Ocean Sci. Discuss., 11, 575–611, 2014
www.ocean-sci-discuss.net/11/575/2014/
doi:10.5194/osd-11-575-2014

Ocean Science
Discussions
Open Access

Coastal sea level response to the tropical cyclonic forcing in the north Indian Ocean

P. Mehra[1], S. Mohan[1], P. Vethamony[1], K. Vijaykumar[1], T. M. Balakrishnan Nair[2], Y. Agarvadekar[1], K. Jyoti[1], K. Sudheesh[1], R. Luis[1], S. Lobo[1], and B. Harmalkar[1]

[1]CSIR-National Institute of Oceanography (NIO), Goa, India
[2]Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, Goa, India

Received: 13 December 2013 – Accepted: 27 January 2014 – Published: 20 February 2014

Correspondence to: P. Mehra (pmehra@nio.org)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The study examines the observed storm-generated sea-level variation due to deep depression (Event-E1) in the Arabian Sea from 26 November–1 December 2011 and a cyclonic storm "THANE" (Event-E2) over the Bay of Bengal during 25–31 December 2011. The sea-level and surface meteorological measurements collected during these extreme events exhibit strong synoptic disturbances leading to storm surge up to 43 cm on the west coast and 29 cm on the east coast of India due to E1 and E2. E1 generated sea level oscillations at the measuring stations on the west coast (Ratnagiri, Verem and Karwar) and east coast (Mandapam and Tuticorin) of India with significant energy bands centered at periods of 92, 43 and 23 min. The surge dome has a duration of 92.6, 84.5 and 74.8 h at Ratnagiri, Verem and Karwar, respectively. However, on the east coast, the sea level oscillations during Thane were similar to those during calm period except for more energy bands centred at periods of ~100, 42 and 24 min at Gopalpur, Gangavarm and Kakinada, respectively. Multi-linear regression analysis shows that the local surface meteorological data (daily-mean wind and atmospheric pressure) is able to account for ~57 % and ~70 % of daily-mean sea-level variability along the east and west coast of India. The remaining part of variability observed in the sea level may be attributed to local coastal currents and remote forcing.

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). A few studies deal with coastal vulnerability assessment using remote sensing data, in situ observations, numerical modelling and GIS analysis; these studies provided coastal vulnerability maps for select coastal regions such as Kochi (Dinesh Kumar, 2006), Mangalore (Hegde and Raju, 2007), Odisha state (Kumar et al., 2010), Cuddalore region (Saxena et al., 2013) and Kaikhali (Bhattacharya and Guleria, 2012). 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. (2011) 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 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. 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

OSD
11, 575–611, 2014

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 2-D 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 3 h (Platzman, 1971). In the present study our interest is confined to a few minutes to days. For a country like India, a near real–time monitoring and warning of storm surges is of great interest and it is required. An integrated coastal observation network (ICON) providing sea-level and surface meteorological information over internet in near real-time have been developed and established at select coastal & Island locations of India (http://inet.nio.org) by CSIR-NIO. This study is intended to investigate the sea level variations at select locations in the BOB and AS due to tropical cyclones (TCs) and meteorological disturbances that occurred in 2011. Section 2 introduces the data and methodology, Sect. 3 presents our findings and discussions, and Sect. 4 provides conclusions.

OSD
11, 575–611, 2014

2 Data and methodology

In the present study, we report the response of the sea-level to the episodic meteorological events at various coastal and Island locations of India from 1 September 2011 to 31 January 2012. Study encompasses two episodic meteorological events: (i) deep depression in November 2011 (E1) in AS and (ii) the tropical cyclone "Thane" (E2) in BOB as shown in Fig. 1. Summary of observations is given in Table 1. The Radar Gauge (RG), which measures sea-level, is described in detail by Prabhudesai et al. (2006, 2008) and the evaluation and comparative studies have been reported by Mehra et al. (2013). RG acquires samples over 30 s window at 1 min interval and the average over 5 min is recorded at 5 min interval. The surface meteorological variables are collected by autonomous weather station (NIO-AWS). AWS samples (wind, air temperature, air pressure and relative humidity) data every 10 s over a window of 10 min, averaged and then recorded at every 10 min interval. In the present study, we have used time-series data at 5 (10) min interval from the RG (AWS). Both the systems have been designed and developed in the Marine Instrumentation Division, CSIR-NIO, Goa. The observed parameters (Table 1) and the periods covered for different events are as follows:

- Event 1 (E1): 26 November–1 December 2011, occurrence of deep depression in the Arabian Sea.

- Event 2 (E2): 25–31 December 2011, passage of Thane cyclone in the Bay of Bengal.

The tropical cyclone track data are obtained from http://weather.unisys.com/hurricane/, http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks and http://www.imd.gov.in, which provide location and intensity of tropical cyclones at 6 h intervals. The storm translational speed is calculated using the positions every 6 h reported in the JTWC tropical cyclone best track data.

OSD
11, 575–611, 2014

Sea-level data is de-tided using TASK tidal analysis and prediction program (Bell et al., 2000) to obtain sea-level residual (SLR). The 5 min sea-level data is high-pass filtered using 5th order Butterworth filter to remove oscillations with periods greater than 2 h in order to distinguish the nature of oscillations induced by tropical cyclones at various locations. The spectrum of SLR data is obtained using "pwelch" function from Matlab with Hamming window of 256 data points and 50 % overlap. 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). The data duration for estimating the spectrum of the SLR during E1 (background) is from 26 November–1 December (1 September–20 November) 2011. Similarly, the data duration during the event E2 (background) is 25–31 December (1 September–10 December) 2011 respectively.

A multi-linear regression model linking sea level and atmospheric parameters has been established. The model can be described in general as:

$$\eta = B0 + B1U + B2V + B3A_P + \epsilon, \quad (1)$$

Where 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). $B1$, $B2$ and $B3$ are the coefficient of regression. The regression is performed using daily-mean SLR, U, 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.

3 Results and discussions

3.1 Cyclone overview

The north Indian Ocean experienced ~9 meteorological events in the year 2011, with 4 (5) such events occurred in AS (BOB) as shown in Fig. 1. The data and information about these episodic meteorological events is taken from www.imd.gov.in.

OSD

11, 575–611, 2014

In Arabian Sea, the first episodic meteorological event, a depression named "Keila" originated at 13° N, 62° E, and started moving west-northwards on 29 October 2011. Keila intensified as a cyclonic storm with maximum sustained surface winds reaching up to 30 kts. Keila crossed Oman coast close to north of Salalah (near lat. 17.10° N and long. 54.30° E) between 16:00 and 17:00 UTC on 2 November 2011. The system weakened by 4 November 2011 into a low pressure area over the west central Arabian Sea off Oman coast. Second, a depression originating at 10° N, 65° E, started moving westwards on 6 November 2011. It then turned northward with maximum sustained surface winds reaching up to 30 kts. System weakened on 10 November 2011, into a well marked low pressure area over the west central Arabian Sea off Oman coast. Third one, within a couple of weeks, developed on 26 November 2011 at 7.5° N, 76.5° E near the southern tip of Indian sub-continent and moved west-northwards. By 28 November 2011 00:00 UTC, it intensified as a deep depression with maximum sustained surface winds reaching up to 30 kts (Fig. 2a) and the minimum estimated central pressure (ECP) ~ 998 mb (Fig. 2b). The average translational speed of this system remained steady to ~ 6.5 m s^{-1}. However, during the minimum ECP, the translation speed also reduced to ~ 2 m s^{-1} on 29 November and again increased to ~ 6 m s^{-1} on 30 November. The system weakened into a well marked low pressure area over the west central Arabian Sea.

Similarly, during the study period, three meteorological events occurred in BoB. First, a depression originated on 22 September 2011 at 21.5° N, 87.5° E with maximum sustained surface winds of ~ 25 kts, which weakened into a well marked pressure area over Jharkhand close to Jamshedpur on 23 September 2011. Another depression developed on 19 October 2011 at 20.5° N, 90.5° E, which further intensified into a deep depression with maximum sustained surface winds of ~ 30 kts. The system then weakened into a low pressure area over Myanmar and adjoining Bangladesh, Mizoram and northeast Bay of Bengal. Third cyclonic system named "Thane" initially originated as a depression on 25 December 2011 at 8.5° N, 88.5° E and moved north-westward (Fig. 2). Thane intensified into a very severe cyclonic storm with maximum sustained

OSD
11, 575–611, 2014

surface winds peaked up to ~ 45 m s^{-1} as shown in Fig. 2d and ECP falling to ~ 956 mb (Fig. 2e). The cyclone track turned to westwards on 29th, with an average translational speed of ~ 4 m s^{-1} and then became steady at ~ 3.5 m s^{-1} as shown in Fig. 2f. The translation speed of a storm can exert significant control on the intensity of storms by modulating the strength of the negative effect of the storm-induced sea surface temperature (SST), and reduces further storm intensification (Mei et al., 2012). Thane crossed the Tamil Nadu coast just south of Cuddalore between 01:00 and 02:00 UTC of 30 December 2011 and weakened into a well marked low pressure area over north Kerala and its neighbourhood.

