Rayalaseema, Coastal Andhra Pradesh and North Interior Karnataka show significant increasing trends.

2.4. *Extreme rainfall and its variability*

During the southwest monsoon season JJAS many parts of India including the west coast of the peninsula, northeast and central region of the country receive heavy to very heavy rainfall during the 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 is 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 Krishna 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 and can have major impacts on society, environment and the economy of the country. There are many past instances of Indian stations having recorded as much as half of their annual mean rainfall, and sometimes even more than their annual mean rainfall, 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).

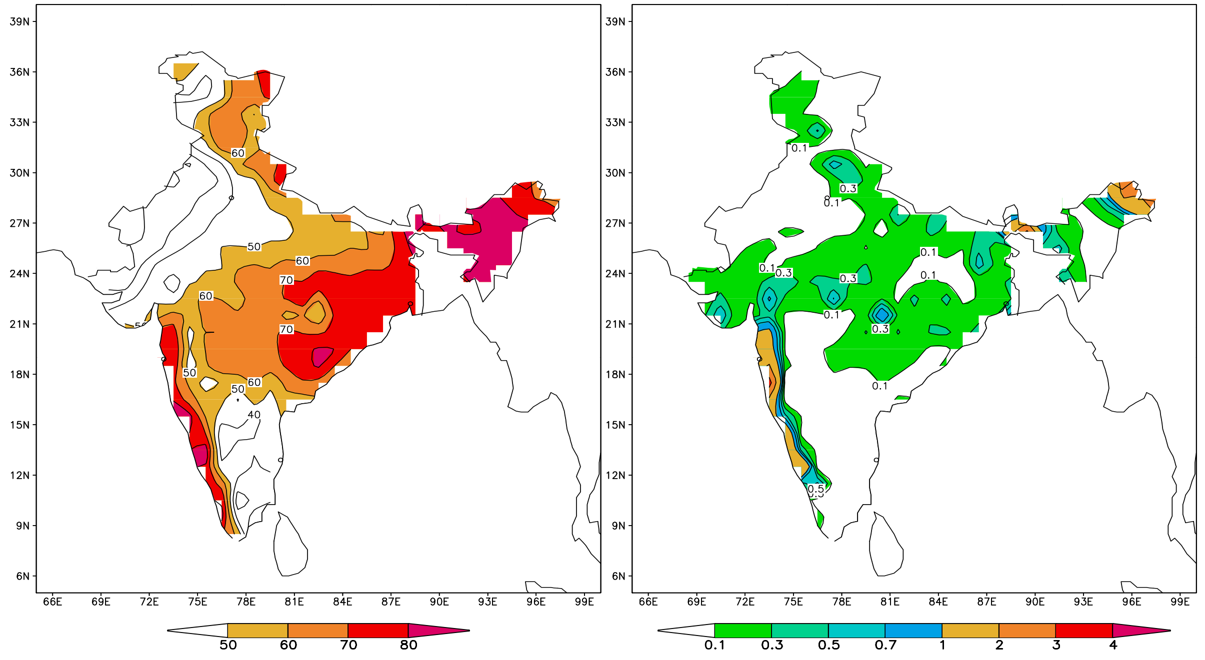
(a) % of no rain days

(c) % of very heavy rain days

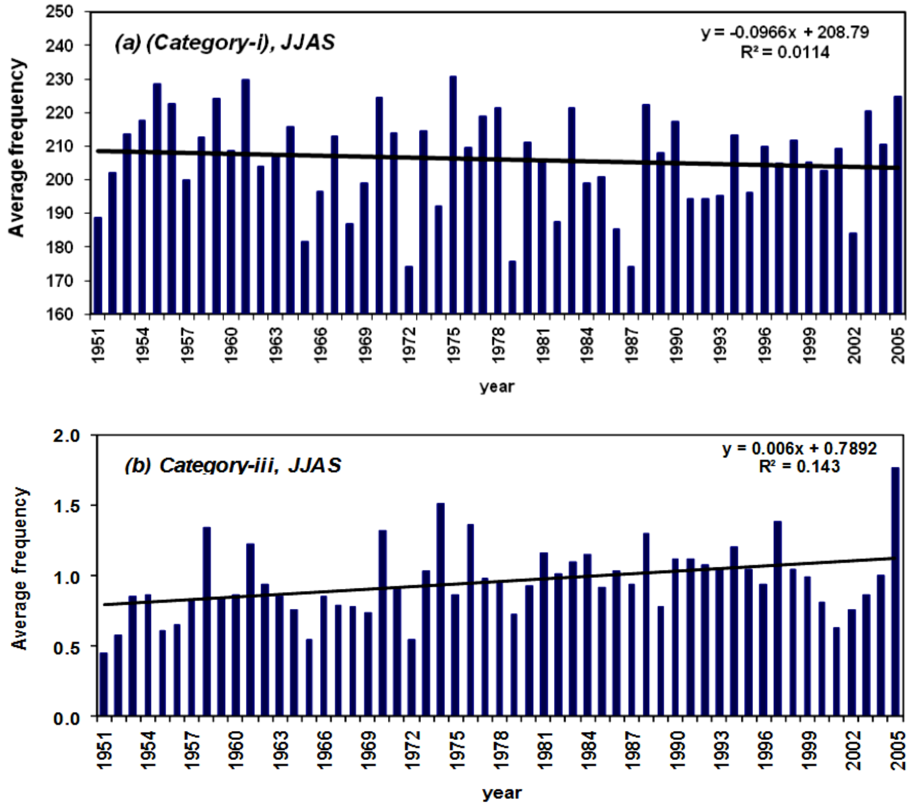


(b) % of heavy rain days

(d) % of exceptional heavy rain days



Figs. 5(a-d). Average percentage of frequency of no-rain days and different categories of rain days identified in Table 1 during the monsoon season (June to September) from 1951 to 2005. (a) % of no-rain days, (b) % of Category i rainfall days, (c) % of Category ii rainfall days and (d) % of Category iii 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).



Figs. 6(a&b). Average frequency (count per day) of occurrence of different rainfall (R) events during monsoon season (June to September) from 1951 to 2005. (a) Category-i with 'R' ≤ 64.4 mm in a day and (b) Category-iii with 'R' > 124.4 mm in a day

Climate change studies have indicated increasing frequency of extreme weather events including the frequency of heavy rainfall over the globe. Many modelling studies indicate changes in intense precipitation 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 (Rajeevan *et al.*, 2006; 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 the frequency of heavy rainfall events over the Indian region 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 (Rajeevan *et al.*, 2006). 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 event such as (*i*) light to rather heavy rainfall ($0<R \leq 64.4$ mm), (*ii*) heavy rainfall ($64.4<R \leq 124.4$ mm) and (*iii*) 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 is 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 Figs. 5(a-d). The no rain days as shown in Fig. 5(a) gradually increases towards northwest parts of India where the number of rainy days in a season JJAS are less, whereas Fig. 5(b) shows the highest frequency of Category-i rainfall days (more than 70%) over the west coast, eastern and north east regions, gradually decreasing towards the northwest of India. The average frequency of Category-ii and

Category-iii rainfall as shown in Fig. 5(c) and Fig. 5(d) respectively is very small compared to the frequency of Category-i rainfall over almost the entire country with the highest frequency over the west coast of India (more than 10% for Category-ii and more than 3% for Category-iii), 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. Fig. 5(d) 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. They found that the frequency of extreme rainfall (Rainfall ≥ 124.4 mm) show increasing trend over the Indian monsoon region during the southwest monsoon season JJAS and is significant at 98% level [Fig. 6(b)]. Their study also found that the increasing trend of contribution from extreme rainfall events during JJAS is [Fig. 6(b)] balanced by a decreasing trend in category-i (rainfall ≤ 64.4 mm/day) rainfall events [Fig. 6(a)]. On monthly scale the frequency of extreme rainfall events show significant (95% level) increasing trend during June and July, whereas during August and September the increasing trend is not significant statistically (Fig. Not shown). 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).

