

## **Observed characteristics of tide-surge interaction along the east coast of India and the head of Bay of Bengal**

**Charls Antony\* and A.S. Unnikrishnan**

CSIR-National Institute of Oceanography, Dona Paula, Goa, 403004, India

\*Corresponding author

E-mail: cantony@nio.org ; Telephone number: 091 (0) 832 2450400

### **Abstract**

Hourly tide-gauge data at Chennai, Visakhapatnam and Paradip along the east coast of India and at Hiron Point, at the head of Bay of Bengal, were analysed statistically for tide-surge interaction. Dependency of surge maxima on magnitude and phase of the tide were examined separately and interaction was quantified for each site. Along the east coast of India, interaction is found to be less, but significant. The degree of interaction is highest at Hiron Point, where surges peak more frequently about 4 hours before the high tide. Application of a simple model shows the observed surge peak distribution at Hiron Point can be explained in terms of phase alteration of tide due to surge and surge modulation by tide. The degree of interaction tends to increase northward as the tidal range and surge height increases.

**Keywords:** tides; storm surges; tide-surge interaction; statistical analysis; east coast of India; Bay of Bengal

## **1. Introduction**

The Bay of Bengal is the breeding ground of some of the deadliest cyclones of the world. Favourable prerequisites for cyclone formation make it one among the cyclone prone water bodies on the globe. The North Indian Ocean basin comprising of the Bay of Bengal and the Arabian Sea, accounts for 5-6 cyclones per year and the ratio of frequencies of formation of cyclones in the Bay of Bengal to that of the Arabian Sea is 4:1 (Niyas et al., 2009). In general, the cyclones in the bay are weak and short lived compared to those in other basins. The effects of cyclones become catastrophic due to the very large surges, they produce. The cyclones originate in the central and northern Bay of Bengal mostly during the period May to December, with high frequency of formation during November and a secondary high in May. These cyclones move mostly westward or north-westward. A few of them then turn and move towards the north east direction. Due to the low-lying nature of the coast and cyclone tracks, the east coast of India and the Bangladesh coast are highly vulnerable to damages caused by storm surges. Moreover, the head bay is characterised by large tidal ranges. Storm surges in conjunction with large tides can produce very high sea levels. The tides in the head bay and along the east coast of India are nearly semi-diurnal type, except in the southern part. For instance, at Chennai they are slightly mixed semi-diurnal in character. The tidal range increases from Chennai to Hiron Point considerably. The characteristics of tides in the bay are described using numerical modelling in Murty and Henry (1983) and Sindhu and Unnikrishnan (2013).

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

The storm surge problem in Bay of Bengal has gained much scientific attention due to the large impacts caused by the surges. The coastal regions adjoining the bay are densely populated, which results in a massive loss of life and property during the storm surges. Non-linear interaction between tides and surges forms an integral part of storm surge studies. It is crucial to understand and incorporate tide-surge interaction for the precise forecasting of storm surges and for the estimation of return periods of extreme sea level.

The total water level during a storm is considered as the superposition of tide and surge. But at certain locations, in particular, in shallow seas and estuaries, significant interaction occurs between tides and surges, which produce changes in amplitude and phase of the surges. The tide-surge interaction has been well studied along the UK coastline, where it has been found that larger surges occur more frequently at rising tide or in the lower tidal bands (Prandle and Wolf, 1978; Dixon and Tawn, 1994; Horsburgh and Wilson, 2007). This non-linear interaction between tides and surges has

been reported in many other regions such as, off the east coast of Canada, northeastern United States (Bernier and Thompson, 2007), north Queensland coast of Australia (Tang et al., 1996), Gulf of Suez (Rady et al., 1994) and Taiwan Strait (Zhang et al., 2010).

