16 April 2014

To

The Editor
Ocean Science

Sub: Reply to the comments of reviewer#2 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#2 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 #2

Received and published: 22 March 2014

Reviewer's comment:
This paper describes and analyses the coastal sea level response to two storm events at the end of 2011 in the north Indian Ocean. The authors use 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). Although there are no new findings, it gives a fair idea of the causes of the sea level variation in response to these strong atmospheric events. The Figures, Tables and References are clear and support well the present text. It is also interesting to have an analysis done at large scale and on both sides of the Indian Subcontinent (Arabian Sea and Bay of Bengal).

The scientific quality of the paper is good but in my opinion the presentation of the results is poor and makes the paper hard to read and the purpose of the authors difficult to follow. For this reason I suggest major revision of the manuscript. Indeed the two main results concerning regression model and the HF response (harbor resonance) are treated together which make the paper very difficult to read. I strongly suggest that the HF analysis was treated separately in the text. I also would like to see more discussion about the possible remote part of the surge (what about the propagation of the surge along the coast as a coastal trapped wave for example).

Authors' response: We thank the reviewer for appreciating the scientific quality of the manuscript (MS), text, methods used, figures etc.

Based on the reviewer's observation on the clarity in readability of the MS, we have modified the MS as below:

1. Introduction
2. Data and Methodology
3. Observed coastal sea-level response to meteorological events
4. High frequency response and harbour resonance
5. Regression model
6. Results and Discussion
7. Conclusions

The authors' response to the comments regarding the separation of high frequency response and propagation of coastally trapped waves have been addressed in section 4 and section 6 respectively as mentioned under replies to other comments

Minor Comments:

Introduction:

Reviewer's comment: The introduction is well documented but it sounds like an inventory. Reformulation to make the text more seamless is required.

Authors' response: As suggested by the reviewer, the "introduction" is revised. Please refer to the revised "introduction" as provided after the interactive comments. Thanks.

Section 2:

Reviewer's comment: 578,L26 : Define JTWC

Authors' response: Thanks for pointing out. Also, in response to the reviewer#1's comments about P 579, L 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?)".

a) Fig. 2 is replaced by modified figure using available cyclone track data from different sources.

b) P 579, L 22-26 is modified as:

"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 differences in wind speeds 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: 579 all : This section is really disconcerting, as all data processing methods (detiding, high-pass filtering, spectrum computation and multi-linear regression) which have different purposes are given all together like an inventory. I strongly suggest that details information which concern *only* the multi-linear regression model (the de-tiding + equation model) should appear in this section. The 5 minutes high-pass could be introduce in the dedicated paragraph, as well as spectrum. The Sea Level Residual (SLR) acronym is used in the text either for the detited sea level or for its high-pass component. You should introduce a hf-SLR (or whatever) to distinguish between this 2 quantities in the text.

Authors' response: As suggested by the reviewer, following modifications have been made in the revised MS:

Section 2 Data and Methodology
Based on the reviewer's suggestion, the inventory-like portions in this section have been removed and shifted to the dedicated paragraph. Furthermore, information about sea-level data, surface meteorological data, cyclone track data, and multi-linear regression model (de-tiding + equation model) have been incorporated in this section.

Section 4. High frequency response and harbour resonance
This section describes the high pass filtering and spectral analysis. In the revised MS, the high pass filtered sea level residual is named as hf-SLR to distinguish between the detided sea level residual (SLR) and hf-SLR. Thanks for bringing out the clarity issue.

Reviewer's comment: equation 1: epsilon should be defined

Authors' response: Thanks for pointing out the lapse. Modified text with regard to equation 1 is inserted 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:

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

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:

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

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

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.."

Please note that the equations 2 and 3 have been introduced based on suggestions of rewiever#1.

Section 3.2
Reviewer's comment: 581,L23 : Define what you call a Surge Dome ? and how you compute it ?

