Surface circulation off the Andaman Islands from HF radar observations

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Surface circulations off the Andaman Islands are least studied, much of the fundamental understanding of the circulations are from model studies. A pair of High-Frequency Radar (HFR) systems, as a part of the Indian Coastal Ocean Radar Network operated by the National Institute of Ocean Technology, MoES measures surface currents as far as 200 km from the coast since 2010. The present study focuses on the coastal circulation and its variability along the east coast of the Andaman Islands. The general circulation pattern in this region shows a poleward flow during December and January with November and February as transition months, and in the remaining months the flow is more or less equatorward. The current present in the HFR coverage is strongly influenced by the tides. Semidiurnal tidal constituents dominate surface current with a maximum variability of 24%. The amplitude of M2 component varied between ~5 and 10.5 cm s^{-1}. The major tidal constituents matched well with tide gauge measurements in the study region. These findings point towards the strong influence of remote forcing on the currents along the east coast of the Andaman Islands.

Keywords: HF radar, surface currents, tidal ellipse, waves.

Introduction

THE Andaman Sea in the northeastern Indian ocean is one of the least studied oceanic basins due to its remote location and proximity to the exclusive economic zones of four different countries[1]. The Andaman Sea is bounded by Myanmar on the north, Indonesia on the south, coasts of Myanmar and Thailand on the east, and the Andaman and Nicobar Islands on the west[1]. The circulations in the Andaman Sea are mainly controlled by seasonally reversing monsoon winds, which blow northeasterly in winter and southwesterly during summer and also by the remote forcing from the equator[1,2]. The currents in the Andaman Sea are not well studied previously, and much of the fundamental understanding of the circulations in the Andaman Sea is from model studies. Model studies of the circulations[3–5] in the Bay of Bengal (BoB) show the influence of equatorial forcing on the currents in the Andaman Sea and other parts of the BoB. The presence of these Islands influences the local circulation and the circulation in the entire BoB[1].

Here we report the surface current observations from the two HF radar (HFR) systems installed along the Andaman Islands by the National Institute of Ocean Technology (NIOT), MoES Chennai. These systems belong to Indian Coastal Ocean Radar Network (ICORN) and are part of more massive Ocean Observation Network programme of the Ministry of Earth Sciences (MoES), Government of India[6]. HFR measures surface currents in broad swaths of coastal waters up to 200 km offshore in near real time in all weather conditions. HFR systems work on the principle of Bragg scattering[7–9]. A transmitter antenna continuously sends electromagnetic waves in the 3–30 MHz frequency band and is scattered back to the transmitter if it strikes ocean wave of half the broadcast signal's wavelength. Movement of the waves in the ocean causes a shift in the frequency of received echo, this Doppler shift is derived from the dispersion relation of surface gravity waves. However, there will be an additional shift in the received frequency due to the presence of currents in the ocean, and this provides the magnitude of the current towards or away from the transmitter, called as radial current[10]. A single HFR system provides only radial currents (towards or away from the HFR) but combining two or more HFR system will provide a full vector field with a prescribed geometric dilution of precision (GDOP). The radial data from these two stations are combined by a least square technique[11] to produce vector current map. The error in current measurement increases as the two radars look angles become less orthogonal. Reliable current data are obtained when the angle between two radial sites is within the range 30°–150° and the distance between two sites should be between 40% and 50% of the range of the system[12], and the range of the system depends on the transmitting frequency. ICORN uses Seasonde HFR systems (SeaSonde) made by Coastal Ocean Dynamics Applications Radar (CODAR) ocean sensors. The SeaSonde uses compact transmitting and receiving antennas and uses MUltiple SIgnal Classification (MUSIC) algorithm for direction finding. The data from ICORN has been used to study the coastal circulation at different places along the Indian coasts. The small-scale variabilities associated with East India Coastal Current (EICC) were studied with HFR data[13–15]. HFR systems

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were able to capture the high wave activities and variation in surface circulation within its coverage area during major tropical cyclones. HFR systems at the Andaman Islands were able to provide valuable information on surface currents and waves during *Phailin* cyclone[16].

The present study describes the fundamental characteristics of surface currents off Andaman Islands in the western part of the Andaman Sea. We are studying the seasonal circulation and quantifying the tidally driven currents in the HFR coverage area.