The tide-surge interaction studies commenced in the Bay of Bengal with numerical modelling experiments by Johns and Ali (1980). They used a non-linear model to determine the interaction between tides and surges in the head bay and the river systems. Some general interaction characteristics observed are: the surge elevation due to interaction of tide and surge ( $\zeta_{S+IST}$ ) is less than the elevation due to surge alone ( $\zeta_S$ ) at times of high tide and greater than  $\zeta_S$  at times of low tide, and the peak values of total water level ( $\zeta_{S+T+IST}$ ) consistently occur after the time of high tide. As surge reaches inside the river, the interaction effects changes and  $\zeta_{S+IST}$  was less than  $\zeta_S$  at all stages of the tide. Later, Johns et al. (1985) studied the tide-surge interaction in the Bay of Bengal by simulating two storm surge events that affected the coasts of Odisha and Andhra (Figure 1). They found significant interaction along the Odisha coast and relatively weak interaction along the Andhra coast. Sinha et al. (2008), through numerical modelling experiments of the 1999 Odisha cyclone, found an additional rise in sea level due to tide-surge interaction from 0.2 m to 0.6 m for selected stations along the Odisha coast. There have been some studies on tide-surge interaction in the estuaries bordering the Bay. Sinha et al. (1996) performed numerical experiments in the Hooghly estuary (Figure 1) and concluded that the storm surges influence the arrival of tidal high and low waters by as much as one hour. As-Salek and Yasuda (2001), through numerical modelling studies in the Meghna estuary (Figure 1) found that peak surges can develop during any tidal phase, and the one that develops around the time of local peak tide, travels faster than the surge that develops in any other tidal phase. The tide-surge interaction studies in the Bay of Bengal are not extensive and all of them were based on numerical modelling, which concentrate on a selected number of events. There were only a few studies, which made use of the hourly tide-gauge data for long duration at these sites for extreme sea level and storm surge studies (Unnikrishnan et al., 2004; Sundar et al., 1999). No efforts have been made so far to analyse hourly tide-gauge data to study the nature of tide-surge interaction. In the present study, we analysed nearly thirty years of hourly tide-gauge data from four stations (Figure 1), three along the east coast of India and one in the head of the Bay of Bengal.

## **2. Data and Methodology**

Hourly tide-gauge data from three ports, Chennai, Visakhapatnam and Paradip along the east coast of India and data from the station Hiron Point, in the head bay (Figure 1), were taken for the present analysis. The hourly data along the Indian coast 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. Figure 2 gives the duration of data used for the four stations. The non-tidal residuals were obtained through harmonic analysis of hourly data. Harmonic analysis was done for each year. The residuals were carefully checked for various errors such as datum shifts, timing errors and spikes. The raw sea-level data were then corrected for these errors and the harmonic analysis was repeated for the quality checked data. The harmonic analysis was carried out using the Tidal Analysis Software Kit (Bell et al., 1996) with standard set of 63 constituents. These constituents include  $M_m$ ,  $M_{sf}$  and  $M_f$  and those having seasonal periods such as  $S_a$  and  $S_{sa}$ . The process of quality checking has reduced the data percentage in certain years. A few years of data showed error in the predicted tide due to less data percentage. These years were excluded from the further analysis. The number of valid data (in percentage) obtained after quality check is presented in Figure 2.

### **Preferred position of Figure 2**

Several statistical methods are available to estimate tide-surge interaction. For the present study, the method put forward by Dixon and Tawn (1994) was used. This method detects the dependency of residuals on the magnitude of the tide. Along with this, a modified version of the above method (Haigh et al., 2010), which identifies the dependency of residuals on the different phases of tide, was also used. Both the methods are described briefly below. The present study concentrates on positive surges (residuals above mean sea level), so the distribution of extreme positive surges is considered. In fact, frequency of negative surges (residuals below mean sea level) is found to be low at these sites.

In the first method, the astronomical tidal range was split into five equal bands (each twenty percent of sorted tide data forms a band). Now the non-tidal residuals have equal probability of falling into any of these bands. If the surge and tide were independent processes, the number of surges per tidal band expected to exceed a threshold,  $u$ , would be the same for all the bands. On the contrary, if interaction is present, then the number of surges per tidal band which exceed  $u$  would be expected to differ from one tidal band to another. The level  $u$  is taken to be the 99<sup>th</sup> percentile of the residual series. The peak surge value associated with individual surges separated by 48 hours (to avoid counting of an event twice) above the 99th percentile and corresponding tide magnitudes were identified. This data was plotted over the five equal tidal bands to obtain the observed surge peak distribution. A chi-square test was performed to compare observed distribution with the distribution expected. The test statistic is

$$\chi^2 = \sum_{i=1}^B [(N_i - e)^2 / e] \quad (1)$$

where  $N_i$  is the observed number of surges per tidal band,  $e$  is the expected number of surges per tidal band, which is equal to number of events above the level  $u$ , divided by the number of bands. At the 95% significance level, the test statistic is,  $\chi^2_{4,0.95} = 9.5$  (critical chi-square from theoretical distribution), where the degrees of freedom are four. Interaction is significant if the computed chi-square value exceeds the critical chi-square at 95% significance level.

