Unprecedented drought in North East India compared to Western India

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The rainfall distribution over Western and North East India during the southwest (SW) monsoon season is geographically distinct with the heaviest seasonal rainfall occurs over the North Eastern Region (NER), while the lowest rainfall occurs over the Western region (Saurashtra and Kutch in Gujarat, and also in Rajasthan). Gujarat is located in arid to semiarid region and has more drought-prone areas. In contrast, Assam and Meghalaya have humid climate and occurrence of drought is unusual. Here, we analyse the percentage departure of rainfall for nearly two decades (1997–2014) along with crop statistics. Our results indicate that the SW monsoon rainfall in the NER has gradually dropped in recent years compared to the 1980s and 1990s. As a result, these regions have witnessed frequent unprecedented drought than Western India. In NER, probability of drought occurrence was 54%, and it is 27% for Western India in the recent decade (2000–2014). The frequent drought has caused adverse agricultural impacts and our results show a significant negative rice production anomaly during drought years 2005–06 and 2009 in Assam. Drought impacts were also reported from other states in NER during 2010–11 and 2013. Drought associated with El Niño was not so strong; however, increasing temperature and increased monsoon season rainfall variability have an impact on global climate change. This may cause warming-induced drought leading to adverse impact on agriculture and food security in the NER.

Keywords: Crop production, meteorological and agriculture drought, monsoon season, rainfall departure.

DROUGHT is a hydro-meteorological natural hazard and often catastrophic in nature causing widespread impact on the society. It is defined as 'a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area'. On the basis of their nature and severity, droughts are classified as meteorological, hydrological, agricultural, socio-economic and ecological. According to India Meteorological Department (IMD), meteorological drought arises when actual rainfall over an area is significantly less than the climatological mean of that area. IMD defines the rainfall categories for smaller areas like different meteorological districts or a sub-division by their deviation from normal rainfall for a meteorological area – excess (+20% or more above normal); normal (+19% above normal to –19% below normal), deficient (–20% to –59% below normal); and scanty (–60% or more below normal). This may not cause agricultural drought but in the event of extreme rainfall deficiency, agricultural drought impacts are unavoidable. Agricultural drought refers to a situation, in which the moisture in the soil is no longer sufficient to meet the needs of the crops growing in the area.

Droughts are recurring climatic events and are recognized as a major limiting factor to the regional economic development by affecting agriculture, water resources and food production. It produces widespread impacts on society, especially in the agriculture sector, by a decrease in foodgrain production depending upon the intensity, duration and spatial coverage of drought stress. It can lead to increased migration from rural to urban areas, posing additional pressures on diminishing food production. Drought often hits the Indian subcontinent, causing massive water shortages, financial losses and adverse social consequences. During the British rule, the Great Famine of 1876–1978 severely affected the entire Southern peninsula of India and spread to Central and northern parts of the country. The famine due to intense drought was spread over 16.7 m ha and mortality was estimated as 5.5 million people. Davis[1] explored the impact of colonialism and capitalism during the extreme climatic condition 'El Niño Southern Oscillation (ENSO)' drought-related famines of 1876–1878, 1896–1897 and 1899–1902 in India. In the second half of the 19th century, the India subcontinent witnessed a near-permanent cycle of droughts, meagre harvest and famine. Subsequently, the Bengal famine of 1943–44 triggered crop failures and food shortages and at least 3 million people died from starvation, malnutrition and related illnesses during the famine[2].

During the last three decades, rapidly increasing populations have added to the growing demand for water, food and other natural resources. The drought during 2000–2004 across South Asia affected more than 462 million people, with severe impacts in western India (Gujarat and Rajasthan), Pakistan's Sind and Baluchistan provinces and in parts of Iran and Afghanistan[3]. During the last three decades (1980–2014), more than 832 million people across south Asia affected by drought were forced to abandon their land[4]. Over this period, Emergency Events Database (EM-DAT)[4] reported seven occurrences (1982, 1987, 1993, 1996, 2000, 2002 and 2009) of drought in India and about 751 million people were affected (i.e. ~90% of south Asia). According to EM-DAT[4], since 1970 there have been 36 events of drought in south Asia. India witnessed nine such events over the period 1970–2014 and accounts for a quarter of the south Asian events. However, many drought events observed in

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different districts and sub-divisions of the country were not included in the report[4].

