16 April 2014

To

The Editor
Ocean Science

Sub: Reply to the comments of reviewer#1 on 'Coastal sea level response to the tropical cyclonic forcing in the north Indian Ocean' by Mehta et al. (OSD).

Sir,

Kindly find the reply to the comments of reviewer#1 on the manuscript submitted by Mehra et al. (OSD) entitled "Coastal sea level response to the tropical cyclonic forcing in the north Indian Ocean".

Thanks & regards

Prakash Mehra
NIO, Goa, India

Interactive comment on "Coastal sea level response to the tropical cyclonic forcing in the north Indian Ocean" by P. Mehra et al.

Anonymous Referee #1
Received and published: 6 March 2014

5/3/2014
Comments on 'Coastal sea level response to the tropical cyclonic forcing in the north Indian Ocean' by Mehta et al. (OSD)

[a] Reviewer's comment: This paper discusses tide gauge data at several sites in India during a few months in which cyclones resulted in two modest surges on the Indian coast. The analysis methods are based on tidal analysis of the gauge data, so as to separate tide and residual (surge) components, and then use linear regression on the daily averages of the residuals in terms of local meteorological parameters from weather stations, so as to learn how sea level responds to local forcings.

Authors' response: The authors agree with reviewer's views.

[b] Reviewer's comment: This is a well-established technique that has been used many times in the past, al-though regressions are usually performed using local wind stress rather than winds as these authors have done, but is not as good as using synoptic meteorological information and a surge model. The paper also discusses the high frequency components of the records that are presumably due to seiches.

Authors' response: The study is aimed to understand the characteristics and response of the north Indian Ocean to tropical cyclones and meteorological disturbances using sea-level and surface meteorological measurements at select locations. Therefore, the methods and tools used are well established, which increases the confidence in the analysis and the results presented in this study. We had also established a surge model using the cyclone parameters as shown in Fig. S1, for the events E1 and E2 in AS and BOB respectively using MIKE-21 software. Fig. S2 shows the estimated surge by the model is ~50% of the measurements at the locations in AS (please refer Fig. S2 and Table S1). However, at Kakinada the estimate and measured surges are comparable. At Gangavaram, the model does not work as the port experiences harbour resonance.

The other limitation of the surge model is that the cyclone parameters are not available once it hits the coast, whereas the coastal sea-level variation are expected to persist for few more days. For example, the Thane duration was 25-31 December 2011, however the daily-mean sea-level remained high from 23 December 2011 to 9 January 2012. In the present study, we also aimed to understand the contribution of various local meteorological forcing to the sea-level variations prior, during and after the event.

[c] Reviewer's comment: The time series are short, the surges discussed are small by Indian standards, the methods are not new, and there are no conclusions other than such analyses are useful within a surge monitoring system.

Authors' response: While analysing short-period events such as tsunamis, meteotsunamis, cyclones etc. the conventional practise is to examine the dataset relevant to the event duration. The dataset used in the present study is ~153 days, whereas the event E1(E2) is

~6 days only. Thus, the dataset used in the present study is much longer than the event duration. The dataset preceding the event was used to examine the background spectrum of the study location. This is the method generally used in the analysis of event-based studies (e.g., Rabinovich (1997, 2009), Monseratt et al. (2006), Joseph et al. (2006), Mehra et al. (2012)). Thus, the method used in the present study conforms to the established norms.

The surges are small as the measurement locations are ~500 km from the cyclone track. However, the study is to emphasis the various characteristics of the sea-level response in terms of the frequency spectrum during the presence (absence) of the event. Also, the study tries to bring out the differences/similarities in the spectra at different locations due to the topographical aspects and the differences in arrival of long waves from the open ocean during the event. The small magnitude of the signal is not an impediment to warrant neglecting such studies. For example, Tang et al. (1997) reported sea level residuals (SLR) of ~60 cm due to 1983 Tropical Cyclone Jane, which crossed the North West Coast of Australia generating a storm surge. Tkalich et al. (2013) found climatological sea level anomalies (SLAs) in Singapore Strait (SS) to be positive, and of the order of 30 cm during NE monsoon, but negative, and of the order of 20 cm during SW monsoon. The largest anomalies were associated with intensified winds during NE monsoon, with historical highs exceeding 50 cm. In a study, Mehra et al. (2012) examined the observed storm-generated sea-level oscillations (June 2007 and November 2009) along with the Sumatra geophysical tsunami (September 2007), indicating similarities in the sea-level response in the Mandovi estuary of Goa in the eastern Arabian Sea where the SLR peaked up to ~40 cm.

The surges generated at different locations by the cyclones in the present study are up to ~43 cm on the west coast and ~29 cm on the east coast of India. Thus, the magnitude of the surge signals addressed in the present study are comparable to those investigated by other researchers as indicated above. In any case, signals even smaller in magnitude have been studied to characterise short-period sea level related events such as storm surges, meteotsunamis and geophysical tsunamis (Joseph, 2011).

About the methods used are not new, the reply to comment [b] suffices here too.

The conclusion provides due emphasis to:

- Importance to meso-scale weather and sea-level monitoring network.
- Spectral characteristics of various locations.
- Harbour resonance noticed at Gangavaram site in Bay of Bengal.
- Difference in surge levels at different locations in response to different cyclone track relative to the coastline.
- Contribution of different local atmospheric parameters to the observed surge levels.

[c] Reviewer's comment: The paper itself is written well enough, although the absence of 'the', 'a' and 'an' in sentences is irritating. But the authors have not learned the lesson that less is more sometimes. There is a large amount of irrelevant descriptive detail. Some of the figures are poor (figure 1 is too dark, figure 10 font is unreadable).