In the second method, the timing of the surge peaks relative to the nearest high water is noted. The tide is then divided into thirteen hourly bands with respect to the timings of high tide (see Figure 3b). Each surge above the level  $u$  will have equal chance of falling in any of these bands. The interaction is tested with the same statistics (Equation 1) as in the previous method, except that chi-square values are summed over thirteen bands. At the 95% significance level, the test statistic is,  $\chi^2_{12,0.95} = 21$  (critical chi-square), where the degrees of freedom are twelve.

### 3. Results

Figure 3a shows the frequency distribution of surge peaks above 99<sup>th</sup> percentile against the tide level for each station. Chennai is characterised by small surges and low tidal range (up to 1.5 m). A gradual increase in surge height and tidal range are found towards north and at Hiron Point surge height and tidal range (up to 4m) become large. At Hiron Point, surge peaks are found to occur largely on mid and low tide levels and their occurrence are hardly noticed on high tide levels. At Paradip, Visakhapatnam and Chennai, the occurrence of surge maxima is more on mid and high tide levels, with less surge peaks on low tide levels. The chi-square test statistic values indicate statistically significant tide-surge interaction in all the stations. Hiron Point has the highest degree of interaction. For the rest of the stations, the degree of interaction is found to be less.

#### Preferred position of Figure 3

In Figure 3b, the frequencies of surge peaks above 99<sup>th</sup> percentile were plotted with respect to the timings of high tide for each station. The surge peak frequency pattern has multiple peaks, with each peak on rising and falling tides. Chi-square statistic shows that estimations are statistically significant in all the stations. Hiron Point has the highest degree of interaction. Some features to be noted here are, the surges tend to peak more frequently on the rising tide (4 hours before high tide). A less

dominant peak at 5 hours after the high tide is also observed at this location. It may also be noted that none of the surge peaks occur at high tide and only a few of them occur closer to high tide. Though there is a frequent peaking of surges at 4 hours before high tide at Paradip, it is not as pronounced as that in Hiron Point. The degree of interaction here is less than that at Hiron Point. The degree of interaction further decreases towards Visakhapatnam and Chennai. The occurrence of surge peaks is high at 2 hours before and 3 hours after high tide in Visakhapatnam, whereas it is 3 hours before and 4 hours after high tide in Chennai.

Surge heights and tidal ranges increase from Chennai to Hiron Point; accordingly, an increase in surge dependency on tide magnitude and phase is also noticed. We repeated the analysis for surge distributions above 99.5<sup>th</sup> percentile and found that the surge characteristics were similar to those described earlier. Both the methods show significant interaction at all the locations and the results are found to be consistent.

#### 4. Discussion

To examine the causes of tide-surge interaction, we followed the approach described in Horsburgh and Wilson (2007). They gave an explanation for the unique clustering of surges on the rising tide through a very simple model and found that phase alteration of the tidal signal, due to surge causes preferential clustering of residuals on rising tide. An observed sea level may be represented by  $O=A\cos(\omega t)$  and the predicted tide as  $T=A\cos(\omega t-\varphi)$ , where  $A$  and  $\omega$  are the amplitude and frequency respectively and  $\varphi$  is the phase shift. The residual,  $R=O-T$ , which may be deduced as

$$R = B\cos(\omega t+\theta) \quad (2)$$

where  $B$  and  $\theta$  are the amplitude and phase, given by

$$B = A(2-2\cos\varphi)^{1/2} \quad (3)$$

$$\theta = \tan^{-1}[\sin\varphi/(1-\cos\varphi)] \quad (4)$$

For small values of  $\varphi$ , a good approximation is that  $\theta$  will advance observations by close to 90°. This causes the residual peak to be at rising tide. Now, the residual peak will be on falling tide when observation lags the prediction. Earlier, Rossiter (1961) had arrived at a similar conclusion but in a qualitative sense. Tide and surge propagate as shallow water waves, with phase speed of  $\sqrt{gh}$ , where  $h$  is the water depth and  $g$  is the acceleration due to gravity. Phase shift occurs when a positive surge increases the phase speed of both tide and surge and hence the observed sea level will lead the