Generally, drought occurrence in India varies from once in 2–3 years (Rajasthan and Gujarat) to once in 15 years (Assam and Meghalaya). Based on the literature, drought-affected states (districts) in western India are Gujarat (Ahmedabad, Amrely, Banaskantha, Bhavnagar, Bharuch, Jamnagar, Kheda, Kutch, Mehsana, Panchmahal, Rajkot, Surendranagar) and Rajasthan (Ajmer, Banaswada, Barmer, Churu, Dungarpur, Jaisalmer, Jalore, Jhunjunu, Jodhpur, Nagaur, Pali, Udaipur). In central and peninsular India, the states affected are Madhya Pradesh, Chhattisgarh, Andhra Pradesh, Karnataka and Tamil Nadu. In North East (NE) India, Assam (Bongaigaon, Cachar, Dhubri, Goalpara, Golaghat, Kailakandi, Jorhat, Kanpur, Karbi-Anglong, Kokrajhar, Lakhimpur, Morigaon, Nagoan, Nalbari, Sivasagar, Sonitpur) and Meghalaya have experienced drought consecutively during 2005 and 2006 though this humid region is classified under rare drought event and frequency is once in 15 years. Subsequently in 2009, all the seven states in the North Eastern Region (NER) were severely affected. In Assam, about 10–14 districts were affected in three consecutive years during 2009–2011 which suggests that frequent droughts were observed in the recent decade[5]. Deficient rainfall (–9%) during the *kharif* season 2014 also caused severe drought and affected 12–14 districts across the state; it also severely affected crop production, including tea production. Droughts were found to affect more people compared to other hydro-meteorological natural hazards, comprising about 50% of those affected in the country. In view of larger impacts, assessment and monitoring of drought is critical in most parts of the country, as droughts are expected to rise here due to climate change.

Drought in agricultural area leads to decline in food grain production depending upon the intensity, duration and spatial coverage of drought stress. It has been reported that about 68% of the area in India is prone to drought and most of the areas are vulnerable under recurring drought. Drought-prone areas are mainly confined to western and peninsular India – primarily arid, semi-arid and sub-humid regions. Recently, India has faced the worst drought episodes (2002 and 2009) in terms of magnitude, dispersion and duration, with an impact on human and livestock as well as economic losses. Thus, monitoring drought is of utmost concern to decision-makers from the viewpoint of food security and trade. The point-based meteorological drought indices such as SPI, PDSI and CMI have been extensively used for drought monitoring[6,7]. But sparse meteorological network and lack of timely availability of weather data hinder the accurate and timely monitoring of regional drought.

Innovations in remote sensing technology have provided new dimensions of spatial solutions to many environmental problems, including natural hazard monitoring. Satellite remote sensing has become crucial, particularly for timely detection and monitoring of drought due to timely availability of spatio-temporal data. The most commonly used normalized difference vegetation index (NDVI) from remote sensing is often not able to detect drought events instantaneously because of a lagged vegetation response to drought[8]. On the other hand, surface temperature (T_S) is sensitive to water stress and has been identified as a good indicator of water stress[9]. Accurate real-time drought monitoring, therefore, needs a combination of the thermal and visible/near-infrared wavelength to provide information on vegetation and moisture conditions simultaneously. The T_S–NDVI space relationship has been widely exploited to derive various types of hydrological information such as air temperature, evapotranspiration and soil moisture[10]. Many drought indices like temperature vegetation dryness index (TVDI), water deficit index (WDI) and the crop water stress index (CWSI) have been explored for quantification and real-time monitoring of the spatial extent and magnitude of drought[11,12]. In an earlier study[12], we have explored the potential of TVDI from Terra-MODIS satellite to detect spatial distribution of 2002 agricultural drought in semi-arid regions of western India (Gujarat) and 2006 agricultural drought in humid regions of NE India (Assam). The spatial distribution of drought pattern over these two states was also discussed[12].

In this study, we have analysed nearly two decades of rainfall departure data (IMD) and agricultural production data (Ministry of Agriculture, Government of India) for drought development over western India and NER. A meteorological-based drought index called crop moisture index (CMI) has been used to detect the 2002 drought in Gujarat. Particularly, Assam has been considered from NER, since this state has witnessed unprecedented droughts during 2005–06 and subsequently in 2009–2011 that caused heavy damage to agricultural and horticultural crops.