3.2 Response of Sea level to depression in the Arabian Sea (2011)

The sea-level residuals (SLR) at Ratnagiri, Verem and Karwar are shown in Fig. 3. 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. For example, the distance of Verem to the trajectory of Kiela's ECP is ~ 1554 km. The variance of SLR observed during 29 October to 10 November at Ratnagiri, Verem and Karwar is ~ 26.1, 21.57 and 25.79 cm^2 respectively (Fig. 3) However, the deep depression which originated on 26 November 2011 (E1) was in the near proximity to the measurement sites. For example, the distance of Verem from the depression centre on 28 November, 2011 was ~ 490 km (Fig. 1). E1 was able to inflict surges at Ratnagiri, Verem and Karwar which peaked up to ~ 43 cm with SLR variance of ~ 119.45, 95.37 and 108.19 cm^2 respectively during E1 (Fig. 3a–c). The SLR surge dome has a duration of 92.6, 84.5 and 74.8 h at Ratnagiri, Verem and Karwar respectively. The local surface meteorological conditions along with SLR are shown in Fig. 4. During E1 (26 November to 1 December 2011), the wind variance was ~ 1.73, 4.76 and 0.8 m^2 s^{-2} with wind speeds peaking up to 7.4, 9.6 and 4.3 m s^{-1} at Ratnagiri, Verem and Karwar respectively (Fig. 4a.2–c.2). At Karwar, the wind energy is less compared to the other two sites, still the SLR peaks are of same magnitude, indicating the effect of long waves generated by the forcing due to E1 in the open ocean. The wind direction (Fig. 4a.3–c.3) stabilised to ~253, 112 and 246 degrees with respect to North (Table 2) at Ratnagiri, Verem and Karwar respectively. The atmospheric pressure anomaly (Fig. 4a.4–c.4) shows a variance of ~3.6 mb^2 and falls by ~6.0 mb during E1 at the three station. However, anomalous temperature variations due to E1 were not observed (Fig. 4a.5–c.5), but the range narrowed down from 8.3 to 3.0, 13.1 to 6.8 and 15.5 to 8.3 °C, which is the case with relative humidity also (range narrowing down from 62 to 40.4, 65.4 to 41.3 and 64.8 to 33.8 %, respectively at Ratnagiri, Verem and Karwar, refer Fig. 4a.6–c.6).

3.3 Response of Sea level to meteorological events on the east coast of India

Response of sea-level as storm surges at different sites, to the tropical cyclone Thane, E2, which occurred in BOB are shown (listed) in Fig. 3 (Table 3). SLR exhibits maximum oscillations (variance) of 27.4 cm and 26.5 cm (47.8 cm^2 and 11.72 cm^2) at Gopalpur (Fig. 5a.1) and Ganagvaram (Fig. 5b.1) respectively. At Kakinada, the SLR peaked up to 32.9 cm, with a variance of 23.3 cm^2 during E2. 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). However, at the Island station, Port Blair, the SLR variations are within ±10 cm, and less than at sites north of Thane (Fig. 3i). The SLR variability at Mandapam and Tuticorin was less compared to other sites on north of Thane track (Fig. 3d and e), probably due to the following two reasons: (i) the geometrical amplification of the open ocean waves as they propagate northwards and (ii) wind speeds are less near the central depression point and increases towards the periphery. SLR rise is also seen at Mandapam(Tuticorin) by ~24.3 (23.1) cm even during E1. The local surface meteorological conditions along with SLR are shown in Fig. 5. The large scale extent of E2 is evident in wind and atmospheric pressure measurements at all the three locations and very similar meteorological conditions exist at Gangavaram and Kakinada. At Gopalpur, the winds were weak as compared to the other two southern

OSD
11, 575–611, 2014

locations with maximum wind speed reaching up to ~ 6 m s^{-1}; the direction also fluctuated during E2 and remained southerly after 5 January 2012 and maintained this direction till 10 January 2012 (Fig. 5a.2 and a.3, Table 3). During E2, the wind speed remained high from 26 December 2011 till 4 January 2012. The wind speed peaked up to ~ 14.0 m s^{-1}, with corresponding wind variance of ~ 13.76 and 10.27 m^2 s^{-2} at Gangavaram and Kakinada respectively (Fig. 5b.2 and c.2). The wind direction stabilised and remained north-easterly (Fig. 5c.2 and c.2 and Table 3) during E2 at Gangavaram (Kakinada). The atmospheric pressure (Fig. 5a.4–c.4) shows a variance of ~ 2.7 mb^2 and is devoid of any noticeable fall during E2 at Gopalpur, Gangavaram and Kakinada. Similarly, the anomalous variations in temperature due to E2 are not observed, however the range is narrowed down from ~ 9.0°C to 2.7 °C at the three stations (Fig. 5a.5–c.5). Similarly, a reduction in relative humidity range is observed from ~ 62 % to 25 % (46.0 % to 13.6 %) at Gopalpur and Gangavaram (Kakinada).

3.4 Harbour resonance

Harbour oscillations (coastal seiches) as explained by Rabinovich (2009) are specific type of seiche motion that occur in partially enclosed basins (bays, fjords, inlets and harbours) and are connected through one or more openings to the sea. They are mainly generated by the long waves entering through the open boundary (harbour entrance) from the open sea. In order to understand the harbour oscillations, the SLRs are high-pass filtered (time period ≤ 2 h) using a 5th order Butterworth filter (Fig. 6). The amplitude of high frequency SLR oscillations in response to E1 at Ratnagiri is ~ ± 10 cm (Fig. 6a), less at Verem and Karwar (Fig. 6b and c). The Karwar station is located in open ocean and therefore does not have the resonance features of a harbour. However, the Verem station is located in Mandovi estuary and Ratnagiri station is located in a cove and may experience resonance with meteorological disturbances. In a similar study at Verem, Mehra et al. (2012) reported the SLR oscillations of ~ ±15 (10) cm in response to the cyclone Yemyin (Phyan) which occurred in AS during 23–25 June 2007

(9–12 November 2009). The high frequency SLR oscillations at Tuticorin (Mandapam) are up to 10 (5) cm during E1 (Fig. 6d and e). Mandapam sea-level gauge is located on the common boundary of Palk Strait and the Gulf of Mannar, whereas the Tuticorin sea-level gauge is located in the Gulf of Mannar (Fig. 1). The high frequency oscillations of SLR at the stations located in BOB are also shown in Fig. 6. The high pass filtered SLR amplitude due to E2 at Tuticorin, Mandapam is not observable and at Gopalpur a brief amplitude of 10 cm is observed (Fig. 6d, e and f). At Gangavaram (Kakinada) the high frequency SLR variations are $\sim \pm 10$ (5) cm as both the gauges are located in the harbour (Fig. 6g and h), and $\sim \pm 4$ cm at Port Blair.

E1 event and background SLR spectra estimated at Karwar, Verem and Ratnagiri are indicated in Fig. 7 (see Sect. 2 for the method used). The background spectra of different sites have significant differences at high frequencies as seen in Fig. 7, indicating the influence of local topography. The event spectrum at Ratnagiri is high in energy, well lifted above that of background with major peaks at 127, 80, 47, 30, 26 and 14 min during E1 as shown in Fig. 7a. At Verem the event spectra is intertwined with background spectra with peaks at 182, 91, 40 and 20 min as shown in Fig. 7b. However, the event spectrum at Verem was energetic during Yemyin, September Sumatra Tsunami, 2007 and Phyan, where a distinguished peak was observed at $\sim$ 43 min (Mehra et al., 2012). Similarly, the event spectrum during E1 (Fig. 7c) at Karwar is similar to the background with some detectable peaks at 106, 67, 44 and 21 min and further higher frequencies are merged with the background spectra, indicating open-ocean behaviour (lack of harbour resonance). The influence of E1 is also visible at Tuticorin with dominant spectral peaks at 106, 53, 44, 24 and 18 min (Fig. 7d). However, at Mandapam (Fig. 7e) the event spectra is intertwined with background spectra with peaks at 116, 80, 42 and 26 min.