predicted tide (opposite effect for a negative surge). Moreover, reduced bottom friction, caused by increased total sea level, will accelerate the surge and tide during a positive surge (opposite effect for negative surge). In addition, there is another mechanism that takes place. A tidally modulated surge production, in which surge is notably higher at low tide and lower at high tide. The steady state effect of wind stress on sea surface ( $\zeta$ ) slope may be written (Pugh, 1987) as

$$\partial\zeta/\partial x = C_D \rho_A W^2 / g \rho D \quad (5)$$

where  $C_D$  is the Drag coefficient,  $\rho_A$  is the density of air,  $W$  is the wind speed,  $g$  is the acceleration due to gravity,  $\rho$  is the density of water and  $D$  is the water depth. Equation (5) shows that the effects of wind stress on sea level gradient increases inversely with the water depth. Hence, the surge generated by the strong winds associated with cyclones, blowing over a large area and for a few hours, is expected to be higher at low tide than high tide. Horsburgh and Wilson (2007) demonstrated this tidally modulated surge production through numerical experiments, which was consistent with Equation (5). They showed using residual time series, obtained from model simulations, that surge is prevented from peaking at high tide even at strongest meteorological forcing. The surge modulation by tide is incorporated by modifying the Equation (4). The residual peak with respect to high tide is now given by

$$(\theta + \varphi) = \tan^{-1}[\sin \varphi / (1 - \cos \varphi + k)] - \pi \quad (6)$$

where  $k$  is the ratio of local surge modulation to the tidal amplitude.

Horsburgh and Wilson (2007), using Equation (6), showed theoretically that how small phase shift combined with moderate surge modulation causes surges to peak at rising tide. They applied the theory for the surge data at Sheerness, a tide-gauge station along the U.K. coast, where phase alteration and surge modulation are present.

To test the above theories, we analysed the surges at Hiron Point. Thirty one surge events were identified above a threshold of 99.9 percentile at Hiron Point (Figure 4a). These surges were grouped into (i) phase altered, (ii) long duration surges, (iii) surges at low water and (iv) surges at high water, following the classification by Horsburgh and Wilson (2007). Characteristics of each surge type are described in Table 1 along with their number of occurrence. The typical high water events, which belong to category (iv), are absent for surges above 99.9<sup>th</sup> percentile. Figure 4b shows a phase altered event. Thirteen surge events belong to this category, in which there is a phase shift between observed sea level and predicted tide. The phase shifts observed are of about one hour. Figure 4c represents a

long-duration surge with a characteristic dip at the time of high tide (category ii). There were twelve such events in this category, which are caused by modulation of surges by tides. Our observational evidence confirms that phase alteration of tidal signal due to the surge and modulation of surges due to tides are the main cause for the interaction at Hiron Point. From Chennai, where lowest interaction is observed, to Hiron Point, where interaction is highest, the tidal range and surge heights increase gradually. Earlier studies in the North Sea (Prandle and Wolf, 1978) noticed that interaction increases in direct proportion to both surge height and tidal range.

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

### **5. Conclusions**

The present study shows that the tide-surge interaction characteristics observed are identical to those reported in extra tropical regions, such as North Sea. The physical mechanisms which contribute to the typical surge distribution at Hiron Point arise either from the phase alteration of tidal signal and/or due to surge modulation. The present study shows the need for quantifying tide-surge interaction, which needs to be included in the estimation of return periods. Further, detailed numerical modelling studies need to be carried out to understand the factors contributing to the interaction.

### **Acknowledgements**

We thank the Survey of India and the Indian National Centre for Ocean Information Services (INCOIS) for providing the hourly sea level data along the Indian coast. The tide-gauge data for the station at the head bay, the Hiron Point was downloaded from the University of Hawaii Sea Level Centre website. We thank Chris Wilson (Proudman Oceanographic Laboratory, UK) and Ivan Haigh (National Oceanography Centre, University of Southampton, UK), who provided valuable suggestions. We also thank D. Sundar for his suggestions. This investigation is part of a project funded by the Department of Science and Technology (DST), Govt. of India. This is NIO Contribution Number XXXX.



