

## **Observing storm surges in the Bay of Bengal from satellite altimetry**

Charls Antony<sup>1\*</sup>, Laurent Testut<sup>1,2</sup> and A.S. Unnikrishnan<sup>1</sup>

<sup>1</sup>CSIR- National Institute of Oceanography, Dona Paula, Goa, 403004, India

<sup>2</sup>LEGOS/OMP, 14, avenue Edouard Belin, 31400 Toulouse, France

\*Corresponding author

E-mail: cantony@nio.org ; Telephone: 091(0) 832 2450 400

### **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.

**Keywords:** cyclones; storm surges; altimetry; tide gauges; probability; Bay of Bengal

## 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 (Figure 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 (Figure 1b). Frequent occurrence of cyclones in the region coupled with the large tidal ranges give rise to extreme sea 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); Jain et al. (2007); 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.

### **Preferred position of Figure 1**

## **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; Roblou et al., 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.

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

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 Figure 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 2002-2012. Repeat period of ENVISAT was 30-35 days and the ground track separation was 90 km.

### Preferred position of Figure 2

Hourly tide-gauge data from four locations along the coast of western Bay of Bengal (Figure 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.rmchennaieatlas.tn.nic.in](http://www.rmchennaieatlas.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-mean square difference (RMSD) analysis. Tide gauge data as close as possible in time with altimeter data were used. Figure 3 (a, c, e, g) shows RMSD between altimeter SLA and nearest tide-gauge SLAs. RMSD varies between 10-20 cm in the shelf regions. Figure 3 (b, d, f, h) shows the linear correlations between tide-gauge SLA and altimeter SLA. The correlation coefficients within the shelf regions are found to be high (0.6 - 0.8), indicating that the consistency between the two data is good. Crossover points of various tracks, for example, track 53 and track 90 of T/P, which are separated by about one and half day in time, shows inter consistency of the data with similar values of correlation coefficients (Figure 3b).

### **Preferred position of Figure 3**

## **2.3. Identification of storm surge events**

The dates of formation of various low pressure systems (LPSs) and their tracks in the Bay of Bengal for systems having intensities of depression (wind speed between 17-27 knots) and above were obtained from the eAtlas-IMD. Surge events during the corresponding period with minimum surge height of 25 cm were identified from hourly tide-gauge data. More than half of the events recorded in the tide gauges were found to last 2 days (Table 1). About twenty storm events were recorded in two adjacent tide gauges. The satellite tracks within a distance of  $2^\circ$  of tide-gauge location and having a pass within 24 hours of the peak surge, observed in the tide gauge, were considered to identify corresponding surge signals from altimeter data. A minimum surge height of 20 cm was used to identify events in the 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 (see Table A1 for date and time of surge events recorded in tide gauges and altimeters). The mean surge heights and standard deviations of surge heights from both tide-gauge and altimetry data, and duration of surges are shown in Table 1. Mean surge heights tend to decrease from Hiron Point to Chennai. This is evident in the altimetry data also. Figure 4 shows a typical surge observed by altimeter and tide gauges at Hiron Point and Paradip. This particular surge event was caused by a depression which crossed at Hiron Point (inset, Figure 4a). The time evolution of wind and

pressure fields of this depression is shown in Figure 4b. T/P satellite (track 231) crossed Hiron Point just 2 hours prior to the occurrence of surge peak. The altimeter recorded a surge of about 65 cm, about 176 km away from the Hiron Point tide gauge. The maximum surge recorded in the tide gauge was 123 cm and at the time of altimeter pass the surge in the tide gauge was 86 cm, The wind and pressure fields (Figure 4b) show cyclonic circulation in the region extending to Paradip as well. The maximum surge recorded at Paradip was about 51 cm. Tracks 192 and 014 (before and after the event) recorded consistent SLA with respect to Paradip tide gauge. Figure 4d shows the total water level (tide + surge) recorded by the altimeter along the track 231. Figure 4e shows the total water level (tide + surge) records from the Hiron Point tide gauge. The peak surge occurred during rising tide (about 4 h before high tide) and satellite pass was during the low tide. A 15cm difference in the total water levels between tide gauge and altimeter was found during satellite's pass.