Authors' response: P 582, L 23: The line has been modified as:
"The storm surge is a well defined peak with a half-width (see Fandry et al., 1984) of ~ 20, 28 and 26 h at Ratnagiri, Verem and Karwar, respectively."

In this connection, the above mentioned additional reference has also been included in the revised reference list. Thanks.

Reviewer's comment: 582,L2 : You indicate that at Karwar the local influence of the wind is less and you suggest that the surge are partially due to the remote effect of long waves coming from the E1. It would be interesting to estimate the propagation time of the coastal trapped wave between your difference locations and discuss these results. Does the
peak surge time at the difference location match with a theoretical speed of a coastal trapped waves (c=sqrt(gH)) ?

Authors' response: Thanks for the suggestion. The propagation of coastally trapped wave has been discussed under section 6 of the revised MS.

Section 6: Results and Discussion: (Please refer the text and the accordingly modified figure 1 at the end of the interactive comments)

Reviewer's comment:3.4 Harbour Resonance : I suggest you clearly separate this section from the rest.

Authors' response: Thanks for the suggestion. In the revised manuscript, this has been separated as:

Section 4. High frequency response and harbour resonance

Reviewer's comment: 586,L11 : space between *land(sea* Table 1: The time is in IST should appear in Table 2 instead of this table.

Authors' response: P 587, L 9-15. Thanks for pointing out the lapse. In the revised manuscript, space has been provided between "land(sea)", "increase(decrease)", "positive(negative)" etc. Also correction is made in the caption of Table 2 as:.

"**Table 2**. Meteorological and sea level observations at Ratnagiri, Verem and Karwar during E1 from 26 November to 1 December 2011. Time is in Indian Standard Time (IST)".

Interactive comment on Ocean Sci. Discuss., 11, 575, 2014.

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1. Introduction

Tropical cyclones (TCs) 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 distributed 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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6 Results and Discussion

The basic mechanism involved in the generation of coastal surges is the influence of a long-shore wind stress, driving an Ekman transport towards the coast, causing the piling-up of water within a Rossby radius of deformation. The long-shore wind stress of finite horizontal extent associated with a cyclone causes the surge to move along the coastline at speed of $c=\sqrt{(gh)}$, where g is the acceleration due to gravity and h is the depth. Such coastally trapped motions (with the coast to the right (left) in the Northern (Southern) hemisphere) are called forced Kelvin waves (e.g., LeBlond and Mysak, 1977; Gill, 1982). Few parameter estimates of the E1 are listed in Table 1c. To estimate the propagation of the coastally trapped Kelvin wave, we have also added few more locations, where hourly sea-level data is available from www.gloss-sealevel.org (marked as red star in Fig 1). Fig 1C shows the sea level response from Colombo, Sri Lanka to Jask, Iran in the Indian Ocean. Some relevant parameters of the coastally trapped Kelvin wave are listed in Table 2C. The average propagation speed 'c' of this wave is estimated to be ~ 7 ms^{-1}. The E1 moved northward with an average along-shore speed of ~5.6 ms^{-1}, with the track almost parallel to the western coast India. The residual surge lagged the storm by 3, 4, 6.5 and 8.5 hr (Fig. 1 and Table 2C) to its nearest proximity at Colombo, Kochi, Karwar and Verem respectively with constant peak amplitude ~34.6 cm (Fig. C1). However, at Kochi, the development of secondary peak is clearly visible with time difference of ~14 hr between the two peaks of ~13.5 cm. At Ratnagiri and Karachi the surge peak is leading the storm by 1.5 and 9.5 hr with the constant peak amplitude of ~33.5 cm.

