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Description on variability of shelf-edge hydrography and current structure of the South Eastern Arabian Sea during summer and winter monsoons

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Abstract The paper describes the hydrography and vertical current structure along the shelf edge of South East Arabian Sea (SEAS) during summer and winter monsoons based on current profiles from moving Acoustic Doppler Current Profiler (ADCP). During summer monsoon, SEAS was characterized by upwelling with low saline water at the surface along the southern sector (8° N to 11° N). During winter, thermal structure was vertically homogeneous in the upper 80 m, and intrusion of low saline Bay of Bengal waters were found up to 14° N. In the southern sector, turbidity was more than the northern sector during winter and summer seasons. ADCP-derived current profiles during summer along 200-m isobath show dominant northward flow in the south, and southeasterly in the north as part of the West India Coastal Current (WICC). A comparison between ADCP current profiles and Ekman currents during summer indicates dominance of remote forcing (coastal Kelvin waves) over the local wind forcing in the 8–9° N sector whereas a combined influence of both remote forcing and wind in the 9–15° N sector. During winter, the direction of surface current reversed and was poleward generally except at the southern sector (7–8° N) where the flow was southwestward. Sector-wise comparison of ADCP and Ekman current showed less influence of wind on current fields throughout the sector except at south; wind has a major role in the current generation, whereas along the 8–15° N sector, the remote forcing dominates over the wind.

Keywords Shelf edge · Ekman current · ADCP · Circulation · South Eastern Arabian Sea

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Introduction

South Eastern Arabian Sea (SEAS), in the western part of the North Indian Ocean, is under the influence of reversing monsoons. The seasonal reversing monsoon winds, i.e., southwesterly during summer monsoon (June–September) and northeasterly during winter monsoon (November–February), with interim quiescent periods fall inter-monsoon (October) and spring inter-monsoon (March–May), defined the four seasons of the region. The SEAS ecosystem processes are governed by these seasonal atmospheric forcing; summer is characterized with moderate coastal upwelling, and winter is influenced by the intrusion of less saline Bay of Bengal (BoB) water due to the pressure gradient flow resulting from remote forcing (McCreary et al. 1993; Shankar et al. 2002).

Shetye and Shenoi (1988) explained the surface circulation of Eastern Arabian Sea, showing that West India coastal current (WICC) flow southward during summer monsoon and northward during winter monsoon. Signatures of downwelling were seen in the hydrography data, which is the indication of the poleward undercurrent (Shetye et al. 1990; Muraleedharan et al. 1995) which flows opposite to the equatorward surface current. Using high-resolution model, Haugen Vibeke et al. (2002) studied the circulation pattern and well simulated the dominant WICC and weaker undercurrent flowing in opposite direction of WICC along the southwest coast of India. On simulating the dynamics, thermodynamics, and mixed layer processes in the North Indian Ocean, McCreary et al. (1993) found that the sea level changes ensuing the reversal of WICC generate local rise or fall near the Lakshadweep Islands known as Lakshadweep high (LH) and Lakshadweep Low (LL) during winter and summer monsoon, respectively. These LH and LL are developed in association with prevailing coastal Kelvin as well as Rossby wave propagation (westward) in downwelling/upwelling mode (Shankar and Shetye 1997) which are generally categorized as remote forcing or planetary waves.

Smitha et al. (2008) documented that the upwelling process along the southwest coast of India is not spatially uniform based on analysis of 11-year data on upwelling intensities with wind and SST. Amol et al. (2012) showed the contribution of remote forcing to the shelf of west coast of India in addition to the strong alongshore wind contribution in the propagation of coastally trapped waves. Studies addressing the hydrography, circulation, and ecosystem processes during winter monsoon along SEAS are comparatively less compared with summer monsoon period. Shetye et al. (1991) explained the regulatory role of northward pressure gradient-driven flow and intrusion of low saline BoB water (Prasanna Kumar et al. 2004) into the Eastern Arabian Sea with enhanced chlorophyll-a production near the southern part and have given basic understanding of the regional seasonal impacts (Rao et al. 2014). Jineesh et al. (2015) showed that the mesoscale features in the ocean is also responsible to alter the characteristics of coastal currents. The dominant southward flow off Kollam during the initial phase of winter monsoon is associated with the mesoscale eddy in the region that indicates the influence of mesoscale features to alter the characteristics of currents.

The information on the shelf-edge characteristics are very important, as these are merging zones between the coastal (shelf) and oceanic realm, and there are indications of regional modifications in the flow pattern due to the peculiar topographic features. The regional current patterns are significant in regard to the heat exchange, upper ocean temperature, monsoon onset vortex, and extent of stratification. Concentration of nutrients which regulate the plankton biomass and the retention of organism is controlled by the currents, and these have cascading effects until the higher trophic levels. Understanding of the current pattern is thus essential in explaining the physical/chemical and biological attributes of an ecosystem. The offshore extension of the coastal upwelling during summer monsoon is more or less associated with the shelf edge, drifting the

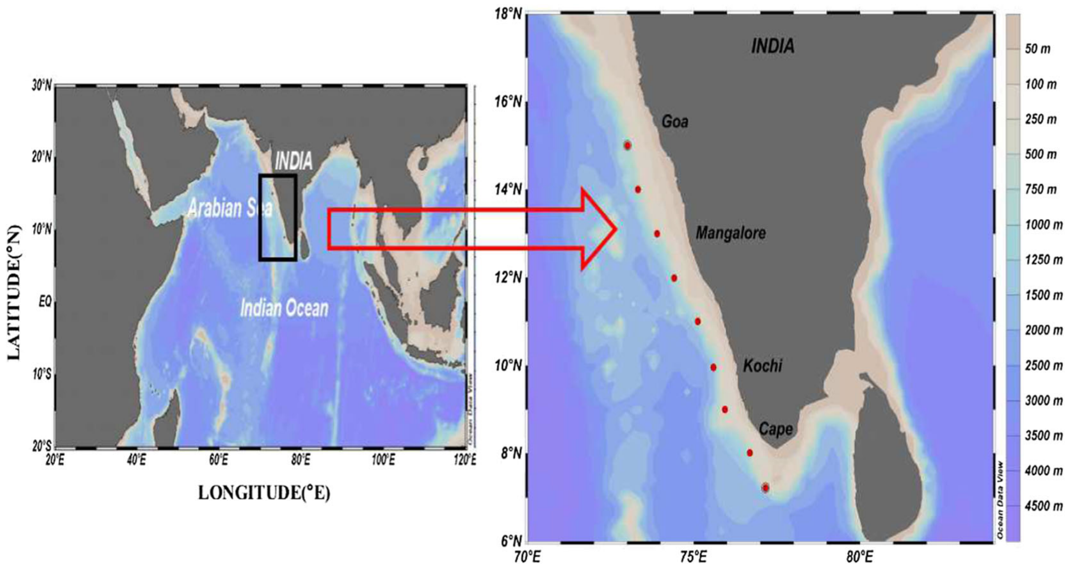

Fig. 1 Map of the study area (South Eastern Arabian Sea). Red dots indicate sampling stations along 200-m isobath off Cape to Goa

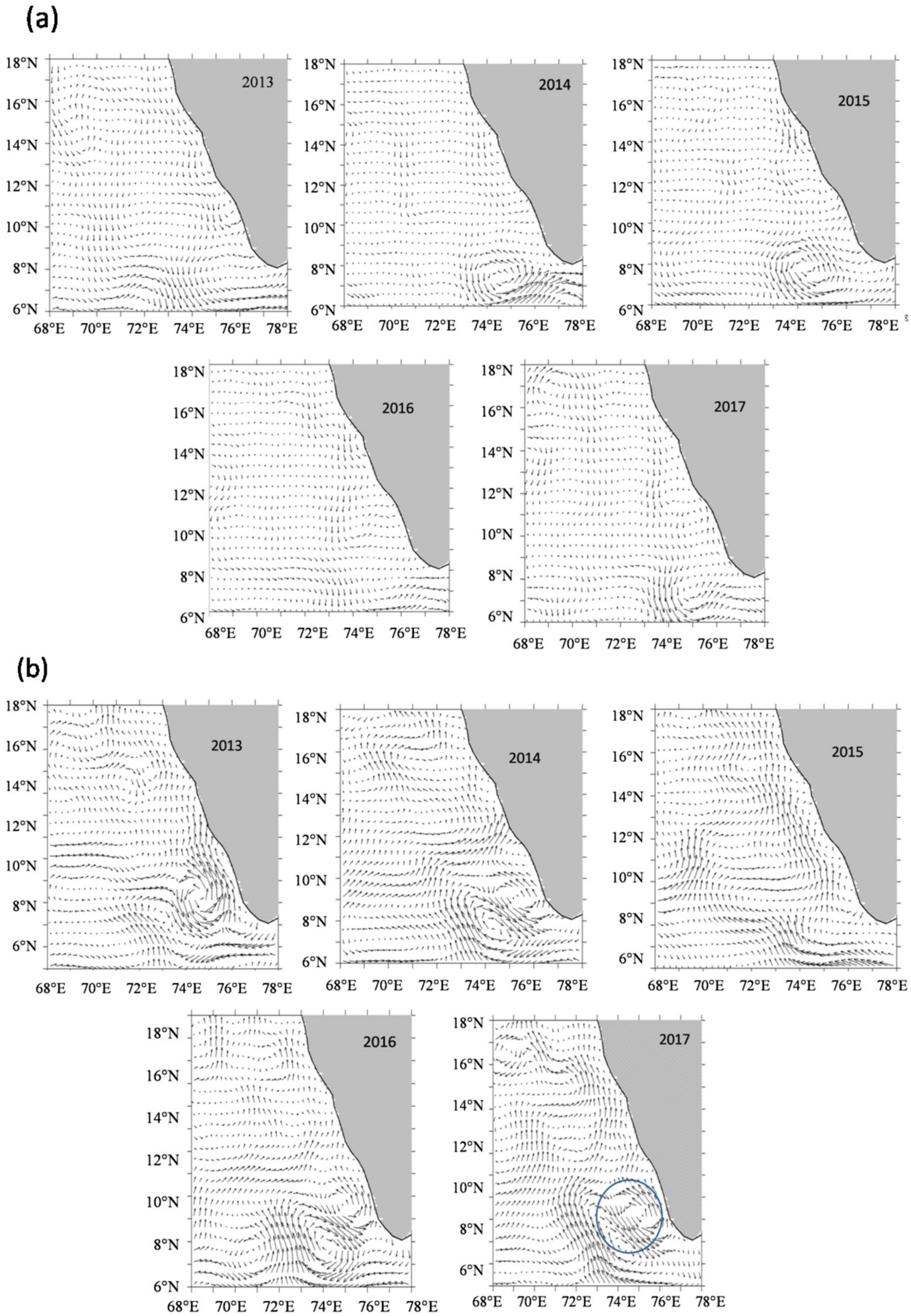

Fig. 2 Geostrophic current and circulation pattern in the South Eastern Arabian Sea (SEAS): (**a**) Summer monsoon 2013–2017 and (**b**) winter monsoon 2013–2017. (source:(https://las.aviso.altimetry.fr/las/)). During winter monsoon 2017, eddy like features (*see circle*) visible in the plot

productive water to offshore resulting in strong biological pumping in the region. In these aspects, understanding on the shelf edge currents is of significant importance, especially the dynamics, forcing mechanism and strength of the flow.