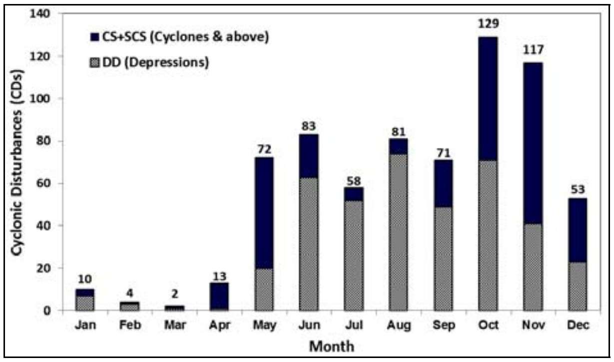


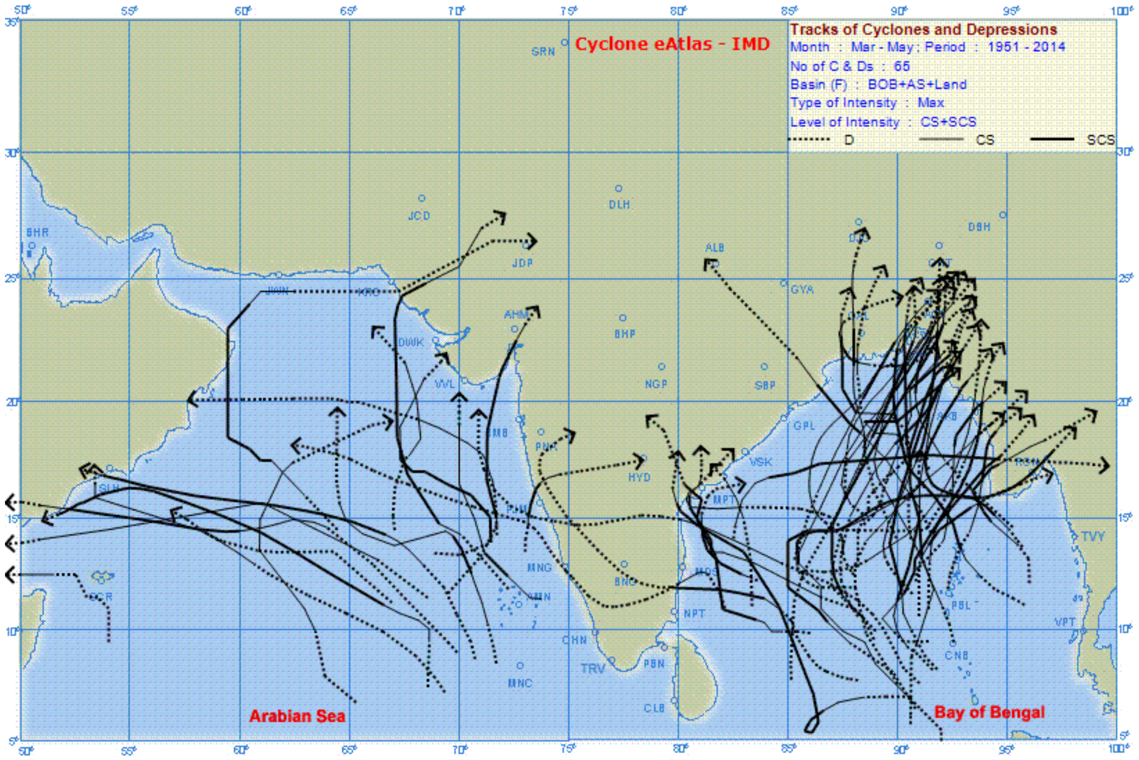
Fig. 7. Climatology (1951-2014) of cyclonic disturbances (CDs) over Bay of Bengal (BoB) during post monsoon season from October to December

3. Tropical cyclone

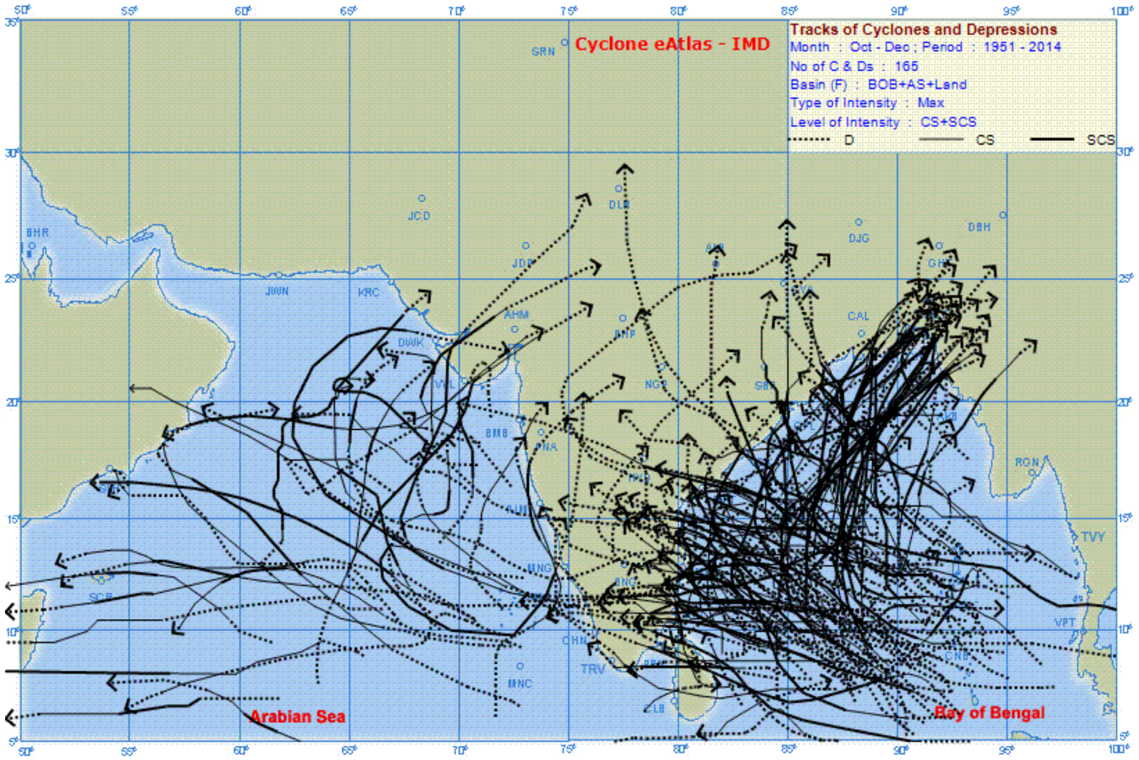
The tropical cyclones (TCs) are one of the most dangerous natural disasters throughout the globe. The major natural disaster that affects the coastal regions of India is cyclone as it has a vast coastline on eastern and western parts. The TC hazard proneness varies along the coast depending upon the frequency of TCs & severe TCs land-falling on the coast and associated heavy rain, wind & storm surge (Mohapatra *et al*., 2012a). These systems form initially as low-pressure areas (when the maximum sustained surface wind is less than 17 knots) over the North Indian Ocean (NIO) and then intensify into depressions (DD; maximum sustained surface wind is between 17 and 33 knots) and occasionally become TCs (Cyclonic Storm (CS); when surface wind speed is between 34 and 47 knots and severe cyclonic storm (SCS) when surface wind speed is between 48 knots to 63 knots; Very Severe Cyclonic Storm (VSCS) when it exceeds 63 knots till 119 kts; Super cyclone when surface wind speed exceeds 119 kts. As shown in some previous studies (Pattanaik 2005; Mohapatra *et al*., 2012b) for the TCs only, the peak is observed during November, followed by October in the post-monsoon season (October to December; OND), followed by the month of May in pre-monsoon season (March to May; MAM). This is also seen from Fig. 7 based on the data of 64 years from 1951-2014, which indicates monthly total cyclonic disturbances (CDs; system with DD, CS, SCS or higher intensity) formed over the NIO during last 64 (1951-2014) years period. These data sets are collected from the storm e-atlas (IMD, 2012a) published by IMD. Over the Bay of Bengal (BoB), the months of October-November are known to produce CDs of severe intensity. The strong winds, heavy rains and large storm surges associated with CDs are the factors that eventually lead to loss of life and property. Rains associated with cyclones are another source of damage. The combination of a shallow coastal plain along with the world's highest population density coupled with low socio-economic conditions in the region surrounding the BoB has resulted in several land falling CDs becoming devastating natural disasters. The super cyclone of October, 1999 hitting eastern coast of India (Odisha state), VSCS Phailin of October 2013 hitting Odisha and VSCS Hudhud of October 2014 hitting eastern coast of India (Andhra Pradesh) is still in our memory.