#### **Preferred position of Figure 4**

### **3 Discussion and Conclusions**

Table 1 presents the number of satellite passes within 24 hours of surge events recorded by each tide gauge. 46% of the surge events identified in tide gauges were also recorded by altimeters, with a minimum of 14% for Chennai and a maximum of about 50% for Hiron Point. Three events were captured in two altimeters. The storm surges recorded by tide gauges and altimeters were compared (Figure 5). The maximum surge recorded in altimeter data during this period is about 93 cm (Figure 5). The number of coexisting events is large at Hiron Point due to large number of adjacent satellite ground tracks (Table 1). In most of the cases, number of surges observed by altimeters was found to be less than those observed in tide gauges. The values recorded by altimeter were taken from off shore locations. For example, closest point of the track 14 is about 16 km away from the coast, whereas closest point on the track 53 is located by about 36 km from the coast. Moreover, the track 116 is close to Visakhapatnam tide gauge by about 15 km, whereas the track 53 is located by about 200 km from Hiron Point tide gauge. Wherever, the distance to the track is large, an exact comparison is not possible. However, the present analysis shows that altimeter is able to capture surge signals and their magnitudes are comparable to those observed by tide gauges. The total water level at the coast is a combination of tide and surge. Storm surges, when combined with high tide results in high sea levels. Total water levels recorded by altimeters are shown in Figure 5 with total sea level recorded by tide gauges at the same

time. The total water level measurements by altimeters are comparable to those in tide gauges. The maximum water level recorded in altimeter data during 1993-2007 is about 2 m.

### **Preferred position of Figure 5**

During the period of analysis, one super cyclone crossed Paradip on 29 October 1999 (IST), which caused immense loss of life and property. During this event, the tide gauge at Paradip was not functioning and hardly any data are available to study the event. However, port authorities in Paradip reported a surge of 3 m (Unnikrishnan et al., 2004). However, a strong signature of this event can be seen at Hiron Point tide gauge, which recorded a surge of about 80 cm (Figure 6a). T/P, which flew close to Hiron Point (track 231) during this event (28 October), recorded a surge of about 60 cm (Figure 6b). The total water level recorded by tide gauge and altimeter are shown in Figure 6a and b respectively. The difference between total water levels measured in tide gauge and altimeter was about 28 cm. 2007 Sidr cyclone was another major event during 1993-2007, which was recorded in altimeters. Cyclone Sidr hit Bangladesh coast in the early hours of 16 November 2007 (IST). Paradip tide-gauge SLA (Figure 7a) shows signature of this event, about 50 cm. On 16 Nov, J-1(Track 231) and ENVISAT (Track 509) recorded SLA about 31 cm and 73 cm respectively. Figure 7a, b and c also shows the total water level measurements during cyclone Sidr from Paradip tide gauge, J-1 and ENVISAT respectively. The total water level measurements from J-1 and ENVISAT are in approximate agreement with Paradip tide gauge measurements with a difference of 23 cm and 13 cm respectively.

### **Preferred position of Figure 6**

### **Preferred position of Figure 7**

In the present study, we showed that probabilities of capturing storm surge events in altimeter data can be significant, especially in regions where multiple tracks of satellites exist. Comparing the data of T/P, J-1, GFO and ENVISAT satellites in the Bay of Bengal with the hourly tide-gauge data, we illustrate that nearly 46% of surge events are observed both in altimetry and tide gauge on an average in this region.

During the two decades of satellite altimetry, probably the most challenging task had been to improve usage of altimetry data in the coastal regions. In addition to X-TRACK processed data, PISTACH (Prototype Innovant de Système de Traitement pour l'Altimétrie Côtière et l'Hydrologie; Mercier et al., 2010) and COASTALT (Gomez-Enri et al., 2008) projects attempted to recover valuable

information of SSH from coastal zones. New initiatives, such as eSurge project (Harwood et al., 2013), promote new research in this direction. Vignudelli et al. (2011) detailed the issues, improvements and future of the coastal altimetry. Storm surge studies using altimetry are still in an initial stage of development. Although altimetry is proven to complement tide gauges, a better strategy will be required for routinely monitoring of storm surges in the future. As the repeat period of the orbit is the key factor to increase the probability of observing surges by a satellite, a high repetitive constellation of altimeter satellites can considerably enhance the chances of capturing of surge signals. Classical altimeters of T/P and J-1 measure sea surface on their nadir. The nadir swath is roughly 2 km and inter track distance is about 315 km at the equator. The new proposed SWOT (surface water ocean topography) mission, provide a 2-D map of the sea surface with wide swath (around 120 km). This new mission certainly complements the standard nadir altimeter data with fine spatial coverage and high resolution.

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## Figure captions

**Figure 1** **a)** Tropical cyclone formation frequencies over the Bay of Bengal during 1891-2007 in  $2.5^\circ \times 2.5^\circ$  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.

**Figure 2** Satellite ground tracks of **a)** TOPEX/Poseidon (same for Jason-1), **b)** Geosat Follow-On, **c)** ENVISAT and **d)** TOPEX/Poseidon interleaved missions. Red circles mark locations of tide gauges used in the present study. Red numerals represent satellite track number.  $2^\circ$  circles around the tide-gauge locations are also shown.