In this background, this paper is framed considering in situ and satellite measurements along the ~ 200-m isobath in the SEAS from Kanyakumari (Cape) to Goa (7° N to 15.5° N) and address the following objectives 1) regional hydrodynamics and circulation pattern along the shelf edge (approximately the 200-m isobath) in the SEAS 2) to examine the role of wind and other forcing in regulating the upper layer hydrodynamics and 3) to delineate the regional variation in the currents, its forcing mechanisms, and intensity.

Data and methods

Study area

South Eastern Arabian Sea (SEAS) spanning from 6–16° N to 68–78° E in the north western Indian Ocean holds a unique place in the World Ocean in respect of occurrence of warm pool followed by the onset of monsoon vortex in the Arabian Sea. It is also one of the most productive regions in the Indian Ocean due to upwelling along the coastal region during summer monsoon (Madhupratap et al. 2001; Gopalakrishna et al. 2008; Sanjeevan et al. 2009). Due to its geographical setting, it has a major role in North Indian Ocean current system, by connecting Arabian Sea and Bay of Bengal which has separated by Indian sub-continent. SEAS undergoes seasonal reversal of winds in association with the monsoons, resulting changes in the upper layer circulation pattern during summer monsoon (SM) and winter monsoon (WM). During SM, the alongshore component of wind towards equator was the driving force of the upwelling system (Shetye et al. 1990), and upwelling regulates the major ecosystem dynamics of the SEAS with increased production potential (Madhupratap et al. 2001) as a result of the enhanced nutrient pumping. During WM, in response to weak northeast trade wind which brings cool and dry continental air, Arabian Sea experiences higher evaporation rate and surface circulation found to be reversed. The coastal current driven by the pressure gradient (McCreary et al. 1993) during WM results in the intrusion of less saline BoB water to the SEAS. The intrusion of low saline water from the BoB and remote forcing contribute major role in dynamics and hydrography setting of SEAS (Shankar et al. 2002; Rao et al. 2014; Asha Devi et al. 2018).

In situ and satellite data

In situ measurements were carried out onboard *FORV Sagar Sampada* during summer monsoon (July–August 2013) and winter monsoon (January 2017) along the shelf edge of SEAS (7–15° N) to study the hydrography and the current pattern. The sampling was carried out at 9 stations along 200-m isobath that represents the continental shelf edge between Kanyakumari (Cape) and Goa (Fig. 1). Though data collection for the winter and summer carried out during different years, the monthly geostrophic current pattern (https://las.aviso.altimetry.fr/las/) (Fig. 2) indicates that general circulation and current pattern along shelf edge in the respective

Table 1 Time and duration of sampling along the stations during summer and winter monsoons

Latitude	Summer monsoon (July/August 2013)	Latitude	Winter monsoon (January 2017)
------	--------	7.2° N	22 January 2017 0800 to 1100 h
8.4° N	16 July 2013 1805 to 2000 h	8° N	23 January 2017 0900 to 1300 h
8.8° N	18 July 2013 0645 to 0830 h	9° N	25 January 2017 0830 to 1300 h
10° N	20 July 2013 0800 to 0930 h	10°N	26 January 2017 0830 to 1300 h
11.4° N	08 Aug 2013 0600 to 0850 h	11° N	28 January 2017 0830 to 1240 h
12° N	08 Aug 2013 2000 to 2200 h	12° N	29 January 2017 0830 to 1300 h
12.8° N	10 Aug 2013 2000 to 2200 h	13° N	29 January 2017 2230 to 2350 h
13.9° N	16 Aug 2013 1000 to 1215 h	14° N	30 January 2017 1100 to 1300 h
14.7° N	17 Aug 2013 14:45 to 1700 h	15° N	1 February 2017 0700 to 1300 h

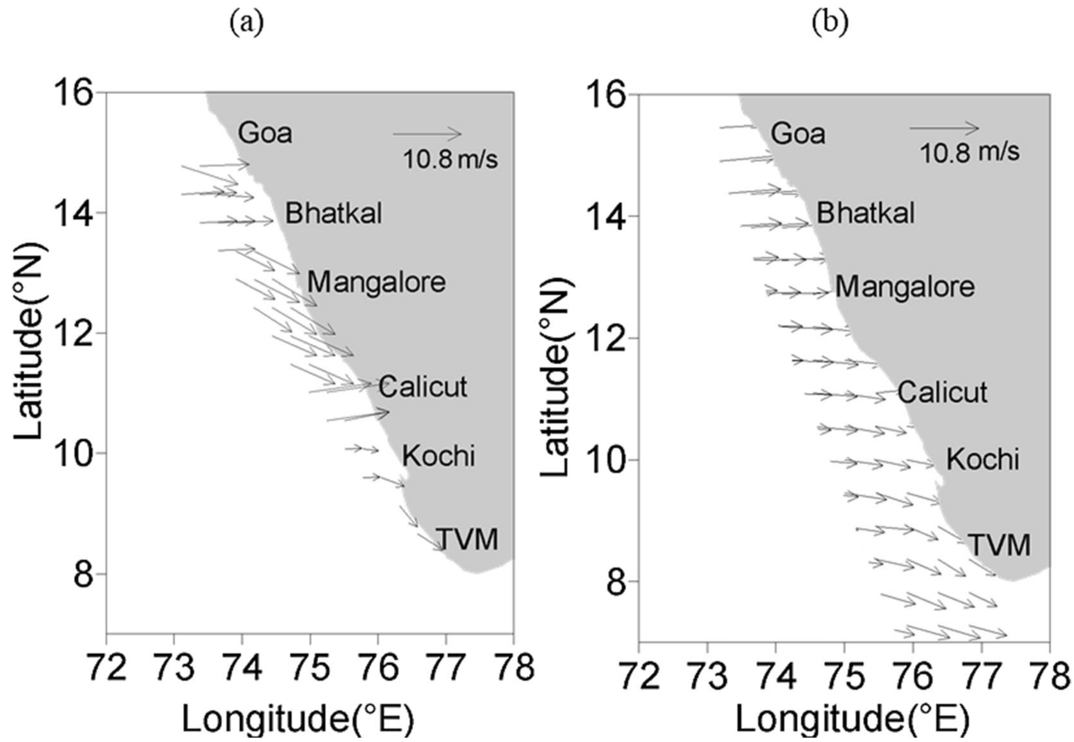

Fig. 3 **a** Measured wind and **b** satellite-derived monthly wind over SEAS during summer monsoon 2013

summer and winter monsoon seasons not showing much deviation in the interannual basis. Hence, the hydrographic data of summer and winter during 2013 and 2017 respectively were considered to explain seasonal difference in the shelf edge characteristics. A seabird CTD (SBE 911 Plus) instrument was used to collect temperature, salinity and turbidity profiles, which has got an accuracy of conductivity ± 0.0003 S/m, temperature ± 0.001 °C, pressure 0.015%, and turbidity of 0.02 NTU from all stations. CTD derived salinities were calibrated against those from the samples collected simultaneously with a rosette sampler and analyzed with Guildline 8400 Autosal. Wind data were collected using automatic weather station (AWS) onboard during the cruises. Data is recorded at an interval of 10 min. Wind speed ranges from 0 to 60 m/s and wind direction has range of 360 degrees. We also used satellite monthly averaged wind data (Metop-A-ASCAT with 0.25° resolution) to supplement the results derived from the in situ wind observations. RDI 75 kHz Ocean Surveyor broadband Acoustic Doppler Current Profiler (ADCP) was used for obtaining vertical profile of currents along the cruise track. ADCP data along the meridional transect has only been processed doing a time-based selection (Table 1). The bin size and blanking distance were set as 8 m, and the data were collected through Moving Vessel Data Acquisition Software (VMDAS) and bin wise data were post-processed for 5 min ensemble using WinADCP. The observed current was resolved into cross shore (*u*) and alongshore (*v*) components using the available method (u = rCosθ, v = rSinθ), and these *u* and *v* components are used to derive the information on dominant flow pattern during the seasons. In addition, resultant current speed and direction was represented using stick plots (FORTRAN and Surfer packages).

The Ekman current velocity (*u* and *v*) at different depths were derived from the in situ wind field using the equations given below Pond and Pickard (1983):

$$\text{Cross shore Ekman velocity}, Ue = V0\ (\cos\Pi/4 + \Pi z/De)\ e^{\Pi z/De}$$
$$\text{Along shore Ekman velocity}, Ve = V0\ (\sin\Pi/4 + \Pi z/De)\ e^{\Pi z/De}$$

where $V_0 = 2\Pi\tau_y/D_e\rho_w f$, where $D_e = 4.3\text{w}/\sin\Phi^{1/2}$f = 2Ωsin$\Phi$ is Coriolis force due to Earth at latitude Φ, and Ω is the angular velocity of Earth rotation and is equal to 7.29×10^{-5} radians per second. $\tau_y = \rho_a C_d V^2$ where $\rho_a =$ 1.29 kg/m^3 is density of air and $C_d = 1.3 \times 10^{-3}$ is a non-dimensional drag coefficient, which is a function of both wind speed and stability.