Data and methodology

Data from two radar stations located along the east coast of Andaman Islands, one at Portblair (11.57°N, 92.74°E) and other at Hutbay (10.59°N, 92.56°E) separated by around 100 km are considered. Hereafter the stations are denoted by PTBL and HTBY respectively. These systems operate at 4.4 MHz with a bandwidth of 25 kHz and sweep rate of 1 Hz categorized as long range HFR, which can cover up to 200 km offshore (between 10°–12°N and 92.5°–94.5°E) as shown in Figure 1. The data has a spatial resolution of 6 km and a temporal resolution of one hour. For the present study data from the Andaman Islands for 2016–2017 has been considered. The data has both spatial and temporal gap, central portion of the HFR domain has higher percentage of data availability (Figure 1). The hourly data is quality controlled by removing the spike which may arise occasionally because of radio interference and environmental noises. Tide data obtained from the Hutbay boat jetty during 2016 is used in our analysis to validate the major tidal component in the currents.

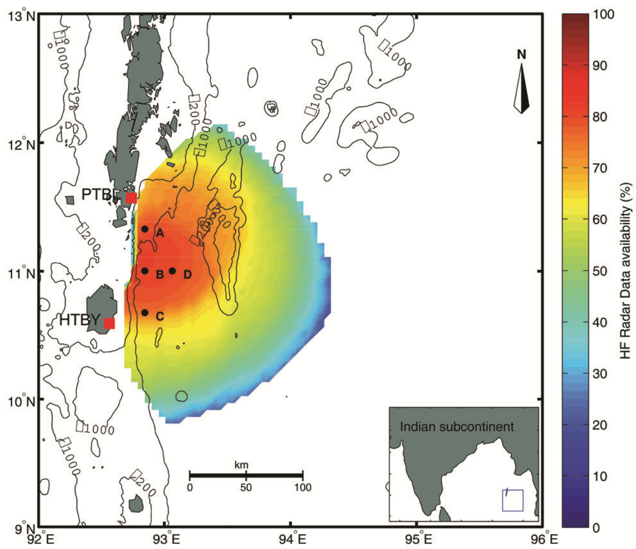

Figure 1. Temporal coverage of HF radar surface current data during 2016–17. Red square represents HFR sites at Portblair (PTBL) and Hutbay (HTBY). Contour lines represent the isobaths of –200 m, –1000 m. Black dots (A, B, C, D) represent the grid points selected for the time series analysis in the manuscript. Inset represents a broader view of the HFR location in the Northern Indian Ocean.

Also, in order to understand the influence of local winds on surface currents the daily ~25 km ASCAT winds are used in our analysis (source: http://apdrc.soest.hawaii.edu/datadoc/ascat.php).

Surface currents at four locations (A, B, C, D) off the Andaman Islands are analysed to understand the seasonal surface circulation patterns and to identify the high-frequency tidal currents (Figure 1). These points are selected to study the total variance over a range of frequencies between near shore and offshore regions. Points A, B, C were chosen to explore the latitudinal variation and study the influence of the gap between the Andaman and the Little Andaman Islands on coastal currents. Point D is selected for analysing the varying currents in the East–West direction and also to study the influence of topography on the currents. The chosen points also have maximum data coverage which is an essential requirement for spectral analysis. Gaps in the data are linearly interpolated if the gaps are less than 6 hours. The rotary power spectrum analysis on u and v current components, by a complex Fast Fourier Transform (FFT), enables a separation of the energy into clockwise or negative sense and counterclockwise or positive sense of the current vector rotation[17]. Multi-taper method is employed to avoid the high variance of the spectral estimate using Jlab Matlab toolbox[18]. The tidal harmonics are calculated to quantify the tidal constituents for both velocity components (zonal and meridional), and characteristics of the tidal ellipses are explored for different seasons. The tidal constituents are then compared with tide gauge measurements.