Authors' response: Thanks for scrutinising the MS thoroughly and indicating the lapses. We also thank the editors for their valuable comments and improving the text. Necessary corrections as regard to absence of 'the', 'a' and 'an' in sentences will be incorporated.

Figures supplied by the authors are of good quality, however compression of figures in OSD lead the reviewer to make the comment about the figures. At appropriate level, the figures in EPS format will be provided.

[d] Reviewer's comment: I am sorry but, while it may be relevant locally, I cannot see why this paper should be published in an international journal.

Authors' response: The MS addresses some of the important characteristics/response of the sea-level oscillations and surge in the north Indian Ocean during episodic events such as the meteorological disturbance in Arabian Sea and a tropical cyclone (Thane) in Bay of Bengal. These type of studies are important contributions to the international communities involved in the study of coastal oceans and hence deserve to be published in an international journal. Thanks.

Minor remarks:

Reviewer's comment: 576, 10 - what is a surge 'dome'? - the peak of the event?

Authors' response: P 576,L10: The line has been revised as:
" The storm surge is a well defined peak with a half-amplitude width of ~ 20, 28 and 26 h at Ratnagiri, Verem and Karwar, respectively." Thanks for pointing out the lapse..

Reviewer's comment: 20 - I don't think tropical cyclones relate to meteotsunamis much. What about tornadoes?

Authors' response: I quote the following text from Rabinovich (2009), pg-227: The references mentioned in the text below is removed.

"Spectral analysis results reveal that harbor resonance is a crucial factor in the formation of rissaga waves, as well as "meteorological tsunamis" in other bays, inlets, and harbors of the World Ocean. Barometric data from the Balearic Islands as well as from Japan and Eastern Adriatic Sea demonstrate that generation of these destructive waves is associated with strong atmospheric disturbances, e.g., trains of atmospheric gravity waves, or isolated pressure jumps. These atmospheric disturbances may have different origin: dynamic instability, orographic influence, frontal passages, gales, squalls, storms, tornados, etc."

Reviewer's comment: 577, 5 and 18 - 'in situ' is Latin, not to be hyphenated

Authors' response: P 577, L 18 has been revised as: "..northwest coast of India, based on in situ and satellite-derived..." Thanks for pointing out the mistake.

Reviewer's comment : P 577, 21 - similarities to what?

Authors' response:P577, L 19-22, has been revised as mentioned below. Thanks for bringing out the clarity.

" Mehra et al. (2012) reported similarities in spectral characteristics of sea-level oscillations in the Mandovi estuary of Goa in the eastern Arabian due to cyclones (June 2007 and November 2009) and the Sumatra geophysical tsunami (September 2007)."

Reviewer's comment: 578, top - I am not sure some of the references given in this literature review are relevant to the present paper.

Authors' response: The "Introduction" has been revised with some of the references removed and few relevant references added in response to the comments of reviewer#2. Please refer to the revised introduction provided after the interactive comments. Thanks.

Reviewer's comment: 579, 25 - perhaps you can explain the difference between the data in the cyclone track data set, which must include the speed of the cyclones, and the translational speed data set. What is JTWC? (tsunami centre?)

Authors' response: Thanks for this suggestion and Fig. 2 has been revised as suggested by the reviewer, showing the differences between the cyclone track data from different sources. Following changes has been made in the revised MS:

a) Fig. 2 has been revised along with the caption. (Please see the figure 2 provided after interactive comments)

b) P 579, L 21-26:

The tropical cyclone track data from India Meteorological Department (IMD, www.imd.gov.in), Joint Typhoon Warning Center (JTWC, www.usno.navy.mil/JTWC/) and UNISYS-Unisys Weather (http:// weather.unisys.com/hurricane/) are shown Fig. 2. The storm translational speed is calculated using the distance travelled between two consecutive positions and time interval. The average difference in wind speed as shown in Fig. 2a & 2d between IMD and JTWC, and IMD and Unysis are -1.1(-4.2) and -3.7 (-2.8) ms^{-1} during E1 (E2). The sea level pressure reported by IMD and JTWC is similar during E1 (Fig. 2b), however during E2, the minimum sea level pressure differed by ~-11 mb with a time lag of ~ 3 hr (Fig. 2e). The cyclone translation speed estimated using JTWC and Unysis data during E1 varied between 2.5 and 6.4 ms^{-1}, expect two spikes of ~ 9 ms^{-1} observed in Unysis data (Fig. 2c). Similarly, the cyclone translation speed estimated using JTWC and Unysis data during E2 varied between 1.0 and 4.5 ms^{-1} , expect few spikes of ~ 5-7 ms^{-1} (Fig. 2f).

Reviewer's comment: P 580, L 8 - the reader will want to know what the Rabinovich method is. It is not good enough to assume they know it.

Authors' response: P 580, L 8 as mentioned below:

"The spectrum of SLR during the event as well as that of the background signal is obtained by applying the method suggested by Rabinovich (1997)."

has been revised as:

"Rabinovich (1997) proposed a new approach to separate the influence of source and topography in observed tsunami spectra. The method assumed a linear tide gauge response to external forcing and is based on comparative analysis of tsunami and background spectra. This method will be used to understand the resonant influence of local topography and spectral characteristics of SLR during an event at a particular location."

Thanks for introducing the clarity.

Reviewer's comment: 18-20 - I understand the daily regression analysis discussed above. I didn't understand the monthly business. Do you mean you make a separate analysis of daily values each month? Is making regressions using daily values good enough to learn about surges? As mentioned above, equation 1 is usually undertaken using wind stress and not wind speeds.