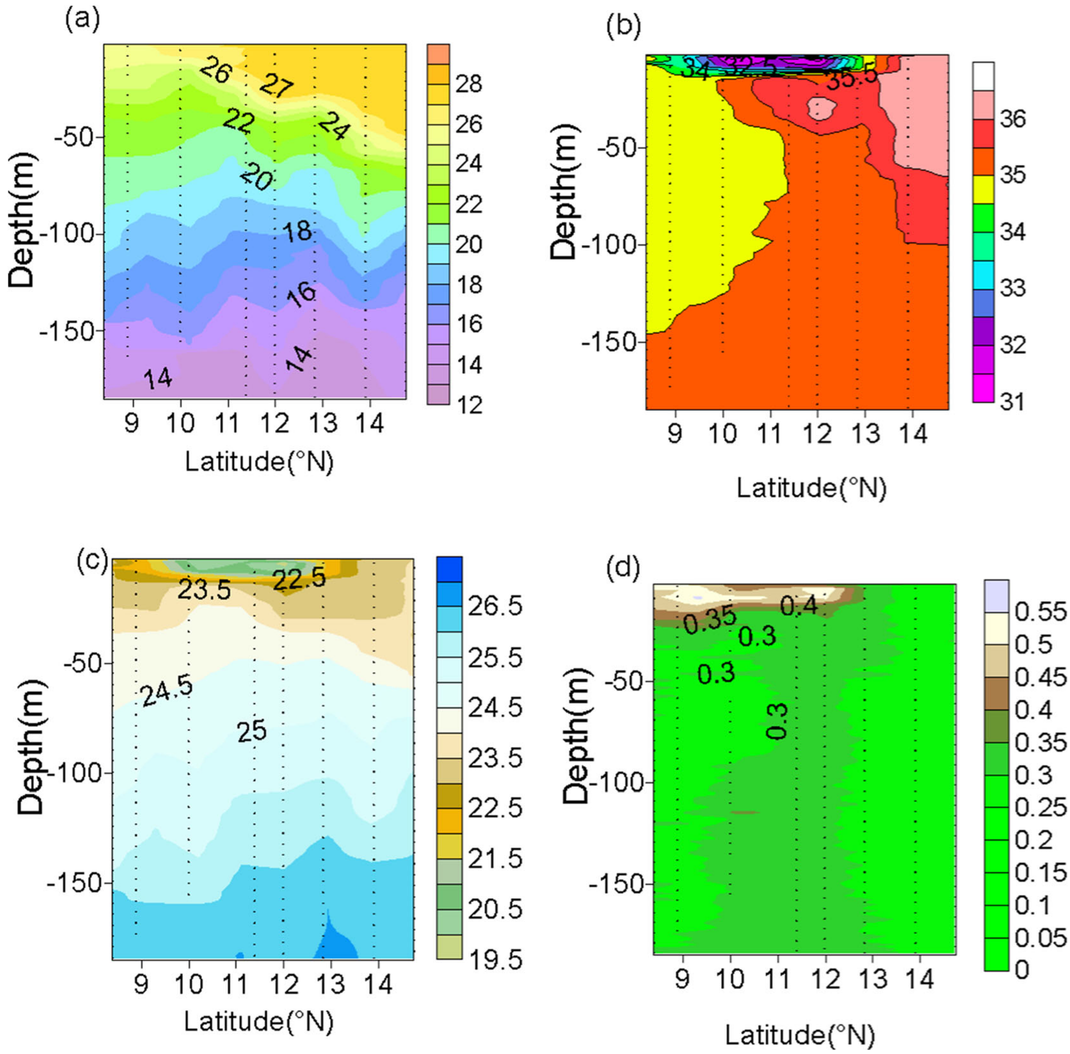

Fig. 4 Vertical section of **a** temperature (°C), **b** salinity, **c** sigma-t, and **d** turbidity (NTU) along the shelf edge of SEAS during summer monsoon 2013

Results

Characteristics of SEAS during summer monsoon

Wind

The wind pattern indicates dominant northwesterly and alongshore winds at the southern (8° N to 10° N) part of the study area leading to thermocline shallowing whereas at the northern section (14° N to 15.5° N), westerly wind dominated **(**Fig. 3a**)**. The monthly satellite wind data **(**Fig. 3b**)** showed the same pattern as observed from the in situ. At the southern sector from Trivandrum (8.4° N) to Kochi (10° N), the wind magnitude was weak (~ 3 m/s in north-north westerly direction) whereas at the middle sector (Calicut (11°N) to Mangalore (13°N)), it was stronger (~ 7 m/s, in westerly-northwesterly). In the northern sector, moderate to strong wind (4 to 7 m/s, in westerly-northwesterly) was observed.

Hydrography

Isotherms along 200-m isobath of SEAS during summer monsoon showed prominent upsloping at south up to surface, occupying low temperature (26 °C) water at surface, whereas at north upsloping was observed in the subsurface water column indicating that the upwelling process is not yet active to reach the surface. The

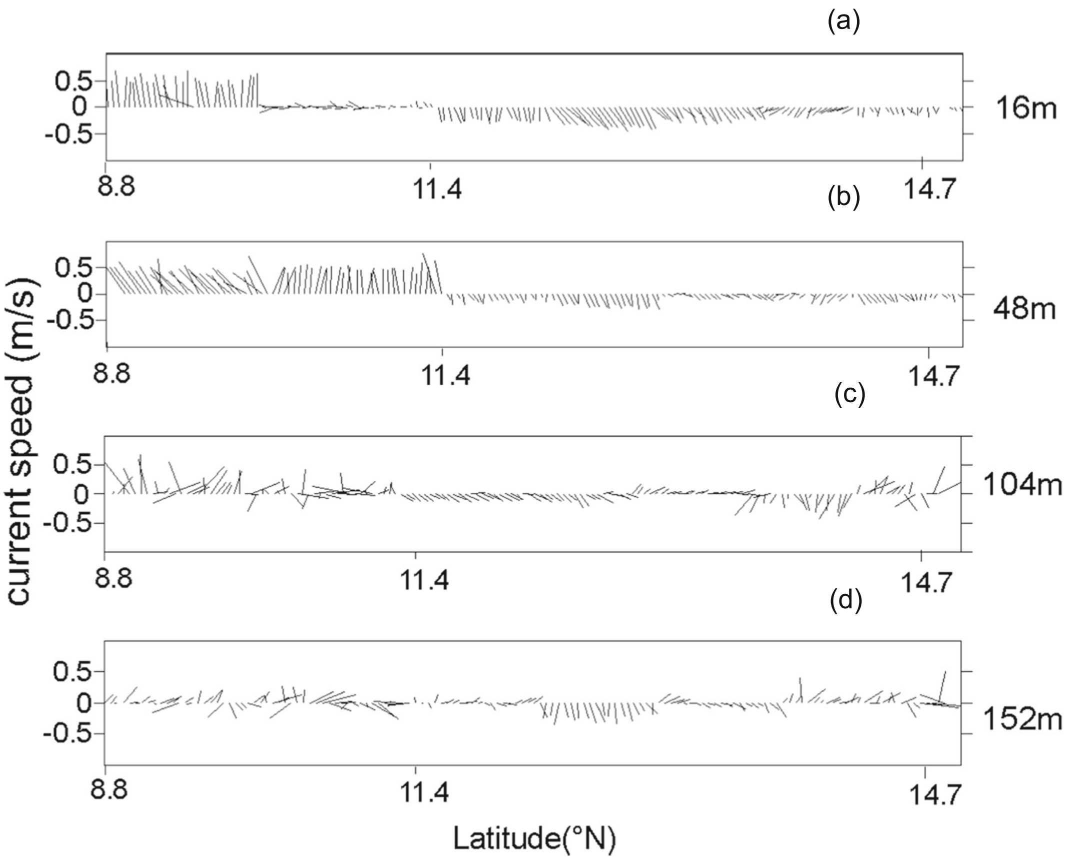

Fig. 5 **a**–**d** Stick plot of ADCP current profile at different depth level (16 m, 48 m,104 m, and 152 m) along the shelf edge of SEAS during summer monsoon 2013

upper layer is comparatively warm recording 28 °C in the surface up to 25 m along 12° N latitude to 50 m depth in the northern part (15° N). In the northern area, the water column was homogeneous up to 50 m (Fig. 4a). This indicates that the upwelling process is active and established in the southern part. In general, the salinity in the water column increases towards north (Fig. 4b). However, observed presence of low saline water (32.0–33.8 psu) in the upper 20 m water column between Kollam (8.8° N) to Mangalore (13° N). This may be due to the heavy precipitation and fresh water runoff from the rivers and estuaries along the Kerala coast during the summer monsoon (Darbyshire 1967; Shetye et al. 1990; Jyothibabu et al. 2008; Fernandes et al. 2014). North of Mangalore, the surface waters were occupied with high saline water (~ 36.0 psu). Below 30 m depth, salinity was almost homogenous (~ 35.2 psu). The density (sigma-t) in the upper 30 m was more influenced by salinity while it was controlled by temperature below to it (Fig. 4c). The southern sector was more turbid (> 0.44 NTU) at surface waters perhaps due to the higher flux, active runoffs, and recorded low turbidity at the subsurface waters as a result of upwelling-induced offshore transport (Chauhan et al. 2011). At the northern sector, turbidity was less for the entire water column (< 0.3 NTU) (Fig. 4d).