Results and discussion

General description of the surface current

Vector time-series plots of the hourly surface current data from HFR are shown in Figure 2, which illustrates the characteristics of the surface currents during 2016–17 at points A, B, C, D. The main focus of the study is to identify the general circulation trends in western Andaman Sea. The time-series plots (Figure 2) show the variation of the surface circulation during different seasons. Points A, B, C and D recorded maximum equatorward velocities of ~0.7 ms^{-1} during May in 2016, and for 2017 maximum values similar magnitudes are observed in January but to the poleward direction. Figure 2 shows that there is not much variation in the circulation pattern for the selected points; however, a seasonal pattern of change in the direction of the current is observed. During December and January, the flow is poleward, February (November) are transitional months with flow changes to equatorward (poleward) respectively, and in the remaining months the flow is equatorward. Maps of the monthly mean current fields show spatial variation of currents for 2016

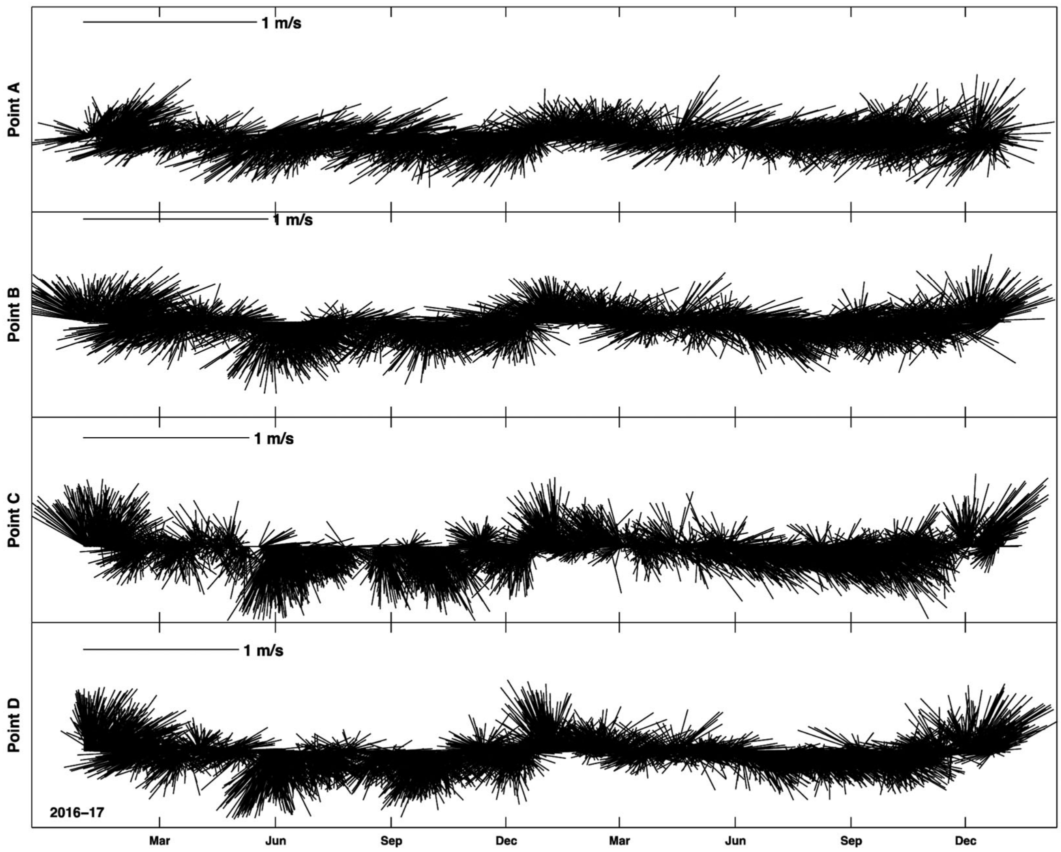

Figure 2. Vector stick plot of the hourly currents drawn at points A, B, C, D shown in Figure 1 during 2016–17.

(Figure 3). Only those grid points having more than 50% of the data are used for the monthly means. These maps show a coherent poleward flow in January and December, and the remaining months have an equatorward flow with November as a transition month. Average speed of current in January is 17 cm s^{-1}, and this get reduced to 10 cm s^{-1} by April, but in May the value increased and reached a maximum mean current of 30 cm s^{-1} for 2016. Mean current in September and October also exceeded 20 cm s^{-1}. In contrast to the strong southward mean flow in May, monthly means in June showed a cyclonic eddy feature with a mean value of 15 cm s^{-1}. To understand influence of local winds on the circulation pattern, satellite derived wind vectors from ASCAT are used (Figure 4). Monthly mean current does not show any correlation with local winds and it is almost contrast to the direction of wind pattern. This shows that the circulation in the western Andaman sea is strongly influenced by the remote forces.

