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Observing storm surges in the Bay of Bengal from satellite altimetry

Q1 Charls Antony [a, *], Laurent Testut [a, b], A.S. Unnikrishnan [a]

[a] CSIR – National Institute of Oceanography, Dona Paula, Goa, 403004, India
[b] LEGOS/OMP, 14, avenue Edouard Belin, 31400 Toulouse, France

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ABSTRACT

In the present study we examined 15 years (1993–2007) of satellite altimeter and coastal tide-gauge records in the Bay of Bengal and demonstrate that satellite altimetry can be a useful complementary dataset for the study of storm surges. We first examined the performance of X-TRACK-processed altimeter data. During the period of study (1993–2007), 30 (19), 21 (09), 10 (07), and 07 (01) storm surge events were identified from tide gauges (altimetry) at Hiron Point, Paradip, Visakhapatnam and Chennai respectively. The magnitudes of surges observed by altimeters are comparable to those recorded in tide gauges. Though observing storm surges by altimeters rely purely on a chance, the presence of multiple satellite tracks in a region considerably enhances the chances of capturing the signals of an extreme event. Moreover, information on cross-shelf variations of storm surges is useful for model validation.

1. Introduction

Observations from satellites were a major breakthrough in the history of oceanography. Satellite observations have given good temporal and spatial coverage of world oceans measuring many oceanographic parameters. These observations include those from altimetry; which have been available since the launch of TOPEX/Poseidon in 1992. Altimeter data are widely used to describe variability associated with major ocean currents, meso-scale eddies and also to study the propagation of planetary-scale waves such as Rossby waves. Altimeter data are used for assimilation in global tidal models, for instance, Ray (1999) and Lyard et al. (2006), which are then used for prediction of tides in the open ocean. More oceanographic applications of satellite altimetry are described in Fu and Cazenave (2001). There have been some rare instances of altimeters capturing tsunami signals, for instance, the Indian Ocean tsunami of 2004 (Gower, 2005). Storm surges are more frequent than tsunamis; therefore, the chances of observing them are higher than those of tsunamis.

Only very little literature exists on satellite altimetry and storm surges. Scharroo et al. (2005) reported for the first time, the records of wind-driven storm surge, associated with the hurricane Katrina, which affected the gulf coast of the United States in 2005. Geosat Follow-On altimeter measured a surge of about 90 cm during the hurricane Katrina. Han et al. (2012) showed a detailed analysis of Jason-2 satellite observations of sea surface heights combined with tide-gauge data during the passage of the hurricane Igor that crossed Newfoundland in 2010. For this event, St. John's tide gauge recorded a maximum surge of 94 cm and Jason-2 (the track located 89 km away from the tide-gauge station) showed positive sea-level anomalies of about 60 cm during the storm event. They noted propagation of a shelf wave, generated by the storm, having a speed about 10 m/s. Recently, Lillibridge et al. (2013) described the spatial extent of the storm surge, generated by the hurricane Sandy that crossed northeastern United States in 2012. In this case, the maximum surge height was found to be about 1.5 m Sirota and Lebedev (2008) reported historical storm surges in the Gulf of Finland and the Neva River observed from the TOPEX/Poseidon and Jason-1 satellites respectively. Altimeter on-board the SARAL/Altika satellite measured storm surge due to cyclone Xaver, which affected the coasts of North Sea in 2013 (Scharroo et al., 2014). These studies have shown that satellite measurements provide useful information about surges, which can be used for comparison with model results or assimilation in models (Madsen et al., 2007). Most of the earlier studies focused mainly on particular extreme surge events. The present paper is the first attempt to identify storm surges over an extended period in a region using altimetry.

The Bay of Bengal, which occupies the northeastern part of the Indian Ocean, experiences 4–5 cyclones in a year. Most of the cyclones are formed over the central and northern part of the bay (Fig. 1a). These cyclones cross the east coast of India and the coast of Bangladesh and a few of them, cross the Sri Lankan and the Myanmar coasts (Fig. 1b). Frequent occurrence of cyclones in the region coupled with the large tidal ranges give rise to extreme sea

* Corresponding author.
E-mail address: cantony@nio.org (C. Antony).

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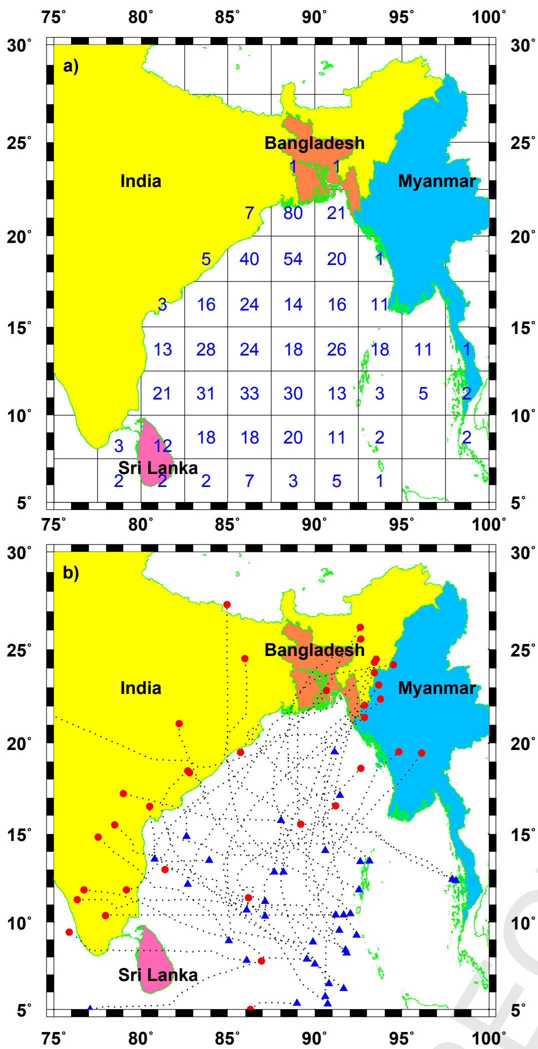