E2 event and background SLR spectra estimated at Gopalpur, Gangavaram, Kakinada, and Port Blair during E2 are shown in Fig. 8. The event spectrum during E2 (Fig. 8a) at Gopalpur is intertwined with the background spectra with some detectable peaks at 106, 80, 60, 45, 36, 21 and 12 min. The spectral peak at 45 and 21 min are also

OSD
11, 575–611, 2014

present in the background signal. The event spectral energy at Gangavaram (Fig. 8b) is higher compared to the background SLR spectra with peaks at 213, 98, 67, 41, 25 and 18 min, however the background spectra shows peaks at ∼ 128, 98 and 17 min. At Gangavaram station the phenomena of harbour resonance is clearly visible (Fig. 5b.1), where it is not the surge but high frequency oscillations triggered by the long waves arriving from the open ocean. At Kakinada (Fig. 8c) the spectra for lower frequencies (time period > 41 min) is similar, but the energy is enhanced for higher frequencies (shorter time-period) oscillations with time-period 41, 37, 25 and 12 min, suggesting resonance occurring in the harbour. At Port Blair, the SLR spectra of both the event and background show similar variability with event peaks at 160, 85, 47, 41, 26 and 17 min. The background SLR spectrum has noticeable peaks at 41 and 26 min and further higher event frequencies are merged with the background spectra, indicates the absence of harbour resonance as Port Blair station provides open ocean conditions.

3.5 Regression model

Multi-linear regression analysis of SLR as the dependent variable with wind components (U, V) and atmospheric pressure (A_P) as the independent variable is performed as explained in Sect. 2 (Eq. 1). How well the model describes the sea level residual is assessed by looking at the percentage of sea level variance explained ($\mathrm{Var_e}$) by the model.

$$\mathrm{Var_e} = \left(1 - \frac{\mathrm{variance}(\varepsilon)}{\mathrm{variance(measured\ SLR)}}\right) \times 100 \tag{2}$$

In order to improve clarity and to make the different sampling durations of sea-level (5 min) and atmospheric parameters (10 min) compatible, sea-level and AWS data are daily-averaged. Therefore, in this section daily-averaged data series of SLR and AWS is used to perform multi-linear regression. To begin with, linear regression is performed with cross-shore (U), along-shore (V) components of winds and atmospheric pressure (A_P) individually as independent variable to regress the SLR. This is would enable us to know, the contribution to the SLR variability by the various surface meteorological variables individually. Then all the three independent variables [U, V, A_P] together are used to regress the daily-mean SLR. Results are listed in Table 4 and plotted in Figs. 9 and 10. The cross- and along-shore components are estimated using the local shoreline angles with respect to North from Google Earth. In AS, the local shoreline angle estimated at Ratnagiri, Verem and Karwar with respect to North is $\sim -12^{\circ}$, -27° and -19° respectively. Similarly, in BOB the local shoreline angle with respect to North is $\sim 52^{\circ}$, 45° and 50° at Gopalpur, Gangavaram and Kakinada respectively. The variations in U, V and A_P results in the SLR variability. The relation between sea-level and atmospheric pressure is $\sim -1\,\text{cm}\,\text{mb}^{-1}$, an inverse barometric effect. The cross-shore wind (U) towards land(sea) will give rise to increase(decrease) in SLR due to wind stress. Since the study region being in the Northern Hemisphere, the along-shore winds towards north with the coast at its right will increase the sea-level due to Coriolis force. Therefore, in AS the positive(negative) U & V will increase(decrease) the SLR (Fig. 9) and in BOB the positive(negative) U & V will decrease(increase) the SLR (Fig. 10).

At Ratnagiri in AS U, V and A_P individually could explain an average 50 % SLR variability, when [U, V, A_P] together are used to regress the daily-mean SLR, the total Var_e is $\sim$ 69 %. Daily-mean U, V and estimated SLR obtained by independent variables [U, V, A_P] is plotted in Fig. 9a. It is observed that the estimated daily-mean SLR during E1 is able to peak up to the measured daily-mean SLR, which is less by $\sim$ 13.6 % (Fig. 9a.2 and Table 5). The monthly Var_e is $\sim$ 50 % during October and December 2011 (Table 4 and Fig. 11a). However, in November 2011, when E1 occurred [U, V, A_P] together is able to explain the SLR variability up to $\sim$ 70 %. In January 2012, the Var_e is less than 21 % at all the three sites in AS and BoB (Fig. 11 and Table 4). At Verem (Fig. 9b), the daily-mean U, V and A_P are able to explain an only average $\sim$ 45 % of the daily-mean SLR variability (Table 4). The total Var_e $\sim$ 76 % is highest at Verem among the three locations in AS, when [U, V, A_P] together are used to estimate the daily-mean SLR as presented in Fig. 9b.2. The monthly Var_e is $\sim$ 75 % for September–November 2011 as shown in Fig. 11a. During E1, the $-U$(V) will tend to decrease(increase) the sea

OSD
11, 575–611, 2014

level at Verem (Fig. 9b.1), still the estimated daily-mean SLR is able to reproduce the comparable response with measured daily-mean SLR, with a minor overshoot by ~6 % (Table 5). At Karwar (Fig. 9c), U,V and A_P could explain the SLR variability by an average ~38 % only, when regressed individually. The total $\mathrm{Var_e}$ increased to 66.3 %, when [U, V, A_P] together are used to multi-linear regress the daily-mean SLR as shown in Fig. 9c.2 (Table 4). At Karwar also the $U(-V)$ will tend to increase(decrease) the sea level during E1 (Fig. 9c.1), however the estimated SLR is able to peak only up to half of the measured daily-mean SLR and is less by ~44.1 % (Fig. 9c.2 and Table 5).

In BOB, the daily-mean U & V measured and estimated SLR is plotted in Fig. 10 for Gopalpur, Gangavaram and Kakinada. The monthly $\mathrm{Var_e}$ is low ~<23 % (20 %) in October(January) for all the three stations in BOB as shown in Fig. 11b. At Gopalpur, U, V and A_P individually are able to account for an average 34 % of daily-mean SLR variability. When all the three variables [U, V, A_P] together are used as independent variables in Eq. (1), the $\mathrm{Var_e}$ increases marginally to 49 % (Table 4). As stated earlier, along the east coast of India in BOB the positive(negative) U & V will decrease (increase) the sea level. Figure 10a.1 shows the $U(-V)$ at Gopalpur, which are seaward(southward) during E2 favouring the sea-level fall(rise). However, by 1 January 2012 both the cross- and along-shore component of wind -U(V) turns landward(Northward), imposing a sea-level rise(fall). Sea-level appears to be influenced more by alongshore wind, where the estimated SLR follows the forcing of V. Figure 10a.2 is plotted with the estimated and measured daily-mean SLR at Gopalpur, during E2 the estimated(measured) SLR is ~22.4 (29.7) cm, i.e. the estimated SLR is 24.7 % less than the measured daily-mean SLR (Table 5). It is also observed that the measured SLR remains high (~15 cm) till 5 January 2012, whereas the estimated SLR falls to zero by 30 December, 2011. At Gangavaram, U, V and A_P individually are able to account for an average 45 % of daily-mean SLR variability. When all the three variables [U, V, A_P] together are used to regress the daily-mean SLR, the $\mathrm{Var_e}$ increases to ~57.2 % (Table 4). The U & V winds are plotted in Fig. 10b.1, where the daily-mean along-shore (V) winds are observed to dominate with a range of ~±10 m s^{-1}. During E2, the estimated (measured)

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

OSD

11, 575–611, 2014

Coastal sea level response to the tropical cyclonic forcing

P. Mehra et al.

daily-mean SLR peaks up to 14.6 (13.8) cm, with an overshoot of ∼6 % (Table 5). At Gangavaram, the rise in SLR residual is predominantly due to high along-shore wind ($-V$), as explained by $\mathrm{Var_e}$ for December 2011 which is 63 %. Also the measured daily-mean SLR remained high from 22 December 2011 to 9 January 2012, whereas the estimated SLR remained high from 24 December 2011 to 3 January 2012 (Fig. 10b.2). Similarly, at Kakinada the U, V and A_P individually are able to account for an average 49 % of daily-mean SLR variability. When all the three variables [U, V, A_P] together are used to regress the SLR, the $\mathrm{Var_e}$ increases to ∼65 % (Table 4). At Kakinada also the V winds (Fig. 10c.1), appears to dominate with peaks up to $\sim -10\,\mathrm{m\,s^{-1}}$. During E2, the estimated SLR peaked up to the measured daily-mean SLR (Table 5). At Kakinada also, the rise in sea residual is predominantly due to high southward wind (V). The measured SLR started rising above zero on 23 December, reached highest level on 29 December and descended by 9 January 2012, whereas the estimated SLR started ascending on 25 December, reached the highest level on 29 December 2011 and then started drop down to zero level by 4 January 2012 (Fig. 10c.2).

We summarise the response of sea-level of the two events in AS and BOB. The SLR rise(fall) in AS due to E1 reflects the winds as is also seen in the estimated SLR. However, the estimated SLR peak value at Ratnagiri and Verem is comparable to the measured SLR during E1 except at Karwar where it is short by ∼44 %. The $\mathrm{Var_e}$ accounted by local surface meteorological parameters is ∼70 %. $\mathrm{Var_e}$ is small in January at all the locations of the present study (Table 4). In a similar study by Mehra et al. (2010), multi-linear regression analysis (every two month duration) was also used to resolve the dependence of sea level on various forcing parameters for 2007 and 2008 at Verem, Goa. During the summer monsoon (May–September), the sea level variability attributable to wind was up to 47 % and 75 % respectively for 2007 and 2008; however, it reduced to <20 % during the winter monsoon (November–February). A significant part of the variability observed in sea-level remained unaccounted for and is attributed to remote forcing. In BOB, the SLR response to E2 is of a plateau shape with rising peaks and prolonged falls during E2, which the estimated SLR is not able to capture.