Authors' response: Yes, the regression is performed using daily-mean data and the coefficients of regression are obtained for monthly data to estimate the SLR. The monthly estimated SLR is merged to generate the time series of estimated SLR for the duration of September 2011 to January 2012.

As per the reviewer's suggestion the text with regard to equation 1 has been revised as (P 580, L 12-20):

"Sea-level data is de-tided using TASK tidal analysis and prediction program (Bell et al., 2000) to obtain sea-level residual (SLR). A multi-linear regression model linking sea level and atmospheric parameters has been established. The model can be described in general as:

$$\eta = B0 + B1\tau_U + B2\tau_V + B3A_P + \in , \quad (1)$$

In the above expression, sea level residual (η) is the dependent variable and the independent variables are crossshore (*U*), alongshore (*V*) component of winds and atmospheric pressure (A_P). Likewise *B0, B1, B2 and B3* are the coefficients of regression and ϵ is the difference between the measure SLR and estimated SLR using multi-linear regression. The cross-shore (along-shore) shear stress $T_U (T_V)$ is estimated as:

$$\tau_U = \rho_A C_D U \sqrt{U^2 + V^2} \quad (2)$$

$$\tau_V = \rho_A C_D V \sqrt{U^2 + V^2} \quad (3)$$

ρ_A = 1.3 Kg m^{-3} is the density of air and C_D ( ) is the drag coefficient. The regression is performed using daily-mean SLR, T_U, T_V and A_p. Coefficients of regression are obtained for monthly data to estimate the SLR. The monthly estimated SLR is merged to generate the time series of estimated SLR for the duration of September 2011 to January 2012.."

The result obtained using surface wind stress are shown in Fig. S3 and Fig S4. Daily-mean estimated SLR is obtained using the multi-linear regression method with daily-mean cross-shore (U), along-shore (V) components of winds-stress and atmospheric pressure (A_p) as independent variables. Table S2 shows the estimated SLR peak obtained using wind and wind-stress (Col. 6 and Col 7) as independent variable. The results are comparable, however overshot in estimated SLR peak is observed at Gangavaram and Kakinada by ~34% and 21%, when wind-stress along with atmospheric pressure are used as per the above equation-1.

Reviewer's comment: 581, 22 and elsewhere - what does 'well marked' mean?

Authors' response: P 581, L 22: may be modified as
"... surface winds of ~25 kts, which weakened into a well marked low pressure area over Jharkhand close to..."

These are Classification of cyclonic disturbances and tropical cyclones in the region (Bay of Bengal and Arabian Sea)

Cyclonic disturbance (generic term)

(i) Low or low pressure area
(ii) Well marked low pressure area**+** (**+**Term used nationally in Bangladesh)
(iii) Depression or tropical depression
(iv) Deep Depression* (*Term used nationally in Bangladesh, India and Pakistan.)

Tropical cyclone (generic term)

(v) Cyclonic storm
(vi) Severe Cyclonic storm
(vii) Very severe cyclonic storm
(viii) Super cyclonic storm

(Refer: World Meteorological Organization Technical Document, WMO/TD No.84, Tropical Cyclone Programme, Report No. TCP-21)

Reviewer's comment: 582 - I don't really care about the history of every storm in the region in this period - if the big events E1 and E2 are of interest, keep the focus of the paper on them Figure 2c is not discussed in the text?

Authors' response: The mention of the other storm during the study period is necessary to show that every event may not generate a noticeable sea-level variations as in the case of tsunamis (Every earthquake in ocean may not generate a tsunami) .

For example (P 582, L10-15):

The visual observation of SLR indicates that it is normally within ±25 cm at all the three locations. Kiela and the subsequent depression from 29 October to 10 November are not able to generate noticeable sea-level variations, probably due to large distance of the measurement sites from the cyclonic tracks. e.g., the distance of Verem to the trajectory of Kiela's ECP is ~1554 km. [P 582, L 14-16]

Whereas a minor dip in SLR ~14.1, 10.3 and 15.0 cm was also observed at the coastal sites located in the AS (Ratnagiri, Verem and Karwar) due to E2 (Fig. 3a–c). [P 583, L 51-17]

P 581, L 17-18 may be modified as:

".... on 29 November and again increased to ~6 ms^{-1} on 30 November (Fig. 2c)."

Thanks for pointing out the lapse.

Reviewer's comment: Sections 3.2, 3.3 etc. I felt I was drowning in detail.

Authors' response: Section 3.2 and 3.3, is a required brief discussion about the variations in surface atmospheric parameters and sea-level at the measurement locations due to the two events E1 and E2.

Reviewer's comment: Section 3.4 - actually I found this interesting myself. There is a great range of variation in seiching around the Indian Ocean (for example, the currents associated with those with short period on the West Australian coast can damage shipping) and if the authors had written this section to put the observations in some regional context it might have been more interesting. As it stands, they show that these stations have seiches. But many tide gauge records contain seiches.
Authors' response: Yes, Harbour oscillations can produce damaging surging (or range action) in some ports and harbours yawing and swaying of ships at berth in a harbour.

If the reviewer agrees, following paragraph may be inserted after L 14 of P 586. Thanks.