Fig. 1. a) Tropical cyclone formation frequencies over the Bay of Bengal during 1891–2007 in 2.5° × 2.5° grid boxes. b) Tracks of tropical cyclones during the period 1993–2007 in the Bay of Bengal. Triangle (circle) represents formation and dissipation points of tropical cyclones.

level in the head bay and surrounding regions. Moreover, low-lying nature of the coast and the dense population in the region make the coasts of the northern Bay of Bengal highly vulnerable to storm surges. Detailed description on the past storm surges in the Bay of Bengal and numerical modelling of surges in the Bay can be found in Murty et al. (1986), Dube et al. (1997), Jain et al. (2006, 2007) and Dube et al. (2009). The present paper is an attempt to identify storm surges from satellite altimeter data and compare them with those recorded by tide gauges. We analysed along-track satellite data from various missions to identify storm surges in the Bay. They were compared with storm surges recorded in the hourly data from four tide gauges.

2. Data and methods

In this study, we used the 1 Hz (6–7 km) along-track spatially filtered (20 km − 3 points) sea level anomalies (SLA) distributed by Center for Topographic studies of the Ocean and Hydrosphere (CTOH), France. These data were computed with the X-TRACK software (Roblou et al., 2007, 2011), which minimizes the loss of information near the coast. The data have been widely used in several oceanographic studies (Melet et al., 2010; Liu et al., 2012; Birol and Delebecque, 2014). Various geophysical and environmental corrections are incorporated by CTOH while estimating SLA. These include ionospheric, dry tropospheric, wet tropospheric corrections, tides (including solid earth tide, pole tide and loading tide), sea state bias (SSB) and dynamic atmospheric corrections (DAC). SLA is calculated using the formula given below.

$$\mathrm{SLA} = \mathrm{SSH} - \{\mathrm{iono} - \mathrm{dry\ tropo} - \mathrm{wet\ tropo} - \mathrm{solid\ earth\ tide} - \mathrm{pole\ tide} - \mathrm{loading\ tide} - \mathrm{SSB} - \mathrm{tide} - \mathrm{DAC}\} - \mathrm{MSSH}$$

where SSH is the sea surface height, observed by the satellite and MSSH is the mean sea surface height.

2.1. Dynamic atmospheric correction (DAC)

Satellite measurements are affected by the oceans' response to atmospheric pressure and wind forcing. DAC is the correction term which accounts for pressure and wind effects. The high frequency (<20 days) ocean response to atmospheric pressure and wind is corrected using the T-UGOm 2D shallow water model outputs (Carrere and Lyard, 2003), while the inverse barometric correction is applied for lower frequencies (>20 days). In the present study, DAC corrections are retained in SLA to get consistent results with tide-gauge measurements.

Along-track data from T/P + J1+J2 (TOPEX/Poseidon, Jason-1 and Jason-2 merged data), GFO (Geosat Follow On), ENVISAT (ENVIronmental SATellite) and T/PN (T/P interleaved) missions were used in the present study. The ground tracks of each satellite over the Bay of Bengal region are shown in Fig. 2. T/P mission started in 1992. The satellite has a repeat time of nearly 10 days. J-1 was launched in 2001 on the same T/P orbit. The ground tracks of T/P and J-1 are wide, about 315 km at the equator. In 2002 T/P was moved to a new ground tracks in tandem with J-1 until the end of the T/P mission in 2006. GFO was launched in 1992 and the mission continued till 2008. The repeat time of GFO was 17 days and the ground tracks were separated by 160 km at the equator. The ENVISAT mission was from 2002 to 2012. Repeat period of ENVISAT was 30–35 days and the ground track separation was 90 km.

Hourly tide-gauge data from four locations along the coast of western Bay of Bengal (Fig. 2) were used in the present study. The data spans 1993–2007. The hourly tide-gauge data along the Indian coast (Paradip, Visakhapatnam and Chennai) were provided by the Survey of India, while those at Hiron Point were downloaded from the research quality data archive of the University of Hawaii Sea Level Centre. The various quality checks made were reported in our earlier work (Antony and Unnikrishnan, 2013). These included correcting datum shifts, removal of quasi-tidal oscillations etc. Sea-level residuals were obtained by de-tiding the hourly tide-gauge data. We performed the harmonic analysis by using the same set of 35 tidal constituents used for tidal correction in the altimeter data processing by CTOH, with the seasonal component (S_a) retained in both the data.

The tracks of cyclones and depressions formed over the Bay of Bengal were extracted from the Cyclone eAtlas-IMD (online version available at the URL: www.rmcchennaieatlas.tn.nic.in), developed by the India Meteorological Department (IMD). We used the wind fields at 10 m and mean sea level pressure from NCEP/NCAR reanalysis (Kalnay et al., 1996) to get evolution of the atmospheric fields during each storm surge event.

2.2. Altimetry data validation

A comparison between X-TRACK SLA and tide-gauge SLA was made by doing a linear correlation between the two and a root-