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Evolution of extreme high waters along the east coast of India and at the head of the Bay of Bengal

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ABSTRACT

The recent evolution of extreme high waters along the severe cyclone-risk coasts of the Bay of Bengal (the east coast of India and Bangladesh) was assessed using long-term (24–34 years) hourly tide gauge data available from five stations. The highest water levels above mean sea level have the greatest magnitude towards the northern part of the Bay, which decreases towards its south-west. Extreme high waters were observed to result from a combination of moderate, or even small, surges with large tides at these stations in most of the cases. Increasing trends, which are significant, were observed in the extreme high waters at Hiron Point, at the head of the Bay. However, the trends in extremes are slightly lower than its mean sea level trend. For the other stations, Cox's Bazaar, Paradip Visakhapatnam and Chennai, no significant trends were observed. At inter-annual time scales, changes in extreme high waters in the Bay of Bengal were found to be influenced by the El Niño Southern Oscillation and the Indian Ocean Dipole.

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1. Introduction

Rising mean sea level (MSL) is one of the climate change phenomena that are of greatest concern. Rising MSL is a pressing concern not only for the small islands but also for the mega-cities and the villages in the low elevation coastal zones. Over a long span of time, rising MSL has the potential to transform these coastal regions, where a large population resides, impacting upon investments and infrastructures. Accompanying the rising MSL is the increased occurrence of extreme sea levels. Extreme sea levels, which arise mostly due to storm surges combined with high tides, cause abrupt destruction of life and property. Aside from MSL change, causative factors for changing extreme sea levels include changing surge (storminess) and/or tide components. Within long-term trends, extreme sea levels and potential coastal flooding are also found at specific times when the peaks of the nodal and perigean tidal cycles occur (Eliot, 2010; Haigh et al., 2011).

Reviews of the literature on these topics may be found in Lowe et al. (2010) and Woodworth et al. (2011). While Menéndez and Woodworth (2010) is notable as a quasi-global study, most other papers are seen in those two reviews to relate to changes in extremes in Europe and the Mediterranean, although some research noted is in regions such as California, British Columbia and Argentina. Most recently, the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) (Church et al., 2013; Rhein et al., 2013) included a review of extreme sea levels. That report concurred with the view that the recent increase in observed extremes worldwide has been caused primarily by an increase in MSL, although the dominant modes of climate variability (particularly the El Niño Southern Oscillation (ENSO) but including the Indian Ocean Dipole (IOD), North Atlantic Oscillation (NAO) and other modes) also have a measureable influence on extremes in many regions, via variability in MSL and/or mode-related changes in storminess. Since the IPCC AR5, there have been a number of studies relating to extreme sea levels. Wahl et al. (2014) reported rapid changes in the seasonal cycle of MSL along the Gulf coast of the US. Seasonal MSL is found to provide the baseline to which storm surges can be added to provide an overall extreme. Consequently, changes in the seasonal cycle, like changes in annual MSL, can change flood risk.

Among recent regional studies, an investigation of extremes in the Baltic (Ribeiro et al., 2014) found that northernmost stations exhibit larger positive trends in extremes since 1916, relative to mean values, unlike those of the southern Baltic, where changes in extremes are more in line with those in MSL. Mudersbach et al. (2013) and Dangendorf et al. (2013) examined long records from six stations on the North Sea coast of Germany and concluded that the observed positive trends in extremes are similar to those in MSL prior to the 1950s and for 1990-onwards, but in between the high sea levels rose faster than MSL due to changes in the amplitudes of major tidal constituents and decadal variability of storm surges. Elsewhere in Europe, Marcos et al. (2009); Haigh et al. (2010) and Tsimplis and Shaw (2010) previously substantiated that the increasing trends in extremes are driven by MSL changes.

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In a study of Caribbean extreme sea levels resulting from tropical storms, Torres and Tsimplis (2014) concluded that the observed trends in extremes are also caused by MSL rise in that region with no evidence of secular changes in the storm activity. Feng and Tsimplis (2014) determined trends in extremes between 1954 and 2012 at 20 tide gauges along the coast of China. They concluded that the trends are primarily driven by changes in MSL, but are also linked with increases in tidal amplitudes at three stations. Neither the Pacific Decadal Oscillation (PDO) nor ENSO are found to be indicators of changes in the magnitude of extremes, but ENSO appeared to regulate the number of tropical cyclones that reach the Chinese coasts. Another study by Feng et al. (2015) concluded that changes in extremes along the coast of China are strongly related to the changes in MSL. Further, they pointed out that these changes are not entirely due to MSL changes, but have contributions due to spatially non-uniform changes in surge and tide components. Increased flooding instances have been reported along the US coasts. Talke et al. (2014) found that increased inter-annual variability together with MSL rise led to the increased flood levels at the New York Harbor. Wahl and Chambers (2015) found significant but small trends in extremes during 1929–2013 along most of the coastline stretches of the US. These trends are primarily due to MSL rise. They also noted multi-decadal variations in extremes which are not related to MSL. Moftakhari et al. (2015) reported an increased frequency of minor flooding instances along the coasts of the US due to sea level rise. Though non-destructive, these floods are capable of causing public inconveniences including frequent road closure etc. and they signify increased risk during severe floods.