As a measure of meteorological drought, we have analysed nearly two decades (1997–2014) of percentage departure of rainfall for Gujarat region (south and north Gujarat) and Saurashtra–Kutch region that represents western India, and also for Assam and Meghalaya (henceforth A&M) that represents NER. The southwest (SW) summer monsoon covers up to 80% of total annual rain and thus the rainfall departure data were obtained for SW monsoon season rainfall (June to September). As a measure of agricultural drought, CMI developed by Palmer[13] was used. It measures the short-term changes in soil moisture conditions of crops and gives the current status of agricultural drought or moisture surplus, which can change rapidly from week to week. It is normally calculated with a weekly time-step using the field-based meteorological data like mean temperature, total precipitation for each week and CMI value from the previous week.

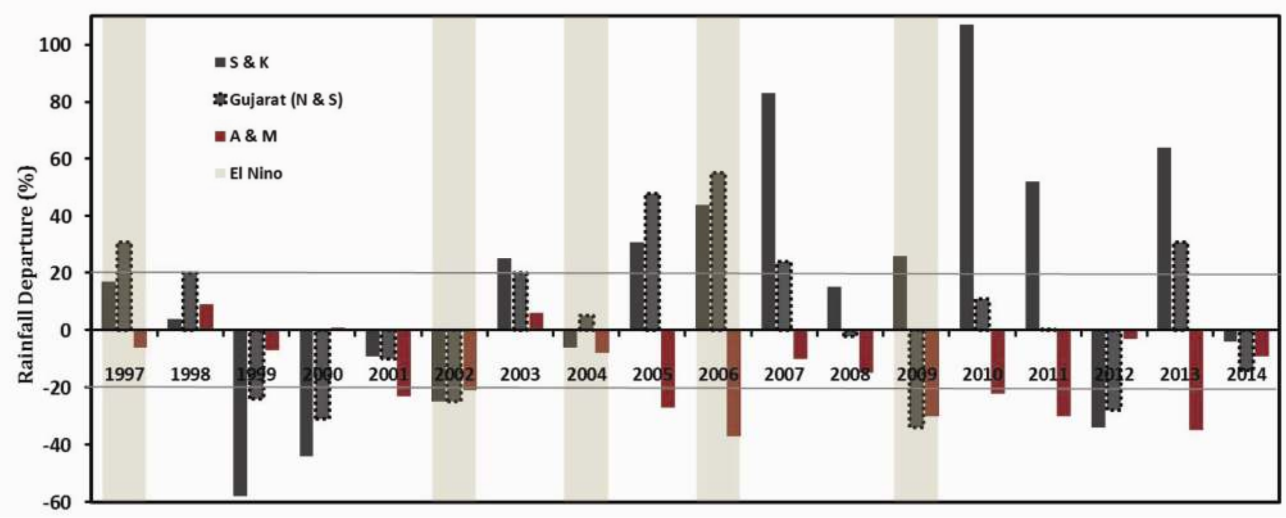

Figure 1. Time series of the percentage departure of seasonal rainfall (June–September) from long-period average for western and North East India during 1997–2014. S&K, Saurashtra–Kutch region.

The long-term crop statistics was analysed to ascertain the impact of drought on agriculture, and production anomalies were computed as the difference between observed production and long-term mean production. Along with food grains and oilseeds, cotton is also an important crop in Gujarat, which produces about one-third of the cotton in the country. Time series data of food grains (rice, wheat, corn, coarse grains, viz. sorghum and millet, and pulses, viz. beans, dried peas and lentils) and oilseeds (groundnut, sesamum, mustard and castor) productivity (1981–2003) were linearly de-trended to remove the effect of improvements in crop science technology. The de-trended yields were derived by subtracting the per year yield variation from historical record of food grain and oilseeds yields. The de-trended yield anomaly (DY_a) is computed as

$$\mathrm{DY}_{ai} = \frac{\mathrm{Y}_{ai}}{\mathrm{Y}_{ti}} - 1, \tag{1}$$

where DY_{ai} is de-trended yield anomaly for the *i*th year, Y_{ai} and Y_{ti} are actual and 22 years time trend based yield ($Y_t = a + b \times \text{year}$) of *i*th year respectively. The slope *b* of this regression line for each district has been used as an indicator of the overall trend in productivity.