OSD
11, 575–611, 2014

This persistence of high daily-mean SLR state may be attributed to: intensity, direction and duration of the event, the distance from the source etc. The distance of Thane (E2) track is ~570 km from Gangavaram as shown in Fig. 1. The slope of the continental shelf will also affect the level of surge in a particular area. For example areas with shallow slopes of the continental shelf (as in AS) will allow a greater storm surge and areas with deep water just offshore experience large waves, but little storm surge (SLOSH, 2003). At Gangavaram, the daily-mean SLR is low (~13.8 cm) compared to the other sites in BOB (Table 5). However, we observe distinct harbour oscillations as seen in Fig. 5b.1. Also note that when Thane crossed the Tamil Nadu coast just south of Cuddalore between 01:00 and 02:00 UTC of 30 December 2011, no distinct surge is observed at Mandapam and Tuticorin, even though Mandapam(Tuticorin) is in close proximity ~237 (360) km to Thane. The highest surges usually occur to the right of the storm track (travelling with the storm) at approximately the radius of maximum wind.

4 Conclusions

It is being realised increasingly that a near real-time network of sea-level and surface meteorological measurements along the coastal and Island locations of India such as ICON (http://inet.nio.org/) established by CSIR-NIO could play an important role in improving the operational(routine) predictions of coastal flooding and enable to completely understand the fundamental dynamics of these events. Presently, there are few meso-scale weather and sea-level network world wide to observe such events. It is also expected that this kind of relatively inexpensive and simple networks, similar to the one in-house developed and established by CSIR-NIO, will be affordable to limited-budget institutions in their natural hazard mitigation efforts.

This study attempts to investigate the meteorologically induced surges and water level oscillation along the select locations in response to the passage of "Storm 5" in Arabian sea and "Thane" in Bay of Bengal. The Water level oscillations observed, such as at Gangavaram during the events are found to be due to the result of harbour resonance. Each location has a typical event spectrum related to the local topography. Most of the locations in the present study showed typical SLR oscillations with time period of ~ 92, 43 and 23 (100, 42 and 24) min in AS (BOB). During E1, even though the local winds are small in magnitude (4–10 $m\,s^{-1}$), the surges are 39–47 cm at Ratnagiri, Verem and Karwar with similar dome in SLR. In this case cyclone track is parallel or at an oblique angle to the coastline and hence flooding occurs on longer stretches of the shoreline. Whereas, during E2 (Thane) the cyclone makes a perpendicular approach to the coast at landfall, the surges are low at Mandapam and Tuticorin as these stations are on the left of the Thane track as compared to the stations on the right (Gopalpur, Gangavaram and Kakinada). SLR at Gopalpur, Gnagvaram and Kakainada remained high for ~ 9 days even after the land fall of Thane. The multi-linear regression using local daily-mean winds (cross- and along-shore) in association with atmospheric pressure is able to account for up to 70 % of daily-mean sea level residual (SLR) at Ratnagiri, Verem and Karwar during E1. However, in BOB up to 57 % of daily-mean SLR is accounted for at Gopalpur, Gangavaram and Kakinada. A significant amount of unaccounted SLR is attributed to remote forcing.

Supplementary material related to this article is available online at http://www.ocean-sci-discuss.net/11/575/2014/osd-11-575-2014-supplement.pdf.

Acknowledgements. Authors acknowledge the support of the Finolex Industries Limited, Ratnagiri, Maharashtra; Indian Naval Office at Verem, Goa; Estuary View Resort and Survey of India office, Karwar, Karnataka; CSIR-CECRI, Tuticorin, Tamil Nadu; CMFRI, Mandapam, Tamil Nadu; Kakinada Seaports Ltd., Kakinada, Andhra Pradesh; Ganagvaram Ports Limited, Visakhapatnam, Andhra Pradesh; Gopalpur Ports Limited, Odisha for providing a safe and secured site for sea-level and surface meteorological measurements. The authors gratefully acknowledge the financial support (2013–2017) given by the Earth System Science Organization (ESSO) – Indian National Centre for the Ocean information Services (INCOIS), Ministry of

OSD
11, 575–611, 2014

Earth Sciences, Government of India for maintenance of Autonomous Weather Stations (AWS) under ICON established by CSIR-NIO. They are grateful to Shri Anil Shirgoankar for his consistent technical support in keeping the systems operational. They also acknowledge the support and encouragement of S. W. A. Naqvi, Director of CSIR-NIO, Goa, in carrying out this work.

References

Antony, C. and Unnikrishnan, A. S.: Observed characteristics of tide-surge interaction along the east coast of India and the head of Bay of Bengal, Estuar. Coast. Shelf Sc., 131, 6–11, doi:10.1016/j.ecss.2013.08.004, 2013.

Bell, C., Vassie, J. M., and Woodworth, P. L.: Tidal Analysis Software Kit 2000 (Task 2000), POL/PSMSL Permanent Service for Mean Sea Level, Proudman Oceanographic Laboratory, UK, 2000.

Bhattacharya, T. and Guleria, S.: Coastal flood management in rural planning unit through land-use planning: Kaikhali, West Bengal, India, J. Coast. Conserv., 16, 77–87, doi:10.1007/s11852-011-0176-x, 2012.

Chittibabu, P., Dube, S. K., Rao, A. D., Sinha, P. C., and Murty, T. S.: Numerical Simulation of extreme sea levels using location specific high resolution model for Gujarat coast of India, Marine Geodesy, 23, 133–142, 2000.

Chittibabu, P., Dube, S. K., Rao, A. D., Sinha, P. C., and Murty, T. S.: Numerical simulation of extreme sea levels for the Tamilnadu (India) and Sri Lanka coasts, Mar. Geod., 25, 235–244, doi:10.1080/01490410290051554, 2002.

Das, P. K.: On the Prediction of storm surges, Sadhana, 19, 583–595, doi:10.1007/BF02835641, 1994.

Dinesh Kumar, P. K.: Potential vulnerability implications of sea level rise for the coastal zones of Cochin, southwest coast of India, Environ. Monitor. Asses., 123, 333–344, 2006.

Dube, S. K., Rao, A. D., Sinha, P. C., Murty, T. S., and Bahulayan, N.: Storm surge in the Bay of Bengal and Arabian Sea: the problem and its prediction, Mausam, 48, 283–304, 1997.

Dube, S. K., Jain, I., and Rao, A. D.: Numerical storm surge prediction model for the North Indian Ocean and the South China Sea, Disaster Dev., 1, 47–63, 2006.

Dube, S. K., Jain, I., Rao, A. D., and Murty, T. S.: Storm surge modelling for the Bay of Bengal and Arabian Sea, Nat. Hazards, 51, 2–27, doi:10.1007/s11069-009-9397-9, 2009.

Fritz, H. M., Blount, C. D., Albusaidi, F. B., and Al-Harthy, A. H. M.: Cyclone Gonu storm surge in Oman, Estuar. Coast. Shelf Sc., 86, 102–106, 2010.
Hegde, A. V. and Raju, V. E. E. R.: Development of coastal vulnerability index for Mangalore coast, India, J. Coast. Res., 23, 1106–1111, 2007.
Jain, I., Chittibabu, P., Agnihotri, N., Dube, S. K., Sinha, P. C., and Rao, A. D.: Numerical storm surge model for India and Pakistan, Na. Hazards, 42, 67–73, doi:10.1007/s11069-006-9060-7, 2007.
Joseph, A., Desai, R. G. P., Mehra, P., SanilKumar, V., Radhakrishnan, K. V., VijayKumar, K., AshokKumar, K., Agarvadekar, Y., Bhat, U. G., Luis, R., Rivankar, P., and Viegas, B.: Response of west Indian coastal regions and Kavaratti lagoon to the November-2009 tropical cyclone Phyan, Nat. Hazards, 57, 293–312, 2011.
Kumar, T. S., Mahendra, R. S., Nayak, S., Radhakrishnan, K., and Sahu, K. C.: Coastal vulnerability assessment for Orissa State, east coast of India, J. Coast. Res., 26, 523–534, West Palm Beach (Florida), ISSN 0749-0208, 2010.
Mehra, P., Tsimplis, M. N., Prabhudesai, R. G., Joseph, A., Shaw, A. G. P., Somayajulu, Y. K., and Paolo Cipollini, P.: Sea level changes induced by local winds on the west coast of India, Ocean Dynam., 60, 819–833, doi:10.1007/s10236-010-0289-z, 2010.
Mehra, P., Prabhudesai, R. G., Joseph, A., Kumar, V., Agarvadekar, Y., Luis, R., and Viegas, B.: A study of meteorologically and seismically induced water level and water temperature oscillations in an estuary located on the west coast of India (Arabian Sea), Nat. Hazards Earth Syst. Sci., 12, 1607–1620, doi:10.5194/nhess-12-1607-2012, 2012.
Mehra, P., Desai, R. G. P., Joseph, A., VijayKumar, K., Agarvadekar, Y., Luis, R., and Nadaf, L.: Comparison of sea-level measurements between microwave radar and subsurface pressure gauge deployed at select locations along the coast of India, J. Appl. Remote Sens., 7, 073569, doi:10.1117/1.JRS.7.073569, 2013.
Mei, W., Pasquero, C., and Primeau, F.: The effect of translation speed upon the intensity of tropical cyclones over the tropical ocean, Geophys. Res. Lett., 39, L07801, doi:10.1029/2011GL050765, 2012.
Murty, T. S., Flather, R. A., and Henry, R. F.: The storm surge problem in the Bay of Bengal, Prog. Oceanogr., 16, 195–233, 1986.
Neetu, S., Lengaigne, M., Vincent, E. M., Vialard, J., Madec, G., Samson, G., Ramesh Kumar, M. R., and Durand, F.: Influence of upper-ocean stratification on tropical