Similar response as above was observed by Fandry et al. (1984), when cyclone 'Glynis' moved slowly and almost parallel to the western coast of Australia in February 1970. In this event, a strong coastal peak travelled down the coast well ahead of the cyclone. In this example $\mu > \frac{U_{mf}}{C}$ and $V_m < c$ (where f is Coriolis parameter and μ is decay time scale), and theory predicts a coastal peak of constant amplitude moving ahead of the cyclone. In their study, they characterised the sea level response to tropical cyclone as:

a) $\mu > \frac{U_{mf}}{C}$ and $V_m < c$: Coastal peak of constant amplitude moving ahead of the cyclone.

b) $\mu < \frac{U_{mf}}{C}$ and $V_m < c$: Coastal peak of increasing in magnitude with speed as the longshore speed of the cyclone.

c)) $\mu > \frac{U_{mf}}{C}$ and $V_m > c$: Coastal peak of constant amplitude moving behind the cyclone.

In the present study, our observations indicate that the surge peak lagged E1 up to Verem and at Ratnagiri and Karwar the surge peak is leading the E1 with amplitude almost constant (Table 2C) at all the four locations from Karwar to Karachi. The impact of E1 in the BOB at Port Blair (Fig. 3i) is not observable and so in the northern parts of east coat of India at Kakinada, Gopalpur and Gangavaram (Fig. 3f-3h). The response of sea-level due to E1 at Masirah (Fig. C1k) is also not observable as the lactation is on the right hand side of the event track. Similarly, the sea level variation at the island location of Minicoy and Haniboobha are negligible due to E1 (Fig. C2), even though the track of E1 is ~170 and 280 Km away respectively. However, absence of closed boundary at these Island location and located towards the left side of the E1 track, theoretically predicts no surges. The impact of the E1 is observed only in the AS at the coastal boundary located towards the right side of the event track.

Table 1c Parameter estimates of the events.

Name	Duration	Average eastward Velocity U_m (m/s)	Average Northward Velocity V_m (m/s)	Minimum Coastal pressure Pc (mb)	Maximum Winds V (m/s)	Maximum Stress T_m (N/m^2)
DD (E1)	26 Nov-1 Dec 2011	0.955	5.6	998	17	0.9
Thane (E2)	25-31 Dec 2011	-1.1	0.3	969	40.8	5.2

Note: $V_m = 3.44(1000 - P_c)^{0.644}$ and $\tau_m = 0.000314V_m^2$ (refer Fandry et al., 1984).

Table 2c Surge propagation parameters during E1 along the west coast of Indian continent.

Location	Peak (cm)	Time of peak (IST)	Path between two locations (km)	Speed c (m/s)
Colombo	31.6	26-Nov-2011 11:30		
Mandapam	24.3	26-Nov-2011 22:00	300	9.0
Tuticorin	21.4	27-Nov-2011 15:00	110	2.0
Kochi (Peak 2)	12.9	27-11-2011 23:30	400	14.9
Kochi (Peak 1)	14.14	27-11-2011 09:30		
Karwar	36.9	28-Nov-2011 12:00	577	8.7
Verem	35.5	28-Nov-2011 17:00	90	5.7
Ratnagiri	37.0	29-Nov-2011 03:00	172	5.4
Karachi	30.0	01-Dec-2011 02:00	1094	7.4
Chabahar	18.4	03-12-2011 19:30	670	3.2
Jask	13.0	04-Dec-2011 10:30	270	5.7