The seasonal rainfall over a district or sub-division is classified as normal if the rainfall departure from the long-period average is within –19% to +19%, excess (≥ 20%), deficient (≤ –20%) and scanty (≤ –60%). Departure of rainfall during SW monsoon season over S&K region shows that six years were normal and eight years were excess, but seven years were observed to have uninterrupted normal rainfall (2003–2011), except 2004 (Figure 1). Departure of rainfall was deficient for four years (1999, 2000, 2002 and 2012). The pattern remains the same for Gujarat region (N&S), except in 2009, which was observed as deficient (–34% departure). For the entire state, five years were observed as meteorological drought and within these 18 years (1997–2014), 2002 and 2009 drought years were associated with El Niño. Over the period 1997–2014, five El Niño years were observed. Western India showed nearly 28% probability of drought in 18 years, but 40% cases were associated with El Niño.

The seasonal rainfall departure from the long-term average rainfall over A&M shows that there is no single year under excess rainfall, but ten years received normal rainfall (1997–2000, 2003–2004, 2007–2008, 2012 and 2014). Departure of rainfall was deficient for eight years (2001–2002, 2005–2006, 2009–2011 and 2013), and 2009–2011 were consecutive drought years. Within these 18 years, 8 years were associated with meteorological drought giving a probability of drought as 44%, whereas 2002, 2006 and 2009 droughts were associated with El Niño. In particular, for the recent decade (2000–2014), 27% cases from western India were observed as drought, whereas 54% cases from NER were observed as drought, suggestive of impacts of global climate change. The analysis reveals that the effect of El Niño on drought incidences was moderate (with 40–50% probability) in the recent decade, which indicates that most of the drought occurrences were linked with the variability of rainfall during the SW monsoon season.

The occurrence of agricultural drought was analysed for Gujarat (20°01′–24°07′N lat. and 68°04′–74°04′E long.). Figure 2 shows a plot of CMI for two meteorological stations, namely Ahmedabad (North Gujarat) and Rajkot (Saurashtra region) for the two El Niño years, wherein 2002 was a drought year and 2004 was a normal year. The CMI plot shows that in both the stations, CMI values are negative (indicating lower soil moisture and agricultural drought) for the year 2002, starting from the beginning of the *kharif* season (Figure 2). In contrast, CMI values are positive for the year 2004 throughout the *kharif* season, indicating higher soil moisture or normal year. These results suggest that CMI could detect agricultural drought stress on a weekly basis and can be further used to ascertain the results obtained from satellite-based indicator as discussed in Parida and Oinam[12].

To assess the effect of the 2002 drought especially on cotton production, we plot in Figure 3, production anomaly for the period 1998–2011. The figure reveals that district-level productions were adversely affected in 2000 and 2002 in both the districts and during 2002 production anomalies were 3.11×10^4 and 1.78×10^5 tonnes in AMD and RAJ respectively. For state-level, the cotton yield was 175 kg/ha during 2002, whereas it was 421 kg/ha during 2004.

The de-trended yield anomaly of food grains and oilseeds are negative for majority of districts in the state during drought years 2000 and 2002. Yield anomaly of AMD and RAJ districts for food grains is negative in the drought years and positive in the non-drought years (Table 1). The average yield anomalies of the state for food grains is also negative in the drought years. Similarly, yield anomalies for oilseeds are negative in the drought years. These negative anomalies provide evidence of the adverse effects of drought on crop productivity. The most affected districts are Ahmedabad, Rajkot, Surendranagar, Banaskantha, Gandhinagar, Jamnagar, Kutchh, Kheda, Sabarkantha, Surat, Dangs and Valsad.

For analysing agricultural drought in the NER, Assam (24°50′N–28°00′N lat. and 89°42′E–96°00′E long.) was chosen as a case study because drought is not a usual phenomenon in these regions. Assam is surrounded by hilly tracts with humid climate and the Brahmaputra River flows from east to west. The state has 27 districts and paddy is the main food crop cultivated during winter, summer and autumn season. Other major food crops cultivated include jute, tea and pulses. Commonly, this region witnesses floods nearly every year due to its geographical setting, high-intensity rainfall and inundation of riverine areas caused by the Brahmaputra River. However, the scenario was just opposite in 2005–06 due to scanty rainfall in many districts of Assam and subsequently during 2009–2011 and 2013 (compare Figure 1). Assam received 30% less rainfall than normal during monsoon season 2006 and consequently, the rainfed rice crops were profoundly affected by drought. Districts critically affected were Dhubri, Nalbari, Jorhat, Morigaon, Nowgong and Sonitpur.