## References

- As-Salek, J. A., Yasuda, T., 2001. Tide-surge interaction in the Meghna estuary: Most severe conditions. *Journal of Physical Oceanography* 31, 3059 – 3072.
- Bell, C., Vassie, J. M., Woodworth, P. L., 2000. POL/PSMSL Tidal Analysis Software Kit2000 (TASK-2000), Permanent Service for Mean Sea Level, CCMS Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside CH43 7RA, U.K.
- Bernier, N. B., Thompson, K. R., 2007. Tide-surge interaction off the east coast of Canada and northeastern United States. *Journal of Geophysical Research* 112, CO6008.
- Dixon, M. J., Tawn J. A., 1994. Extreme sea-levels at the UK A-class sites: site-by-site analysis. POL Internal Document no. 65.
- Haigh, I., Nicholls, R., Wells, N., 2010. Assessing changes in extreme sea levels; Application to the English Channel, 1900-2006. *Continental Shelf Research* 30,1042-1055.
- Horsburgh, K. J., Wilson, C., 2007. Tide-surge interaction and its role in the distribution of surge residuals in the North Sea. *Journal of Geophysical Research* 112, C08003.
- Johns, B., Ali, M. A., 1980. The numerical modeling of storm surges in the Bay of Bengal. *Quarterly journal of the Royal Meteorological society* 106, 1-18.
- Johns, B., Rao, A. D., Dube, S. K., Sinha, P. C., 1985. Numerical modelling of tide–surge interaction in the Bay of Bengal. *Philosophical Transactions of the Royal Society London A* 313, 507–535.
- Murty, T. S., Henry, R. F., 1983. Tides in the Bay of Bengal. *Journal of Geophysical Research* 88, 6069–6076.
- Niyas, N. T., Srivastava, A. K., Hatwar, H. R., 2009. Variability and trend in the cyclonic storms over the North Indian Ocean. Technical report, India Meteorological Department, Pune, IMD Indain Meteorological Monograph No. Cyclone Warning-3/2009, 1-34.
- Prandle, D., Wolf, J., 1978. The interaction of surge and tide in the North Sea and River Thames. *Geophysical Journal of the Royal Astronomical Society* 55, 203 – 216.
- Rady, M. A., El-Sabh, M. I., Murty, T. S., Backhaus, J. O., 1994. Tide-surge interaction in the Gulf of Suez. *Marine Geodesy* 17, 45-62.
- Rossiter, J. R., 1961. Interaction between tide and surge in the Thames. *Geophysical Journal of the Royal Astronomical Society* 6, 29-53.
- Sindhu, B., Suresh, I., Unnikrishnan, A. S., Bhatkar, N. V., Neetu, S., Michael, G. S., 2007. Improved bathymetric data sets for the shallow water regions in the Indian Ocean. *Journal of Earth System Science* 116(3), 261–274.
- Sindhu, B., Unnikrishnan, A. S., 2013. Simulation of tides and tidal constituents in the Bay of Bengal. *Marine Geodesy* DOI: 10.1080/01490419.2013.781088.

Sinha, P. C., Rao, Y. R., Dube, S. K., Rao, A. D., Chatterjee, A. K., 1996. Numerical investigation of tide-surge interaction in Hooghly estuary, India. *Marine Geodesy* 19, 235-255.

Sinha, P. C., Jain, I., Bhardwaj, N., Rao, A. D., Dube, S. K., 2008. Numerical modelling of tide-surge interaction along Orissa coast of India. *Natural Hazards* 45, 413-427.

Sundar, D., Shankar, D., Shetye, S. R., 1999. Sea level during storm surges as seen in tide-gauge records along the coast of India, *Current Science* 77, 1325 – 1332.

Tang, Y. M., Grimshaw, R., Sanderson, B., Holland, G., 1996. A numerical study of storm surges and tides, with application to the north Queensland coast. *Journal of Physical Oceanography* 26, 2700-2711.

