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A case study of coastal currents in relation with tides and winds in a tropical coastal waters of Vengurla, West Coast of India

K Rasheed, G Udhaba Dora, V Noujas*, R S Kankara, M Manikandan, S Sathish & S Arockiaraj
National Centre for Coastal Research (NCCR), NIOT Campus, Pallikarani, Chennai – 600 100, India
*[E-mail: ssm@nccr.gov.in]

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Coastal currents consist of wind-driven, tidal, surface wave and geostrophic flows. These currents have a major role for nearshore sediment transport, but the measured data availability on coastal currents for the Indian coast is relatively less. This study analyze the variability of coastal currents along with the tides at nearshore and offshore waters during two different seasons (fag end of summer monsoon and initial stage of pre-monsoon) at Vengurla, west coast of India. Results of this study exhibited that the tides at Vengurla are mixed semi-diurnal dominated by solar constituent during summer monsoon (September to October); whereas the lunar constituents dominates during pre-monsoon (February to March). The nearshore current was dominated by the westward flow (sluggish current) during monsoon and south eastward flow during pre-monsoon, whereas the offshore flow (strong current) showed seasonality. At offshore, southerly current dominated during summer monsoon, whereas the northerly current played a major role during pre-monsoon. The current profile analysis at offshore revealed that the gradation of strong current at the surface to the sluggish nature of currents at the bottom and were comparatively higher during summer monsoon than pre-monsoon periods. This study revealed a complex pattern among winds, tides and currents at offshore.

[**Keywords**: Coastal currents, Current profile, Tide, Wind, Summer monsoon]

Introduction

Information on tide and current data is important to aid in marine navigation operations, and also these measurements play an important role in terms of people's and the environmental safety. Measurement and prediction of tides and currents are also important for marine traffic operations like movement of marine ships safely into and out of ports, determining the extent of an oil spill, building bridges and piers, determining the best fishing spots, emergency preparedness, tsunami tracking and warning, marsh restoration and much more. In coastal areas, the transport of water and sediment particles become very complex due to offshore and onshore currents prevailing in the area. The coastal currents in most of the areas are controlled by wind, bathymetry, tides and remote forcing waves[1-10]. The existence of strong winds and waves during monsoon period plays a major role in controlling the coastal circulation pattern along the west coast of India. *In-situ* observation of time series coastal currents is very rare along the Indian coastal waters. The available measured data were either for a very short term span (few days)[11-17] or seasonal, occasionally ranging upto few months[8,18-20]. Therefore, a pioneering attempt was made to measure currents for long duration along Chavara and Manavalakuruchi coasts, in Kerala and Tamil Nadu during 1995 and 1996, respectively[21]. The first major attempt to study systematically the currents of the southwest (SW) coast was made by National Centre for Earth Science Studies (NCESS) by establishing two offshore stations, one at a depth of 5 m and the other at a depth of 8 m off Alappad, Kollam during 1999-2001[(ref. 22)]. Currents show seasonal changes with stronger currents during monsoon and weaker currents during non monsoon season. The alongshore components of the currents are mostly much stronger than the cross-shore flows.

The southwest or summer monsoon (June to September); post-monsoon (October to January); and premonsoon (February to May) are the major seasonal classifications along the west coast of India[23]. The seasonal characteristics of the coastal currents along the west coast of India was reported in the past by some researchers[22,24-26]. A weak circulation was observed along the west coast of India during the southwest monsoon[24] and the coastal currents are reported to be influenced by barotropic pressure gradient[27]. It was also reported that the monsoon currents are forced by Ekman pumping and by the winds in the Bay of Bengal[28]. However, the major forcing mechanisms are the winds along the east and west coasts of India and the maximum currents vary from about 1.4 m/s in the open ocean to about 3.2 m/s in the Gulf of Khambhat[29]. The meridional current has prominent southward direction; however the zonal current is too weak to have a considerable impact on the circulation pattern[9]. Thereby, the mesoscale process-induced variation of the coastal current is seen in some parts of the west coast of India[30]. The investigation carried out in this paper mainly focus to analyse the seasonal coastal current pattern from nearshore to offshore at Vengurla, west coast of India. In addition, study explains the vertical current profiles at offshore to distinguish the impact of associated tides as well as non-tidal (residual) components.

Materials and Methods

Study area

Vengurla is located in the coastal region of Sindhudurg district of Maharashtra, west coast of India (Fig. 1). The Vengurla Bay is bounded between two headlands and extends up to 4-5 km along the shore oriented in north-south direction and is exposed to the action of waves approaching from the Arabian Sea. The beach facings have a gentle slope with 10-30 m wide and the beach material is strongly composed of medium sand, with well sorted, fine skewed to coarse skewed with platy kurtic, mesokurtic and leptokurtic sediments[31]. The developments of beach cusp were observed at this beach during the measurement period. A well-developed sand dune has existed beyond the berm line towards onshore and well shattered with vegetation. The meteorological features of Vengurla lie in the tropical monsoon climate. Tides in this region are predominantly mixed semi-diurnal with a range of 2.3 m during spring tide and 1.3 m during neap tide[32]. The wave height varies between 0.49 to 4.5 m and mean wave period varies between 3.6 and 9.5 s during June to September and during October to May those were 0.22 – 1.33 m, 1.0 – 7.5 s, respectively. The predominant wave directions in the study area are south-west (SW), west-south-west (WSW), west (W) and west-north-west (WNW). The southwesterly wave moves the sediments towards north, whereas the WNW waves transport the sediments towards south[33].