Current structure—ADCP

Current structure along the 200-m isobath in the SEAS (Fig. 5) is described based on the in situ measurement done on-board *FORV Sagar Sampada* using moving ADCP (75 KHz). Covering the blanking distance, the first level of observations was recorded at 16 m, and the stick plot (Fig. 5a) shows northward currents of average speed of 0.50 m/s off Kollam. North of Kochi, the currents were weak (0.10 m/s) with varying direction but dominantly towards southwest. Further north, strong

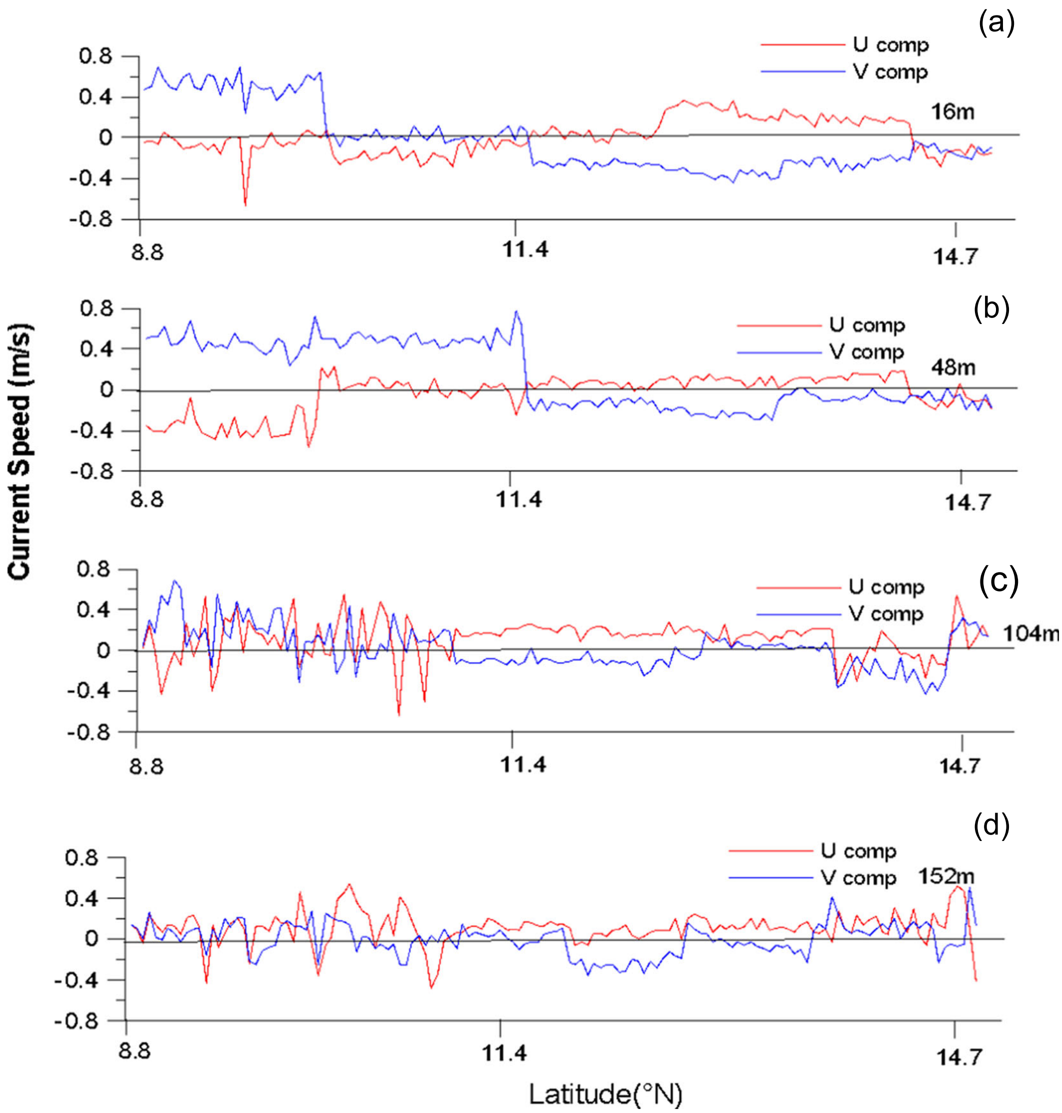

Fig. 6 **a**–**d** The *u* and *v* components of the ADCP current at different depths (16 m, 48 m,104 m, and 152 m) along the shelf edge of SEAS during summer monsoon 2013

south-south easterly flow is dominant which extends up to Karwar with a mean value of 0.40 m/s. Average current speed at the entire study area was 0.30 m/s. The analysis of *u* component (Fig. 6a) indicates dominant flow (− 0.063 m/s) to west at southern sector up to Calicut and towards east (0.17 m/s) at north. The *v* component (Fig. 6a) indicates dominant northward flow (0.52 m/s) at southern sector and southward flow (− 0.20 m/s) at northern sector.

At 48 m, northward current was noticed up to Kochi with a mean current speed of 0.55 m/s, and north of this southward current was observed with an average speed of 0.17 m/s (Fig. 5b). The *u* component shows westerly dominant flow (− 0.16 m/s) at southern sector up to Kochi; thereafter, no dominant flow was noticed. But *v* component shows northward dominant flow (0.48 m/s) up to Calicut and thereafter towards south (− 0.13 m/s) up to Karwar (Fig. 6b).

Along southern sector, northward-directed current with average speed of 0.34 m/s and varying direction was noticed at 104 m depth (Fig. 5c). Between Kochi to Calicut, a southeastward dominant flow was noticed, with varying direction further north. The *u* component shows varying current direction from Quilon to Kochi and eastward dominant flow (0.22 m/s) between Kochi to Calicut (Fig. 6c), leaving no organized pattern in this

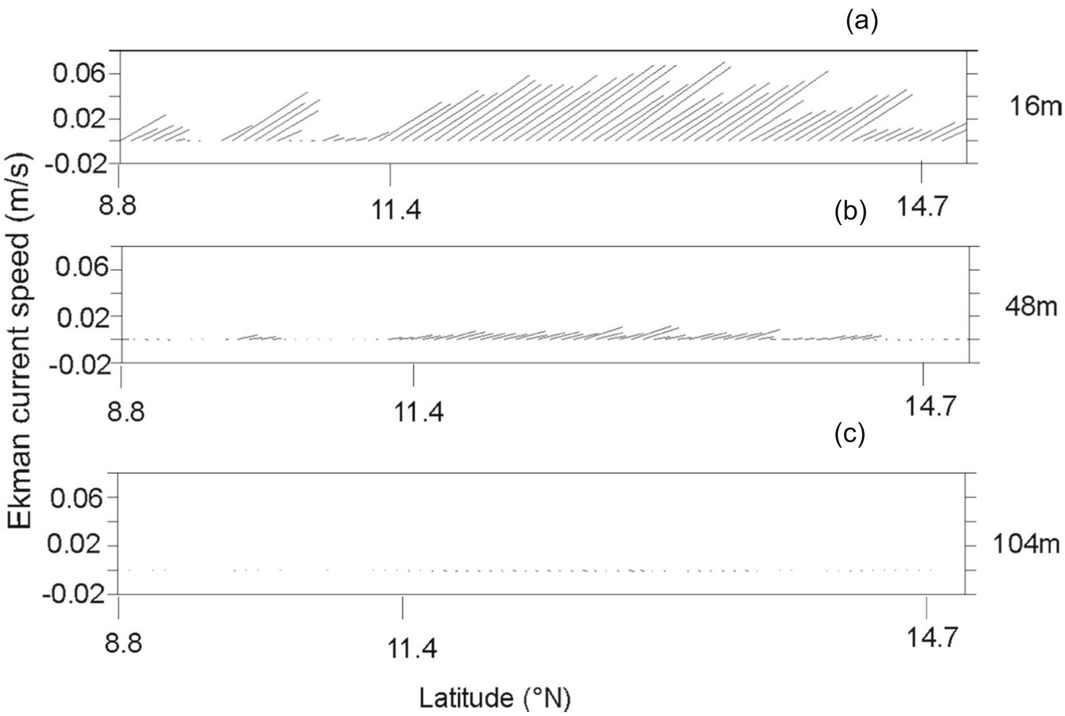

Fig. 7 **a**–**c** Stick plots of Ekman current at different depths (16 m, 48 m, and 104 m) along the shelf edge of SEAS during summer monsoon 2013

depth range. The *v* component shows a northward dominant flow (~ 0.2 m/s) with minor fluctuations up to Kochi, and thereafter at north, weak southward flow (− 0.14 m/s) was recorded.

At 152 m, stick plot (Fig. 5d) shows highly irregular current pattern along the shelf edge with a weak southward component in the middle sector with an average speed of 0.20 m/s. The *u* component (Fig. 5d) shows irregular pattern along southern sector with eastward dominant flow with an average speed of 0.15 m/s. The *v* component indicates irregular flows along the study area except at the middle sector where southward dominant flow (− 0.18 m/s) was recorded.

Current structure—Ekman

Ekman current generally represent the role of wind in the generation of currents in the ocean. Ekman current was computed using the standard formula from surface to 104 m, the upper layer of uniform current pattern. Current pattern at 16-m level indicates northeastward flow throughout the study area with a mean current speed of 0.025 m/s (Fig. 7a). The *u* component indicates westward dominant flow (0.04 m/s) whereas *v* component showed a dominant northward flow with an average value of 0.03 m/s (Fig. 8a).

At 48-m level, the stick plot represents northeast flow at entire sector with a very low value compared with surface level with an average speed of 0.008 m/s (Fig. 7b). The *u* and *v* component also shows similar pattern as observed in surface level with low value (0.011 m/s and 0.002 m/s) which was obvious from Fig. 8b. Ekman current was negligible at 104-m level as evidence from Figs. 7c and 8c.

Characteristics of SEAS during WM

Wind

During winter monsoon, the resultant direction of the wind over the shelf of SEAS is generally easterly at south and northeasterly at north with considerable spatial variations, and it is comparable with the satellite derived data (Fig. 9 a and b) for the period. The maximum (12 m/s) and minimum (1 m/s) wind speed were observed off Cape (southern tip) and off Calicut, respectively.