OSD
11, 575–611, 2014

cyclone-induced surface cooling in the Bay of Bengal, J. Geophys. Res., 117, C12020, doi:10.1029/2012JC008433, 2012.
Prabhudesai, R. G., Joseph, A., Agarvadekar, A., Dabholkar, D., Mehra, P., Gouveia, A., Tengali, S., Vijaykumar, K., and Parab, A.: Development and implementation of cellular-based real-time reporting and Internet accessible coastal sea level gauge – A vital tool for monitoring storm surge and tsunami, Curr. Sci., 90, 1413–1418, 2006.
Prabhudesai, R. G., Joseph, A., Mehra, P., Agarvadekar, Y., Tengali, S., and Vijay kumar: Cellular-based and Internet enabled real-time reporting of the tsunami waves at Goa and Kavaratti Island due to M_w 8.4 earthquake in Sumatra on 12 September 2007, Curr. Sci., 94, 1151–1157, 2008.
Platzman, G. W.: Ocean tides and related waves. Lectures for the American Mathematical Society, 1970, Summer seminars on mathematical problems in the geophysical sciences, held at Rensselaer Polytechnic Institute, Troy, NY, 94 pp., (also in: Mathematical problems in the geophysical sciences, edited by: Reid, W. H., 14, 239–291), 1971.
Rabinovich, A. B.: Spectral analysis tsunami waves: Separation of source and topography effects, J. Geophys Res., 102, 12663–12676, doi:10.1029/97JC00479, 1997.
Rabinovich, A. B.: Seiches and Harbor Oscillations, Chapter 9, Handbook of Coastal and Ocean Engineering, edited by: Kim, Y. C., World Scientific Publ., Singapore, 2009.
Rao, A. D., Jain, I., Murthy, M. V. R., Murty, T. S., and Dube, S. K.: Impact of cyclonic wind field on interaction of surge wave computations using Finite- element and Finite-difference models, Nat. Hazards, 49, 225–239, doi:10.1007/s11069-008-9284-9, 2008.
Rao, A. D., Murty, P. L. N., Jain, I., Kankara, R. S., Dube, S. K., and Murty, T. S.: Simulation of water levels and extent of coastal inundation due to a cyclonic storm along the east coast of India, Nat. Hazards, 66, 1431–1441, doi:10.1007/s11069-012-0193-6, 2013.
Saxena, R., Purvaja, R., Mary Divya Suganya, G., and Ramesh, R.: Coastal hazard mapping in the Cuddalore region, South India, Nat. Hazards, 66, 1519–1536, doi:10.1007/s11069-012-0362-7, 2013.
SLOSH: Sea, Lake, and Overland Surge from Hurricanes, a computerized model developed by the National Weather Service (NWS), US, to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes, SLOSH Display Training, 2003.
Sundar, D., Shankar, D., and Shetye, S. R.: Sea level during storm surges as seen in tide-gauge records along the east coast of India, Curr. Sci., 77, 1325–1332, 1999.

OSD
11, 575–611, 2014

Coastal sea level response to the tropical cyclonic forcing

P. Mehra et al.

Tkalich, P., Vethamony, P., Babu, M. T., and Malanotte-Rizzoli, P.: Storm surges in the Singapore Strait due to winds in the South China Sea, Nat. Hazards, 66, 1345–1362, doi:10.1007/s11069-012-0211-8, 2013.
Wang, Z., DiMarco, S. F., Stossel, M. M., Zhang, X., Howard, M. K., and du Vall, K.: Oscillation responses to tropical Cyclone Gonu in northern Arabian Sea from a moored observing system, Deep-Sea Res., 64, 129–145, doi:10.1016/j.dsr.2012.02.005, 2012.

Table 1. Summary of observations from different coastal and Island locations of India from 1 September 2011 to 31 January 2012. The CSIR-NIO Radar Gauge (RG) measures sea-level (cm) and the CSIR-NIO autonomous weather station (AWS) provides surface meteorological variables such as winds, atmospheric pressure and air temperature. The time is in IST.

Sr No	Measurement Station	Latitude and Longitude		Location type	System	Distance between AWS & RG (m)
		Lat (° N)	Lon (° E)			
1	Gopalpur, Odisha	19.3081 19.3069	84.9613 84.9634	Harbour	AWS Radar gauge	255
2	Gangavaram, Andhra Pradesh	17.6174 17.6235	83.2322 83.2295	Harbour	AWS Radar gauge	726
3	Kakinada, Andhra Pradesh	16.9764 16.9764	82.2832 82.2832	Harbour	AWS Radar gauge	2
4	Mandapam, Tamil Nadu	9.2763 9.2713	79.1295 79.1321	Boundary of Palk Strait & Gulf of Mannar	AWS Radar gauge	615
5	Tuticorin, Tamil Nadu	8.7500	78.2021	Gulf of Mannar	Radar gauge	–
6	Port Blair, Andaman & Nicobar Islands	11.7099 11.6884	92.7386 92.7222	Open Ocean	AWS Radar gauge	2984
7	Karwar, Karnataka	14.8464 14.8030	74.1317 74.1144	Open Ocean	AWS Radar gauge	5154
8	Verem, Goa	15.4554 15.5019	73.8022 73.8120	Mandovi estuary	AWS Radar gauge	5265
9	Ratnagiri, Maharashtra	16.8926 16.8890	73.2758 73.2853	Cove	AWS Radar gauge	525

OSD
11, 575–611, 2014

Table 2. Meteorological and sea level observations at Ratnagiri, Verem and Karwar during E1 from 26 November to 1 December 2011.

SN	Variables	Ratnagiri	Verem	Karwar
1	Sea level residual (SLR in cm)	47	39	42
2	SLR rise time from zero-maxima (h)	44.16	39.33	32.58
3	SLR fall time from maxima-zero (h)	48.5	45.25	42.25
4	SLR peak time	29 Nov 2011 15:15	28 Nov 2011 18:00	28 Nov 2011 12:25
5	Maximum wind speed ($m\,s^{-1}$)	7.4	9.6	4.3
6	Wind direction (degrees)	253	112	246
7	Air temperature, reduction in range (˚C)	8.3–3.0	13.3–6.8	15.5–8.3
8	Atmospheric pressure fall (mb)	5.8	6.3	5.9
9	Relative humidity range fall (%)	62.0–40.4	65.4–41.3	64.8–33.8

OSD
11, 575–611, 2014

Table 3. Meteorological and sea level observations at Gopalpur, Gangavaram and Kakinada during E2 from 26–31 December 2011.

S.No	Variables	Gopalpur	Gangavaram	Kakinada
1	Sea level residual (SLR in cm)	27.4[a]	26.5[a]	32.9
2	SLR rise time from zero-maxima (h)	–	–	123.8
3	SLR fall time from maxima-zero (h)	–	–	233.25
4	Maximum wind speed (m/s)	6.1	15.0	13.3
5	Wind direction (degrees)	184[b]	41.9	60.9
6	Air temperature reduction in range (°C)	10.1–2.6	8.4–3.1	8.5–2.6
7	Relative humidity range reduction (%)	65.75–27.07	57.8–23.8	46–13.6

[a] Maximum of the SLR oscillation at Gopalpur and Gangavaram.
[b] The direction fluctuated during E2 and stabilised to ~184° with respect to North after 5 January 2012 and maintained this direction till 10 January 2012.

OSD
11, 575–611, 2014

Coastal sea level response to the tropical cyclonic forcing

P. Mehra et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 4. The daily-mean sea-level variability explained (Var_e) by linear (U, V, A_P individually) and multi-linear ([U, V, A_P] together) regression during different months from September 2011 to January 2012.