Data collection & methodology

To understand the seasonal current pattern off Vengurla coast, a survey was carried out at nearshore (5 to 7 m), which is nearly 0.7-1.2 km away from shoreline and offshore (15 m) zones, which is around

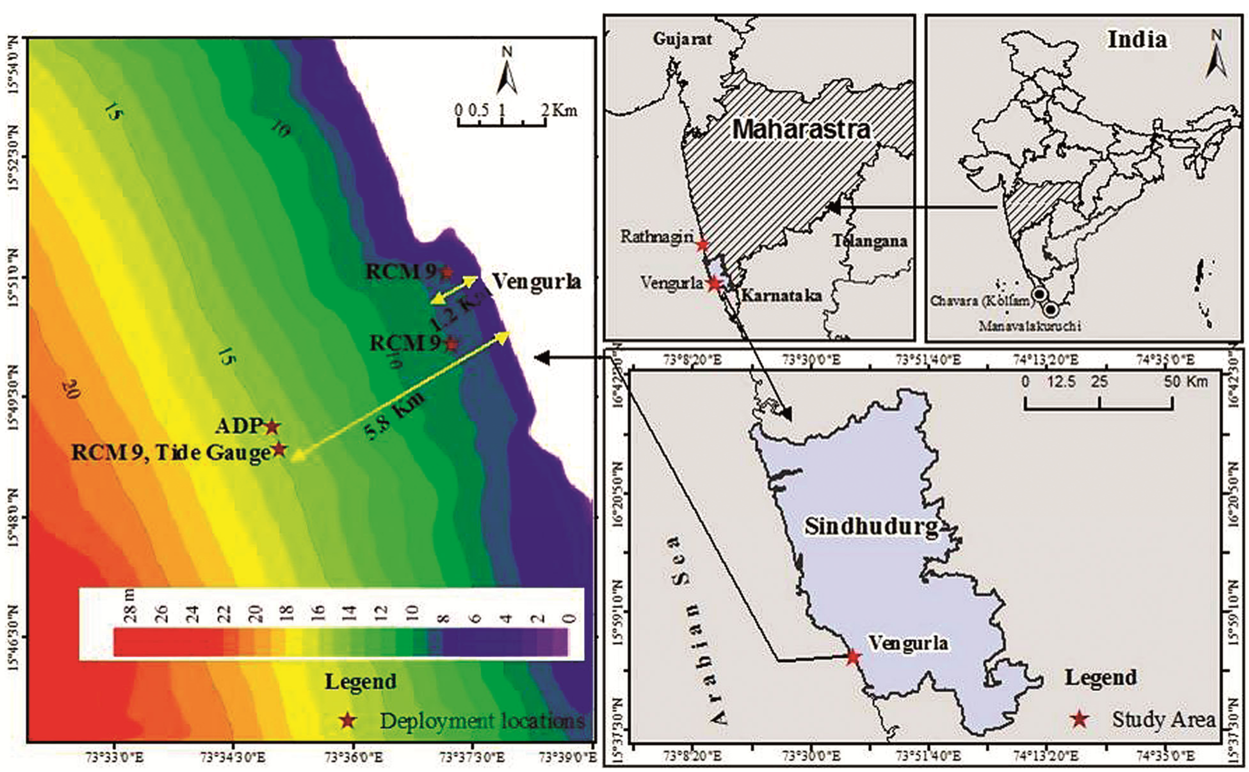

Fig. 1 — Study area and locations of deployed instruments

Table 1 — Mooring locations and deployment periods of oceanic instruments for the measurement of current and tide

Equipment	Water depth (Equipment Position from surface) (m)	Latitude (N)	Longitude (E)	Period (dd-mm-yyyy)		Burst interval	Frequency
				From	To	(min)	(Hz)
			Monsoon				
RCM 9	5 (3)	15°51'3.31"	73°36'57.90"	21-09-2014	07-10-2014	10	2
RCM 9	15 (7)	15°48'57.44"	73°35'39.41"	21-09-2014	07-10-2014	10	2
Tide Gauge	15 (15)	15°48'57.44"	73°35'39.41"	21-09-2014	07-10-2014	10	2
ADP	15 (15)	15°48’58.71"	73°35’38.02"	21-09-2014	30-09-2014	10	2
			Pre-monsoon				
RCM9	7 (3)	15°50’11.19"	73°37"14.28"	13-02-2015	07-03-2015	10	2
RCM9	15 (7)	15°48'57.44"	73°35'39.41"	13-02-2015	07-03-2015	10	2
Tide Gauge	15 (15)	15°48'57.44"	73°35'39.41"	13-02-2015	07-03-2015	10	2
ADP	15 (15)	15°48’58.71"	73°35’38.02"	13-02-2015	07-03-2015	10	2