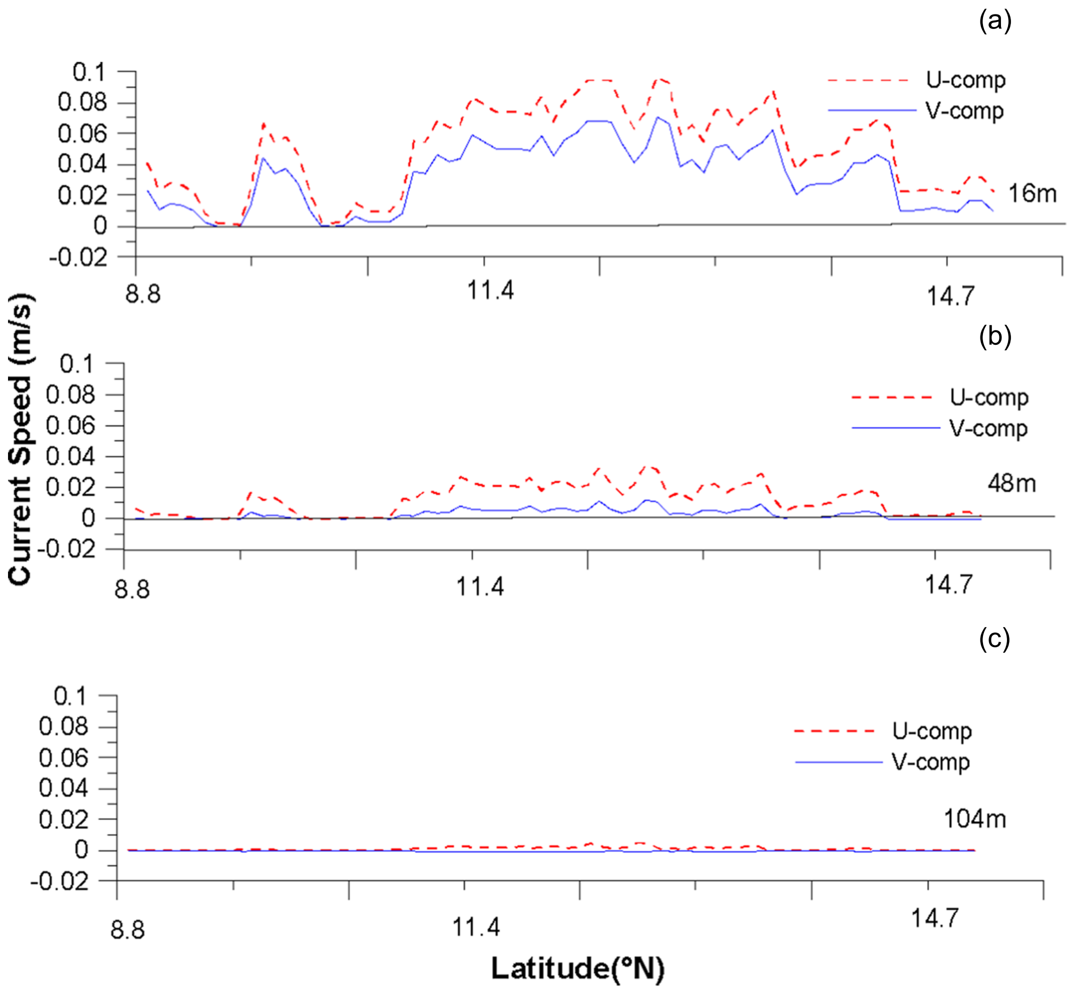

Fig. 8 **a**–**c** The *u* and *v* components of the Ekman current at different depths (16 m, 48 m, and 104 m) along the shelf edge of SEAS during summer monsoon 2013

Hydrography

Thermal structure shows there is no major variation in SST between south and north shelf of SEAS (Fig. 10a). At south (7–8° N), SST was of the range ~ 27.5 °C, and along the rest of the sections, it varied between 28.0 and 28.5 °C. The low temperature at south may be due to the gap winds (between Cape and Sri Lanka) originating from the northeast. Based on satellite data analysis and modeling study, Luis and Kawamura (2002) also identified the presence of gap winds between the Cape and Sri Lanka. This indicate that a permanent cold water exists during winter season primarily due to strong northeasterly wind (~ 10 m/s) blowing over southern tip of India. Thermal structure was vertically homogeneous for the top 80 m, and below to it, strong stratification was observed along the entire shelf of SEAS.

The upper 20 m water column at south (Fig. 10b) was occupied with low saline water (33.2–34.4 psu) along 7–14° N sectors originated from BoB water. A strong halocline (34.0–35.6 psu) and pycnocline was observed between 30 and 80 m water depths along the shelf area (Fig. 10b and c). Below this depth, salinity was vertically homogeneous. In winter low turbidity was noticed except off Kochi (10 N) at a depth of 50 m where high turbidity (~ 0.2 NTU) shown and at bottom waters (Fig. 10d).

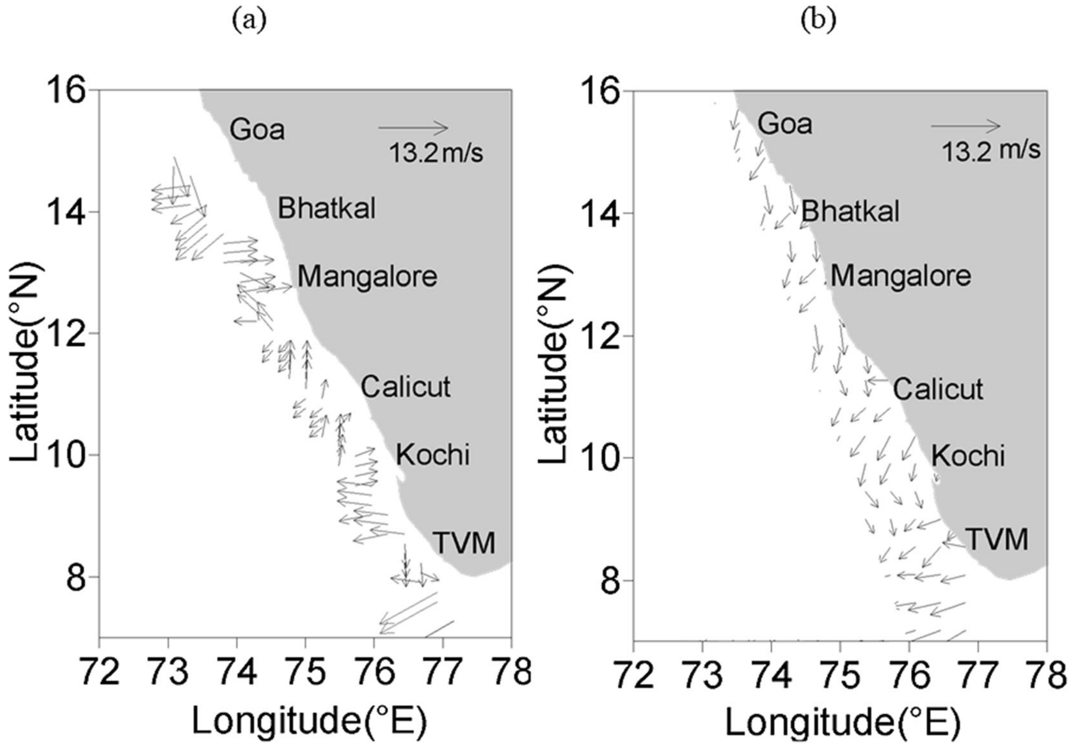

Fig. 9 **a** Measured wind and **b** satellite-derived monthly wind over the study area during winter monsoon 2017

Current structure—ADCP

Current pattern at surface (16-m level) indicates north and northwestward flow along the study area with a mean current speed of 0.40 m/s except between 7–8° N and 11–12° N where the flow was southwestward (Fig. 11a). The *u* component indicates westward dominant flow (0.34 m/s) whereas *v* component showed prominent northward flow except off Calicut and south of Trivandrum (Fig. 12a). At 48-m level (Figs. 11b and 12b), the stick plot and *u* and *v* component represents almost similar pattern as that of 16-m level with less intensity in respect of the current speed. Mean current speed computed at 48 m is 0.33 m/s. At 104-m level, stick plot (Fig. 11c) shows southward flow up to 8° N, thereafter a northward flow was observed to the entire sector, however, of a weak magnitude (~ 0.3 m/s). Average current speed at 104-m level is 0.26 m/s. The *u* component shows irregular east and westward flow along the study area whereas *v* component indicates southward dominant (− 0.24 m/s) up to Trivandrum (9°N), and north of this northward component is dominant (0.24 m/s) (Fig. 12c). Stick plot at 152 m depth (Fig. 11d) indicates a southward directed flow up to Mangalore with a mean value of 0.18 m/s, which indicates the presence of equatorward undercurrent (Kesava Das 1992) and thereafter up to Goa, a northward flow pattern was observed. The *u* component shows unorganized current pattern whereas *v* component shows similar pattern up to Mangalore only, and further north, it is dominantly northerly (0.30 m/s) (Fig. 12d).

Current structure—Ekman

Ekman current pattern at 16-m level shows a south-southeastward flow along the study area with a mean current speed of 0.05 m/s except between 7 and 8° N where the flow was northeastward (Fig. 13a). The *u* component indicates eastward dominant flow (0.04 m/s) along the study area whereas *v* component showed general southward flow except at south of Trivandrum where northward flow was noticed (Fig. 14a).