**Figure 3** Root mean square differences (**a, c, e, g**) and Linear Correlations (**b, d, f, h**) between sea-level anomalies of altimeters (T/P - **a & b**, GFO - **c & d**, ENVISAT - **e & f** and T/PN - **g & h**) and tide-gauges. Correlation analysis was performed with the tide-gauge data and the nearest ground tracks. A colored circle with black border represents correlations, which are not statistically significant.

**Figure 4** **(a)** The track of a depression (inset) which crossed near Hiron Point (HIR) on 28 October 1996 and T/P (231) passed west of the landfall region at around 17:30 IST (Indian Standard Time) on 28 shows surge of about 65 cm. Sea level anomalies of T/P tracks (192 and 14) during the event is also show.

**(b)** Shows the wind fields at 10 m and mean sea level pressure taken from NCEP/NCAR reanalysis data to indicate the movement of the depression. **(c)** Shows surge measurements from Hiron Point and Paradip tide gauges. The time of satellite's pass is shown with a vertical line, with the track numbers shown in the x-axis and the maximum surge recorded by altimeter is marked with a horizontal line (blue) on this line. **(d)** Shows total water level (tide + surge) profile and bathymetry along the track 231 (T/P). Vertical line indicates the coastline. **(e)** Shows total water level (mean removed) measured by Hiron Point tide gauge during the storm event and the horizontal line indicates sea level recorded by altimeter.

**Figure 5** Comparison between storm surge heights and total water levels (tide + surge) recorded in tide gauges and altimeters. **(a)** Hiron Point, **(b)** Paradip, **(c)** Visakhapatnam and **(d)** Chennai. Surge heights observed in the tide gauges (altimeters) are represented with red (black) colour bars. Total water level observed in the altimeters and in the tide gauges during altimeter pass are represented with blue and green colour bars respectively.

**Figure 6** **(a)** Tide-gauge measurements of storm surge and total water level (mean removed) during the 1999 Orissa super cyclone at Hiron Point. Vertical line indicates the time of satellite pass. **(b)** T/P along-track SLA and total water level (tide + surge) during pass 90 on 28 October. Vertical line indicates the coastline.

**Figure 7** **(a)** Tide-gauge measurements of storm surge and total water level (mean removed) during cyclone Sidr at Paradip. Vertical line indicates the time of satellite pass. **(b)** J-1 along-track SLA and total water level (tide + surge) during pass 231 on 16 October (IST). **(c)** ENVISAT along-track SLA and total water level (tide + surge) during pass 509 on 16 October (IST). Vertical line indicates the coastline.

## Appendix A

**Table A 1:** Date and time of storm surge events from Tide gauges and Satellites.

Sl No.	Date & time (tide gauge)	Date & time (altimeter)	Tide-Gauge stations	Satellite Track No.	Cycle No.
1	22/11/1998 08:29:00	22/11/1998 18:05:00	Hiron Point	T/P 014	212
2	09/11/1995 17:29:00	09/11/1995 17:37:00	Hiron Point	T/P 053	100
3	26/06/1997 22:30:00	26/06/1997 16:10:00	Hiron Point	T/P 053	160
4	10/06/1999 15:30:00	10/06/1999 14:23:00	Hiron Point	T/P 053	232
5	26/07/2003 01:30:00	26/07/2003 18:36:00	Hiron Point	J-1 053	384
6	07/05/1996 09:30:00	07/05/1996 15:36:00	Hiron Point	T/P 090	118
7	19/10/1999 00:30:00	18/10/1999 22:27:00	Hiron Point	T/P 090	245
8	29/10/1999 09:30:00	28/10/1999 20:26:00	Hiron Point	T/P 090	246
9	27/08/2003 15:30:00	26/08/2003 22:58:00	Hiron Point	J-1 090	387
10	17/06/1993 17:30:00	17/06/1993 04:34:00	Hiron Point	T/P 231	011
11	18/08/1994 05:30:00	17/08/1994 13:31:00	Hiron Point	T/P 231	054
12	28/10/1996 19:30:00	28/10/1996 17:31:00	Hiron Point	T/P 231	135
13	14/06/1998 21:30:00	15/06/1998 16:01:00	Hiron Point	T/P 231	195
14	17/06/1999 09:30:00	17/06/1999 13:07:00	Hiron Point	T/P 231	232
15	27/07/1999 14:29:00	27/07/1999 05:03:00	Hiron Point	T/P 231	236
16	23/11/1998 08:00:00	22/11/1998 18:05:00	Paradip	T/P 014	212
17	18/08/1994 10:00:00	17/08/1994 13:31:00	Paradip	T/P 231	054
18	28/10/1996 06:00:00	28/10/1996 17:31:00	Paradip	T/P 231	135
19	17/06/1999 03:00:00	17/06/1999 13:07:00	Paradip	T/P 231	232
20	17/08/2006 09:59:00	17/08/2006 06:39:00	Paradip	J-1 231	496
21	16/11/2007 12:59:00	16/11/2007 09:30:00	Paradip	J-1 231	542
22	03/12/1996 09:59:00	02/12/1996 21:28:00	Visakhapatnam	T/P 116	139
23	30/10/1999 03:59:00	29/10/1999 20:48:00	Visakhapatnam	T/P 116	246
24	28/10/2005 14:00:00	29/10/2005 05:23:00	Visakhapatnam	J-1 116	467
25	23/09/2007 06:00:00	23/09/2007 07:41:00	Visakhapatnam	J-1 116	537
26	01/12/2005 20:00:00	01/12/2005 22:55:00	Chennai	J-1 218	470
27	26/07/2003 01:30:00	26/07/2003 18:45:00	Hiron Point	T/PN 053	032
28	27/08/2003 15:30:00	26/08/2003 23:03:00	Hiron Point	T/PN 090	035
29	19/10/2000 03:00:00	19/10/2000 13:49:00	Visakhapatnam	GFO 367	016
30	13/06/2004 09:00:00	13/06/2004 12:36:00	Visakhapatnam	GFO 453	094
31	27/08/2003 15:30:00	26/08/2003 21:22:00	Hiron Point	ENVI 0423	010
32	27/08/2003 15:30:00	27/08/2003 09:45:00	Hiron Point	ENVI 0438	010
33	28/06/2007 23:00:00	29/06/2007 21:28:00	Paradip	ENVI 0509	050
34	16/11/2007 12:59:00	16/11/2007 21:28:00	Paradip	ENVI 0509	054
35	23/09/2007 12:59:00	23/09/2007 21:25:00	Paradip	ENVI 0967	052
36	13/06/2004 09:00:00	13/06/2004 21:45:00	Visakhapatnam	ENVI 0767	017