5.8 km away from the shoreline. The survey was carried out during the fag end of monsoon (21.09.2014 to 07.10.2014) and initial stage of pre-monsoon (13.02.2015 to 07.03.2015) periods by deploying the recording current meter (RCM 9) made by Aanderaa, and tide gauge made by Valeport (Fig. 1). The nearshore and offshore locations are distinguished by considering the coastal morphology. The nearshore current pattern is associated to Vengurla Bay bounded by the headlands while there is no geographical obstruction to the current pattern at offshore locations. The Acoustic Doppler Profiler (ADP) made by SONTEK was deployed at 15 m water depth for interpretation of vertical current pattern. The details of instrument deployed positions and duration of the data recorded are given in Table 1. The RCM was equipped with a speed sensor type of Doppler current sensor 3820 with speed range of 0-300 cm/s at an accuracy of ±0.15 cm/s. The inbuild magnetic compass measures the direction for all angle at an accuracy of ±5°. Tide gauge (MIDAS DWR) were deployed at 15 m water depth, fitted with high accuracy piezo-resistive pressure sensors with a range of 100 dB with an accuracy of ±0.01 %. ADP was deployed at 15 m water depth to measure the velocity of the water parcel which records based on the principle called Doppler shift. It has three transducers mounted on the transducers head of the system. ADP measures the water current velocities along each transducer beam and transforms the velocities into Cartesian (xyz) or Earth (ENU) co-ordinates. The profiling range of an ADP is determined by the user selected values for blanking distance (1.7 m), cell size (1 m) and number of cells (15). The velocity range is ±10 cm/s and accuracy is ±1 % of measured velocity ±0.5 cm/s.

An Automatic Weather Station (AWS) manufactured by Virtual Electronics Company was installed onshore (15°49’25.17’’ N; 73°38’18.63’’ E) at the coast of Vengurla to record the behaviour and pattern of local wind for finding the correlation with observed current pattern. For tidal analysis, the MIKE module that is based on the Institute of Ocean Science (IOS) method is used to derive the tidal constituents[34]. The analysis of the current record was made using sticks plots, progressive vector diagrams (PVD) and time series cross-shore and alongshore current plots. In the stick plots, It can represent both speed and direction together, so that the variation of current velocity with respect to the tide can be understood from these plots. The PVD is used to estimate water transport in the coastal region from point measurements (Eulerian) of velocity time series, although it will exhibit only approximate particle trajectory in the regions. The time series cross-shore and alongshore current plots reveals the dominant flow of current pattern at nearshore and offshore regions.

Results

Tides

The measured tide at 15 m water depth off Vengurla during the monsoon and pre-monsoon periods showed that the tidal range during the period was 1.85 and 2.37 m, respectively (Figs. 2a & 3a). The harmonic analysis was made using this tide data, based upon the assumption that the rise and fall of the tide in any locality can be expressed mathematically by the sum of a series of harmonic terms having certain relations to

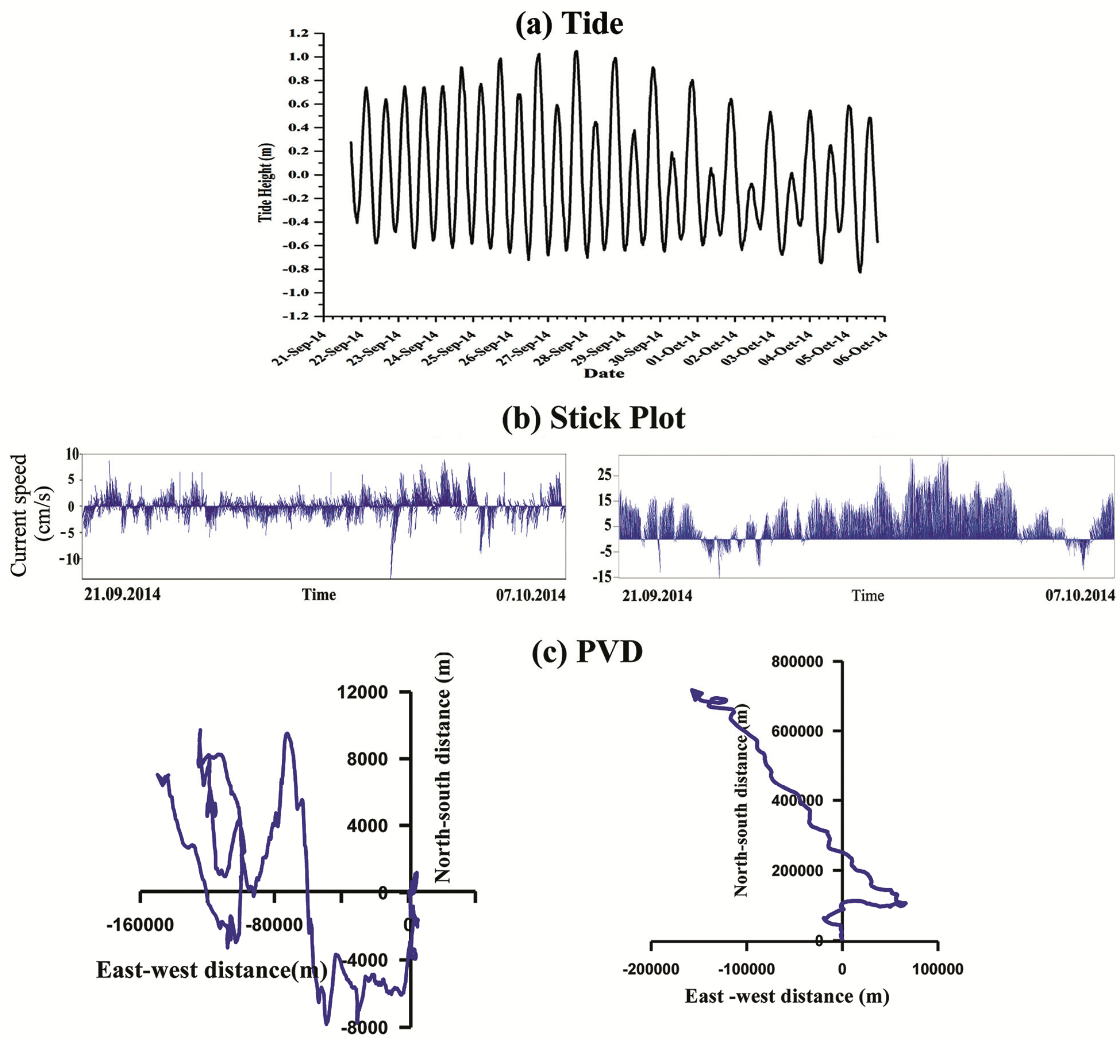

Fig. 2 — (a) Measured tide during monsoon, (b) Stick plots and (c) PVD at 5 m (Left) and 15 m (Right) water depth off Vengurla