Rotary spectra

Hourly data sets for three different seasons (October–January, February–April, May–September) are considered. Data gaps are filled using the average of linear–spatial and linear–temporal interpolation on grid cells with 60% or greater coverage. A rotary power spectral analysis was carried out at points A, B, C and D. The rotary spectra at all points showed peak variance at semidiurnal and diurnal frequency indicating the importance of tidal band variability on surface current along the coasts of the Andaman Islands (Figure 5). A strong semidiurnal (M2) peak for both the positive and negative sense of rotation is prevalent in all points for all the three seasons. The K1 and M4 component also shows strong presence in the current. The strong tidal signals in the rotary spectral analyses may be related to the steep gradient in the bathymetry which is a common phenomenon in coastal zones in Islands.

Tidal analysis

Tidal analysis has been carried out on the complex-valued HFR surface current during 2016–17 using an uninterpolated data set with the T_Tide Matlab toolbox toolbox[19]. This helps to understand the influence of tides on the coastal currents along the Andaman Islands. The total tidal variance during 2016–17 at four locations A, B, C and D were 6.7%, 17.8%, 17.4% and 23.5% respectively. The variance was larger in the V direction (north–south) at points A (17.4%) and C (28.1%) compared 1.7% and 2.8% in the U direction (east–west). However, for points B and D the variance was larger in the east–west direction, with variance values for U (18.7% and 33.5%) and for V (16.9% and 8.2%) respectively. The M2 and S2 ellipse major axis amplitudes were the major constituents at locations A-D, however the low frequency components MM (lunar monthly) and MSF (lunar–solar fortnightly) showed strong presence in the surface current data.

Tidal harmonics at points A, B, C, D are extracted and quantified for the seasons as mentioned earlier (Figure 6). The values of semi-diurnal components (M2 and S2) at points A–D are (M2: 5.94 cm s^{-1}, 9.03 cm s^{-1}, 9.83 cm s^{-1}, 10.33 cm s^{-1}, S2: 2.89 cm s^{-1}, 5.28 cm s^{-1}, 4.35 cm s^{-1}, 4.42 cm s^{-1}). The semi-diurnal components are stronger at D compared to other points. But the lunar monthly constituent (MM) at point C has an amplitude of 6.57 cm s^{-1}, which is greater than the S2 component. Tidal analysis on the tide gauge data from the Hut Bay jetty during June–September 2016 also shows the strong semi-diurnal peaks (Figure 6), which substantiate the observations from HFR.

Figure 7 shows the spatial distribution of the M2 tidal ellipses explored for each month during 2016. Counter-clockwise (red) ellipses are predominant in nearshore region and clockwise (blue) ellipses are present in middle and outer portions of HFR coverage. For May, August and October the tidal ellipse was not drawn because of the low percentage data availability. Majority of the M2 ellipses were perpendicular to the isobaths near the coast with the steep gradient in the bathymetry. M2 ellipses were stronger in January and September but were weaker during December. In the outer portion of the HFR coverage ellipses were mostly aligned parallel to the isobaths. The possible factors involved behind this typical pattern of the ellipses can be the barotropic/baroclinic forcing, bathymetry interaction and higher stratification during northeast monsoon.

Conclusions

The high resolution HFR ocean surface currents allow us to understand the coastal circulation and its variability