Station	Variable	Total Var_e (%)	Monthly Var_e (%)				
			Sept	Oct	Nov	Dec	Jan
Arabian Sea							
Ratnagiri	U, V, A_P	45.4, 45.7, 59.2					
	[U, V, A_P]	68.9		52.0	70.3	47.8	2.4
Verem	U, V, A_P	48.9, 29.0, 58.2					
	[U, V, A_P]	75.8	82.7	71.0	72.4	38.7	17.1
Karwar	U, V, A_P	38.1, 30.5, 45.2					
	[U, V, A_P]	66.3	60.5	73.5	66.6	35.5	14.2
Bay of Bengal							
Gopalpur	U, V, A_P	36.6, 33.4, 31.2					
	[U, V, A_P]	49.0	61.7	17.5	39.9	54.4	7.3
Gangavaram	U, V, A_P	42.3, 49.3, 44.2					
	[U, V, A_P]	57.2	66.0	14.8	32.7	70.4	10.0
Kakinada	U, V, A_P	43.2, 59.2, 44.4					
	[U, V, A_P]	65.2	77.4	23.1	61.1	72.3	20.3

OSD
11, 575–611, 2014

Table 5. The peak response of the daily-mean sea level residual (SLR) along with the estimated daily-mean SLR during E1 & E2.

Station	Event	Measured daily-mean SLR (cm)	Estimated Daily-mean SLR (cm)	Difference (%)
Ratnagiri	E1	29.6	25.5	13.6
Verem	E1	25.8	27.3	–6.1
Karwar	E1	27.7	15.5	44.1
Gopalpur	E2	29.7	22.4	24.7
Gangavaram	E2	13.8	14.6	–6.0
Kakinada	E2	22.3	22.3	0.0

OSD
11, 575–611, 2014

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

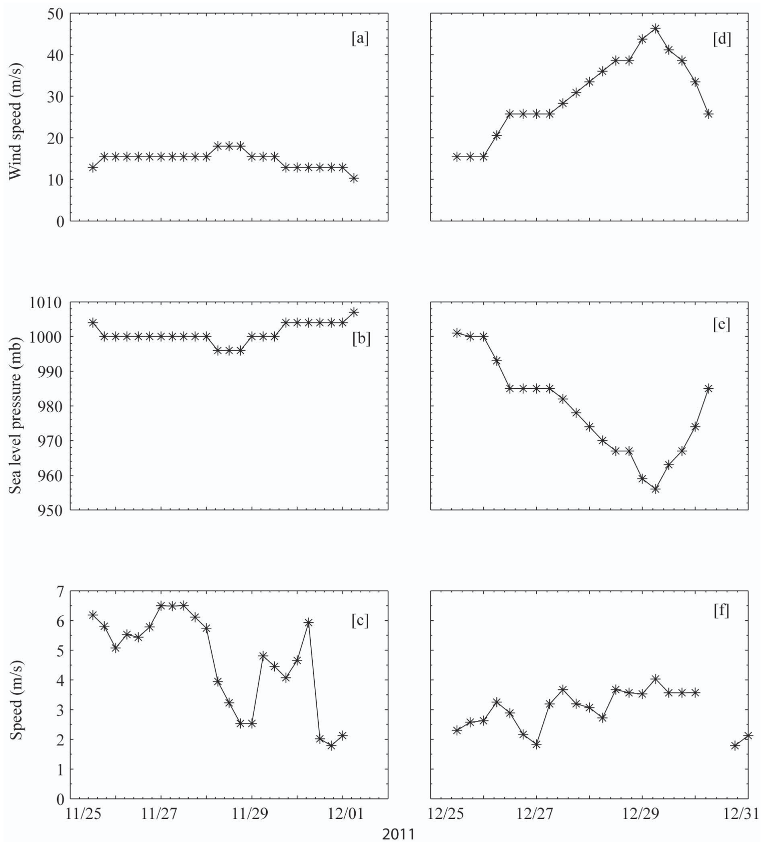

Fig. 2. Cyclone parameters **(a)** and **(d)** Maximum sustained wind speed during E1 and E2, **(b)** and **(e)** Minimum sea level pressure, **(c)** and **(f)** Storm forward translation speed.

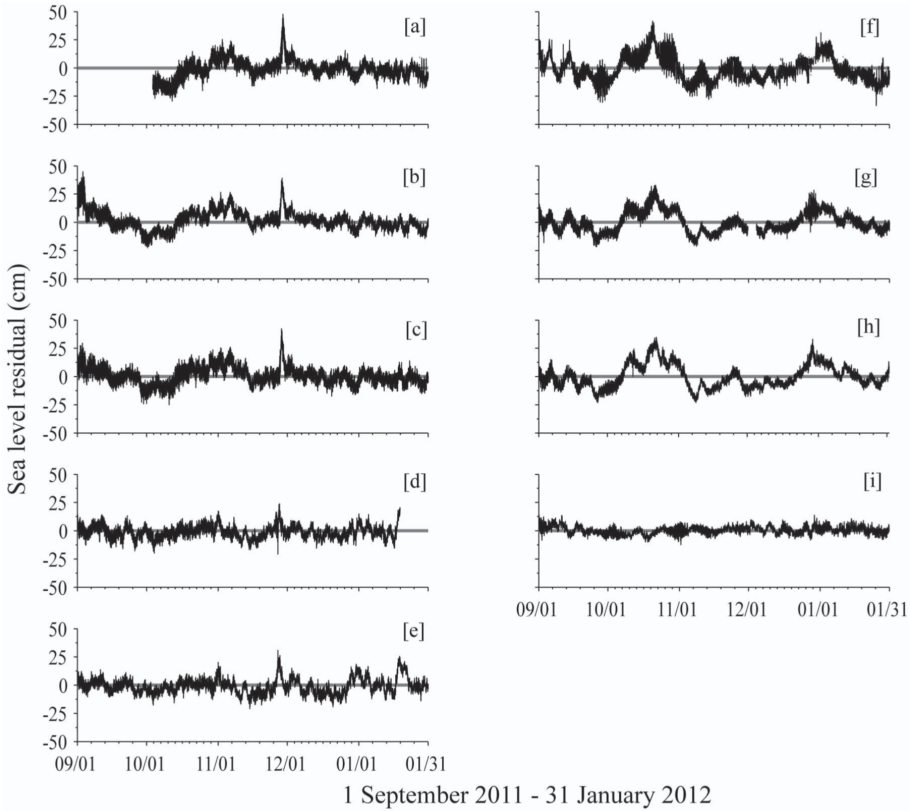

Fig. 3. Sea level residual (SLR) at **(a)** Ratnagiri, **(b)** Verem, **(c)** Karwar, **(d)** Tuticorin, **(e)** Mandapam, **(f)** Gopalpur, **(g)** Gangavaram, **(h)** Kakinada and **(i)** Port Blair.

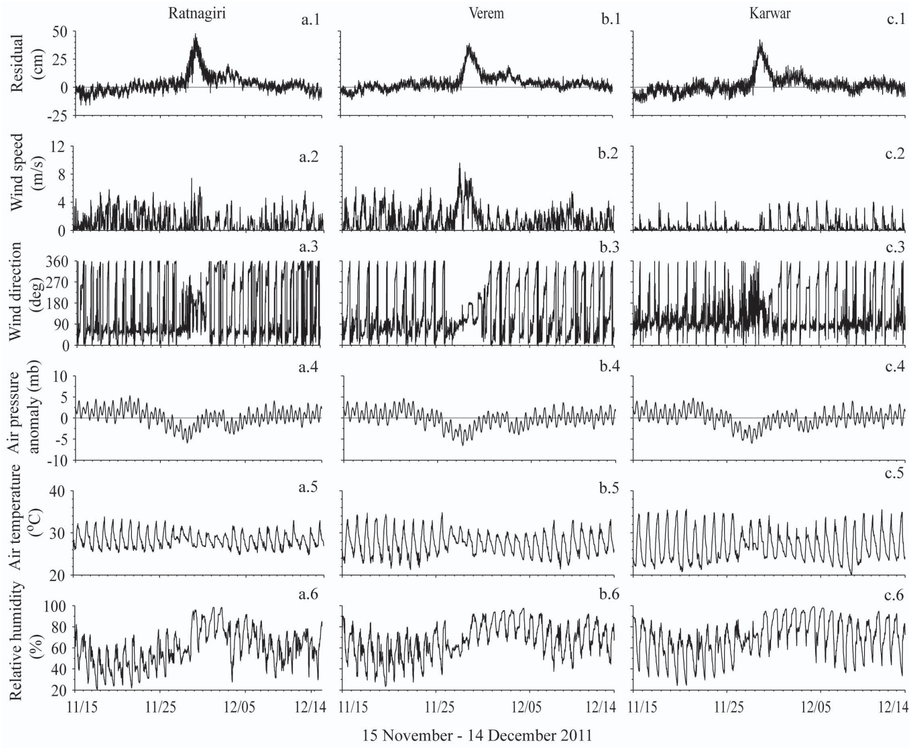

Fig. 4. Sea level residual and surface meteorological parameters during the episodic event E1. **(a.1** to **a.6)** SLR, wind speed, wind direction, atmospheric pressure anomaly, air temperature and relative humidity at Ratnagiri, Maharashtra. **(b.1** to **b.6)** same as in **(a)** at Verem, Goa. **(c.1** to **c.6)** same as in **(a)** at Karwar, Karnataka. The atmospheric pressure anomaly is estimated by subtracting the mean atmospheric pressure (1 September 2011 to 31 January 2012) from the measured atmospheric pressure for respective stations.