astronomical conditions. The results showed a considerable variation in the major constituents (O1 & K1) between different seasons (Table 2), whereas the change was negligible in minor constituents (N2 & M4). The study exhibited that the tides at Vengurla was mixed semi-diurnal, dominated by solar constituents during monsoon, whereas the semi-diurnal lunar constituents dominated during pre-monsoon. The amplitude of the major constituent O1 was 3.8 times during monsoon as compared to pre-monsoon while K1 was 2.5 times. However, the amplitude of M2 and S2 were exhibited 0.8 times during monsoon as compared to pre-monsoon. Also, the amplitude of minor constituent N2 was 0.6 times during monsoon to that observed during pre-monsoon while M4 was 0.5 times. Simultaneously, the phase of O1 and K1 were 0.7, 0.2 times during monsoon as compared to pre-monsoon, while the phase of S2 and N2 were exhibited very close during these two seasons. However, the M2 and M4 were 6.0 and 2.9 times during monsoon as compared to pre-monsoon (Table 2).

Table 2 — Major tidal constituents at Vengurla coastal waters during monsoon and pre-monsoon

Tidal Const.	Amp. (m)	Phase (°)	Amp. (m)	Phase (°)
	Monsoon		Pre-monsoon	
O1	0.64	36.74	0.17	51.62
K1	0.76	16.28	0.31	73.27
M2	0.57	307.37	0.68	51.62
S2	0.25	334.98	0.32	356.53
N2	0.11	271.93	0.19	291.67
M4	0.01	17.66	0.02	06.12

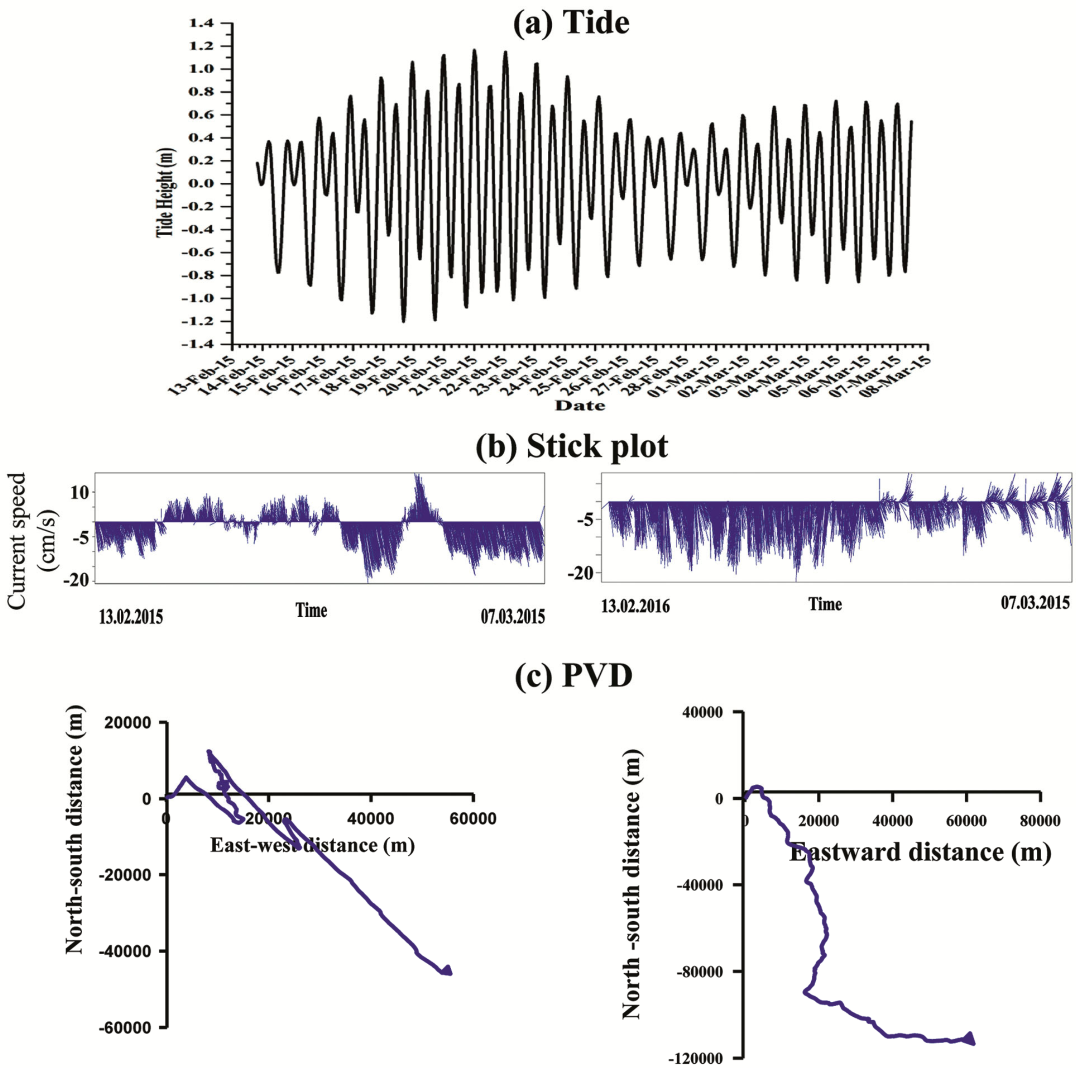

Fig. 3 — (a) Measured tide during pre-monsoon, (b) Stick plots and (c) PVD at Vengurla at 7 m (Left) and 15 m (Right) water depth off Vengurla