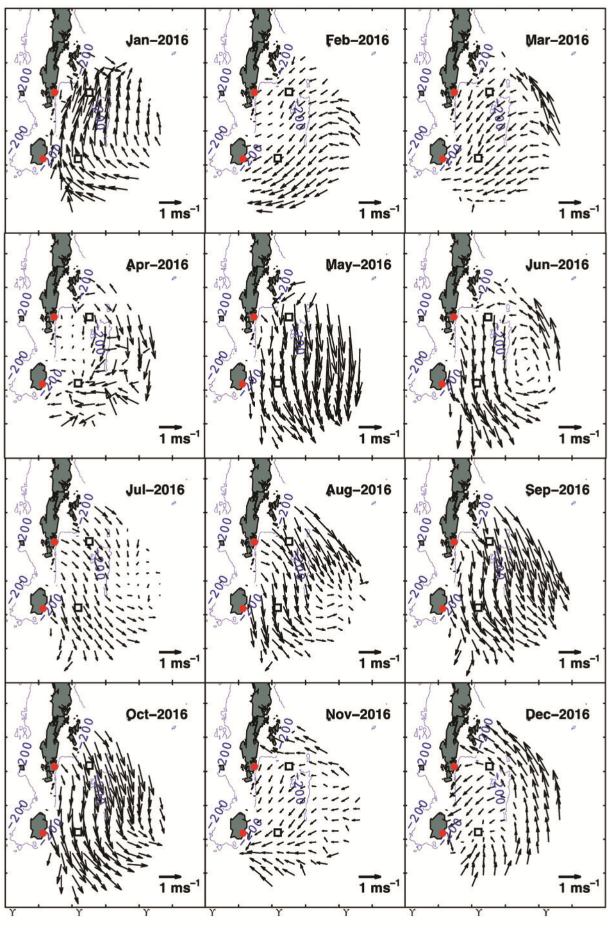

Figure 3. Monthly averaged currents during the year 2016. B&W square represents the HFR locations and scale of the vectors is provided in the bottom right corner. Every second vector is drawn for better clarity. Percentage of hourly data greater than 50% is considered for the averaging.

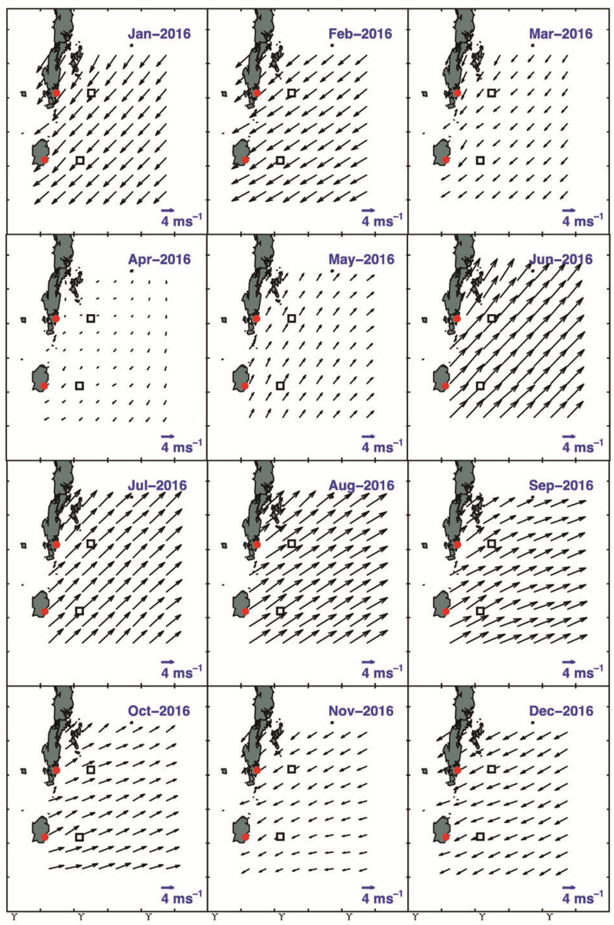

Figure 4. Monthly averaged ASCAT winds during the year 2016. B&W square represents the HFR locations and scale of the vectors is provided in the bottom right corner.