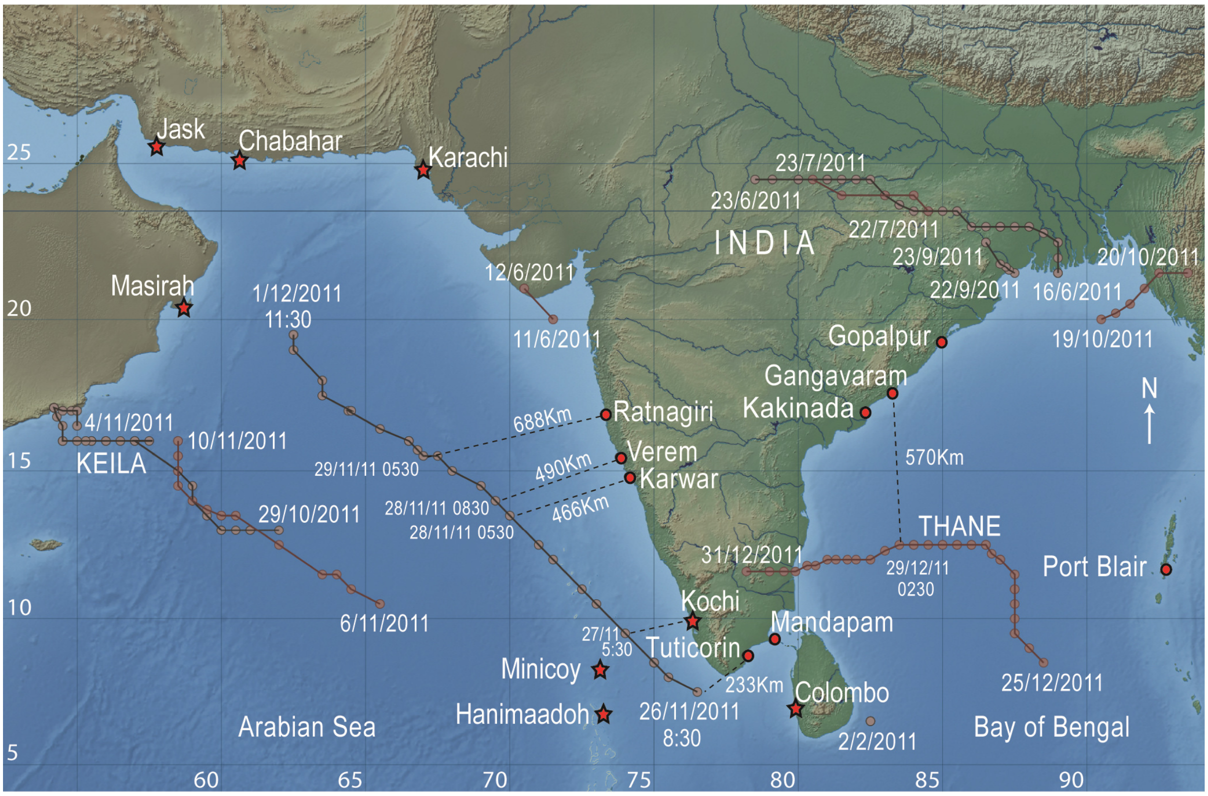

Fig. 1 Study location showing the tracks of meteorological events during the year 2011.

Note: Sea level data at Colombo, Kochi, Karachi, Chabahar, Jask, Masirah, Minocoy and Hanimaadhoo are downloaded from www.gloss-sealevel.org and are shown with red stars. [Time is in Indian Standard time (IST)]