The track of TCs over the NIO during two cyclone seasons MAM and OND during 1951-2014 are shown in Figs. 8(a&b) respectively. The incidence of TCs with intensity of severe to very severe cyclones cross Tamil Nadu and Andhra Pradesh is high during the north east monsoon season (OND), whereas, the highest annual number of CSs and SCSs occur in Odisha-West Bengal coast. As the Figure indicates most of the systems during OND form over BoB have westward/north-westward tracks and cross the Indian land mass and few of the BoB systems also re-curve and move in north-eastwards and cross Bangladesh and north-eastern parts of India. As seen from Fig. 8(b) some systems also form over the

(a) Mar-May, Cyclonic Storms (1951-2014)



(b) Oct-Dec, Cyclonic Storms (1951-2014)



Figs. 8(a&b). Observed tracks of TCs during (a) MAM and (b) Oct-Dec seasons during the period from 1951-2014

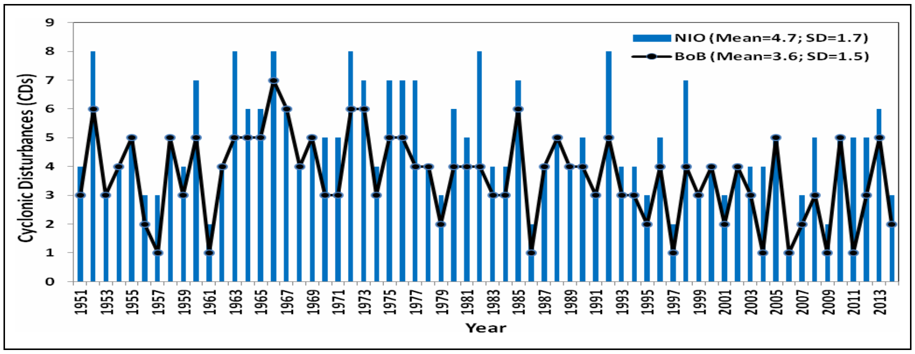


Fig. 9. Frequency of cyclonic disturbances (CDs) over North Indian Ocean (NIO) and Bay of Bengal (BoB) during post monsoon season from October to December, 1951-2014

Arabian Sea and mostly move west/north-westwards and do not affect Indian coast. However, few of them re-curve and cross north-western coast of India. During MAM season most of the systems form over BoB have northerly/northeasterly track, whereas, over the Arabian Sea it moves in northwesterly direction except few of them recurve and cross Gujarat coast [Fig. 8(a)]. The year to year frequency of CDs during OND season over the BoB and NIO during the 64 years period from 1951 to 2014 is shown in Fig. 9, which does not show any significant trend. During most of the years the BoB dominate the formation of CDs, however, during some years like 1982 and 2011 the CDs over Arabian Sea is much higher than that over the BoB. As seen from Fig. 9 the mean CDs frequency over the BoB and the NIO is found to be 3.4 and 4.6 respectively.

4. Heat wave and abnormal high temperatures

Pre-monsoon : 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 (*T*max) 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 almost 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 *T*max 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 *T*max departure is 5 °C to 6 °C and Severe HW (SHW) if *T*max departure ≥ 7 °C; When normal *T*max of a station > 40 °C, HW if *T*max departure is 4 °C to 5 °C and SHW if *T*max departure ≥ 6 °C) almost during every year causing sunstroke, dehydration and death. As reported the death tolls that were recorded over an entire summer some 10 years ago over India now routinely occur in just one week (Larsen, 2003). The global climate anomalies have indicated that 1998 was the warmest year in last century (Jones & Briffa, 1992) with more than 1000 people have died over India due to scorching temperatures over Orissa, Coastal Andhra Pradesh, Rajasthan and Tamilnadu during May/June. Similarly, in May 2003 the heat wave claimed over 1,600 lives throughout the country with some 1,200 individuals died in the state of Andhra Pradesh alone. Like in 2003, during 2005 also 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 neighbourhood (Bhadram *et al.*, 2005). 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).

A recent study (Perkins *et al.*, 2012), based on the analysis of multiple indices derived from the latest HadGHCND daily maximum temperature, minimum temperature and average temperature for the period 1950-2011, found increasing global trends in the intensity, frequency and duration in the observed summer time heat waves and annually calculated warm spells. The study also observed that in some regions, the non-summer warming events are driving the trends in the annual events. 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). A recent report by IPCC (IPCC, 2007) indicates increasing trend of the mean annual global (land + ocean) surface air temperature by about 0.74 °C during last 100 years (1906 to 2005) with land