**Table 1:** Details of storm surge events from tide gauges and altimeters

Tide gauge Stations	Satellite ground Tracks	No. of events (1993-2007)		Mean surge height (standard deviation) in cm		Surge duration <sup>a</sup> (Tide gauge)		
		Tide gauge	Altimeter	Tide gauge	Altimeter	< 2 days	2-4 days	> 4 days
Hiron Point <sup>b</sup>	14, 53, 90, 231, 53 90, 210, 223, 296 309, 395, 337, 352 423, 438, 524, 795 881, 896, 967, 982	30	19	81.06 (28.37)	51.19 (19.43)	14	14	02
Paradip	14, 192, 231, 14 231, 51, 124, 137 223, 137, 152, 509 524, 595, 610, 967	21	09	45.21 (14.92)	48.35 (18.95)	10	09	01
Visakhapatnam	116, 155, 116, 192 281, 367, 453, 223 238, 309, 767, 782 853	09	07	38.79 (7.23)	39.75 (7.93)	02	05	00
Chennai	218, 23, 23, 567	07	01	36.34 (12.86)		03	03	00

T/P+J1, T/PN, GFO, ENVISAT

<sup>a</sup>Duration of storm surge events, which are not fully recorded, are not included<sup>b</sup>Tide gauge data at Hiron Point is available upto 2003