At 48-m level, Ekman currents represent a south-southeastward flow along entire sector with an average

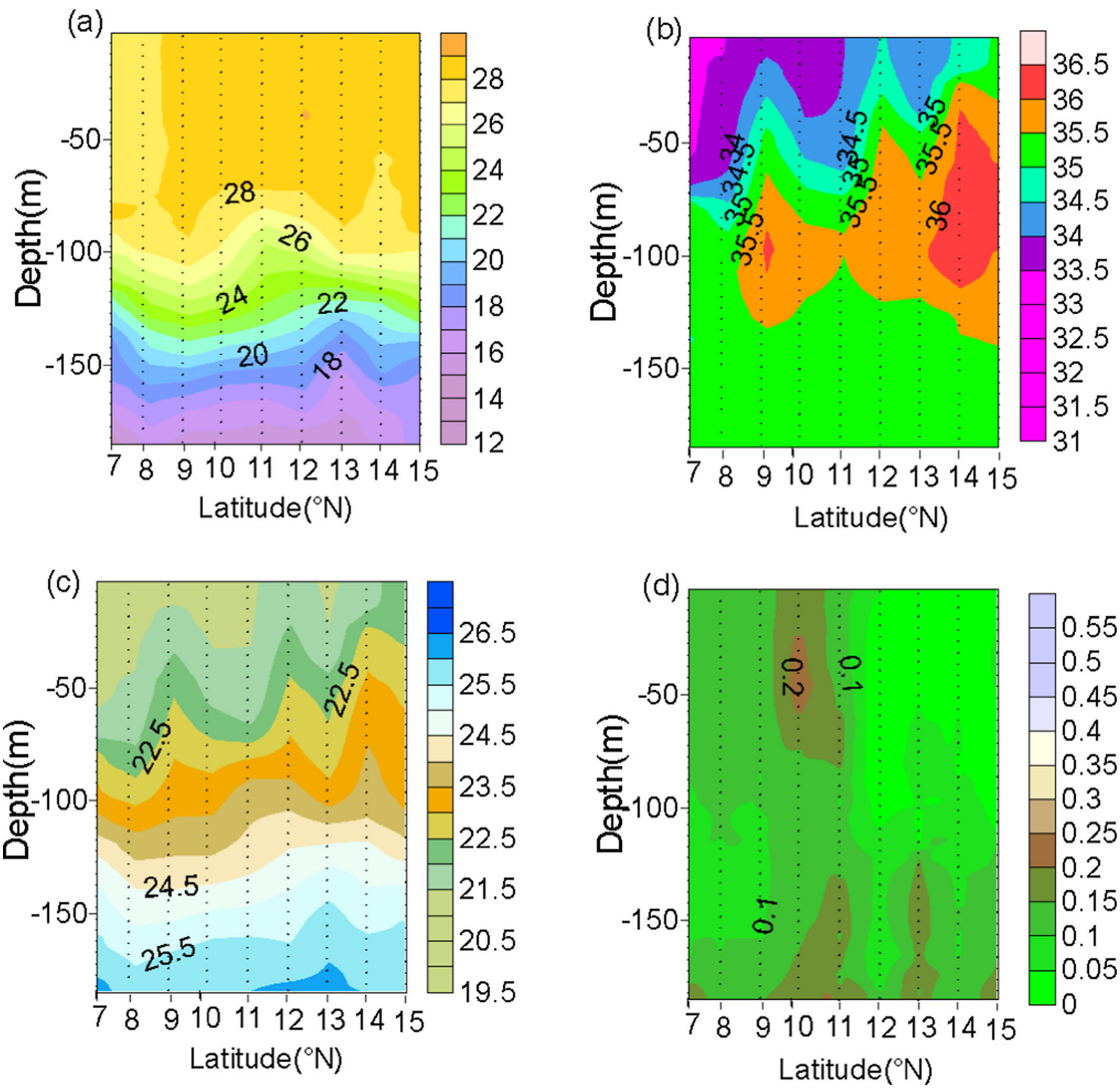

Fig. 10 Vertical sections of **a** temperature (°C), **b** salinity, **c** sigma-t, and **d** turbidity (NTU) along the shelf edge of SEAS during winter monsoon 2017

speed of 0.03 m/s (Fig. 13b). South of Trivandrum (8.5°N), the *u* component shows eastward dominant flow with an average speed of 0.028 m/s (Fig. 14b). The *v* component shows southward flow at 7–8° N; thereafter, no dominant flow was noticed towards north. The average speed of *v* component was 0.01 m/s. At 104-m level (Fig. 13c), the flow was southward at south of Trivandrum with a mean speed of 0.003 m/s. The *u* component shows no dominant flow (0.001 m/s) along the entire sector and *v* component shows southward dominant flow (0.008 m/s) south of Trivandrum (Fig. 14c).

Discussion

SEAS is an area of interest for the researchers due to its peculiar characteristics with influential role in the monsoon dynamics, coastal upwelling sustaining

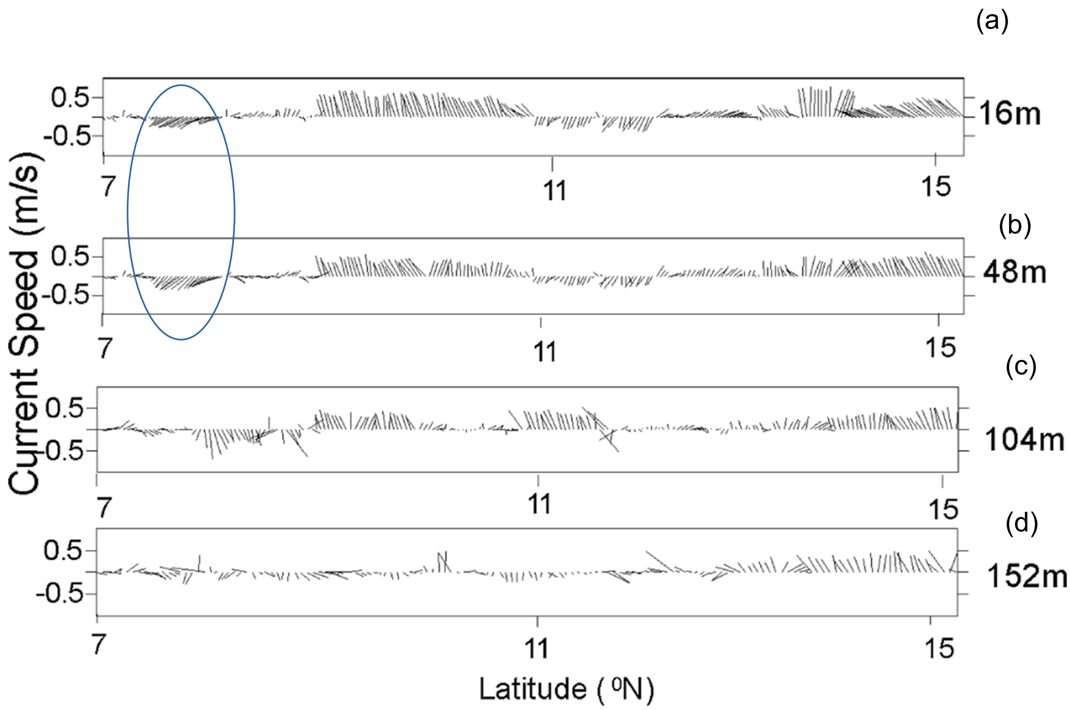

Fig. 11 **a**–**d** Stick plot of ADCP current profile at different depth level (16 m, 48 m, 104 m, and 152 m) along the shelf edge of SEAS during winter monsoon 2017. Eddy-like features (*see circle*) visible at 16 m and 48 m

enhanced biological production during summer, and rich pelagic fishery contributing substantially to the country's economy. During SM, alongshore component of wind towards equator which generates Ekman transport toward offshore and the propagation of coastal Kelvin/Rossby waves are responsible for upwelling which is observed along SEAS (McCreary et al. 1993; Shankar and Shetye 1997). The clear indication of upwelling is the upsloping of isotherm with maximum intensity during July and August (Rao et al. 2005; Rao and Joshi 2008). The seasonal wind pattern, hydrography, and current structure and its spatial variation along shelf edge (~ 200-m isobath) are explained based on the above observations. The dominant northwesterly and alongshore winds observed along the southern sector (8 to 10° N), results in thermocline shallowing of the area. The observed upsloping of isotherm (26 °C) and isopycnal to the surface at south and subsurface water column at north indicates that the upwelling process is established at south and not yet active to reach the surface at north. In general, shelf hydrography of the southern sector during summer monsoon is controlled by upwelling process which brings cool water to the surface. At northern shelf upwelling features are restricted at the subsurface due to the suppressible effect of Arabian Sea High SalineWaters (ASHSW) carried by the WICC (Shetye et al. 1990) resulting limited offshore transport in upwelling (Smitha et al. 2008). Presence of turbid water was recorded at south as a result of upwelling and associated churning of water (Anilkumar et al. 2006; Chauhan et al. 2011). In winter, the shelf hydrography of the southern sector is mainly regulated by intrusion of low saline water from the BoB and associated deep homogeneous isothermal layer (80 m). As indicated by the distribution of low saline water, < 34.5 psu, the extension of the BoB water was evinced up to the shelf of 14° N and further north high saline water occupied in the water column. During WM, low saline BoB waters were carried into SEAS by EICC and WMC which feeds poleward WICC along west coast of India (Shenoi et al. 1999; Prasanna Kumar et al. 2004). This poleward WICC is fed by an anticyclonic eddy as evident in the geostrophic current pattern shown for 2013–2017 (Fig. 2, marked region). The eastern peripheral flow is well reflected in the vertical current profiles from ADCP during 2017 at 16 m and 48 m (Fig. 11a, b marked region), with velocity between 0.2 and 0.4 m/