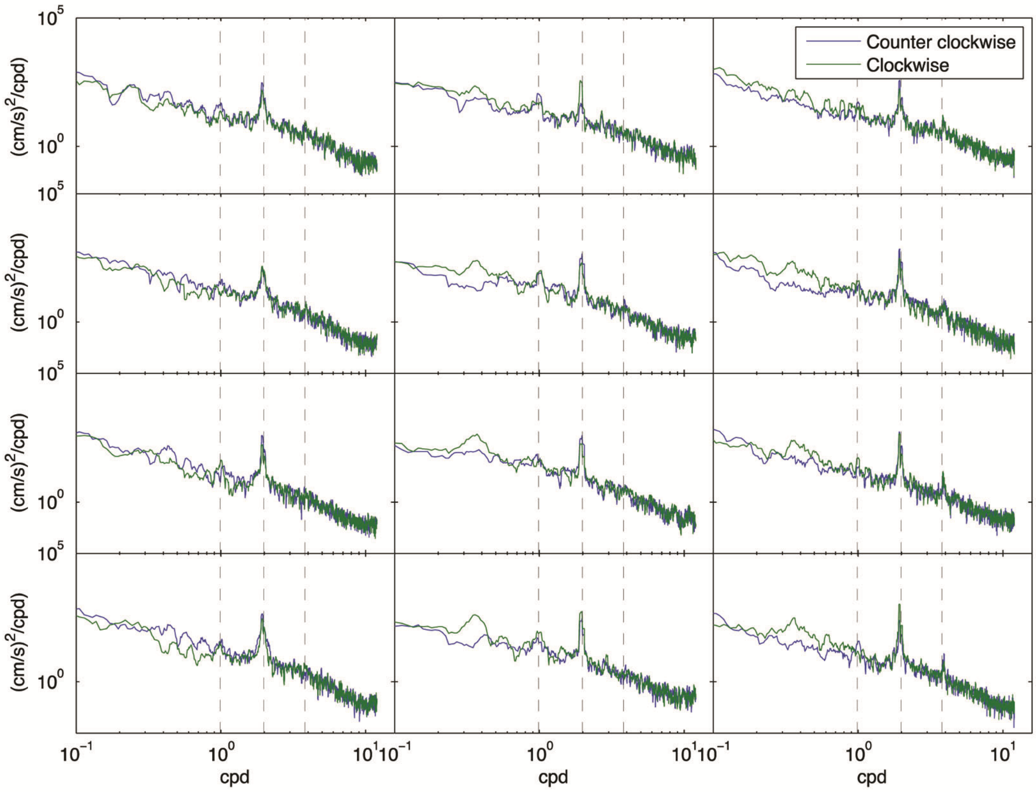

Figure 5. Rotary spectra analysis (cycles per day) for October–January, February–March and May–September at points A, B, C and D. The black dotted line represents the major tidal constituents.

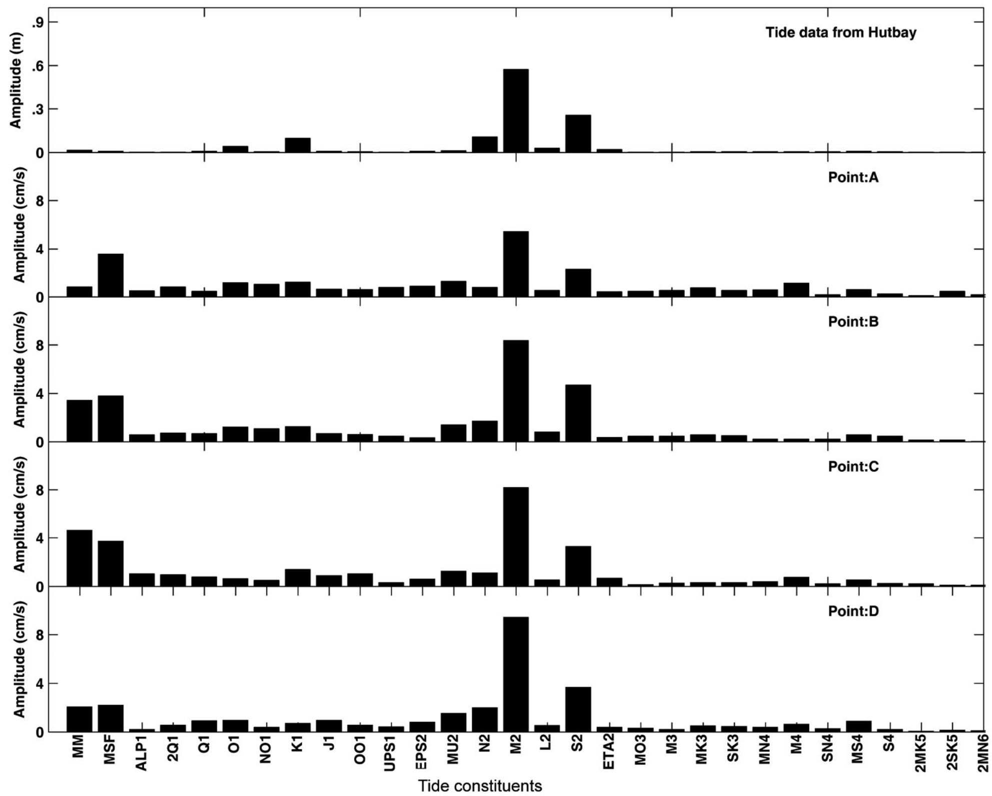

Figure 6. Major tide constituents from tide gauge at Hutbay boat jetty and the points A, B, C and D.