Coastal currents

Nearshore currents at 5 m depth

The stick plot showed that the currents in the nearshore waters off Vengurla were partially controlled by the tides (Figs. 2a, b & 3a, b). Mean current values during the monsoon and pre-monsoon periods were 3.89 and 7.81 cm/s, respectively (Table 3). The PVD showed that the movement of water parcels was initially towards south and then current pattern directed to westward during the monsoon (Fig. 2c (Left)), while the movement was towards southeast during pre-monsoon period (Fig. 3c (Left)). Both the cross-shore (u-component) and alongshore (v-component) current did not show any prominent flow pattern during monsoon at nearshore, generally both of them show a lower value, but higher value (> 15.0 cm/s) alongshore current was observed during pre-monsoon (Fig. 4).

Table 3 — Statistics of current speed measured by ADP at 15 m water depth off Vengurla coast

water depth (m)	Monsoon			Pre-monsoon		
	Min. (cm/s)	Max. (cm/s)	Mean (cm/s)	Min. (cm/s)	Max. (cm/s)	Mean (cm/s)
2	0.80	92.20	34.28	0.05	22.15	9.02
4	0.50	53.20	12.76	0.19	22.60	9.01
6	0.00	41.90	9.99	0.32	21.21	8.45
8	0.40	37.10	10.1	0.42	20.05	8.07
10	0.40	37.20	10.88	0.16	20.27	8.19
12	0.20	31.40	11.54	0.17	21.01	7.92
14	0.20	28.70	10.36	0.21	19.90	7.42