A property of harbour oscillations is that even small vertical motions (sea level oscillations) may be accompanied by large horizontal motions (harbour currents), resulting in increased risk of damage of moored ships, breaking mooring lines as well as affecting various harbour procedures (Rabinovch, 2009). These waves are similar to tsunami, however the catastrophic effects are normally observed in specific bays and inlets. At some specific sites that have favourable conditions for the resonant generation of extreme ocean waves regularly, have been listed by Monserrate et al., (2006), Rabinovich (2009) and Joseph (2011). For example: Nagasaki bay has been known for extreme atmospherically generated seiche oscillations (locally known as "abiki waves") for about 100 years (Honda et al., 1908). Wang et al. (1987) observed that the amplitude of seiches are generally very small in Chinese coastal waters. They analysed 23 years of continuous tide gauge records (1957–1958 and 1961–1981) of Longkou harbour located at the mouth of Bohai Bay (Yellow Sea) in China and found 137 events had maximum trough-to-crest wave heights greater than 40 cm. Most of these events were found to occur in May–August, while in winter months (January–February) strong seiches were never observed. “Rissaga” waves observed on the coast of the Balearic Islands and the eastern Iberian Peninsula are probably the best know and best examined type of meteotsunamis (Monserrate et al., 2006 and other reference provided therein). For example, the tides in Ciutadell harbour (western Mediterranean) are relatively small (~20 cm). Few "rissaga" waves (~1 m) occur normally during summer or during September, However, "rissaga" of 21 June 1984 and 15 June 2006 were catastrophic events with large waves of heights of ~4 m, causing damage to many boats and estimated economic loss of tens of millions euro's (Rabinovich and Monserrat, 1996 and Monserrate et al., 2006). Similar, phenomena occurs on the southern west coast of India, mainly during pre-southwest monsoon (April or May), the term used in local language is "Kallakkadal", meaning "sea that arrives like a thief" (unnoticed) (Kurian et al., 2009).

Reviewer's comment: Section 3.5 - I have no reason to think that the analysis has not been done well at a technical level. The problems are that the techniques are not new, the data sets are short and the results are not particularly interesting.

Authors' response: This paper describes and analyses the coastal sea level response to two storm events at the end of 2011 in the north Indian Ocean. We have used the sea level and atmospheric observations at 9 locations along the Indian coast and perform a classical but robust analysis (spectral analyses and multi-linear regression). The MS addresses some of the important characteristics/response of the sea-level oscillations and surge in the north Indian Ocean during episodic events such as the meteorological disturbance in Arabian Sea and a tropical cyclone (Thane) in Bay of Bengal. These type of studies are important contributions to the international communities involved in the study of coastal oceans and hence deserve to be published in an international journal. Thanks.

Reviewer's comment: 590, 19 - sentence 'Presently ..'. This isn't true for surges in general, it may well be for tropical surges.

Authors' response:L19, P 590, The sentence has been revised as:

"Presently, there are few meso-scale weather and sea-level network in some coastal segments of Indian and east Atlantic oceans to observe such events."

Reviewers Comment: 25 - 'Storm 5' is presumably the same as E2? Don't confuse the reader with different names.
Reply: Page-16, line-25: The line mentioned by the reviewer may be modified as " ....response to the passage of the storm (E1) in Arabian Sea and 'Thane (E2)' in Bay of Bengal."

I didn't look at the Supplementary Material.
Interactive comment on Ocean Sci. Discuss., 11, 575, 2014.

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1. Introduction

Tropical cyclones (TC) are the most destructive weather systems on earth, producing intense winds, resulting in high surges, meteotsunami, torrential rains, severe floods and usually causing damage to property and loss of life. In north Indian Ocean, both the Bay of Bengal (BOB) and the Arabian Sea (AS) are potential genesis regions for cyclonic storms. Intense winds associated with TCs, blowing over a large water surface, cause the sea surface to pile-up on the coast and leads to sudden inundation and flooding of the vast coastal regions. Also, the heavy rainfall causes flooding of river deltas in combination with tides and surges. A number of general reviews and description of individual cyclones and associated surges in BOB and AS have been published previously by several investigators (Murty et al. 1986; Dube et al. 1997; Sundar et al. 1999; Fritz et al. 2010; and Joseph et. al. 2011). Developments in storm surge prediction in the Bay of Bengal and the Arabian Sea have been highlighted by Dube et al. (2009) and references therein (e.g., Das, 1994, Chittibabu et al., 2000 & 2002, Dube et al., 2006, Jain et al., 2007 and Rao et al., 2008).

Apart from the studies carried out with a view to assessing the coastal vulnerability, few studies concentrated on the variations in characteristics of different oceanographic parameters in response to tropical cyclones. Joseph et al., (2010) examined the response of the coastal regions of eastern Arabian Sea (AS) and Kavaratti Island lagoon to the tropical cyclonic storm 'Phyan', during 9–12 November 2009 until its landfall at the northwest coast of India, based on in situ and satellite-derived measurements. Mehra et al. (2012) reported similarities in spectral characteristics of sea-level oscillations in the Mandovi estuary of Goa in the eastern Arabian due to cyclones (June 2007 and November 2009) and the Sumatra geophysical tsunami (September 2007). Wang et al. (2012) reported the variations in the oceanographic parameters due to the tropical Cyclone Gonu, which passed over an ocean observing system consisting of a deep autonomous mooring system in the northern Arabian Sea and a shallow cabled mooring system in the Sea of Oman. Near-inertial oscillations at all moorings from thermocline to seafloor were observed to be coincident with the arrival of Gonu. Sub-inertial oscillations with periods of 2–10 days were recorded at the post-storm relaxation stage of Gonu, primarily in the thermocline of the deep array and at the onshore regions of the shallow array. In BOB, Neetu et al., (2012) reported the influence of upper-ocean stratification on tropical cyclone-induced surface cooling. Study of Tkalich et al., (2013) in Singapore Strait (SS) using a tide gauge along with satellite data, revealed that the wind over central part of South China Sea is an important factor determining the observed variability of sea-level anomalies (SLAs) at hourly to monthly scales. Climatologically, SLAs in SS are positive and of the order of 30 cm during NE monsoon, but negative, and of the order of 20 cm during SW monsoon. Antony and Unnikrishnan (2013) used 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, to analyse statistically the tide-surge interaction. Recently, Rao et. al. (2013) simulated surges and water levels along the east coast of India using an advance 2D depth-integrated circulation model (ADCIRC-2DDI).