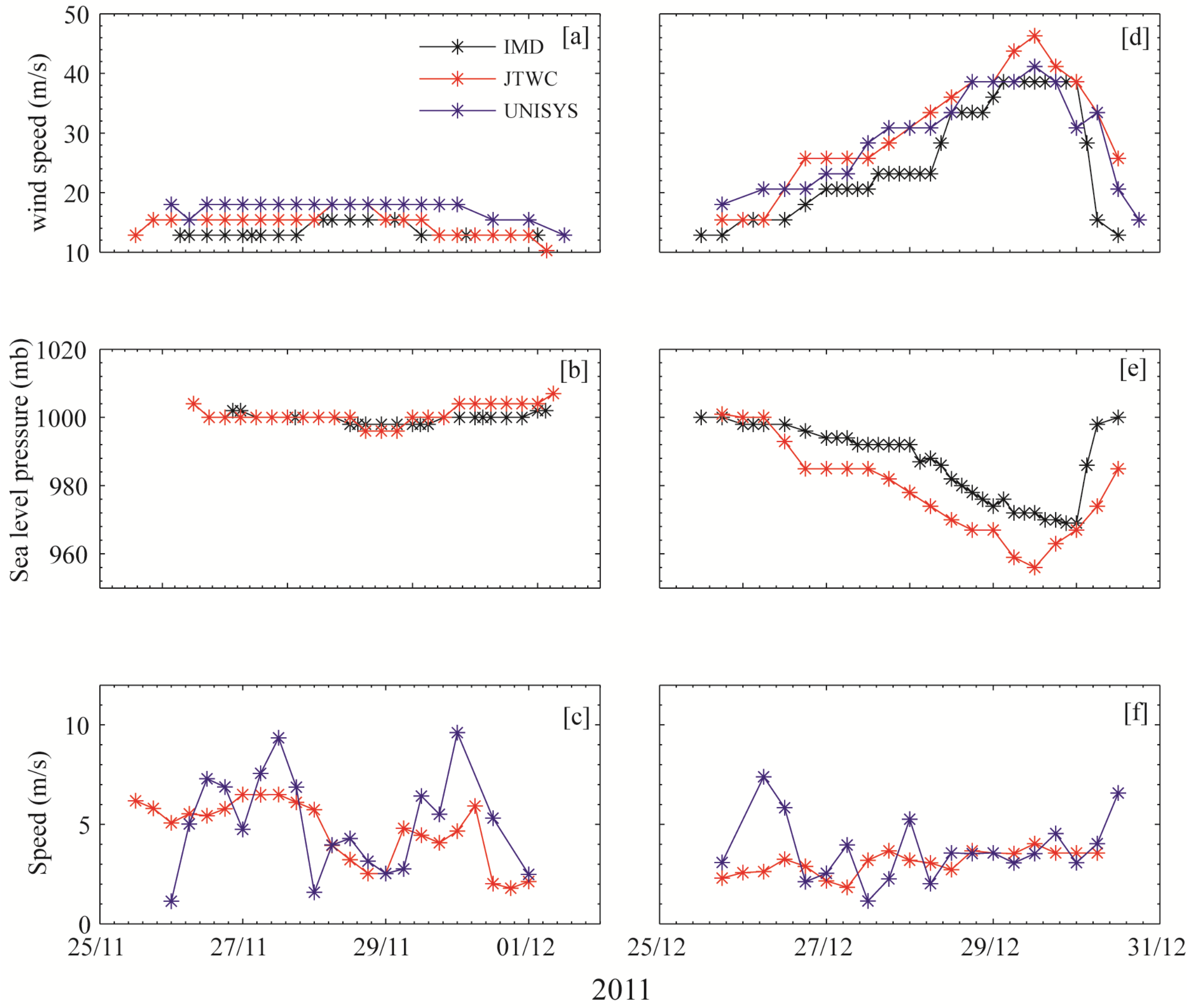

Fig. 2. Cyclone parameters **(a)** and **(d)** Maximum sustained wind speed during E1 and E2, **(b)** and **(e)** Minimum sea level pressure, **(c)** and **(f)** Storm forward translation speed.