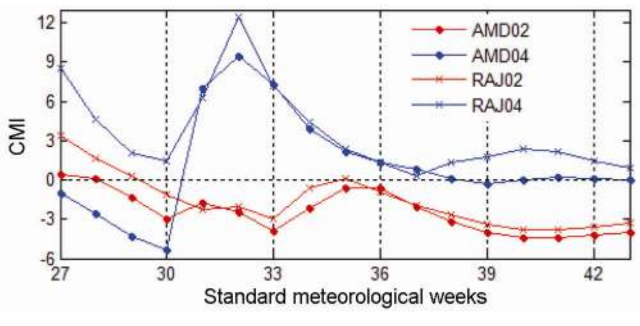

Figure 2. CMI plotted for the meteorological standard week between 27 and 43 weeks (i.e. 2 July to 28 October) representing *kharif* season (rainy season). Week nos 35–43 (i.e. early September to end of October) indicate late stage of the crop. AMD and RAJ represent two meteorological stations located at Ahmedabad and Rajkot respectively. CMI plotted for the year 2002 (red line) and 2004 (blue line).

Here, we have analysed the total rice production from three seasons for two districts, namely Dhubri and Nalbari. Rice production anomaly plot (Figure 4) indicates that production anomalies are negative in these districts; they show a sharp dip during 2005 and 2006 and again during 2009 compared to the normal years with positive anomalies. Rice production anomalies for 2005–06 are -4.71×10^4 and -3.29×10^4 tonnes for Nalburi and Dhubri respectively. In 2010 and 2012, these two districts received annual rainfall of 2224–2730 mm, and because of normal rainfall drought impacts on rice production were not observed. However, in other districts the impacts of drought were observed during 2010 and 2011 (ref. 5). The negative anomalies during drought years provide corroboration of drought impacts on agriculture in NER. Thereby, occurrence of intense drought in this region may have an adverse effect on food security under global climate change.

Our key finding on the unprecedented meteorological drought in NER compared to western India is more persistent in the recent decade (2000–2014). It was observed that over these 15 years, probability of drought was 27% and 54% in western India and NER respectively. These findings suggest that NER experienced more frequent unprecedented droughts (two times more) than western India. Drought probability associated with El Niño was nearly 40–50% in western India as well as NER, which indicates that most of the drought events were associated with the variability of rainfall during the SW monsoon season. The association between drought

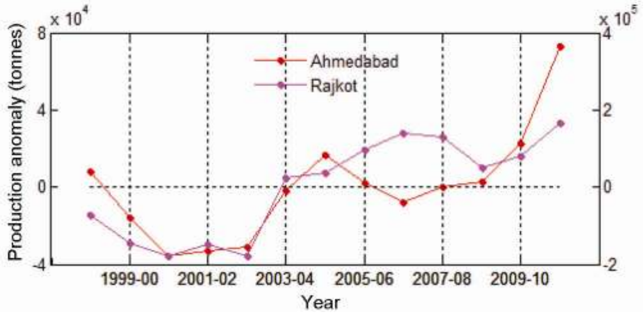

Figure 3. Cotton production anomaly for Ahmedabad (primary axis) and Rajkot (secondary axis) districts for the period 1998–2011.

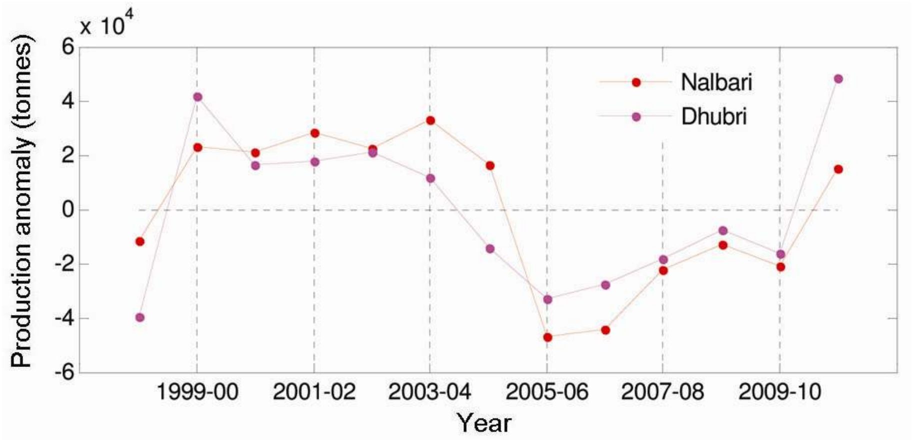

Figure 4. District-level rice productions anomaly during 1998–2011. The mean production is 1.52×10^5, 1.78×10^5 tonnes for Nalbari and Dhubri respectively.