It is necessary that the problem of storm surge must be seriously addressed by the countries of the various regions through collective efforts and in an integrated manner. Storm surge is generated partly by the atmospheric pressure variations, but the main contributing factor is wind acting over the shallow water and it is an air-sea interaction problem. The atmosphere forces the water body, which in turn, responds by generating oscillation of water level with various frequencies and amplitudes. In the spectrum, the storm surges are centred about 10^{-4} Hz, which corresponds to a period of about 3h (Platzman, 1971). The generation of storm surges by surface wind stress and atmospheric pressure variations moving along the coastline have been extensively studied as forced Kelvin waves (LeBlond and Mysak, 1977; Gill, 1982). Thomson (1970), found that only the long-shore wind stress and atmospheric pressure variations can generate the Kelvin waves, which then travel away from the force discontinuities at a speed $c=\sqrt{(gh)}$, where g is the acceleration due to gravity and h is the depth.

The principal objective in the present study is to examine the characteristic of the sea-level variation at spatially distribute topologically different locations in AS and BOB due to tropical cyclones (TCs) and meteorological disturbances that occurred in 2011. Our interest is confined to a few minutes to days. This study is also intended to investigate the Kelvin-type coastal response due to a time and space varying long-shore surface wind stress distribution, moving almost parallel to the coast. Theoretically the surge characteristics including its propagation speed and amplitude in a particular coastal region are dependent upon the major cyclone properties such as its strength, forward speed, and radius of maximum winds. The above theoretical aspects are tested against the selected observations of the cyclone-induced surges along the western coast of India.

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Table S1 Comparison of hourly averaged measured and model-estimated SLR.

Station	Residual (hourly averaged) cm	Model output (cm)	Difference (%)
Ratnagiri	40.3	18.9	53.1
Verem	35.3	19	46.1
Karwar	36.9	17	53.9
Kakinada	28.2	23	18.4

Table S2. The peak response of the daily-mean sea level residual (SLR) along with the estimated daily-mean SLR.

Col:4 The estimated daily mean SLR are obtained by multi-regression method using along-shore, cross-shore winds and atmospheric pressure [U,V, A_p]

Col5 The estimated daily mean SLR are obtained by using multi-regression method using along-shore, cross-shore winds-stress and atmospheric pressure [τ_U, τ_V, A_p].

Station	Event	Measured daily-mean peak SLR (cm)	Estimated daily-mean peak SLR (cm) using [U,V, A_p]	Estimated daily-mean peak SLR (cm) using [τ_U, τ_V, A_p].	Difference (Col3-Col4)*100/Col3 (%)	Difference (Col3-Col5)*100/Col3 (%)
Ratnagiri	E1	29.6	25.5	28.5	13.6	3.7
Verem	E1	25.8	27.3	27.4	-6.1	-6.5
Karwar	E1	27.7	15.5	13.6	44.1	50.9
Gopalpur	E2	29.7	22.4	32.4	24.7	-8.9
Gangavaram	E2	13.8	14.6	18.5	-6.0	-34.1
Kakinada	E2	22.3	22.3	27.1	0.0	-21.5

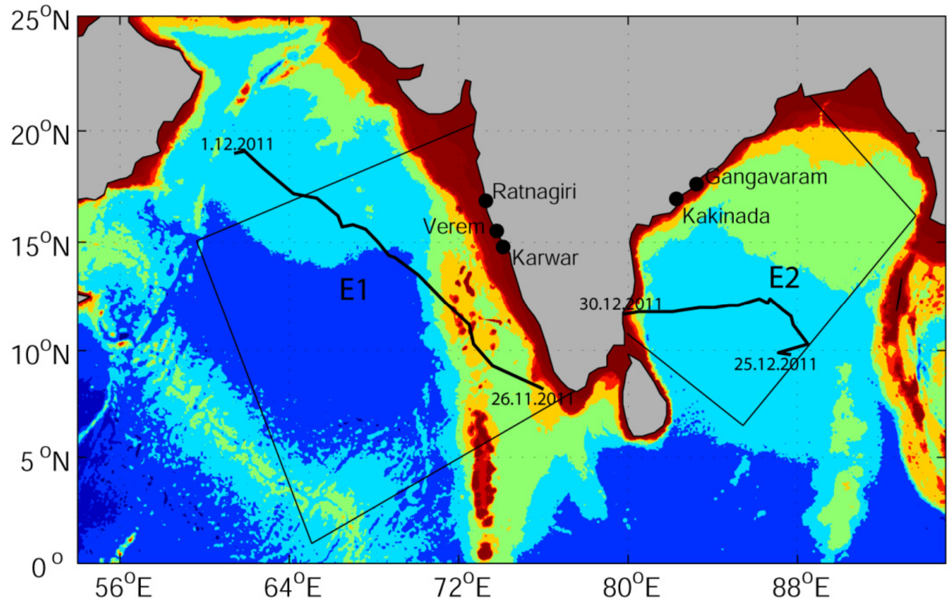

Fig. S1. Setup of storm surge model (Mike) domain for the events E1 and E2.