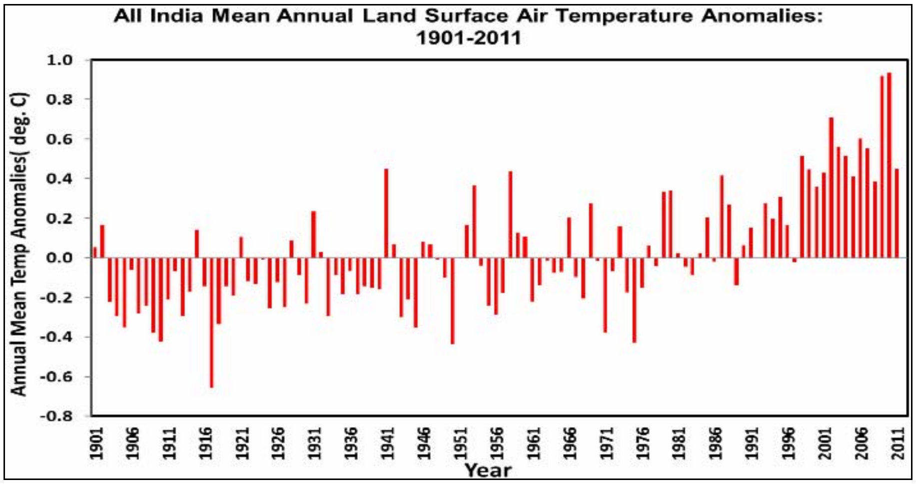
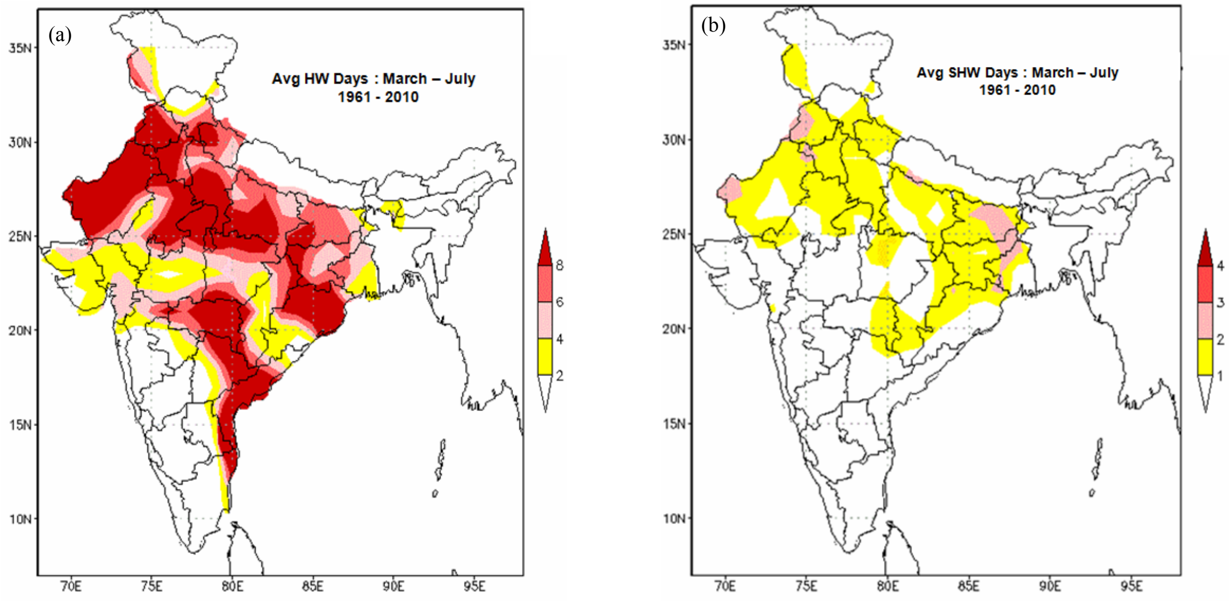


Fig. 10. Annual mean land surface air temperature anomalies averaged over the country as a whole (All India) for the period 1901-2011. The period of 1971-2000 was used for computing the anomalies. (*Source* : IMD, 2012b)

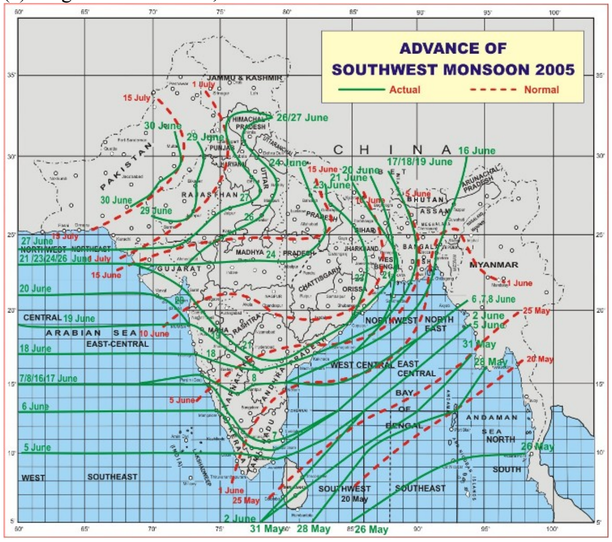


Figs. 11(a&b). (a) Seasonal climatology map of number of HW days during the hot weather season (March - July) over India. The climatology was computed by averaging the number of HW days for the period (1961-2010) and (b) Same as 'a' but for number of SHW days. (Adopted from Pai *et al*., 2013a)

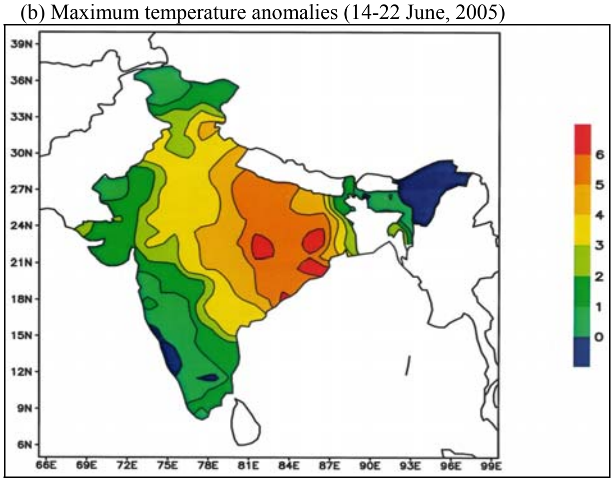
temperature increasing at much higher rate than this. This report also indicates significant increasing trend of 'HW' over different parts of the globe. The similar increasing trend of global surface air temperature is also reported over India, which can be seen from Fig. 10 for last 111 years from 1901 to 2011, with the linear trend per 100 years in the annual mean land surface air temperature anomalies averaged over India was 0.62 °C. The 10 warmest years on record in order are: 2009 (0.77), 2010 (0.75), 2003(0.61), 2002(0.59), 1998(0.49), 2012(0.48), 2014 (+0.53), 2006(0.43), 2007(0.41) and 1987(0.40). It may be mentioned that 7 out of the 10 warmest years in India were during the recent past decade (2001-2010) making it the warmest decade on record with decadal mean temperature anomaly of 0.49 °C.

Many authors have made detailed studies of 'HW' over India in recent times (De *et al*., 2005;

(a) Progress of monsoon, 2005



(b) Maximum temperature anomalies (14-22 June, 2005)