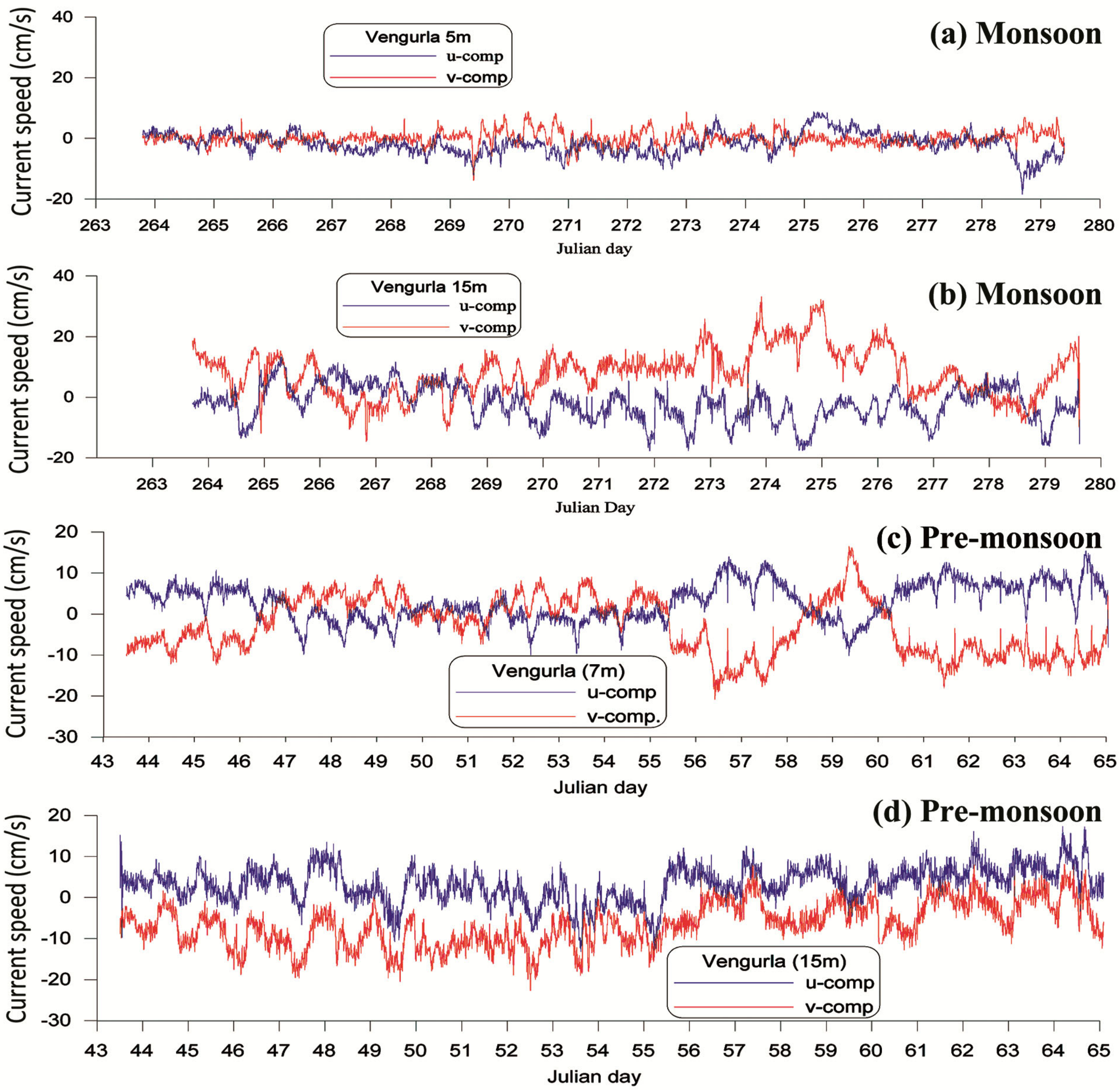

Fig. 4 — Time series cross-shore and alongshore component of currents at Vengurla at 5 m and 15 m water depth during monsoon (a & b) and pre-monsoon (c & d)

Offshore currents at 15 m depth

The stick plots of currents at offshore during monsoon showed that the currents were mainly controlled by the tidal effects during the initial period of observations (Figs. 2a, b (Right)). Thereafter, a unidirectional (northerly) current was observed in remaining period. During pre-monsoon, unidirectional (southerly) currents were noticed during the initial period of observation, thereafter tidally dominant flow was evident (Figs. 3a, b (Right)). PVD plots showed apparent movement of water parcel initially towards east and there after moving towards the north-west, which is evident from the Figure 2 (Right), but it was observed to be initially towards south and then directed to south-east during pre-monsoon (Fig. 3c (Right). The time series observation of cross-shore and alongshore component of currents, in offshore showed that alongshore component dominated during the monsoon period whereas, cross-shore component dominated during the pre-monsoon (Fig. 4). Mean current during monsoon and the pre-monsoon period was 11.66 and 9.32 cm/s, respectively (Table S1).

Coastal current profile at offshore

The current speed gradually increased from bottom to top during monsoon, which is well perceptible from the stick plots (Fig. 5). The propagation of tide and phase change is conspicuous at bottom water currents when compared to the surface water currents. At bottom, maximum current speed was about 28.7 cm/s while that was about 92.2 cm/s at surface during the monsoon (Table 3). The current profile from ADP at 15 m offshore waters during monsoon revealed that the flow was mainly controlled by the tidal effect that was not standing out fully from the time series observation of RCM 9. During the pre-monsoon period, the offshore profile showed a unidirectional southward flow pattern from surface to bottom (Fig. 6). At bottom, maximum current speed of 19.90 cm/s was noticed while at surface it was 22.15 cm/s (Table 3).

A dramatic change from surface to bottom was observed from PVD plots during monsoon (Fig. 7). Initially, a westward dominant flow was observed at 2 m water depth from surface, thereafter flow directed to northward. At 6 m depth, a southward directed flow was noticed during the initial period, thereafter a westward flow pattern was noticed, then the flow was directed to north-eastward. Finally, the entire current pattern shows in a rotatory motion (Fig. 7). At 10 m depth, initially towards east and then moving to south,

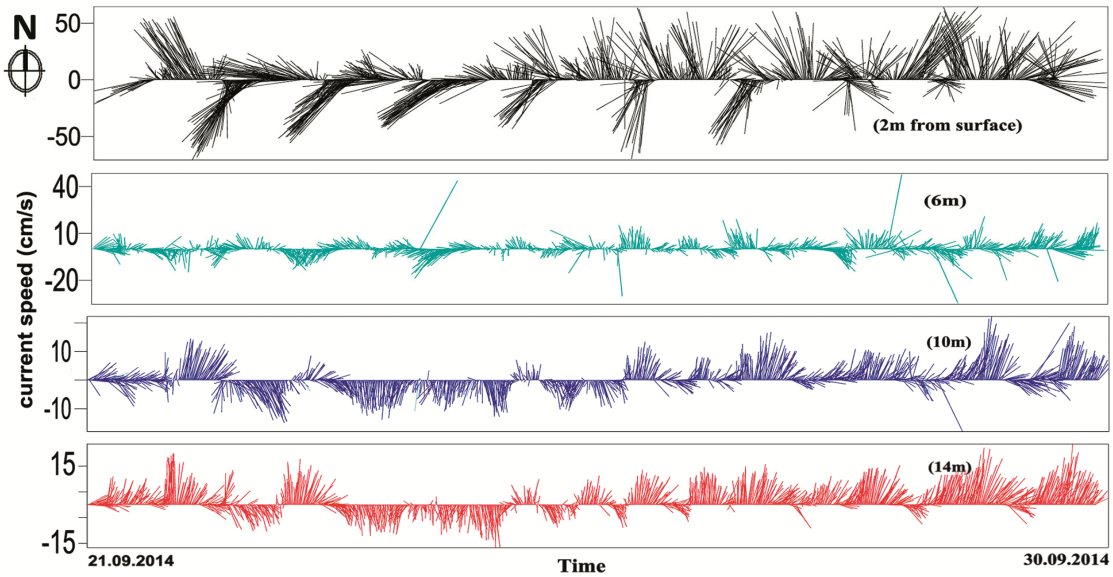

Fig. 5 — Stick plots of current profile at Vengurla at 2, 6, 10 and 14 m water depth (ADP) during monsoon