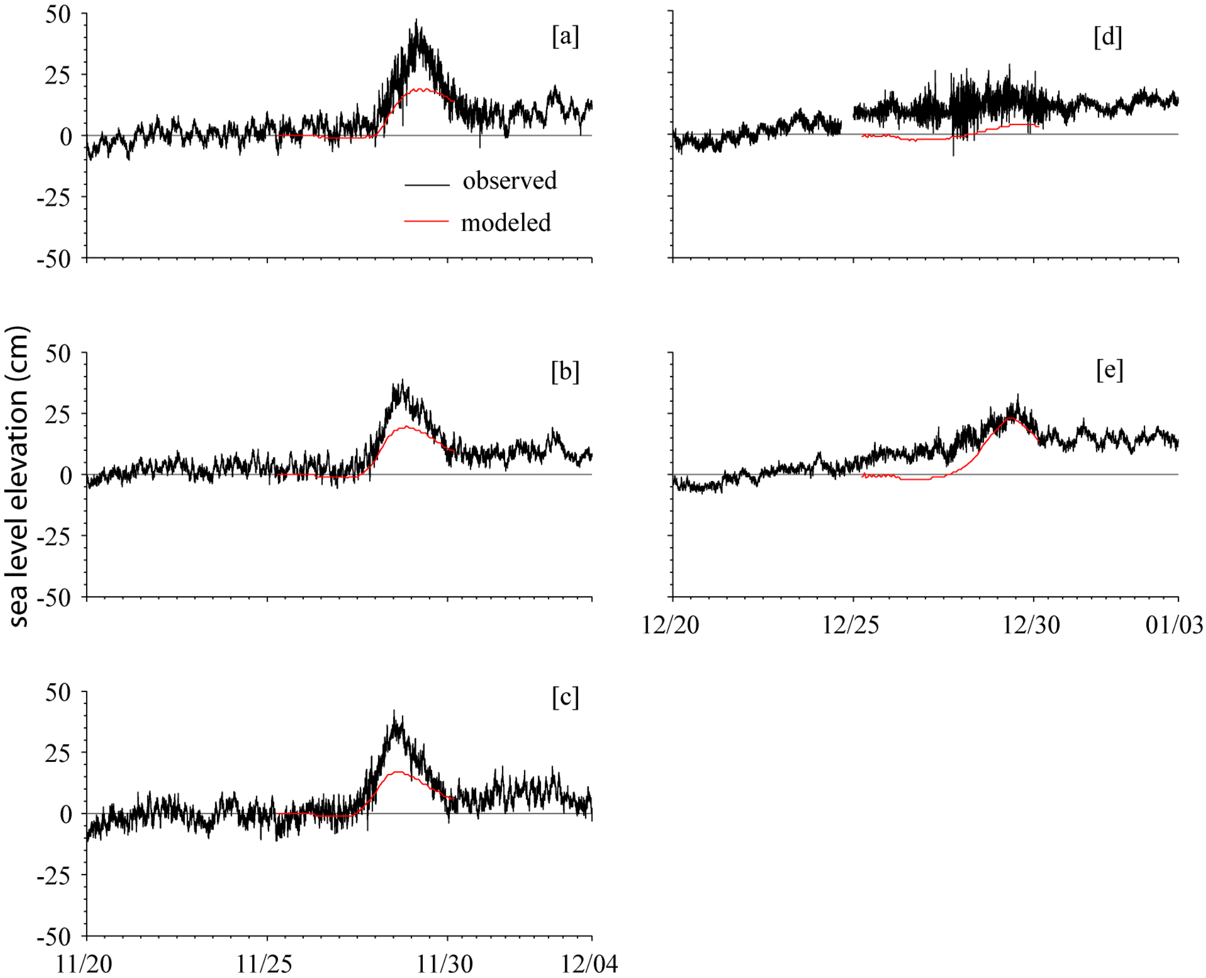

Fig. S2. Measured sea-level residual (black) and SLR estimated by storm surge model (red) at [a] Ratnagiri, [b] Verem, [c] Karwar, [d] Gangavaram and [e] Kakinada.