OSD
11, 575–611, 2014

OSD
11, 575–611, 2014

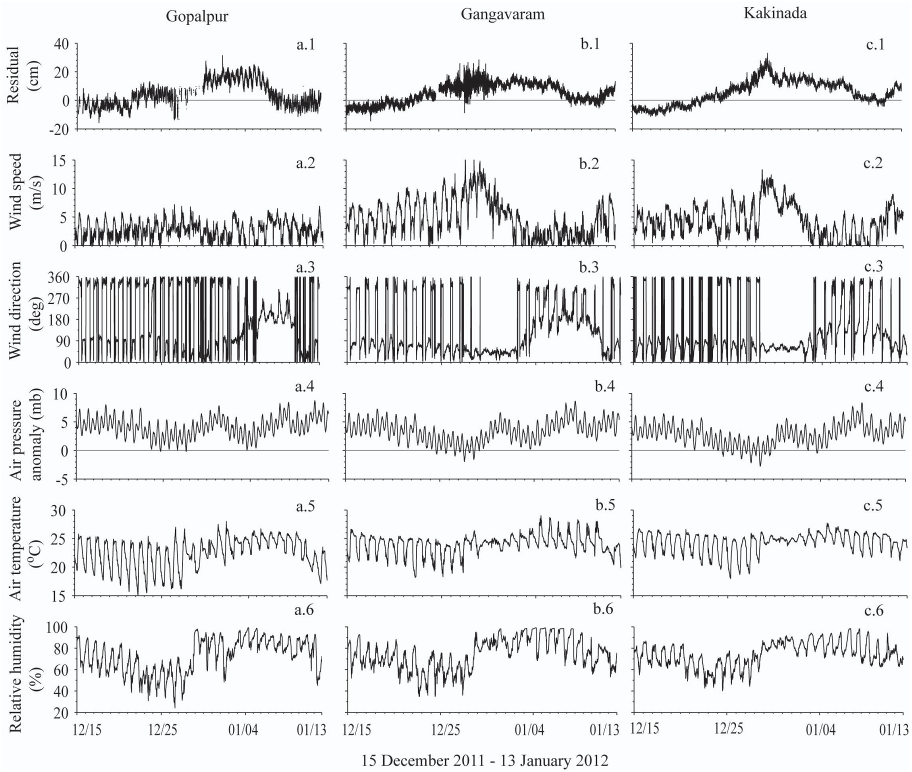

Fig. 5. Sea level residual and surface meteorological parameters during the episodic event E2. **(a.1** to **a.6)** SLR, wind speed, wind direction, atmospheric pressure anomaly, air temperature and relative humidity at Gopalpur, Odisha. **(b.1** to **b.6)** same as in **(a)** at Gangavaram, Andhra Pradesh. **(c.1** to **c.6)** same as in **(a)** at Kakinada, Andhra Pradesh. The atmospheric pressure anomaly is estimated by subtracting the mean atmospheric pressure (1 September 2011 to 31 January 2012) from the measured atmospheric pressure for respective stations.

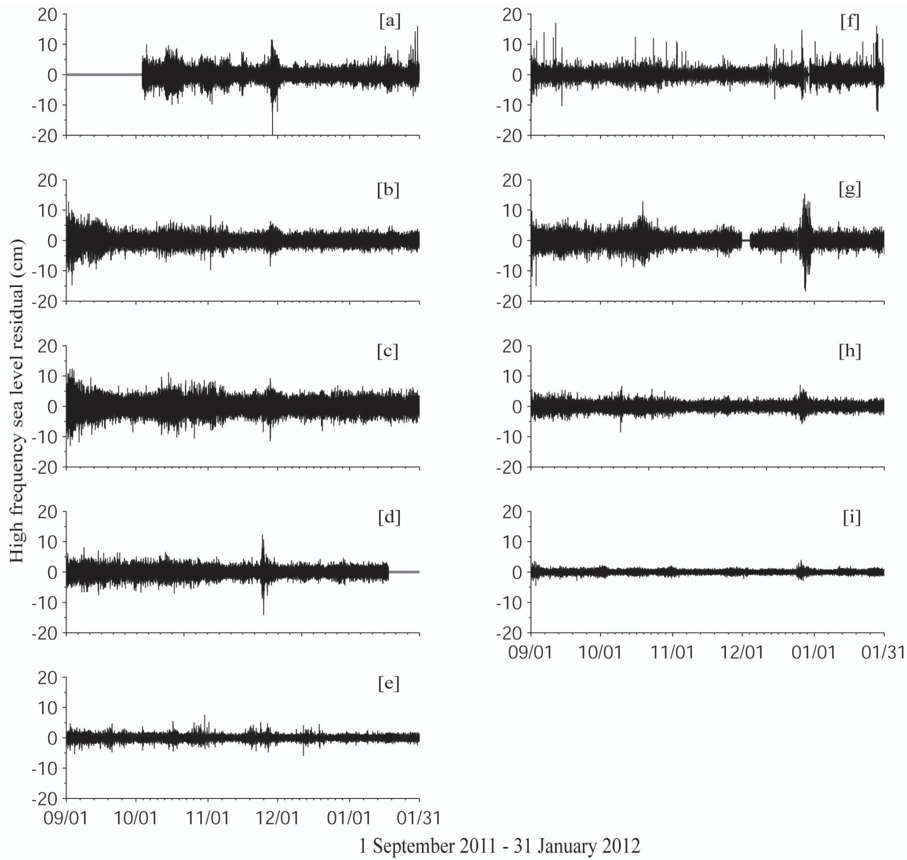

Fig. 6. High-pass filtered sea-level residual (SLR) using a 5th order Butterworth filter (time period ≤ 2 h) at **(a)** Ratnagiri, **(b)** Verem, **(c)** Karwar, **(d)** Tuticorin, **(e)** Mandapam, **(f)** Gopalpur, **(g)** Gangavaram, **(h)** Kakinada and **(i)** Port Blair.

OSD
11, 575–611, 2014

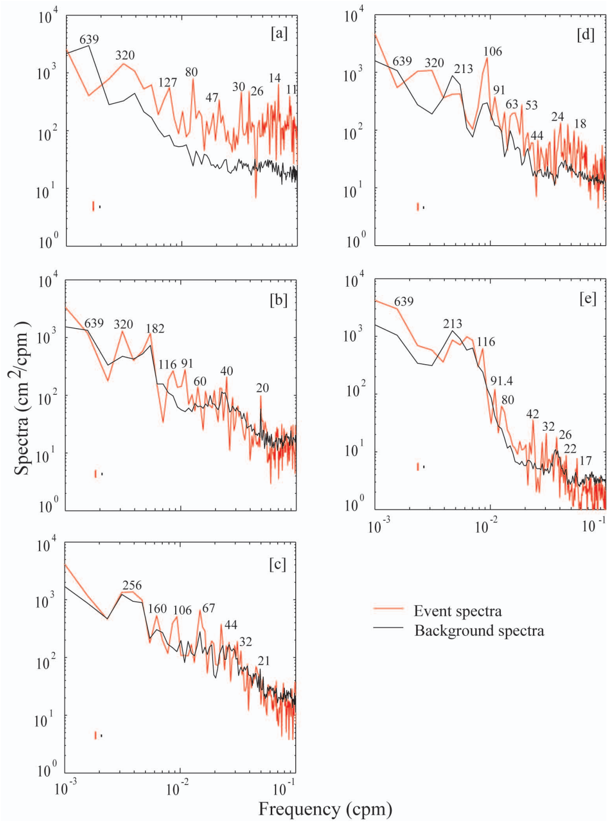

Fig. 7. Spectrum of sea level residual (SLR) during E1 at **(a)** Ratnagiri, **(b)** Verem, **(c)** Karwar, **(d)** Tuticorin and **(e)** Mandapam. The data duration for estimating the spectrum of the SLR during E1(background) is from 26 November–1 December (1 September–20 November) 2011. Vertical red(black) line shows the 95 % confidence interval of the event(background) spectrum for the respective stations.