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

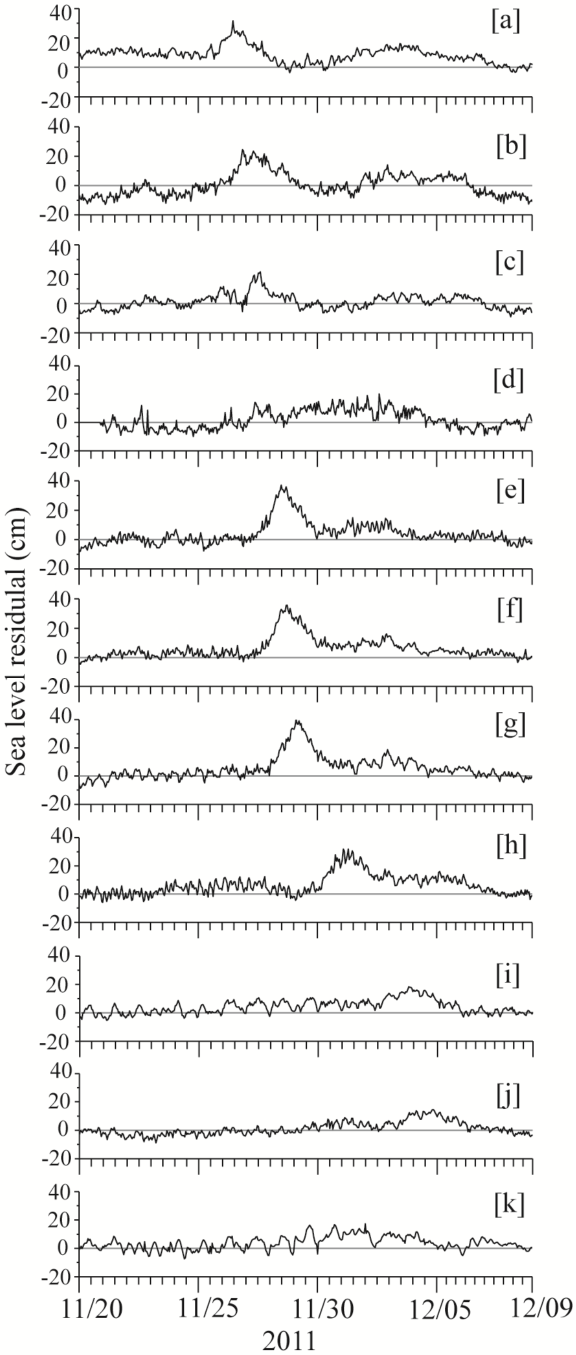

Fig. 1C Hourly sea level residual at [a] Colombo, [b] Mandapam, [c] Tuticorin, [d] Kochi, r, [e] Karwar, [f] Verem, [g] , Ratnagiri, [h] Karachi, [i] Chabahar, [j] Jask and [k] Masirah.

Note: 1 Sea level residual data at Mandapam, Tuticorin, Karwar, Verem and Ratnagiri is hourly averaged.

2 Sea level data at Colombo, Kochi, Karachi, Chabahar, Jask and Masirah is at hourly interval and downloaded from www.gloss-sealevel.org. .

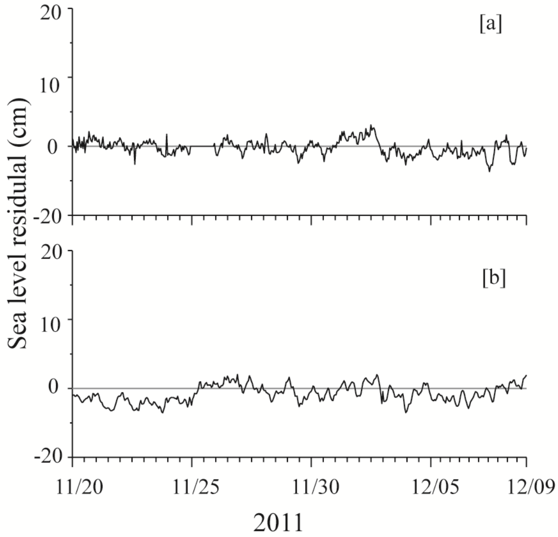

Fig 2C Sea level residual at [a] Minicoy and [b] Hanimaadhoo.
Note: 1 Sea level data at Minicoy [b] Hanimaadhoo is at hourly interval and downloaded from www.gloss-sealevel.org.

Reference:

Fandry, C.B., Leslie, L.M., Steedman, R.K.: Kelvin-type coastal surges generated by tropical cyclones, Journal of Physical Oceanography, Vol. 14, 582-593, 1984.

Gill, A.E.: Atmosphere-Ocean Dynamics, *Academic Press, 662 pp,*1982.

LeBlond, P.H., and L.A., Mysak: Waves in the Ocean, Elsevier, 602 pp, 1978.

Thompson, R.E.: On the generation of Kelvin-type waves by atmospheric disturbances, J. Fluid Mech., 42, 657-670.