Figure 1

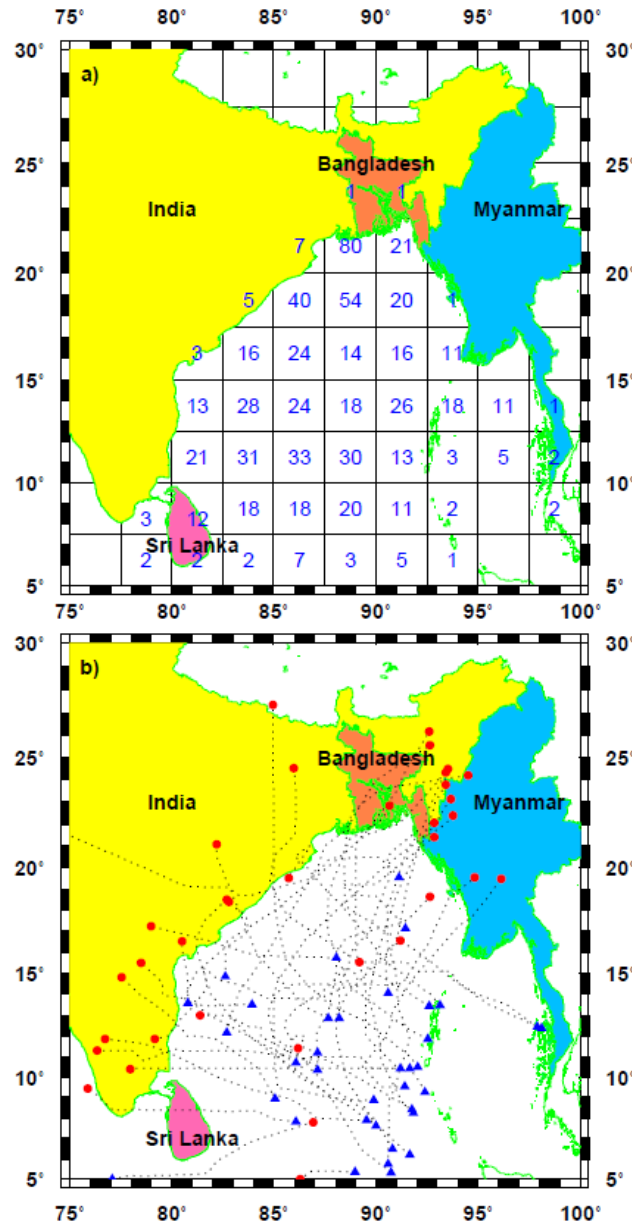


Figure 2