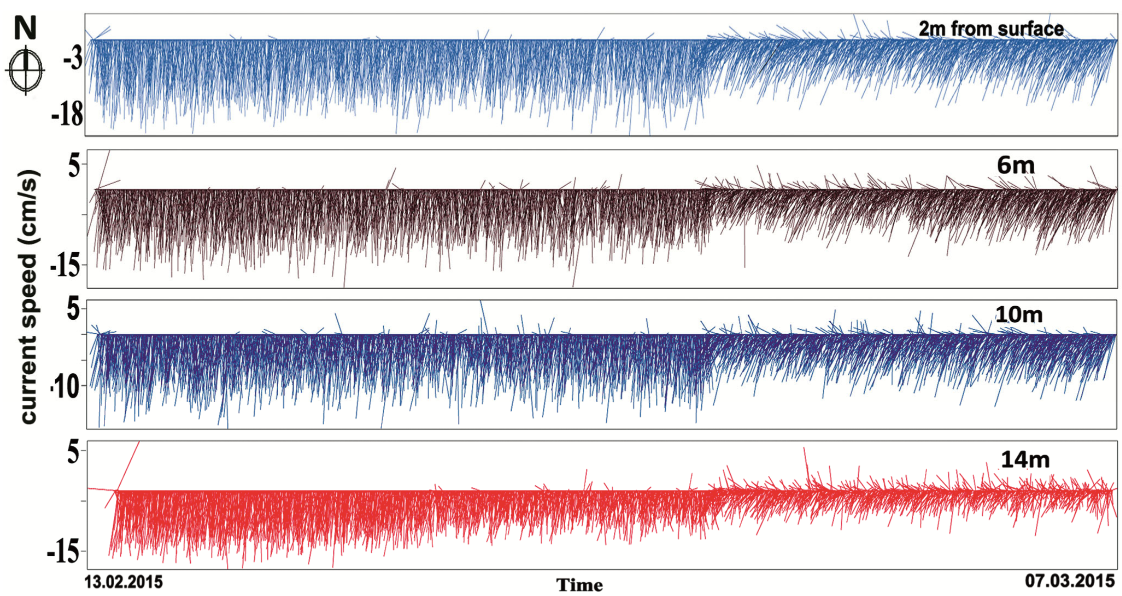

Fig. 6 — Stick plots of current profile at Vengurla at 2, 6, 10 and 14 m water depth (ADP) during pre-monsoon

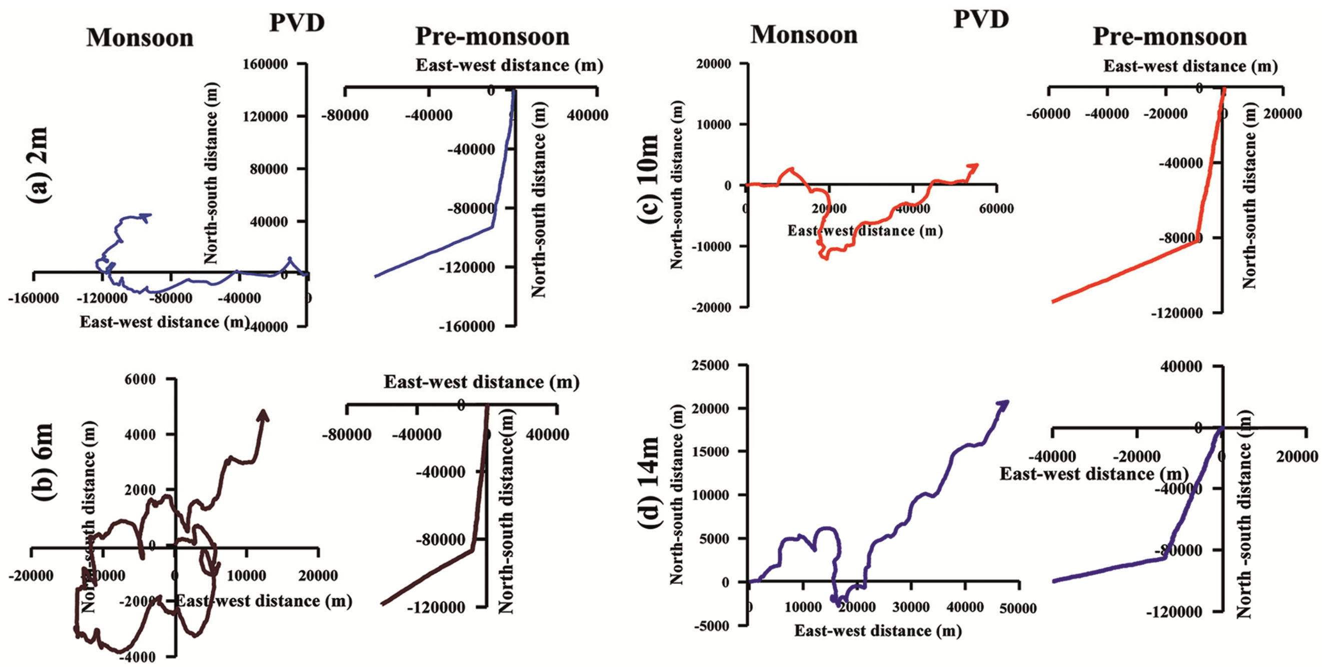

Fig. 7 — PVD measured by ADP at 2, 6, 10 and 14 m water depth off Vengurla coast during monsoon (left) and pre-monsoon (right)

thereafter north eastward flow was well evident. General current pattern at 10 m was towards East. However, at 14 m, a north eastward flow was noticed. The mean current speed during monsoon at the surface and bottom was 34.3 cm/s and 10.36 cm/s, respectively (Table 3). During pre-monsoon, PVD from surface to bottom shows a same pattern, southward to southwestward flows were dominant (Fig. 7). The mean current speed during pre-monsoon at the surface was 9 cm/s and at bottom was 7.42 cm/s (Table 3). The statistics of the current profile at various depths are also given in Table 3.