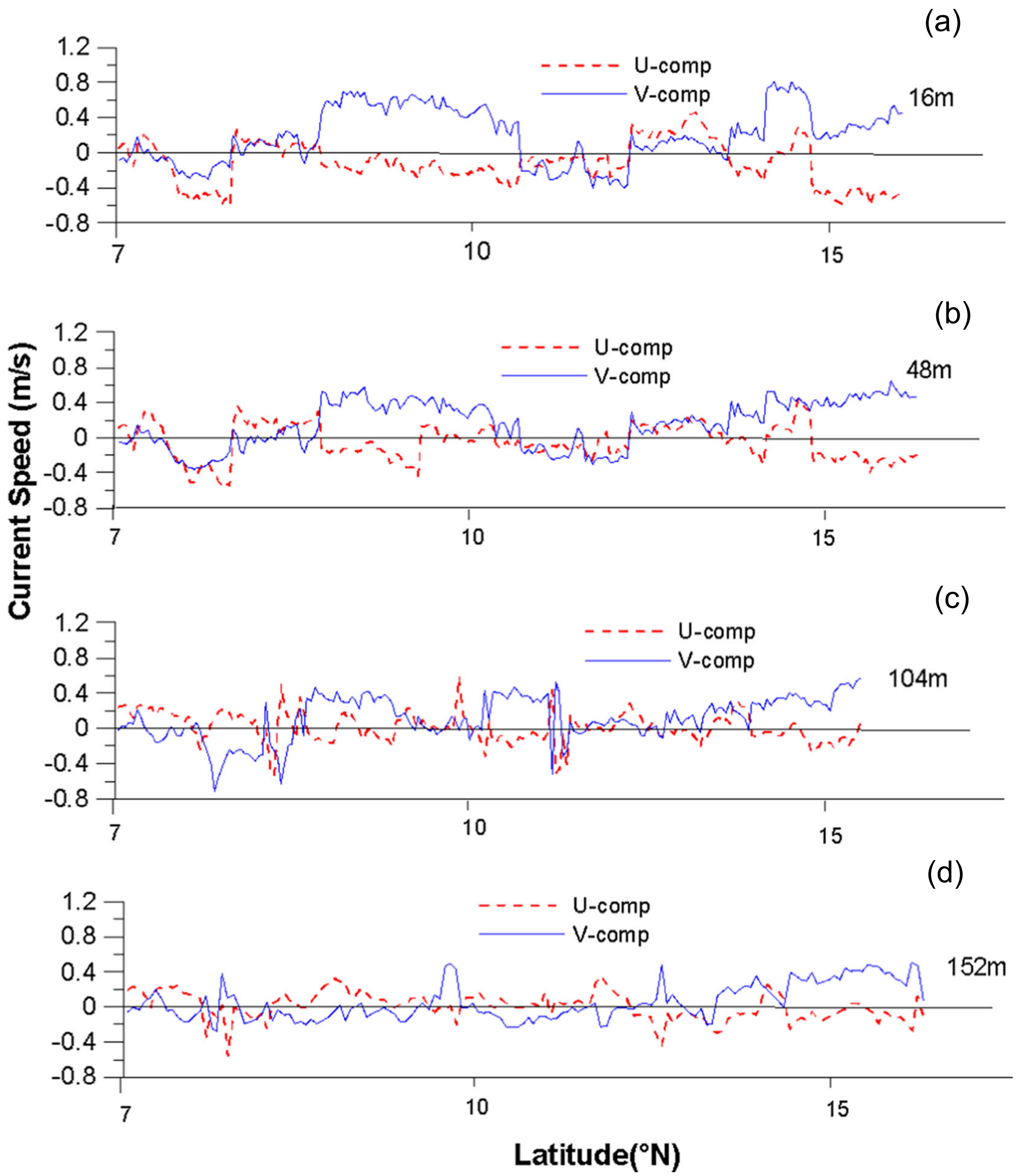

Fig. 12 **a**–**d** The *u* and *v* component of the ADCP current at different depths (16 m, 48 m, 104 m, and 152 m) along the shelf edge of SEAS during winter monsoon 2017

s in southward direction. This was associated with a comparatively deep MLD (~ 55 m) for the region, wherein mixed layer for other parts of the shelf especially towards the north is thin and as low as 10 m. The hydrography was observed to be modified by the shelf width, and thus the flow pattern of the northward coastal currents for the varying latitudes. Turbidity of the waters, especially in offshore waters, indicate the mixing/churning with the coastal systems. Frontal areas or zones where two water mass meets would be more turbid. Summer and winter is observed with more turbid waters at south, while the summer was more turbid (0.44 NTU) compared with winter (0.2 NTU), because of the upwelling resulted churning and mixing with the oceanic waters (Chauhan et al. 2011).

The current structure at surface level (16 m) along the shelf break (Fig. 5a–d) during summer monsoon

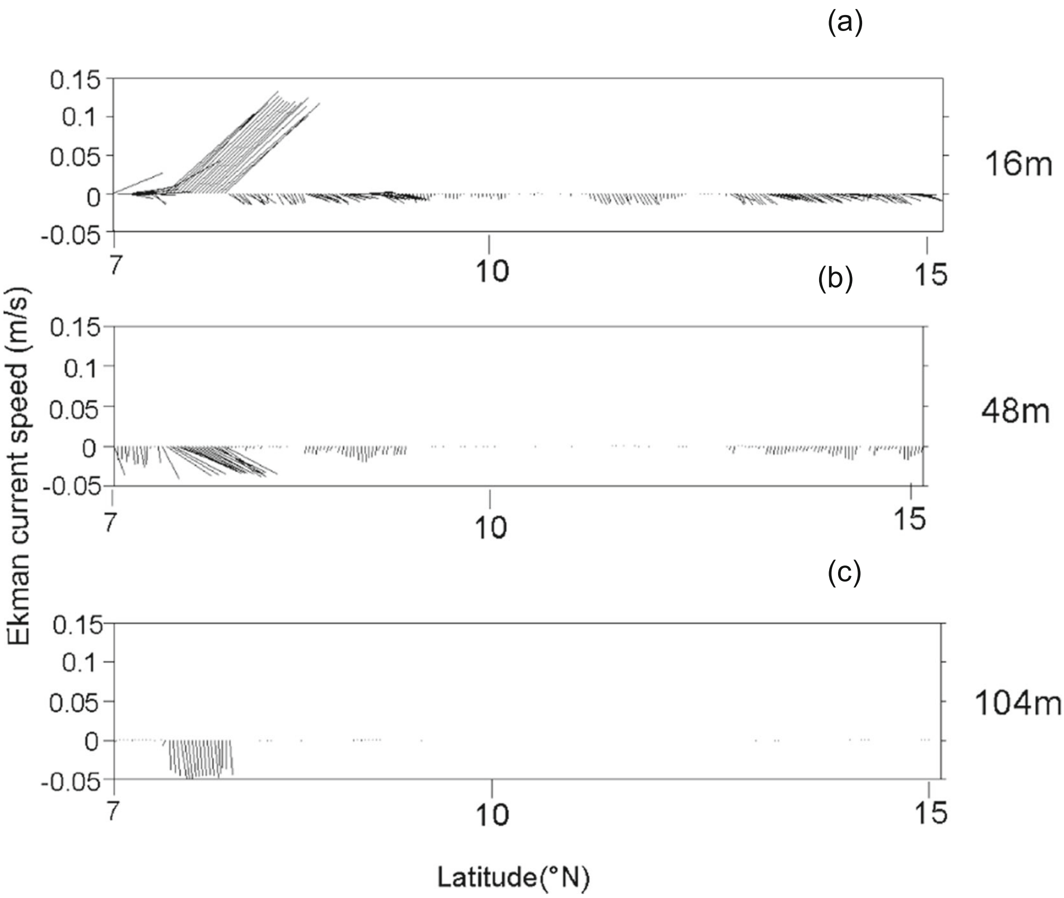

Fig. 13 **a**–**c** Stick plot of Ekman current profile at different depth level (16 m, 48 m, and 104 m) along the shelf edge of SEAS during winter monsoon 2017

indicates the currents were northward in the southern sector up to Kollam (9° N) and southwards further north. The northward flow, well organized up to 50 m depth with average speed of 0.5 m/s, indicates the eastern arm of the Lakshadweep low/cool pool (Shankar and Shetye 1997; Rao et al. 2006) which is a recurring process in the SEAS during summer monsoon. The survey track being in the eastern flank of the eddy identified, the currents were north-north westerly in the ADCP profile up to about 150 m. At 48 m water column, the poleward (northward) current extended up to Kochi (10°N), and further north, it was in the opposite direction. Measurements at 104 and 152 m indicate a highly irregular current pattern except for the middle sector where dominant flow was recorded to the south. In general, the *u* component shows a westerly dominant pattern at southern sector indicating the extended offshore transport due to upwelling to the shelf break at south. The surface flow is limited up to 104 m as evidenced in the easterly dominant flow at northern sector up to 104 m. The *v* component shows a northerly dominant flow up to Calicut, whereas southerly dominant flow at rest of the sectors. Below 104 m, *u* and *v* component shows no dominant pattern indicating the change of the direction of current as evident in Fig. 6a–d. The analysis shows that during monsoon period, the surface current pattern along the shelf edge is a part of WICC and is fed by the mesoscale features like eddies/Lakshadweep Low associated with this southward current. The circulation pattern of WICC was earlier tracked by Shetye et al. (1990), Haugen Vibeke et al. (2002), Luis and Kawamura (2004), Vimal Kumar et al. (2008); Rao et al. (2008a, b), Amol et al. (2012), and Subeesh et al. (2013), and the observations presented here are well agreeing to the same.

Ekman currents and drifts indicate the wind contribution in the current pattern (Shankar et al. 2002). The SM current pattern as estimated from Ekman indicates