Unnikrishnan, A. S., Sundar, D., Blackman, D., 2004. Analysis of extreme sea level along the east coast of India. *Journal of Geophysical Research* 109, C06023.

Zhang, W.-Z., Shi, F., Hong, H. -S., Shang, S. -P., Kirby, J. T., 2010. Tide-surge Interaction Intensified by the Taiwan Strait. *Journal of Geophysical Research* 115, C06012.

<http://ilikai.soest.hawaii.edu/uhs/c/html/0134A.html> (Last accessed: 14 June 2013).

### **Figure Captions**

**Figure 1** Map showing the locations of the tide-gauges used for present study. The 200m depth contour using improved bathymetry data of Sindhu et al. (2007). Coastline marked in black (blue) represent Odisha (Andhra) coast.

**Figure 2** The hourly tide-gauge data used in the present study. Fully red coloured bars represent those years removed from analysis after quality check.

**Figure 3** Surge peaks above 99<sup>th</sup> percentile plotted (a) with respect to tidal heights (in cm). The horizontal lines on the plots separate equal tidal bands. Lines of HAT (Highest Astronomical Tide) and LAT (Lowest Astronomical Tides) are shown. (b) With respect to timing of the high water (in hours) for the four stations. Surges peaks are classified depending on the magnitudes and different colours represent each magnitude range. The computed chi-square and critical chi-square (in brackets) are presented for each station.

**Figure 4** Surges above 99.9<sup>th</sup> percentile with respect to timing of high tide at Hiron Point (a). Surges representing each category (Table 1) at Hiron Point (b-d).