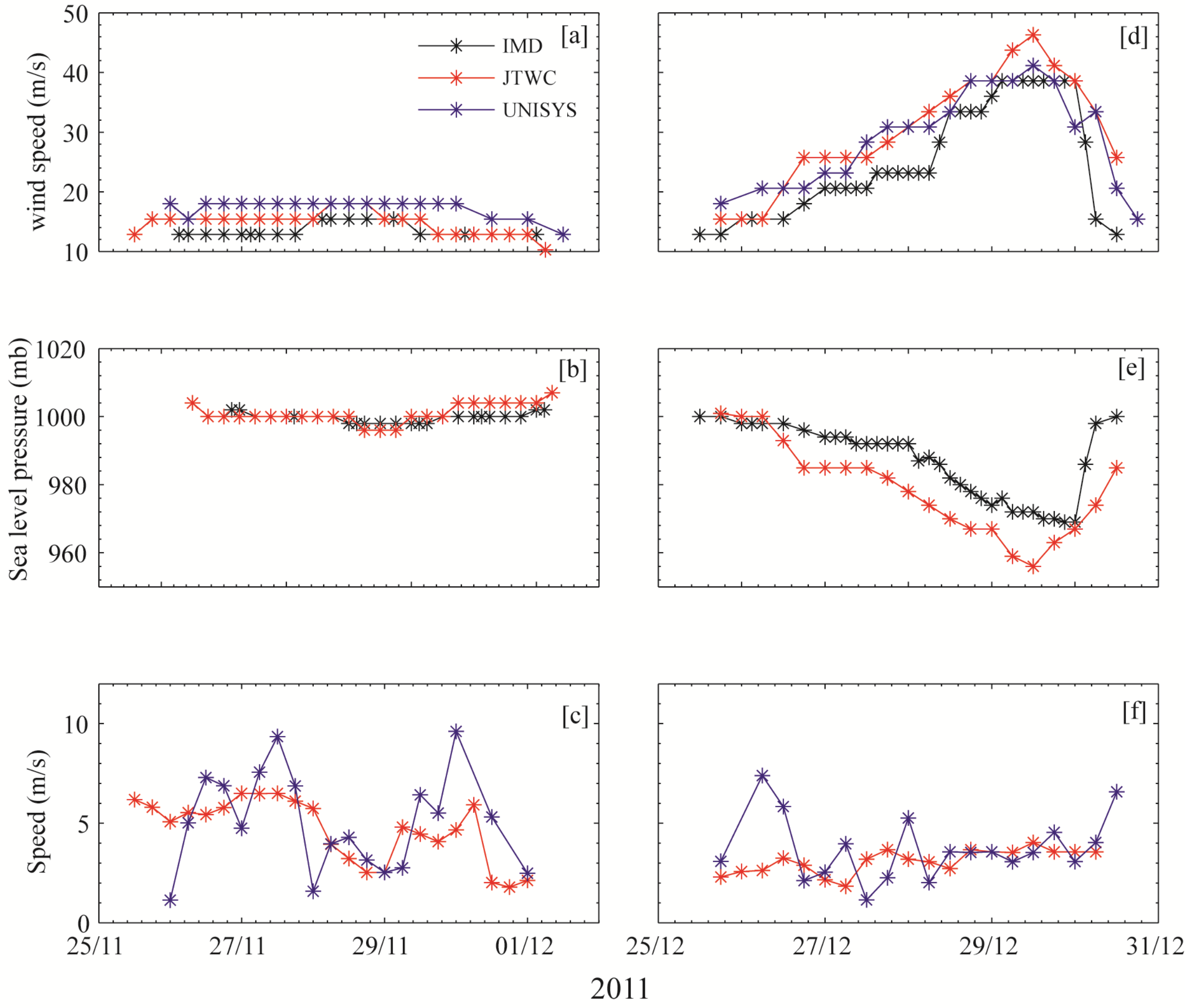

Fig. 2. Cyclone parameters **(a)** and **(d)** Maximum sustained wind speed during E1 and E2, **(b)** and **(e)** Minimum sea level pressure, **(c)** and **(f)** Storm forward translation speed.

Note: IMD-India Meteorological Department; JTWC-Joint Typhoon Warning Center; UNISYS-Unisys Weather (http://weather.unisys.com/hurricane/)