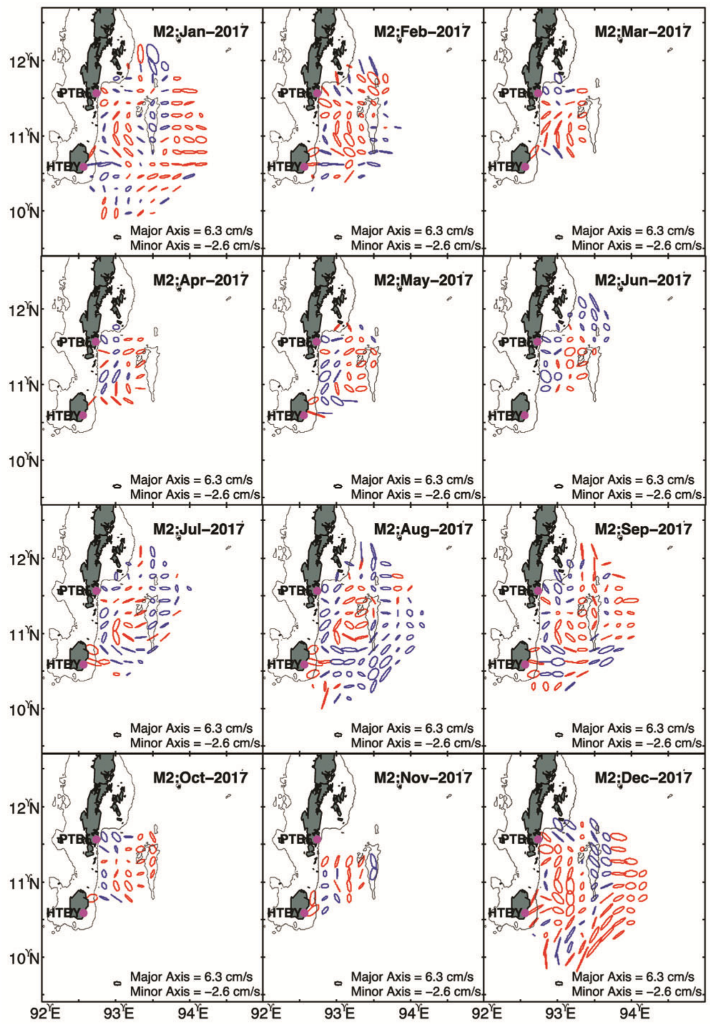

Figure 7. M2 Tidal ellipses for each month having more than 60% of data. The red (blue) ellipses represent anticlockwise (clockwise) rotation. The magenta dots represent the HFR stations.

along the coast of the Andaman Islands. Temporal variation of the hourly vector stick plots at selected points for two years shows that currents follow a seasonal pattern. During December and January, the flow is poleward and the flow is equatorward in all other months with February and November as transition period. The spatial variation of current in the HFR domain also shows similar pattern (Figure 3). Maps of the monthly mean current field showed a coherent poleward flow in January and December, and a southward flow in the remaining months with November and February as transition period. This is nearly opposite to the current pattern observed in EICC[13–15]. Presence of eddy structures was also evident in the monthly maps of June and monthly mean current does not show correlation with monthly averaged winds from ASCAT (Figures 3 and 4). The tidal analysis performed on the selected points shows a strong tidal variability of 24% at an offshore point compared to nearshore points. M2 constituent dominated surface current with a maximum value of (10.33 cm s^{-1}) followed by another semi-diurnal component S2, however the low frequency MM, MSF constituents showed their strong influence on the surface current data, with MM values exceeding the S2 amplitudes at point C. The analysis showed that surface currents off the Andaman Islands are strongly depend on the tide but are least correlated with local winds, so further studies are required to identify the remote forces that influence the currents.

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