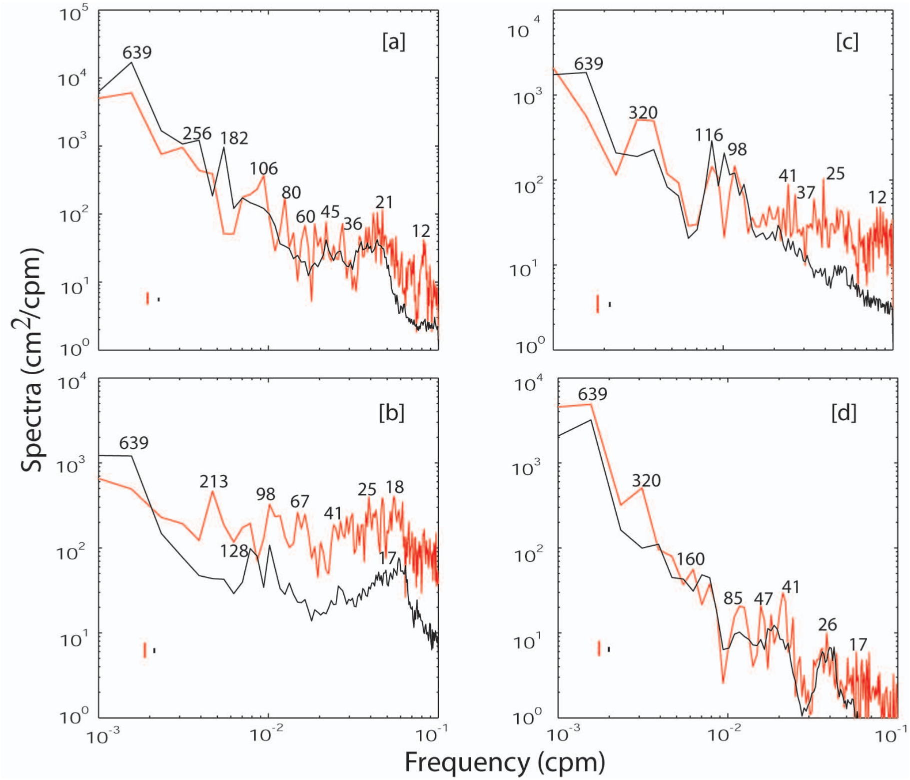

Fig. 8. Spectrum of sea level residual (SLR) during E2 at **(a)** Gopalpur, **(b)** Gangavaram, **(c)** Kakinada and **(d)** Port Blair. The data duration for estimating the spectrum of the SLR during E2(background) is 25–31 December (1 September–10 December) 2011. Vertical red(black) line shows the 95 % confidence interval of the event(background) spectrum for the respective stations.

OSD

11, 575–611, 2014

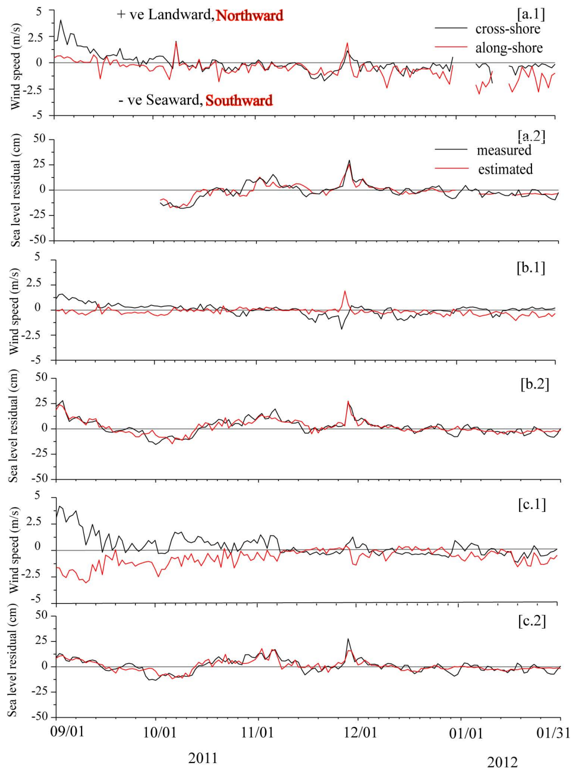

Fig. 9. Daily-mean wind and sea-level residual from September 2011 to January 2012 at **(a)** Ratnagiri, **(a.1)** daily averaged cross-shore (black) and along-shore (red) winds, **(a.2)** daily-mean measured sea level residual (black) and estimated residual (red); **(b)** Verem, **(b.1)** and **(b.2)** same as in **(a)**; **(c)** Karwar, **(c.1)** and **(c.2)** same as in **(a)**; the daily-mean estimated SLR is obtained using the multi-linear regression with daily-mean cross-shore (*U*), along-shore (*V*) components of winds and atmospheric pressure (A_P) as independent variables.

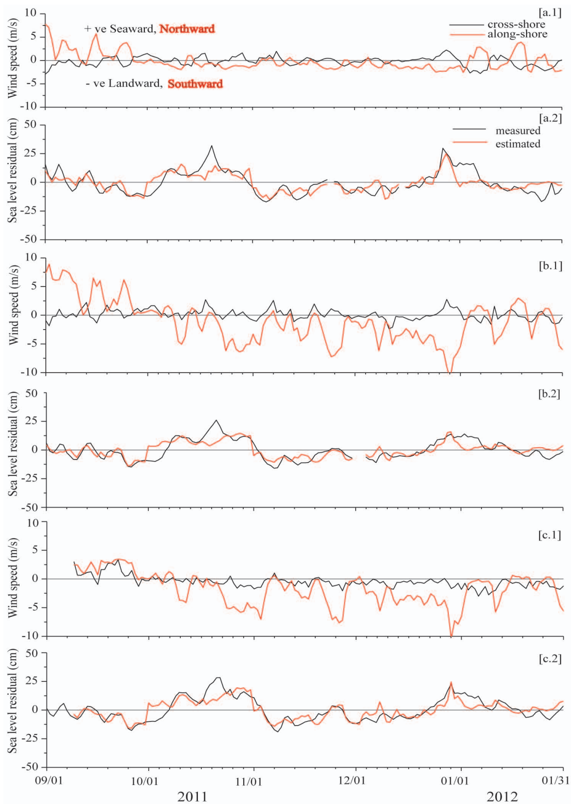

Fig. 10. Daily-mean wind and sea-level residual from September 2011 to January, 2012 at **(a)** Gopalpur, **a.1** daily-mean cross-shore (black) and along-shore (red) winds, **(a.2)** daily-mean measured sea level residual (black) and estimated residual (red); **(b)** Gangavaram, **(b.1)** and **(b.2)** same as in **(a)**; **(c)** Kakinada, **(c.1)** and **(c.2)** same as in **(a)**; the daily-mean estimated SLR is obtained using multi-linear regression with daily-mean cross-shore (U), along-shore (V) components of winds and atmospheric pressure (A_P) as independent variables.

OSD
11, 575–611, 2014

Coastal sea level response to the tropical cyclonic forcing

P. Mehra et al.

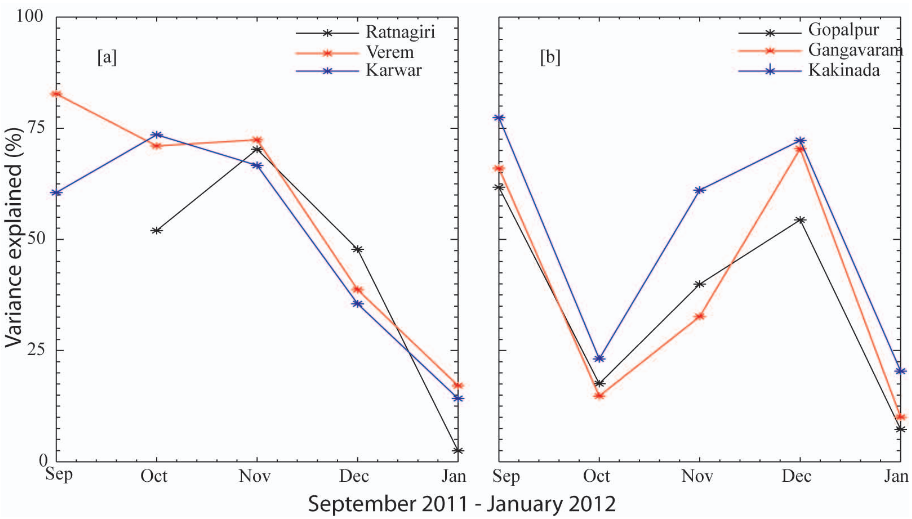

Fig. 11. Daily-mean sea-level variability explained (Var_e %) by the multi-linear regression during different months from September 2011 to January 2012. **(a)** Var_e (%) at Ratnagiri (black), Verem (red) and Karwar (blue). **(b)** Var_e (%) at Gopalpur (black), Gangavaram (red) and Kakinada (blue).

OSD
11, 575–611, 2014