Ocean & Coastal Management 129 (2016) 10–14

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Opinion paper

India contemplates climate change concerns after floods ravaged the coastal city of Chennai

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ARTICLE INFO

Article history:
Received 19 December 2015
Received in revised form
17 April 2016
Accepted 25 April 2016
Available online 7 May 2016

Keywords:
Flood
Weather
Coast
Ocean
Climate change
India

Ever since the Kyoto protocol came into existence in 1992, the issue of climate change has received the attention of many nations (www.ipcc.ch/report/ar5/wg). Public sentiments on the impact of global climate change leading up to varying weather phenomena are on the rise. The recent flooding in Chennai (Fig. 1), one of India's four major metropolitan cities, is a reminder that unpredictable weather patterns may create chaos in future. Chennai (erstwhile Madras) has a long history and the St. George Fort built in 1644 was the country's first British settlement (Neilda, 1979). Climatologically, Chennai lies on the equator and along the southeastern coastline thus obligating to hot and humid climate. The highest and lowest mean monthly temperatures (T, °C) calculated from a 30-year (1970–2000) record showed significant annual variations that ranged from 33 to 45 °C and from 13.9 to 21 °C (Fig. 2; https://en.wikipedia.org/wiki/Chennai#cite_note-NOAA-101), respectively. The highest temperature of 45 °C was recorded in May (pre-monsoon) and the lowest of 13.9 °C in December (NE monsoon). Similarly, the mean monthly rainfall during this period ranged from 2.2 to 407.4 mm (Fig. 2), with lowest in February (pre-monsoon) and highest in November (NE monsoon). The mean relative humidity varied from 57% to 78% (Fig. 2), with lowest in June (SW monsoon) and highest in November (NE monsoon). In 2015, many parts of India recorded high temperatures that crossed 45 °C, and even reached up to 48 °C in states such as Andhra Pradesh and Telangana (http://timesofindia.indiatimes.com/india/Youre-experiencing-worlds-5th-deadliest).

Chennai (population 4.7 million) receives monsoon rains between October and January, when the cooler dry NE monsoon winds from the Himalayas and Indo-Gangetic Plain draw water vapor from Bay of Bengal and then pours it over India and parts of Sri Lanka. Since the city is located along the SE coast (Fig. 1), it is prone to cyclones that form over Bay of Bengal (Alam et al., 2013; Rajasekhar et al., 2014). On 1 Dec 2015, Chennai received 490 mm rainfall, the highest in 107 years (www.thehindu.com/sci-tech/energy-and-environment/chennai-rains-freak-weather). The downpour literally drowned large areas while displacing thousands. Given the current state of CO_2 and other greenhouse gases influencing the global weather patterns, the consequences are not only dire for India, but also for adjoining islands and coastal nations. India, by the way, has a vast coastline, stretching over 7517 km (Agoramoorthy et al., 2014). A few days after the Chennai floods, thousands were evacuated due to massive flooding across Great Britain. The rainfall from 4th to 6th Dec 2015 at Cumbria (NW England) reached 262.6 mm, which was half of what Chennai received in one day (www.bbc.com/news/uk-35023558). When people battled the floods in Chennai, world leaders congregated at Paris to participate in the UN Climate Change Conference (COP 21). At that meeting, the Indian delegation declared that the Chennai flooding was due to climate change.

India's monsoon research has been debated for centuries. Historical records show that India's Meteorological Department's 1st Director, HF Blanford (from 1875 to 1889) told, “The order and regularity are as prominent characteristics of India's atmospheric

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http://dx.doi.org/10.1016/j.ocecoaman.2016.04.017
0964-5691/

Fig. 1. A Google map showing the locations of Bay of Bengal, Chennai, Buckingham Canal, Adyar, Cooum and Korattalaiyar rivers discussed in this study.