Discussion

The results of harmonic tidal analysis showed that the solar constituents (O1, K1) dominate during monsoon, whereas the lunar constituent (M2) dominate during pre-monsoon period at Vengurla coastal waters. The ratio of $K_1 + O_1$ to $M_2 + S_2$, which is the form number (F) or the amplitude ratio, is used to describe the tide in an area[35]. At Vengurla coastal waters, the form number is 1.72 during the monsoon and 0.55 during pre-monsoon, which indicates that the local sea level variation come under a mixed semi-diurnal tide. Tides along the west coast are predominantly semi-diurnal in nature, and hence the direction of current changes in every quarter of the day[22]. The tidal analysis at Vengurla coast showed that there were two highs and two lows for each tidal cycle with minute differences in their highs and lows (Figs. 2a & 3a).

During monsoon period, the nearshore current data at a depth of 5 m and pre-monsoon period data at a depth of 7 m were collected. Those nearshore locations are within headland which is existing on either side of the bay. Hence, coastal current speed is less and sluggish during monsoon and pre-monsoon at nearshore (Table S1). At offshore (15 m), being a part of the open sea, the seasonal circulations were strong, and hence the currents were comparatively higher during both seasons (Table S1). The current speed along the southwest coast of India was maximum around 15-20 cm/s and majority of currents were observed to be less than 10 cm/s[22]. At Ratnagiri coast (north of Vengurla), alongshore component of the velocity decreases towards the coast due to increase in bed friction, this was based on observation as well as model outputs[9]. The present results in the variation of coastal current from offshore to nearshore zone at Vengurla showed similar observations to that of earlier researchers[9]. Observations also showed that northward currents prevailed throughout during monsoon, whereas southward currents prevailed during pre-monsoon at offshore zone along with some meager changes of flow pattern (Fig. 4).

The current profiles during monsoon period showed that, at bottom layer tide is having a dominant role in controlling the circulation, but at surface waters, both tide and other forcing agents like wind may have an important role in controlling the circulation and result is compatible with the recent study conducted at Ratnagiri coastal waters[9]. Surface currents are slightly stronger than the bottom currents along Karnataka coast[36]. Coastal currents are not only controlled by the tides, but other forcing agents like wind and remote forcing wave have also a dominant role[4-6,8-9].

Thereby, using the observed data, the surface current pattern by ADP with respect to AWS wind and *in-situ* observation of tide data on 15 m water depth were analyzed. During the monsoon, the surface current speed was up to 92.2 cm/s with an average of 34.28 cm/s while the direction was varying frequently. The wind speed was up to 8.6 m/s with an average of 2.1 m/s. The wind speed having more than 4 m/s was frequently observed while the wind was from the second quadrant (270-360°). The wind from first quadrant was weak and rarely reached wind speed more than 4 m/s. There was no significant correlation between tide and wind speed and direction. Further, there was no considerable relation of current speed and direction with respect to wind and tide. During pre-monsoon, the surface current speed was up to 19.8 cm/s with an average of 9.4 cm/s while the direction was towards coast. The current direction was narrowing towards 210° from the wide range while the speed increased. There was two phases in the wind direction which exhibits the existence of coastal breeze. The wind speed was up to 11 m/s with an average of 2.3 m/s. The wind speed having more than 4 m/s was observed during the sea breeze. The wind was weak during land breeze and rarely reached wind speed more than 4 m/s. The current pattern during this phase also did not show any linear relation with the wind condition. Further, the relation of current with respect to tide shows very weak relation. The observation showed an existence of complex pattern among these three parameters (Fig. S1). Hence, there was no reasonable statistical analysis could be carried out. The study revealed that the surface current speed as well as direction is not only controlled by the local wind and tidal pattern alone while the possibility of the impact of deep ocean current on local current pattern was presumed.

Conclusion

The tides at Vengurla coastal waters are generally mixed semi-diurnal type and the tidal range is around 1.85 m and 2.37 m during monsoon and pre-monsoon, respectively. The analysis revealed that considerable variations were only in major tidal constituents between two seasons but the variation was negligible in minor tidal constituents. It is understood that from subsurface to bottom the coastal currents at 15 m water depth off Vengurla are mainly controlled by the tides. The current profile in these waters is varying with depth with gradual increase in current speed from bottom to surface during monsoon but there was no such type of gradient during pre-monsoon while a unidirectional current pattern exist. At nearshore, very low (sluggish) current occurs and cross-shore flow is directed eastward, but strong current with a unidirectional pattern exists at offshore, which is towards north during the monsoon and towards south during the pre-monsoon. The study revealed a complex pattern among tide and currents at offshore. Moreover, it is understood that the surface current pattern is not only controlled by the tides, but other forcing agents like wind and remote forcing waves also have a dominant role in controlling the coastal surface current pattern. This information will be useful for model validation as well as understanding the general circulation pattern of similar coastal areas.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at http://nopr.niscair.res.in/jinfo/ijms/IJMS_50(04)277-286_SupplData.pdf

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Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

KR: Conceptualization, data analysis and writing; GUD & VN: Formal analysis and writing; RSK: Conceptualization and Supervision; MM, SS, & SA: Data analysis and writing.

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