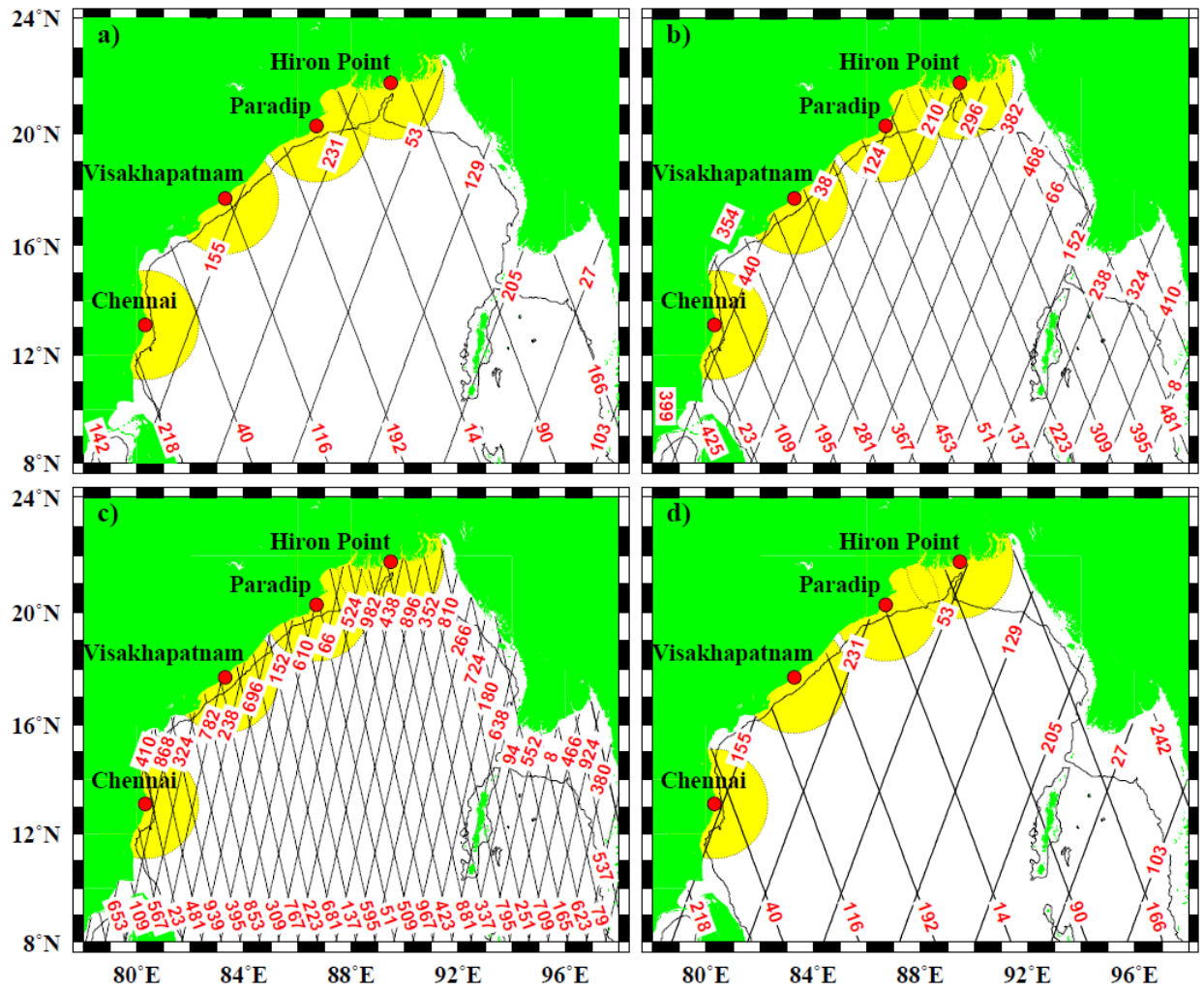


Figure 3

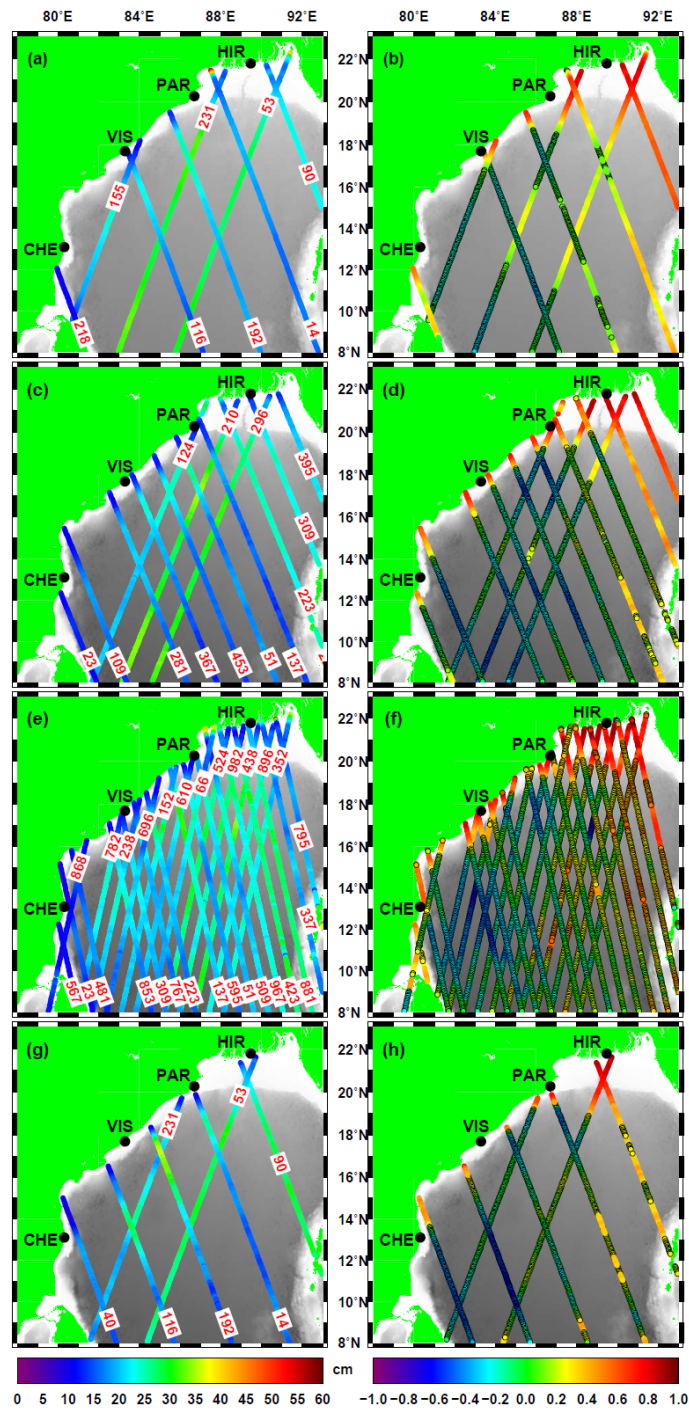