Table 1. District-level de-trended food grains and oilseeds yield anomaly during 2000–2003

	Food grains yield anomaly				Oil seeds yield anomaly			
	2000	2001	2002	2003	2000	2001	2002	2003
Ahmedabad	–46.31	48.36	–81.79	82.29	5.09	–35.94	–58.96	–48.46
Rajkot	–16.89	84.01	–27.60	116.89	–11.46	–28.41	–30.59	1082.85
State level average	–28.17	31.45	–11.20	43.85	–20.50	–36.22	–35.49	85.15

and El Niño over different metrological sub-divisions in India was not strong, which is consistent with the previous findings[14]. Studies have shown that the SW monsoon rainfall over India usually decreases during El Niño years[15], but recent studies indicate that their relationship no longer holds and thus normal monsoon rainfall may prevail[16,17].

Deficient rainfall has led to agricultural drought, especially during 2002 in Gujarat and 2005, 2006, 2009–2011 and 2013 in Assam[5,18]. During these years, agricultural production as well as yield at both district and state level were lower compared to the normal years (Figures 3 and 4). Besides A&M, other states in the NER such as Manipur, Mizoram, Tripura and Arunachal Pradesh also witnessed unprecedented drought during 2009 (refs 5, 18). As rice is the predominant crop in this region that occupies about 84% of cultivated area, rainfall deficiency at transplanting stage can lead to a complete loss of crop. Moreover, due to absence of irrigation facility, paddy cultivation faces a serious threat of crop failure in this region. According to the Department of Irrigation, Government of Assam, the overall irrigation implemented across the state so far is only 25% (6.95 lakh ha) against the irrigation potential of 66% (i.e. 27.00 lakh ha). Therefore, irrigation facilities with water management practices could help overcome such situations of less rainfall observed during the monsoon season.

In the contemporary period (2000–14), NER has witnessed more unexpected frequent drought, suggesting the impacts of global climate change. This region falls under the zone of high rainfall with subtropical and humid type of climate. However, under the influence of global climate change, the NER has witnessed drought-like situations in the current years (2000–11, 2013). The impacts of climate change are well known, particularly in NER which may exaggerate the vulnerability and risk of agriculture associated with variability of SW monsoon rainfall. Since the Industrial Revolution, atmospheric concentration of greenhouse gases, particularly CO_2 has increased significantly. The annual mean temperatures are expected to further increase by 3–5°C in NER[19]. There is high confidence that projected rising temperatures and the resultant warming could lead to more droughts and desertification. IPCC[20] reported decreasing trends in annual rainfall observed across NER. Change in temperature owing to warming and increased summer season rainfall variability may cause warming-induced drought with severe impacts on agriculture and food security.

With the shift in rainfall pattern and change in temperature effective drought management policies and frameworks need to be formulated in India. In this context, the WMO, FAO and the UN Convention to Combat Desertification (UNCCD), and other partners have formulated a National Drought Policy in 2013 to focus on drought preparedness and management policies. This emphasizes on quantification of drought impacts and monitoring drought development. But the ability of governments and international relief agencies to deal with droughts is constrained by reliable data, and lack of technical and institutional capacities. Desertification or land degradation is one of the most serious problems of the region and is often related to poor land-use practices. Further drought can deepen the effect of land degradation. Declining vegetation cover due to drought stress may enhance soil erosion and can lead to an irreversible loss of nutrients and subsequently desertification. Hence, modification of agricultural and water policies in the drought-affected areas may require additional national-level actions and measures to mitigate the drought-affected areas. While significant achievements have been made in post-disaster response and reconstruction, there are still challenges to reducing the risk of future disasters as the frequency and intensity of droughts and extreme weather events are expected to increase in the coming decades. Thus, disaster management is becoming difficult due to increasing population and climate change. The only way to reduce such disasters is to improve disaster and also better preparedness.