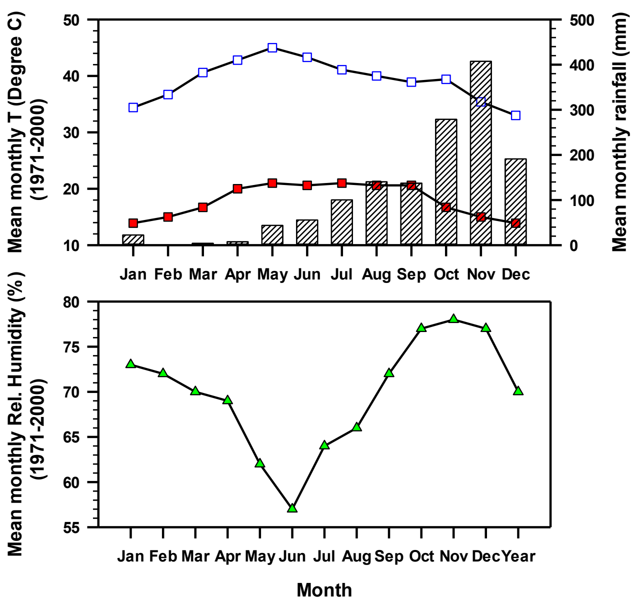

Fig. 2. Thirty-year (1971–2000) record of (top) mean monthly temperatures (T) with the highest T (blue squares) and the lowest T (red squares), and mean monthly rainfall (vertical bars); (bottom) mean monthly relative humidity for the same period. Data Source: (1) Chennai-Climatological Information, India Meteorological Department-Retrieved 29 May 2014. (2) Ever Recorded Maximum Temperature, Minimum Temperature and 24 Hours heaviest rainfall up to 2010; India Meteorological Department-Retrieved 29 May 2014. (3) Madras (Chennai) Climate Normals 1971–1990 (National Oceanic and Atmospheric Administration-Retrieved 25 March 2015; https://en.wikipedia.org/wiki/Chennai#cite_note-NOAA-101). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phenomena" (Blanford, 1891). Besides, GT Walker (3rd Director General of the Observatories of Meteorological Department from 1904 to 1924) alleged that the relationships of world weather appeared to be so complex and patterns of that can only be explained by accumulating facts empirically over long periods of time (Walker, 1923, 1924). This statement stands out even today, as India experiences extreme weather patterns, both in summers and winters. While investigating a century old rainfall records, scientists have predicted that flood-related hazards will increase (Goswami et al., 2006; Rajeevan et al., 2008). The prediction is consistent with an increasing trend in severe tropical storms, especially over the North Indian Ocean in recent decades (Webster et al., 2005). Such an increasing drift of extreme events found to be fueled by sea surface temperature variations over the Indian and Pacific Oceans (Ashok et al., 2001; Goswami et al., 2006; Rajeevan et al., 2008).

On millennial-centennial time scales, the Asian monsoon is largely controlled by both external and internal forcing during the Holocene period (Gupta et al., 2003; Selvaraj et al., 2007). The probable players associated with the Indian monsoon vagaries on an interannual to interdecadal time scales include: (i) El Niño Southern Oscillation or ENSO, (ii) Intra-seasonal variability, (iii) Eurasian and Himalayan dynamics, and (iv) Indian/Pacific Ocean Sea Surface Temperatures or SSTs (Walker, 1923, 1924; Ashok et al., 2001; Goswami et al., 2006; Rajeevan et al., 2008). The Pacific-based El Niño is notably the most precarious driver of global climate and it was implicated in the 2015 extreme weather phenomenon, as ENSO events increased floods, droughts, and heat waves disrupting the circulation of global atmosphere (McPhaden, 2015). It triggered severe heat waves in India killing 2300 people, mostly in the states of Andhra Pradesh and Telangana, north of Chennai city (timesofindia.indiatimes.com/india/youre-experiencing-world-5th-dealiest-heatwave).

India recorded the highest temperatures of >47 °C in 2015, which is the second deadliest heat wave on record (timesofindia.indiatimes.com/india/youre-experiencing-world-5th-dealiest-heatwave). The 1st heatwave was recorded in 1998 that killed 2541. In fact, El Niño can stop or delay monsoon rains and India's historical records show that continuous monsoon failures created almost all the past famines (Agoramoorthy, 2015). Even now, India's agriculture largely depends on rains and 68% of the population depends on agriculture-related livelihoods (Agoramoorthy and Hsu, 2015; Chinnasamy and Agoramoorthy, 2015; Chinnasamy et al., 2013). The recent occurrence of both extreme heat waves and floods within few hundred miles in south India shows that the severity likely caused by developmental course of an extreme El Niño, which was thought to be reinvigorated from the decaying phase of 2014 El Niño, as demonstrated in a recent model (Cai et al., 2014; McPhaden, 2015).

The exact cause of unprecedented rains in a single day at Chennai is not fully comprehensible. Monitoring the SST from earth-orbiting infrared radiometers had a wide impact on ocean and climate sciences. The National Oceanic and Atmospheric Administration derives the SST by using satellite-based instruments since 1972 (coralreefwatch.noaa.gov/satellite/publications/NOAA.Tech.Report.142). The National Environmental Satellite Data anomaly pinpoints regions of elevated SSTs in oceans. It facilitates assessment of El Niño development, monitors tropical storm "wake" cooling, and observes major shifts in coastal upwelling. In order to understand the effects of El Niño on the unprecedented 2015 extreme rains of Chennai, we have analyzed the NOAA/NESDIS global analysis of SST anomaly (°C) at 50 km resolution for 20-days interval from 11 to 30 November 2015 (Fig. 3). Even though it did not show any apparent evolution of SST anomaly over Indian Ocean (Fig. 3), it actually showed a pool of warmest waters in the eastern tropical Pacific as a key feature for the strongest El Niño effect in the Pacific (Fig. 3).

NASA's Tropical Rainfall Monitoring Mission data reveal that the precipitation over Chennai from 28 Nov to 8 Dec 2015 was huge and continuous (Fig. 3). The amount was equal to or higher than the precipitation in nearby oceanic areas (Fig. 3). The low-lying coastal cities around the world were considered to be affected mainly by higher sea levels, increasing temperatures, changes in precipitation, larger storm surges, and increased ocean acidity since El Niño played a key role in these extreme climate factors (Balica et al.,