Figure 1

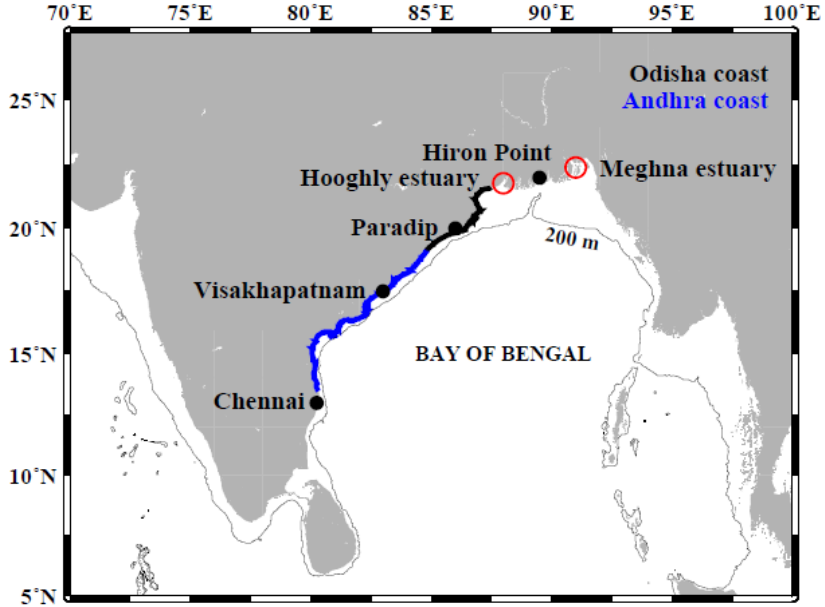


Figure 2

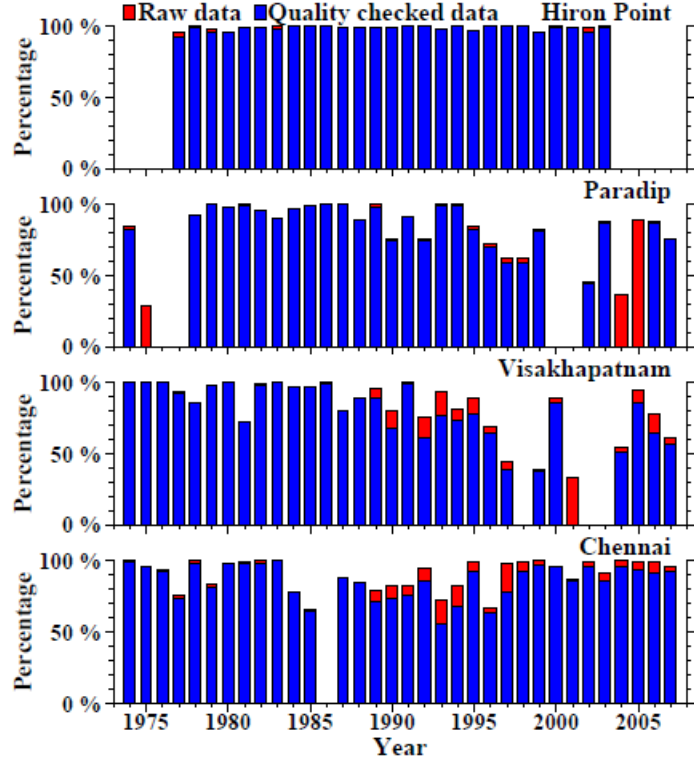


Figure 3

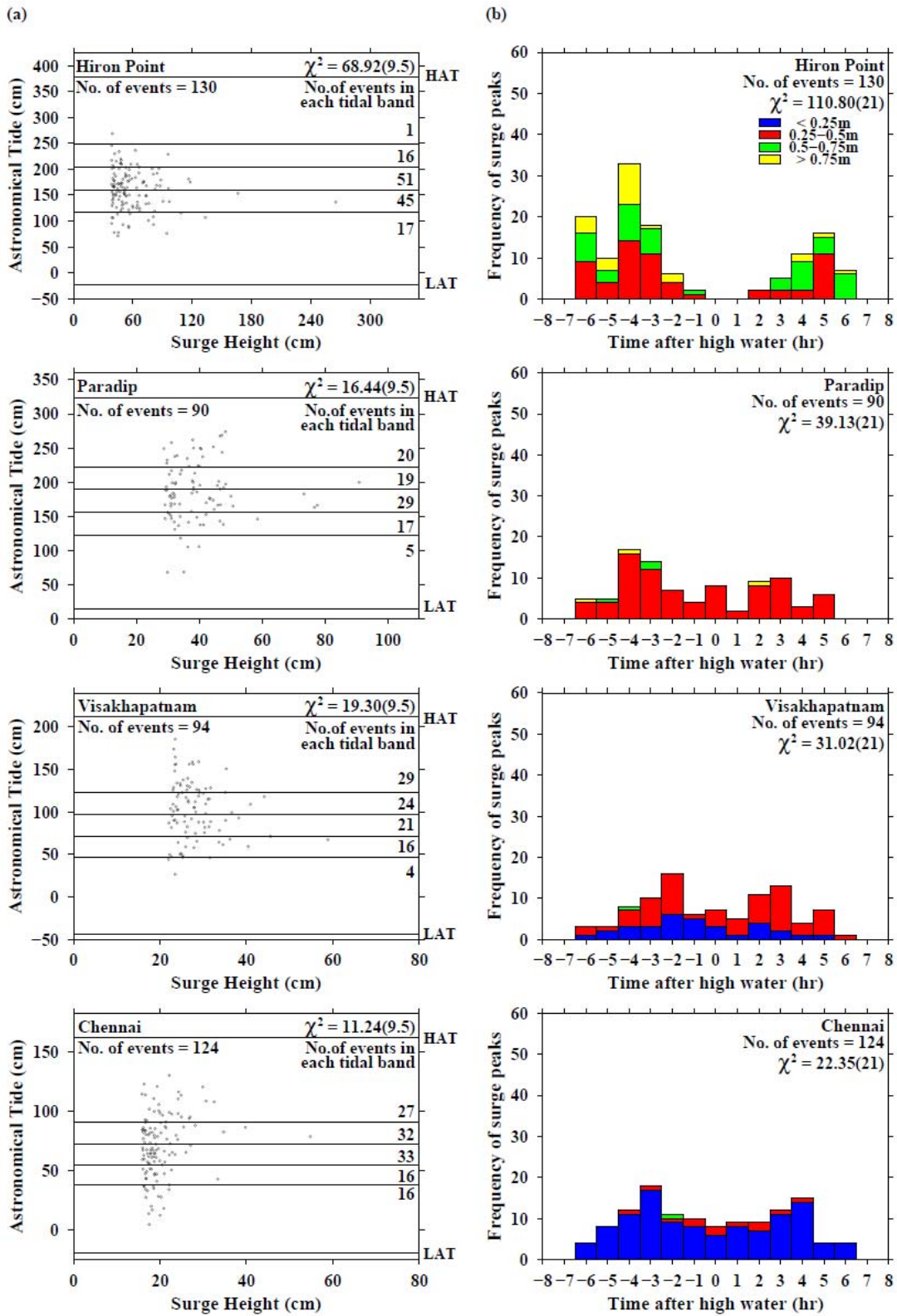
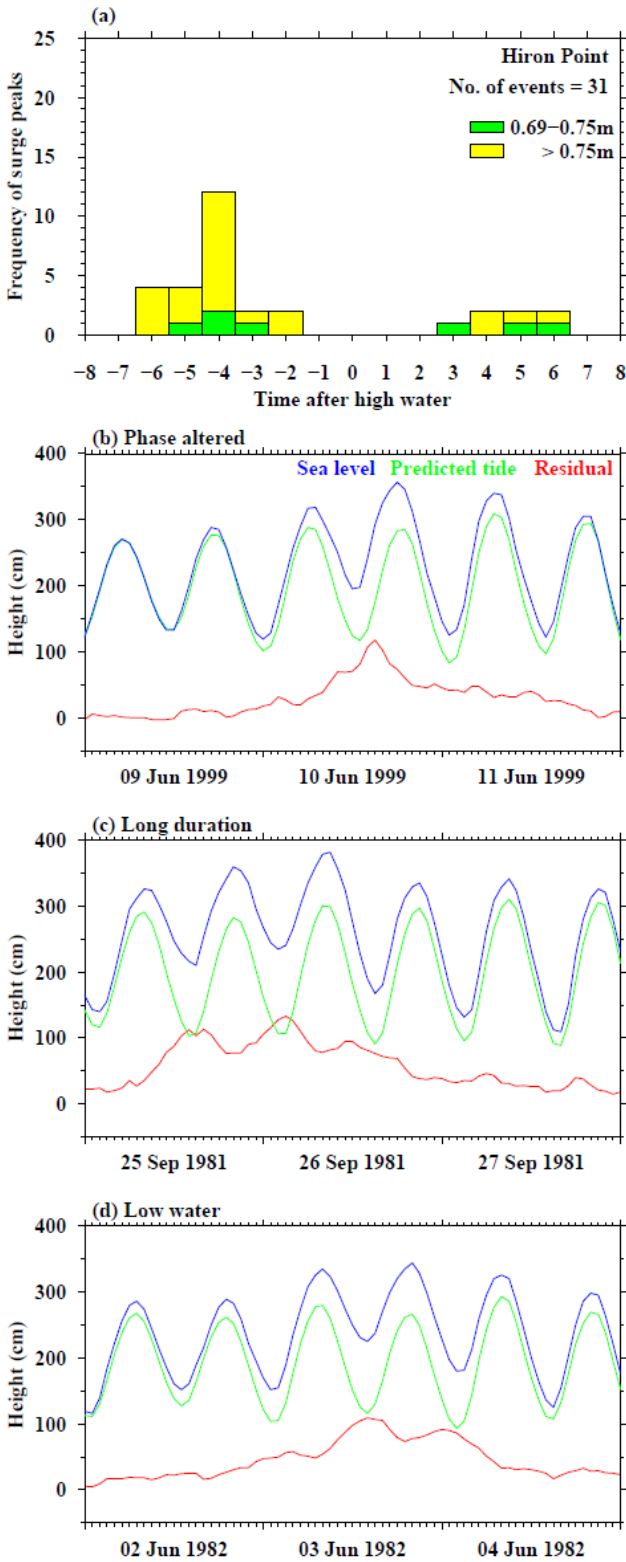


Figure 4



**Table 1** category of surges above 99.9<sup>th</sup> percentile at Hiron Point

Type occurrence	Characteristics	Number of
Phase altered between sea level and predicted tide.	Phase alteration	13
Long duration more high tide. A dip in surge during high tide.	Surge is significant for two or more high tide.	12
Low water significant at low tide.	No phase alteration. Surge is	4
High water significant at high tide.	No phase alteration. Surge is	0