1. Davis, M., *Late Victorian Holocausts: El Niño Famines and the Making of the Third World*, Verso, London, 2001, p. 9.
2. Appadurai A., How moral is South Asia's economy? – a review article. *J. Asian Stud*., 1984, **43**, 481–497.
3. Thenkabail, P. S., Gamage, N. and Smakhin, V., The use of remote sensing data for drought assessment and monitoring in south west Asia. IWMI Resarch Report 85, IWMI, Colombo, 2004, p. 25.
4. EM-DAT: The OFDA/CRED International Disaster Database, Université catholique de Louvain, Brussels, Belgium; www.emdat.be
5. Annual Report 2011–12, North Eastern Space Applications Centre, Meghalaya, Department of Space, Government of India.
6. Kumar, M. N., Murthy, C. S., Sesha Sai, M. V. R. and Roy, P. S., Spatiotemporal analysis of meteorological drought variability in the Indian region using standardized precipitation index. *Meteorol. Apps*., 2012, **19**, 256–264.
7. Patel, N. R., Parida, B. R., Venus, V., Saha, S. K. and Dadhwal, V. K., Analysis of agricultural drought using vegetation temperature condition index (VTCI) from Terra/MODIS satellite data. *Environ. Monitor. Assess*, 2012, **184**, 7153–7163.
8. Park, S., Feddema, J. J. and Egberts, S. L., MODIS land surface temperature composite data and their relationships with climatic water budget factors in the central Great Plains. *Int. J. Remote Sensing*, 2004, **26**, 1127–1144.
9. Jackson, R. D., Idso, S. B., Beginato, R. J. and Pinter, P. J., Canopy temperature as a crop water stress indicator. *Water Resour. Res*., 1981, **17**, 1133–1138.
10. Moran, M. S., Clarke, T. R., Inoue, U. and Vidal, A., Estimating crop water deficit using the relation between surface air temperature and spectral vegetation index. *Remote Sensing Environ*., 1994, **49**, 246–263.
11. Sandholt, I., Rasmussen, K. and Anderson, J., A simple interpretation of the surface tempera-ture/vegetation index space for assessment of the surface moisture status. *Remote Sensing Environ*., 2002, **79**, 213–224.
12. Parida, B. R. and Oinam, B., Drought monitoring in India and the Philippines with satellite remote sensing measurements. *EARSeL eProc*., 2008, **7**, 81–91.
13. Palmer, W. C., Keeping track of crop moisture conditions, nationwide: The new Crop Moisture Index. *Weatherwise*, 1968, **21**, 156–161.
14. Shewale, M. P. and Kumar, S., Climatological features of drought incidences in India. *Meteorological Monograph (Climatology 21/2005)*, National Climate Centre, India Meteorological Department.
15. Pant, G. B. and Parthasarathy, B., Some aspects of an association between the southern oscillation and Indian summer monsoon. *Arch. Meteorol. Geophys. Bioklimatol., Ser. B*, 1981, **29**, 245–251.
16. Krishna Kumar, K., Kleeman, R., Cane, M. A. and Rajagopalan, B., Epochal changes in Indian monsoon–ENSO precursors. *Geophys. Res. Lett*., 1999, **26**, 75–78.
17. Krishna Kumar, K., Rajagopalan, B. and Cane, M. A., On the weakening relationship between the Indian monsoon and ENSO. *Science*, 1999, **25**, 2156–2159.
18. Anup, D. *et al*., Climate change in Northeast India: recent facts and events – worry for agricultural management. In ISPRS Archives XXXVIII-8/W3 Workshop Proceedings: Impact of Climate Change on Agriculture, 2009.
19. Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G. and Ravindranath, N. H., Multi-model climate change projections for India under representative concentration pathways. *Curr. Sci*., 2012, **103**, 791–802.
20. Parry, M. L. *et al.* (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2007, p. 976.

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Performance of residential buildings during the *M* 7.8 Gorkha (Nepal) earthquake of 25 April 2015

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The *M* 7.8 earthquake of 25 April 2015 was a significant event in the long seismic history of the Eastern Himalayas, which caused more than 8000 casualties and widespread destruction of various structures in the western and central regions of Nepal. This article discusses the general observations in the earthquake affected regions, with special emphasis on the seismic performance of residential structures in the Kathmandu valley region. Widespread damage was observed in

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