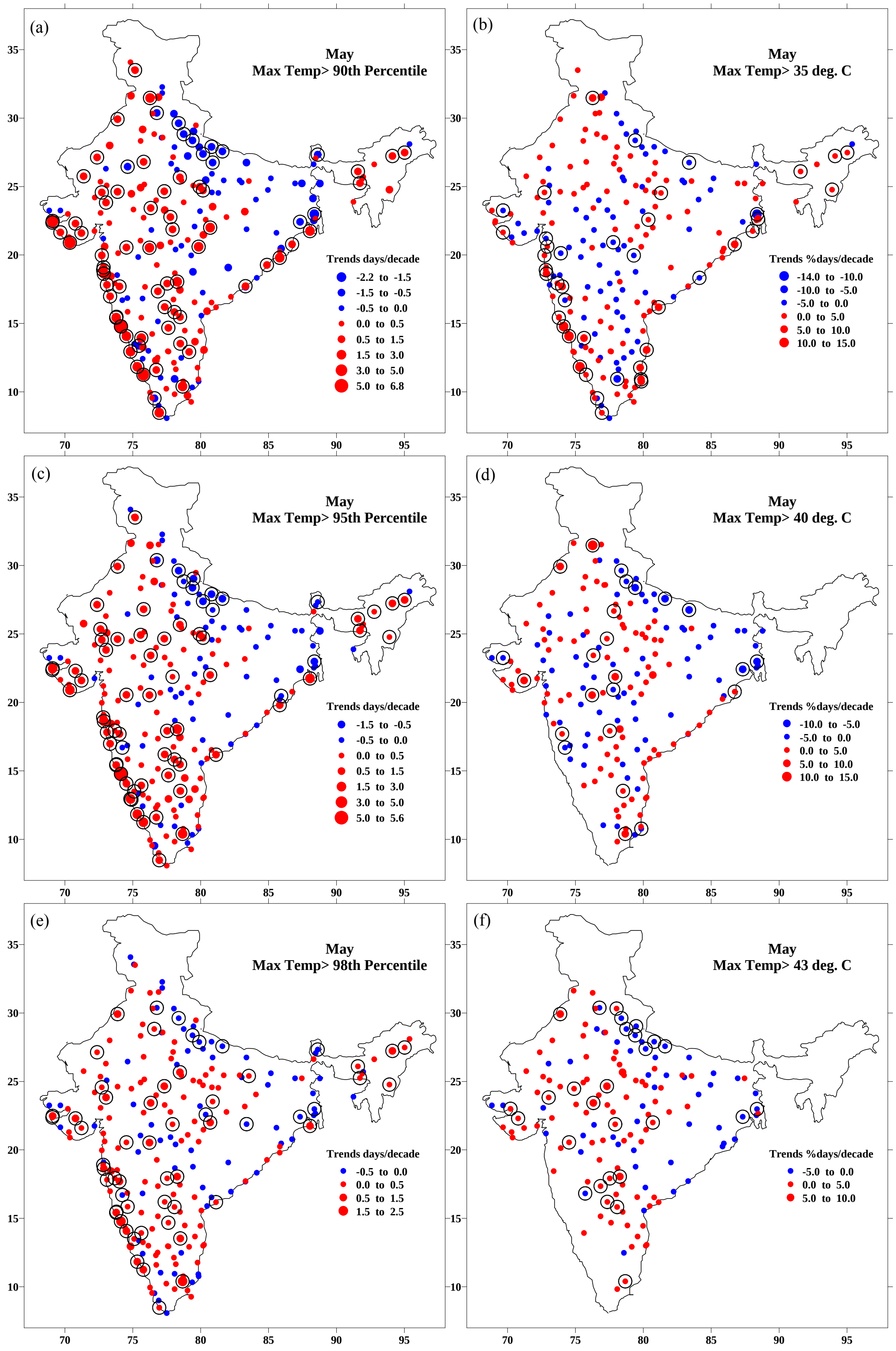


Figs. 12(a&b). (a) Progress of monsoon during 2005 and (b) Maximum temperature anomalies during 14-22 June, 2005 in °C. (Adopted from Pattanaik and Hatwar, 2006)

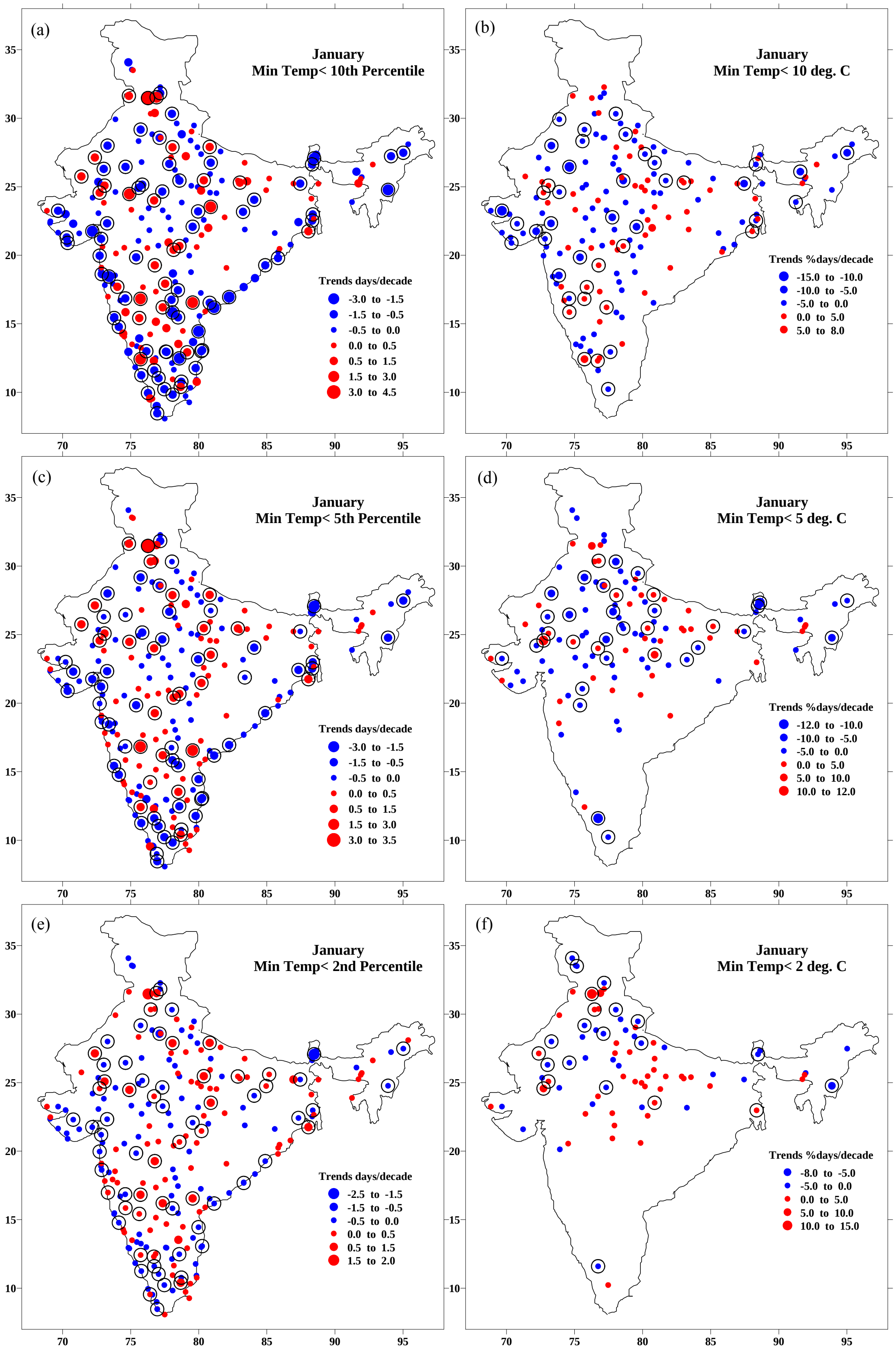
Bhadram *et al*., 2005; Pai *et al*., 2013a; Pattanaik *et al*., 2013 etc.). As shown by Pai *et al*. (2013a) the spatial variation of seasonal climatology of 'HW' days experienced over the country expressed as average 'HW' days per season during last fifty years from 1961 to 2010 during March to July is shown in Figs. 11 (a&b). It is seen from Fig. 11(a) that except over northeast India and large parts of Peninsula (South of ~21° N & 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 & 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. Fig. 11(b) is same as Fig. 11(a) but for average 'SHW' days per season. It is seen that average 'SHW' days of 1-3 days were mainly experienced over northwest, north and eastern parts of the country. Sometime, during late June the 'HW' also occurs over parts of India associated with stagnation in monsoon progress. As shown by Pattanaik and Hatwar (2006) the 'HW' during the middle of June in 2005 was due to such stagnation in monsoon progress over the region [Fig. 12(a)]. During the period from 14-22 June, 2005 the *T*max anomy reported was of the order of 5 to 6 °C [Figs. 12(b)] in some of the eastern states of India, where the maximum death were reported during this period.

It is not only the loss of life associated with 'HW' is important but also the continuous higher temperatures during critical growth stages of rabi crops reduces the crop yields considerably. Change in the characteristics of temperature extremes of different intensities and duration has significant impact on sectors like agriculture and health. Heat wave can kill birds in the poultry firm. It is estimated that about 20 lakhs birds died in May & June 2003 with an estimated loss of 27 Crores 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 effect the growth, puberty and maturity of crossbreed of cows and buffaloes. With respect to the fisheries, mortality of fish lings in shallow water ponds and during 'HW' conditions fish moves into the deeper layers thereby reduces fish catch in the water bodies.