In summary, long-term changes, inter-annual variability and contributing factors in extreme sea levels have been documented globally and in some selected basins (Woodworth and Blackman, 2004; Menéndez and Woodworth, 2010; Merrifield et al., 2013; Marcos et al., 2015). Changes are studied using high frequency tide gauge data, usually sampled at a frequency of once per hour. At most of the tide gauge stations, positive trends in extremes have been found to be due to rising MSL. At inter-annual time scales, extreme sea levels have tended to show a dependence on various modes of climate variability, including ENSO and NAO, depending on the region. Most of these studies have not included detailed discussion of extreme sea levels in the Bay of Bengal.

The Bay of Bengal, a semi-enclosed water body which forms the north-eastern part of the Indian Ocean, is characterised by high tides with amplitudes of M_2 tidal constituent exceeding 1 m towards the head of the Bay and the coasts of eastern Andaman Sea (Murty and Henry, 1983; Sindhu and Unnikrishnan, 2013) and by the presence of some of the most destructive weather systems on the planet, the tropical cyclones. Countries like India, Bangladesh, Myanmar and Sri Lanka are greatly susceptible to tropical cyclones. Tropical cyclones produce strong winds and torrential rains, and at the same time cause sea level to increase dramatically at the coast in storm surges, all of these processes thus affecting the low-lying densely-populated coastal regions of these countries. The annual frequency of tropical cyclones is smaller in the Bay as compared to some other cyclone-risk ocean areas (Gray, 1968). However, their impact is devastating due to large populations residing in coastal regions. Thus, tropical cyclones are a major causative factor of impacts of extreme sea levels in the Bay of Bengal. Although tsunamis have also been observed to cause extreme sea levels, they occur rarely in the Bay of Bengal.

Trends in relative MSL, based on long-term tide gauge data, have been reported for the coasts of the northern Indian Ocean and are consistent with global estimates (1.06 to 1.75 mm yr^{-1} during 1878 to 2004 for records having different time spans, Unnikrishnan and Shankar, 2007). Recent estimates using satellite altimeter observations (Unnikrishnan et al., 2015) have revealed increased sea level rise trends (mean value of 3.28 mm yr^{-1} for the north Indian Ocean) during 1993–2012, which are again consistent with findings for trends in global MSL for the same period. Notably, the head of the Bay is characterised by a higher rate of sea level rise than elsewhere (typically 5 mm yr^{-1}), which is partly due to the subsidence of Ganga-Brahmaputra-Meghna (GBM) river delta. Modes of climate variability, such as ENSO and IOD, have been found to have a pronounced effect on year-to-year sea level variability in the Bay of Bengal (Singh et al., 2001; Han and Webster, 2002; Srinivas et al., 2005; Singh, 2006; Aparna et al., 2012; Sreenivas et al., 2012). Sea level along the east coast of India has been found to decrease (increase) during El Niño (La Niña) events (Srinivas et al., 2005). During the positive (negative) phase of the IOD, sea level tend to decrease (increase) along the east coast of India (Aparna et al., 2012).

Knowledge of extreme sea levels, and insight into their future projections, are essential for managing flood risks in the coastal areas. Sea level observations obtained by tide gauges provide the basis of this knowledge. Subsequently, their analysis using statistical techniques can be used to assess changes in future flood risk under different climate scenarios. Return period and return level estimations of extreme sea levels in the Bay of Bengal have been provided by Unnikrishnan et al. (2004) and Lee (2013) using hourly tide gauge data and Unnikrishnan et al. (2011) using storm surge models, driven by regional climate models to provide present and future return periods of storm surges and extreme sea levels. Extreme sea level projections for GMB delta (Kay et al., 2015) shows increased likelihood of high water events through the 21st century. A number of other studies related to extreme sea levels in the Bay of Bengal include event-specific numerical modeling of storm surges (Dube et al., 2009; Dube et al., 2013) and tide gauge observations to characterise storm surges (Mehra et al., 2015). There have been efforts to study extremes using altimeter observations (Antony et al., 2014).

In the present paper, we investigate and present the spatial patterns and recent changes in extreme high waters in the Bay of Bengal using hourly tide gauge data available along the east coast of India and at the head of the Bay of Bengal. The study intends to estimate changes in extreme high waters on seasonal, inter-annual to longer time scales.

2. Data and methods

Hourly tide gauge data from stations at three ports, Chennai, Visakhapatnam and Paradip along the east coast of India, and from two stations, Hiron Point and Cox's Bazaar at the head of the Bay (Fig. 1a), were selected for the present analysis. The hourly data along the Indian coast were provided by the Survey of India (SOI) and Indian National Centre for Ocean Information Services (INCOIS), while those at the head of the Bay were downloaded from the research quality data archive of the University of Hawaii Sea Level Center (UHSLC).

We used the percentile analysis technique (see Woodworth and Blackman, 2004) to study the changes in the extreme high waters. Only the years that were essentially complete with 50% or more data (Fig. 1b) were used, and all the data have been quality checked as described by Antony and Unnikrishnan (2013). The hourly sea level data for each year were arranged in the order of ascending level. The percentiles of these data were computed such that 99.9th percentiles represent extreme high waters. Following this, percentile time series were constructed for the 99.9, 99.75, 99.5, 99.0, 95.0 and 50th percentiles for each station by combining corresponding percentiles from each year. A second set of percentile time series were also constructed, which were reduced to their median (50th percentiles subtracted). This reduction corresponds approximately to the removal of MSL for each year. The seasonality in the extreme high waters was studied using percentiles computed month-wise. We estimated the mean seasonal cycle from month-wise percentiles by averaging the percentiles over each month (months with at least 50% data were included). Standard deviations were calculated to represent the month-wise variability.

To study the influence of regional climate on the inter-annual variability of extreme high waters, a linear-correlation analysis was carried

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