Figure 4

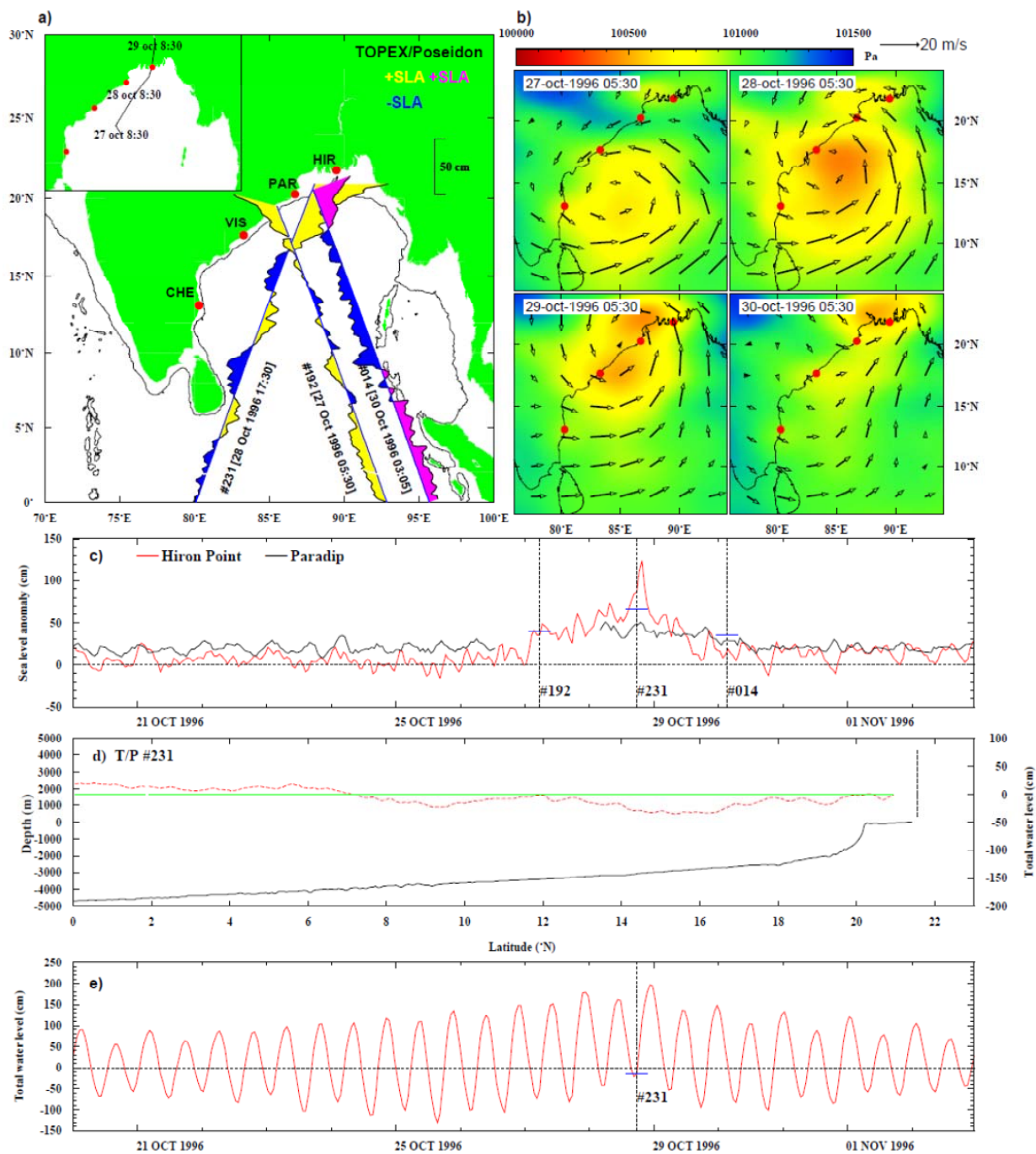


Figure 5

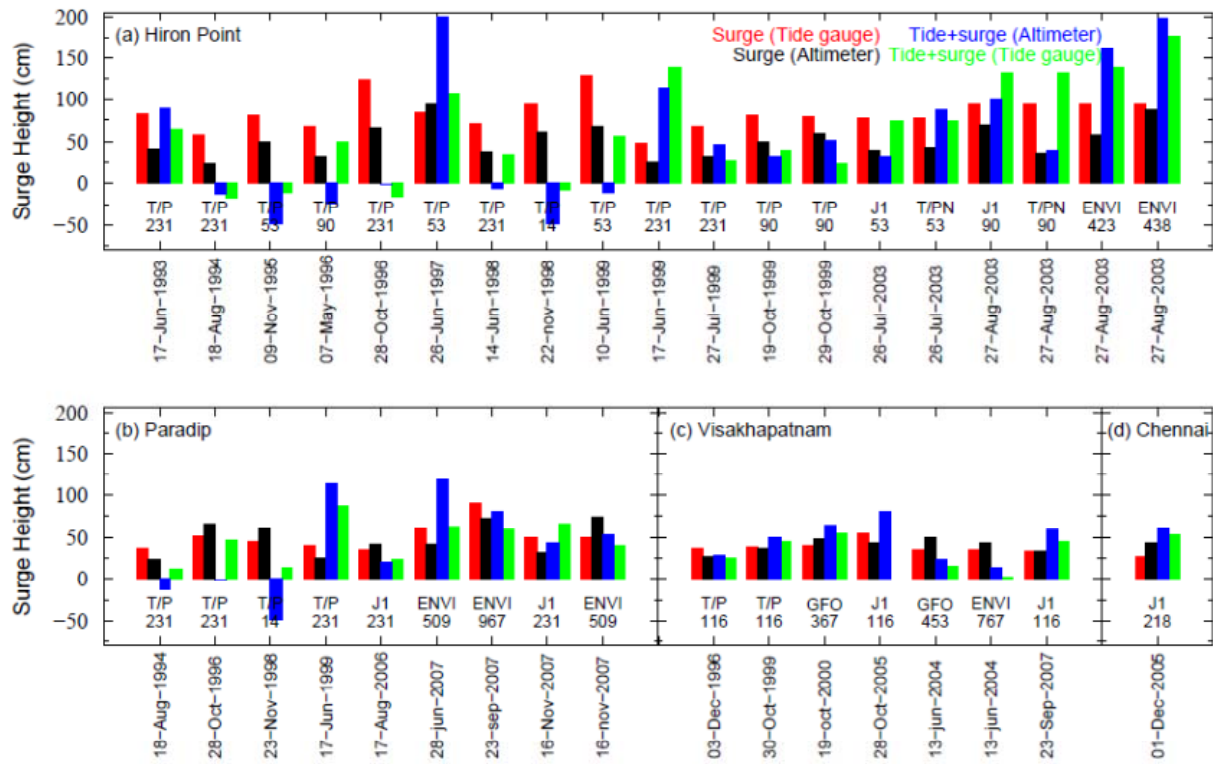