Many studies have indicated observed changes in extreme temperatures 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 increasing trend in the number of warm days in summer is noticed only in the interior peninsula. In the entire country and on the east coast and west coast, the maximum number of warm days in summer has been noticed only during the last decade, 1996-2005. There results broadly suggest warming trends in large 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



Figs. 13(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



Figs. 14(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 events in India. Jaswal *et al*., (2014) studied monthly temperature extremes over India during summer using daily temperature data for 1969-2012 by using both the percentile and absolute values simultaneously. On the basis of percentiles and absolute values of daily *T*max 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 Figs. 13(a-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 increasing over west coast of India in all summer months.

- There is significant decrease in hot, very hot and extremely hot days over Indo-Gangetic plains in the month of May [Figs. 13(a-f)].

5. Cold wave, abnormal low temperatures and fog

The season from December to February is the wintertime in almost all over India and experience 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 on every winter parts of north India, northwest India and central India experiences cold wave (CW) and severe cold wave (SCW) conditions. Occurrences of extreme low temperature in association with incursion of dry cold winds from north into 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 so 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 Agriculture point of view *T*min is very important about the protection of plant from frost injury. As plenty of moisture is available in the atmosphere immediately after the passage of a western disturbance and with other favourable regional and synoptic scale conditions 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 has been increased associated with the rise of pollution causing a fall in *T*max in winter.

Kothawale *et al*. (2010) have found widespread decreasing trend in those of 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 *T*min over India during 1969 to 2012 simultaneously Jaswal *et al*., (2014) by 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 Figs. 14(a-f). The percentile and absolute value based data series of CN, VCN, ECN are prepared for all 227 stations for winter months from December to February for the period 1969-2012. The main findings from their study are : decreasing trend of cold, very cold and extremely cold nights in December, mixed trend in January [Figs. 14(a-f)] while in February, there is significant decreasing trend in north India and mixed trend in south India.

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 1971-80, in Jammu and Kashmir in 1981-90, 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 1969-75.

6. Thunderstorm, hailstorm and tornadoes

Thunderstorm is a severe weather phenomenon, the impact of which is being increasingly felt by all the sectors of society. Thunderstorm is one of the most spectacular weather phenomenon offered by nature. It is having giant cumulus cloud developing into a towering dark cumulonimbus accompanied with lightning flashes

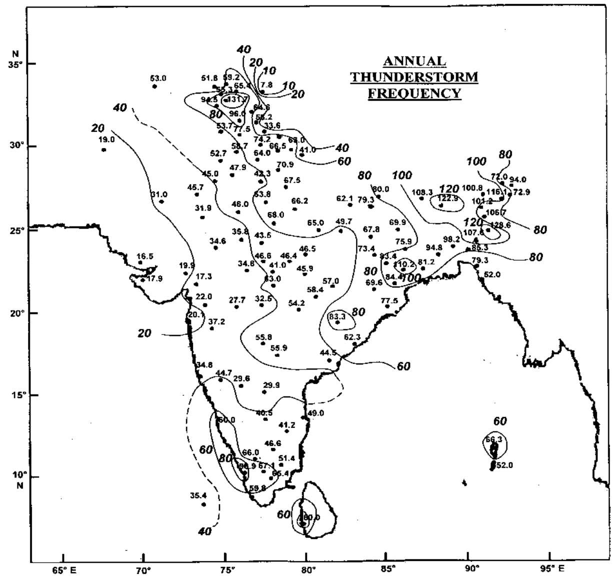


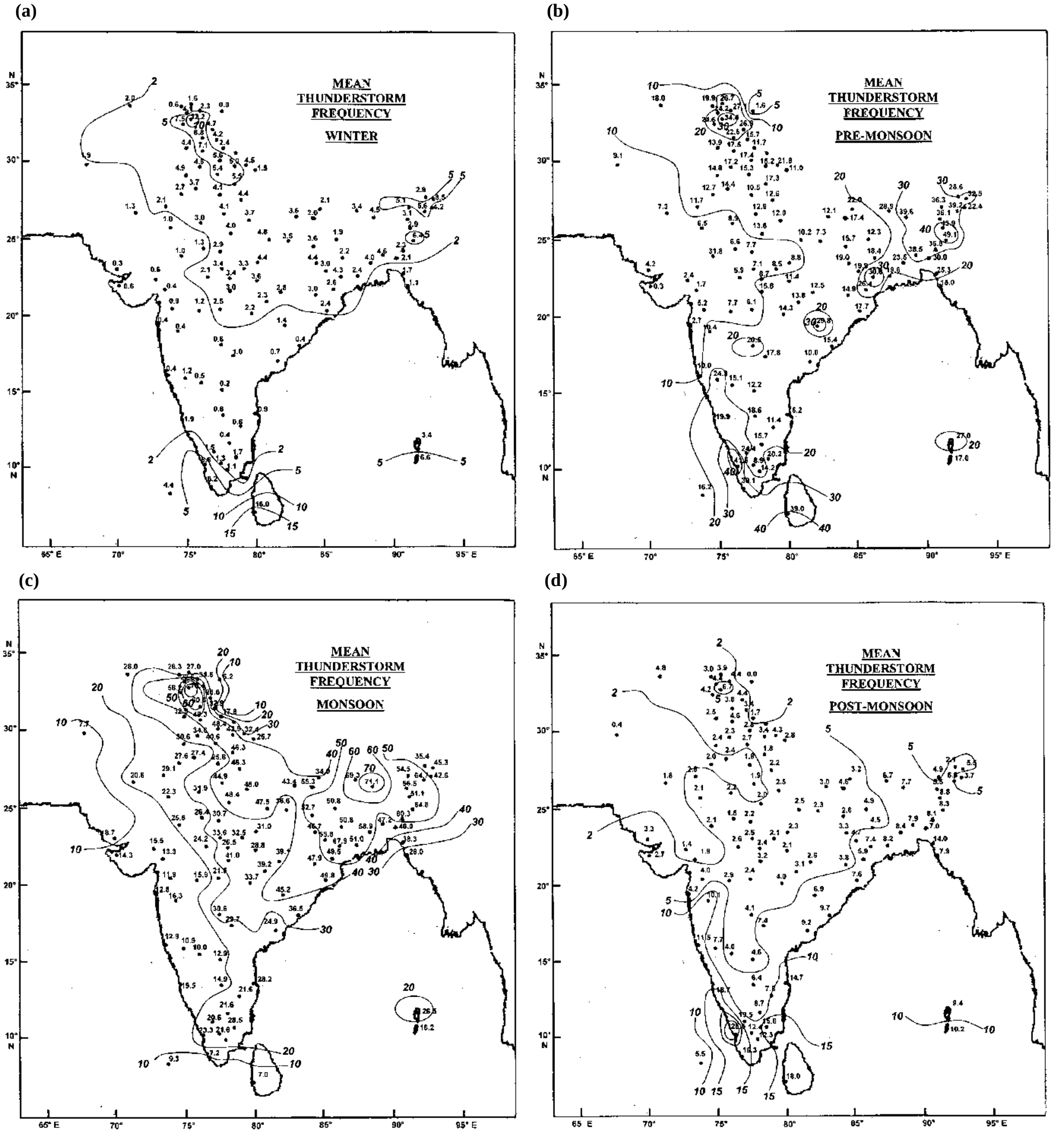
Fig. 15. Annual mean frequency of thunderstorm days (Adopted from Tyagi, 2007)

and thunder. While farmers welcome thunderstorm for rains and consequent benefits. However, sometime the high impact weather phenomenon on mesoscale like hailstorm, heavy rain and squalls are caused by thunderstorms, which can cause loss to life, crops and property. The pre-monsoon season from March to May also witness severe thunderstorm and sometime associated with hailstorms. With the arrival of spring season, the temperature rises initially in the southern parts of India, which gives rise to thunderstorms and squally weather which are hazardous in nature. This is very common over eastern and northeastern parts of the India. Though the tornadoes associated thunderstorms are rare in India but some of them are quite devastating. A tornado struck Delhi on 17th March, 1978 injuring over 1000 people and inflicting a damage of rupees ten million in terms of losses to properties and infrastructures (De *et al.*, 2005).