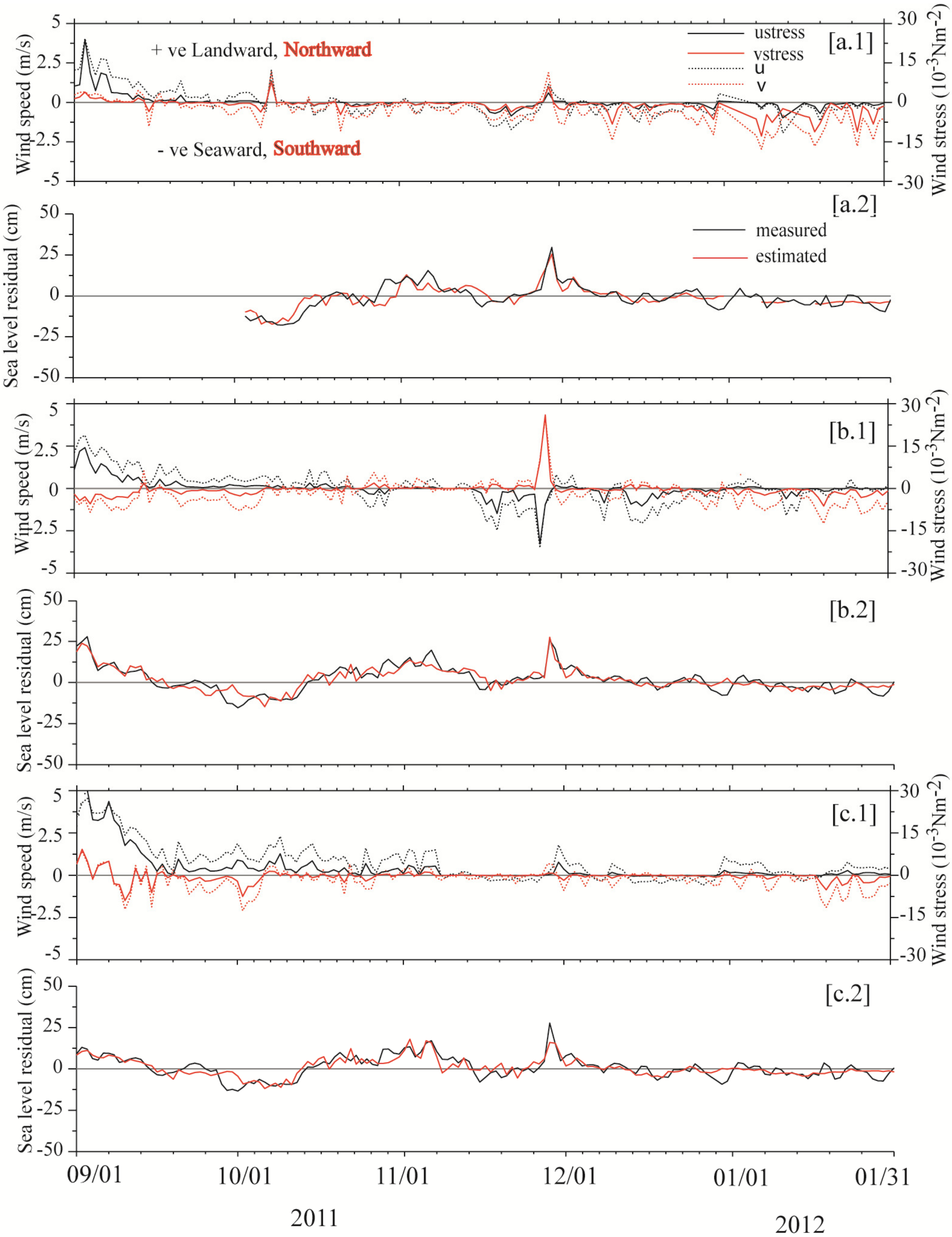

Fig. S3 Daily-mean wind, wind-stress, measured sea-level residual and estimated sea level residual from September 2011 to January 2012 at [a] Ratnagiri, [a.1] daily averaged cross-shore (black) and along-shore (red) winds-stress along with respective winds (dotted black or red), [a.2] daily-mean measured sea level residual (black) and estimated residual (red); [b] Verem, [b.1] and [b.2] same as in [a]; [c] Karwar, [c.1] and [c.2] same as in [a];

Daily-mean estimated SLR is obtained using the multi-linear regression method using daily-mean cross-shore (U), along-shore (V) components of winds-stress and atmospheric pressure (AP) as independent variables.

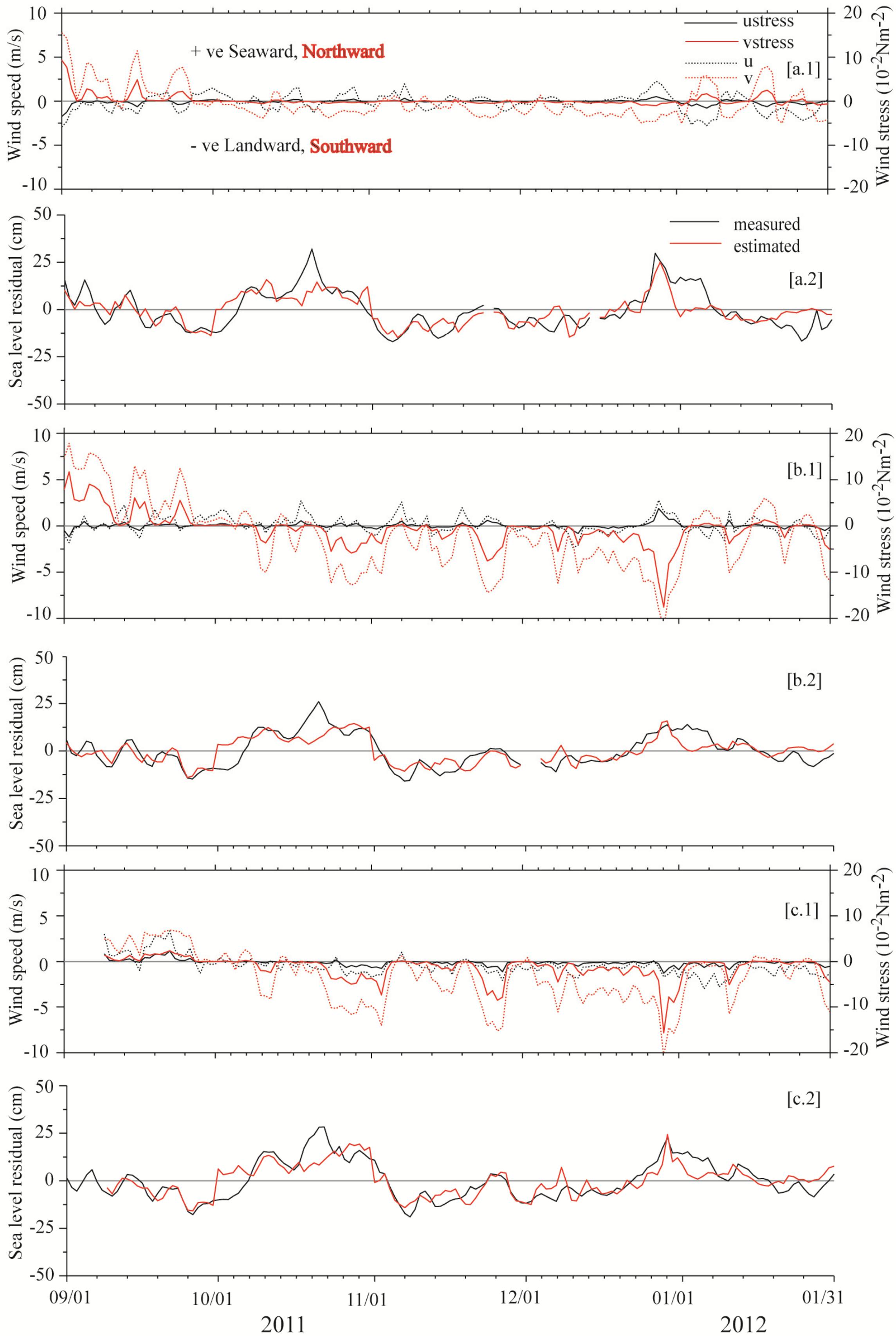

Fig. S4 Daily-mean wind, wind-stress, measured sea-level residual and estimated sea level residual from September 2011 to January 2012 at [a] Gopalpur, [a.1] daily averaged cross-shore (black) and along-shore (red) winds-stress along with respective winds (dotted black or red), [a.2] daily-mean measured sea level residual (black) and estimated residual (red); [b] Gangavaram, [b.1] and [b.2] same as in [a]; [c] Kakinada, [c.1] and [c.2] same as in [a];

Daily-mean estimated SLR is obtained using the multi-linear regression method using daily-mean cross-shore (U), along-shore (V) components of winds-stress and atmospheric pressure (AP) as independent variables.

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