Figure 6

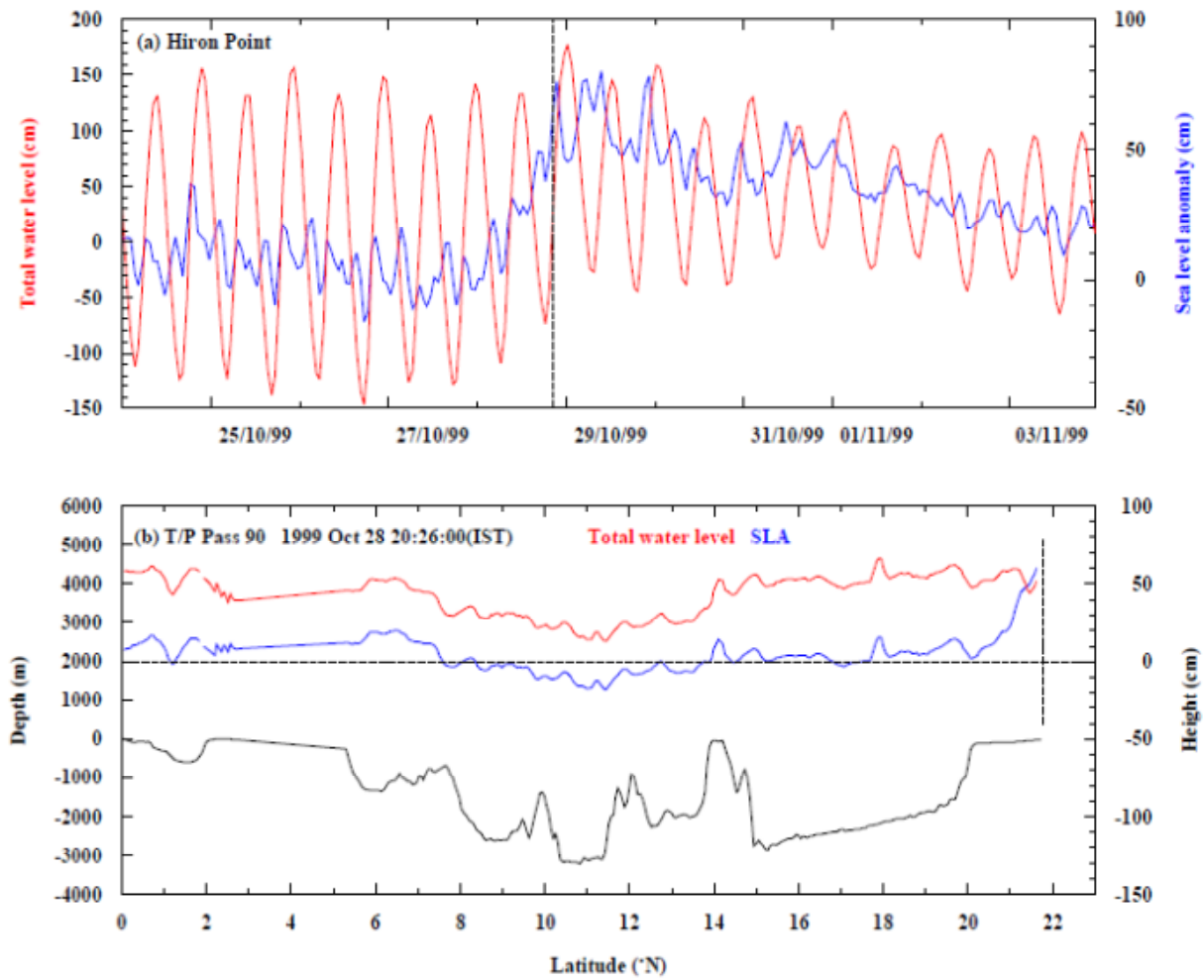


Figure 7