The earliest study of thunderstorm frequency in India was by Dallas (1900) who took only 10 stations data for India during the year 1897. Rao and Raman (1961) used data of 20 years to present monthly and annual frequency of thunderstorm in India in the form of chart with brief description. They showed higher frequency of 75 days over northeast India, Bangladesh, West Bengal and adjoining areas with more than 100 days over northeastern parts of Assam. Raman and Raghavan (1961) for the first time systematically studied the diurnal variation of thunderstorm occurrence over India. Mukherjee and Sen (1983) studied the diurnal variation of thunderstorm for some selected stations to understand the influence of different physical features *viz.*, plain stations, hill stations, coastal stations, island stations etc. Tyagi (2007) made a detailed study on climatological distribution of thunderstorm frequency over India and neighbourhood. The study has brought out higher (100-120 days) annual frequency (Fig. 15) of thunderstorm as compared to those given by earlier studies (80-100 days). The highest annual frequency (100-120 days) is observed over Assam and Sub Himalayan West Bengal in the east and Jammu region in the north. The lowest frequency (less than 5 days) is observed over Ladakh region. Plains of Gangetic West Bengal and Bangladesh record between 80 and 100 days of thunderstorm annually. Kerala records highest (80-100 days) thunderstorm frequency over peninsula. Udhampur observatory (132 days) in Jammu sub-division records highest number of thunderstorms in the country followed by Kumbhigram (Silchar) observatory (129 days) in south Assam and Hasimara (123 days) in Sub Himalayan West Bengal. In the plains Saurashtra and Kutch record lowest number (less than 15 days) of thunderstorm in the country.

With respect to the seasonal distribution the winter season has the lowest number of thunderstorms and it is primarily due to stable and dry atmospheric conditions prevailing over most parts of the subcontinent with the exception of Sri Lanka and southern Kerala. During the season highest frequency over Sri Lanka (16 days) associated with northeast monsoon activity [Fig. 16(a)] is seen followed by second maxima (13 days) over windward side of Pir Panjal range over Jammu and adjoining region associated with western disturbances. During the pre monsoon season from March to May there is characterized by increase in thunderstorm activity over all parts of the country with significant increase over northeast India, Bangladesh, West Bengal, south peninsula and Jammu region [Fig. 16(b)]. Highest frequency of more than 40 days is observed over Meghalaya and adjoining Assam, Sub-Himalayan West Bengal and Kerala and more than 30 days over rest of northeast India and parts of Bangladesh and West Bengal. In the north, Jammu sub-division records highest frequency (25-30 days) of thunderstorm in the premonsoon season. Topography, insolation and advection of moisture under favourable wind regime contribute to thunderstorm maxima over these areas. Synoptically, Western Disturbances and induced lows in the north and easterly waves in south provide favourable conditions for the occurrence of thunderstorm over these regions. Over the plain area thunderstorms occur between 20 and 30 days over West Bengal and adjoining Jharkhand and Orissa, South Tamil Nadu and Karnataka.

Availability of moisture and favourable synoptic features contribute to general increase of thunderstorm activity over all parts of the country outside Kerala during the monsoon season JJAS [Fig. 16(c)]. The highest thunderstorm activity in the country continues to be over



Figs. 16(a-d). Seasonal mean frequency of thunderstorm days (Adopted from Tyagi, 2007)

northeastern states, Bangladesh, West Bengal and adjoining states, which record more than 50 days of thunderstorm during the season with maxima of 70 days over Sub-Himalayan West Bengal [Fig. 16(c)]. Another maximum of 70 days is seen over wind ward side of Pir Panjal range in Jammu region. Topography in conjunction with favourable wind regime during break monsoon conditions contributes to thunderstorm maxima over these two regions. During the post-monsoon season from October to December, after the withdrawal of monsoon, country outside Tamil Nadu coastal Andhra Pradesh and Kerala witnesses marked decrease in thunderstorm activity. Thunderstorm occur on less than 2 days over Gujarat, Rajasthan, Haryana and west UP and between 2 and 4 days over rest of north and central parts of country [Fig. 16(d)].

During 21st April, 2015 an intense thunderstorm activity from 1730 hrs (IST) to 2300 hrs (IST) of 21 April, 2015 hit Purnea and neighbouring districts of Bihar. The north and north eastern parts of the state were most affected. At least 44 people were killed and 100 others injured as a heavy storm with rain and hail swept through northern and north-eastern districts of Bihar, destroying standing crops and property worth several crores of rupees. Thus, from operational and climatological point of view, there is need to establish at least one full time current weather observatory in each district to ensure proper reporting of all thunderstorm occurrences and to build district level thunderstorm climatology in the country. As tremendous amount of observational and research infrastructure were developed in India between 1950 to 2000, atmospheric research community conceived a program called Severe Thunderstorm Observation and Regional Modelling (STORM) in 2005, to carry out intensive observational research and apply meso-scale dynamical models to understand and predict Norwesters (Mohanty *et al*., 2006). The program was funded by the Department of Science and technology from 2006 to 2008, which was later supported by Ministry of Earth Sciences under the aegis of IMD. The Program received the attention of SAARC Meteorological Centre, Dhaka and with their effort a new program known as SAARC STORM was adopted. The Program since 2013 covers all SAARC countries (Ray *et al*., 2014).

7. Hailstorms

The pre-monsoon season from March to May also witnesses severe thunderstorm and sometime associated with hailstorms. This is very common over eastern and northeastern parts of the India. Sometime hailstorms occur over large scale over different parts of India. Recently unprecedented hailstorm associated with untimely rain caused a lot of damage to farmers of different states of India. The study by Philip and Daniel (1976) found that the hailstorm frequencies are highest in the Assam valley, followed by hills of Uttarakhand, Jharkhand and Vidharbha region of Maharashtra. However, thunderstorms also occur in Kolkata, Delhi, Jaipur and Ahmedabad. Sometime thunderstorms are associated with Tornadoes, although it is very rare in India. It has been seen that tornadoes have caused extensive damage and destruction in the country.

During first half of December, 2014 unprecedented hail storms occurred over different parts of Maharashtra causing loss of crops in large scales. As documented (CRIDA, 2014), the Hail storm struck several villages of Niphad, Sinnar, Malegaon, Chandwad, Baglan, Deola and Yeolatalukas in Nasik districts on 11th December. This storm was associated with high winds and un-seasonal rain. Deola received a rainfall of 16.3 mm and Yeola received 10.4 mm on 11th December. Subsequently a rainfall of 18.5 mm was received in Dindoritaluka and 17.5 mm in Sinnartaluka on 12th December. The untimely rain has caused a lot of damage to farmers of Marathwada, Vidharbha and Western region. Almost 8 lakh hectares of crop has been damaged. Standing crops like wheat, jowar, pulses, sunflower suffered extensive damage due to hailstorm for over eight days in many parts of the state. The damage to agricultural and horticultural crops due to hail storms was stated to be severe in some villages like Ruee, Satana, Chandwad and Wadner Bhairav. Crops like grapes, pomegranate, onion, maize, vegetables and wheat in the hail storm struck areas were damaged. Apart from Nasik district, some areas in Dhule and Jalgaon districts were also affected due to hail storms. Leaf shedding, damages to fruits/branches, flower/fruit drop were the type of damages occurred due to this hail episode. The extent of area affected due to hailstorms was initially put at about 38,000 ha.

8. Cloud burst and landslides

India particularly the western Himalayan region sometime witnesses cloud burst with heavy downpour during active monsoon conditions (Bhan *et al*., 2004). The recent disaster of cloud burst resulting in flash floods and mudflow in Leh and surrounding areas of 6th August, 2010 caused severe damage in terms of human lives as well as property. There was a reported death toll of 196 persons, 65 missing persons, 3,661 damaged houses and 27,350 hectares of affected crop area (MHA, 2011).

Landslides constitute another major natural hazard in our country, which accounts for considerable loss of life and damage to communication routes, human settlements, agricultural fields and forest lands. Heavy rainfall events in western Himalayas often produce landslide across the hilly terrain (Sengupta *et al*., 2010; Gabet *et al*., 2004). Landslides mainly affect the Himalayan region and the western ghats of India (MHA, 2011). Based on the general experience with landslides, a rough estimate of monetary loss is of the order of 100 crore to 150 crore per annum at the current prices for the country as a whole. It is estimated that 30 percent of the world's landslides occur in the Himalayas. The Himalayan Mountains, which constitute the youngest and most dominating mountain system in the world, are not a single long landmass but comprises a series of seven curvilinear parallel folds running along a grand arc for a total of 3400 kilometers. Due to its unique nature, the Himalayas have a history of landslides that has no comparison with any other mountain range in the world. Scientific observation in north Sikkim and Garhwal regions in the Himalayas clearly reveal that there is an average of two landslides per sq. km and the mean rate of land loss is to the tune of 120 meter per km per year and annual soil loss is

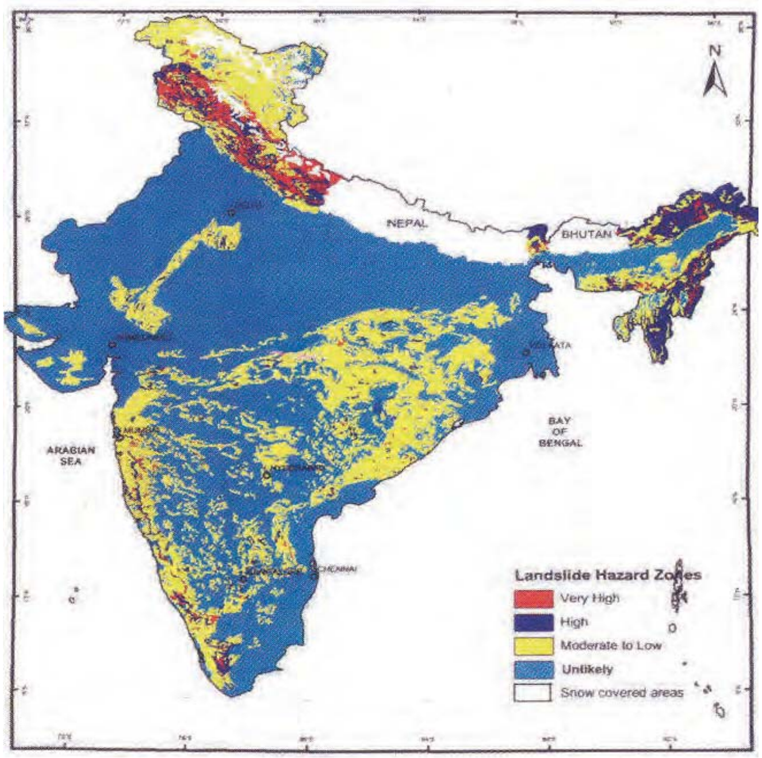


Fig. 17. Landslides hazard zones of India (*Source*, BMTPC)

About 2500 tones per sq km (MHA, 2011). The landslide hazard zones in India is shown in Fig. 17 (MHA, 2011).

9. Summary and conclusions

Extreme weather events such as floods, droughts, heavy rainfall, cyclones, thunderstorms/lightning, hailstorms, dust storms, heat and cold waves, fog, cloud burst landslides, etc. are very common to the country like India due to its unique geographical and climate regime. Every year these major natural hazards in our country accounts for considerable loss of life and damage to properties, human settlements, agricultural outputs and finally economy of the country.

The inter-annual fluctuations in the summer monsoon rainfall over India during June to September are sufficiently large to cause devastating floods or serious droughts. 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. The western part of the country, including Rajasthan, Gujarat and some parts of Maharashtra are hit very frequently by drought situation. If monsoon worsens the situation spreads in other parts of the country too. The interannual variability of monsoon rainfall shows more number of drought years (23 years ≈20.2%) compared to the flood years (14 years ≈ 12.2%) during the period 1901 to 2014. The year 1918 received the lowest rainfall (75.1% of LPA) followed by the years, 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 exceeds 2 SD (≈ +20%) value. Although the large variability of AISMR and monthly rainfall does not show any significant linear trend, however, there exists trend in the sub-divisional rainfall with three subdivisions, *viz*., Jharkhand, Chattisgarh, Kerala show significant decreasing trend and eight subdivisions, *viz*., Gangetic West Bengal, West Uttar Pradesh, Jammu & Kashmir, Konkan & Goa, Madhya Maharashtra, Rayalaseema, Coastal Andhra Pradesh and North Interior Karnataka show significant increasing trends.

Every year the plain region of India is affected by floods during the monsoon season associated with heavy rainfall. It is found that the frequency of extreme rainfall (Rainfall ≥ 124.4 mm) show increasing trend over the Indian monsoon region during the southwest monsoon season JJAS and is significant at 98% level. It is also found that the increasing trend of contribution from extreme rainfall events during JJAS is balanced by a decreasing trend in category-i (rainfall ≤ 64.4 mm/day) rainfall events. On monthly scale the frequency of extreme rainfall events show significant (95% level) increasing trend during June and July, whereas during August and September the increasing trend is not significant statistically. 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.

The major natural disaster that affects the coastal regions of India is cyclone as it has a vast coastline. The track of TCs over the NIO during two cyclone seasons MAM and OND during 1951-2014 shows most of the systems during OND form over BoB have westward/ north-westward tracks and cross the Indian land mass. The incidence of TCs with intensity of severe to very severe cyclones crossing Tamil Nadu and Andhra Pradesh is high during the north east monsoon season (OND), whereas the highest annual number of CSs, SCSs occur in Odisha-West Bengal coast.

With respect to surface air temperature like the increasing trend of the mean annual global surface air temperature similar increasing trend of global surface air temperature is also reported over India for last 111 years from 1901 to 2011, with the linear trend per 100 years in the annual mean land surface air temperature anomalies averaged over India was 0.62 °C. It is also seen that 7 out of the 10 warmest years in India were during the recent past decade (2001-2010) making it the warmest decade on record with decadal mean temperature anomaly of 0.49 °C. With respect to the heat wave frequency over India during last 5 decades from 1961 to 2010 indicates that except over northeast India and large parts of Peninsula (South of ~21° N & west of 80° E), most areas of the country have experienced on an average ≥ 2 heat wave days. Sometime, during late June the heat wave also occurs over parts of India associated with stagnation in monsoon progress. It is also found that 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. Similarly the other temperature extreme like cold-wave conditions observed in the hilly regions in the north of India and adjoining plains are usually influenced by the weather systems called the western disturbances. Study also 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.

The pre-monsoon season from March to May also witness severe thunderstorm and sometime associated with hailstorms. With the arrival of spring season, the temperature rises initially in the southern parts of India, which gives rise to thunderstorms and squally weather which are hazardous in nature. This is very common over eastern and northeastern parts of the India and sometime associated with large hailstorms.

Finally, the monitoring and forecasting of these extreme weather events over India will be very helpful in minimizing its adverse impacts on agriculture and many other sectors.

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