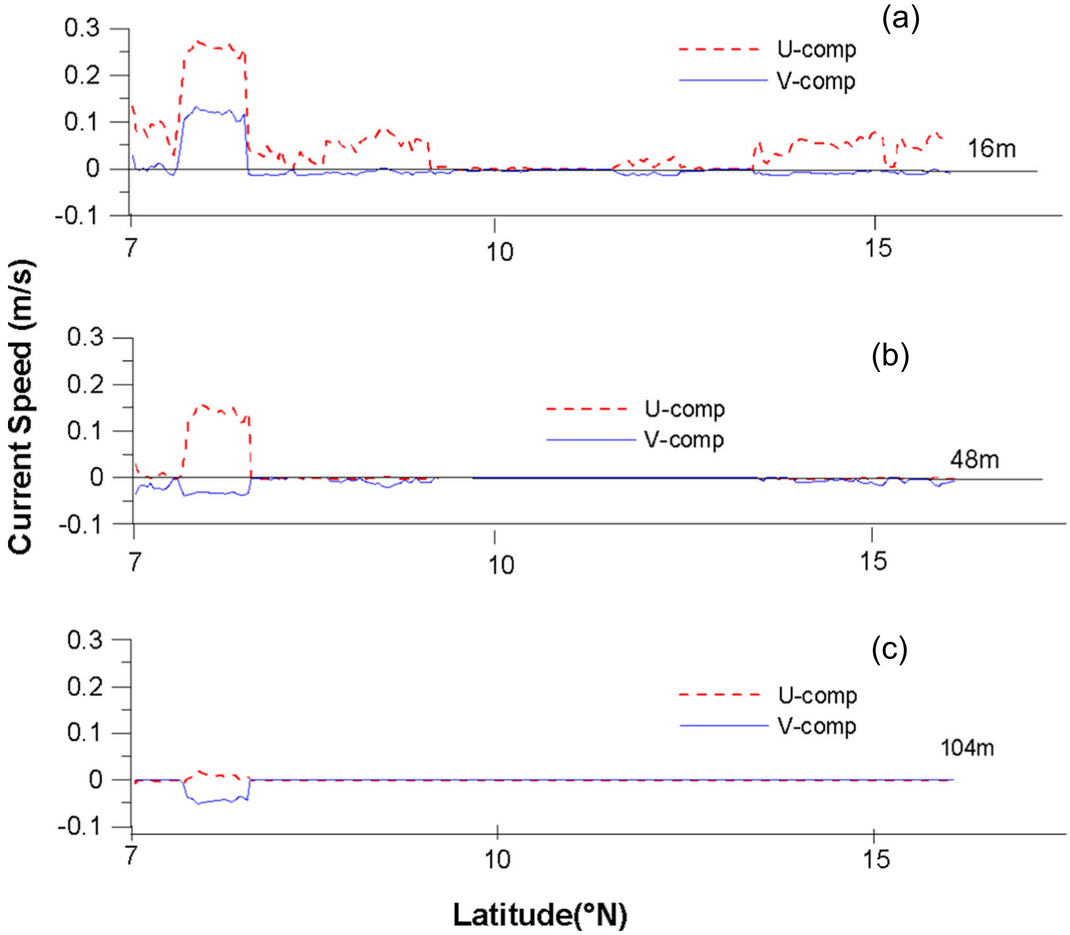

Fig. 14 **a**–**c** The *u* and *v* component of the Ekman current at different depths (16 m, 48 m, and 104 m) along the shelf edge of SEAS during winter monsoon 2017

northeastward flow throughout the study area with a mean current speed of 0.025 m/s at surface, 0.008 m/s at 48 m, and negligible at 104 m. The contributory role of wind and other remote forcing in regulating the flow pattern is addressed, comparing the ADCP as well as the Ekman outputs. This clearly depicts the weak role of wind forcing in determining the upper layer circulation of the study area (Table 2). ADCP measurements give relatively strong currents in the southern sector (8–9° N) with an average speed of 0.54 m/s, while the Ekman current (0.02 m/s) were very weak with 96.3% effect of remote forcing on the total current. This evinces the

Table 2 Sector-wise comparison of ADCP and Ekman current during summer monsoon

Depth(m)	16 m		48 m		104 m	
Lat (°N)	ADCP (m/s)	Ekman (m/s)	ADCP (m/s)	Ekman (m/s)	ADCP (m/s)	Ekman (m/s)
8–9° N	0.54	0.02	0.21	0.002	0.365	0.00004
9–13° N	0.29	0.07	0.3	0.02	0.24	0.001
13–15° N	0.17	0.05	0.5	0.008	0.41	0.0005

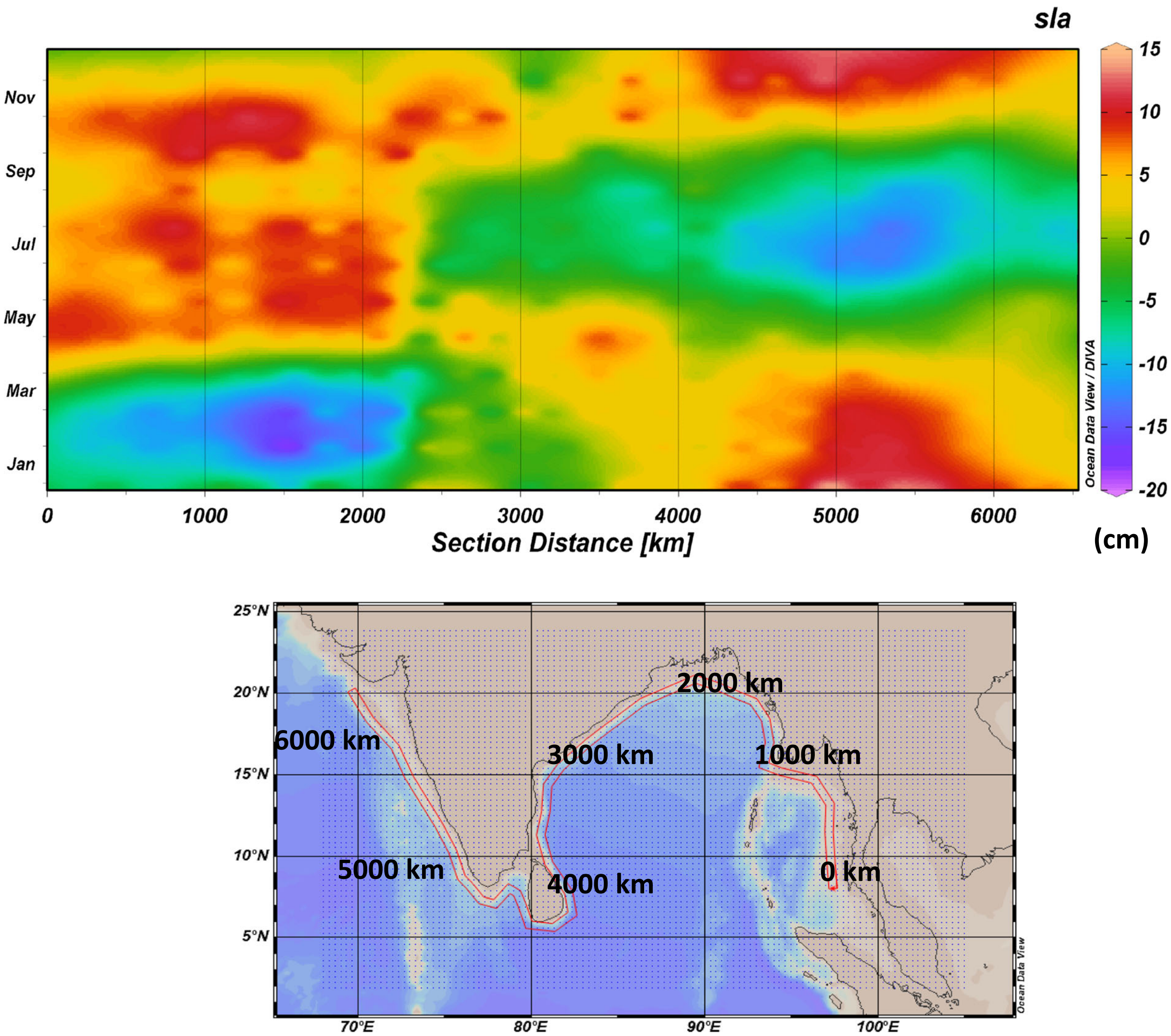

Fig. 15 Top panel indicates time distance plot of monthly climatological SLA (cm) along the shelf edge of the BoB and Eastern Arabian Sea indicating propagation of Kelvin waves. Bottom panel shows the section distance taken along the shelf boundary of the eastern BoB to the shelf boundary of the Eastern Arabian Sea

Table 3 Sector-wise comparison of ADCP and Ekman current during winter monsoon

Depth(m)	16 m		48 m		104 m	
Lat (°N)	ADCP (m/s)	Ekman (m/s)	ADCP (m/s)	Ekman (m/s)	ADCP (m/s)	Ekman (m/s)
7–8° N	0.33	0.19	0.33	0.09	0.26	0.02
8–9° N	0.4	0.02	0.21	0.002	0.365	0.0006
9–13° N	0.352	0.02	0.3	0.003	0.24	0.0001
13–15° N	0.621	0.05	0.5	0.009	0.41	0.0004

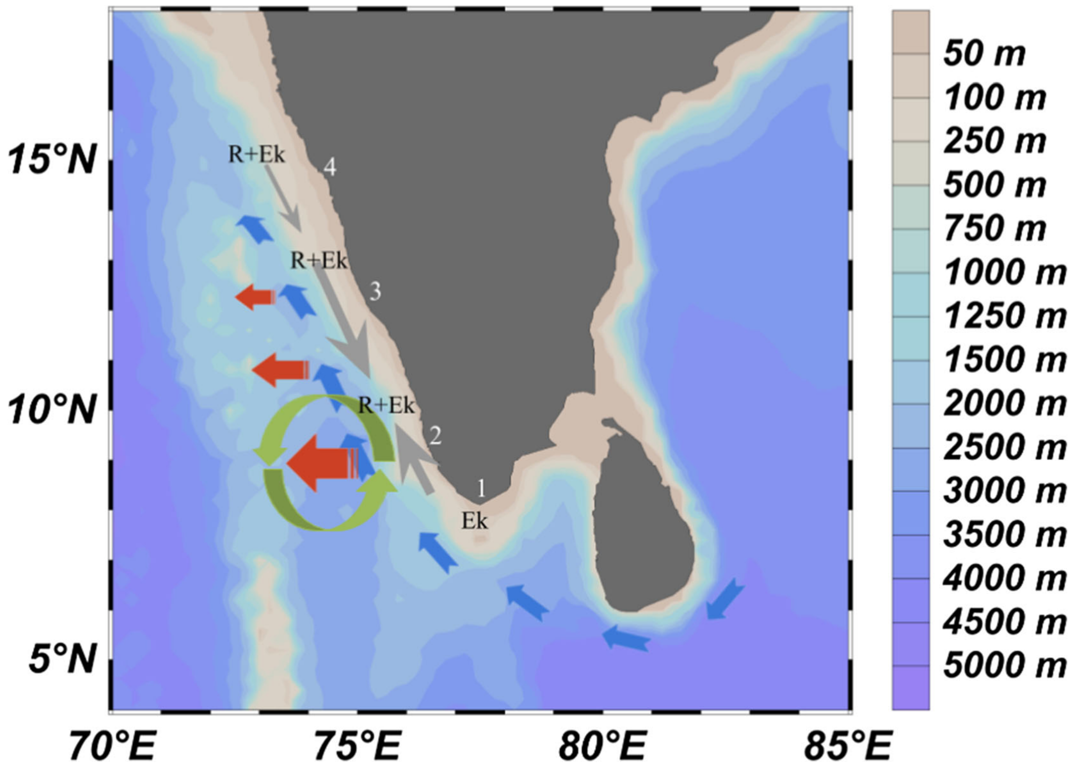

Fig. 16 Schematic representation of different zones of currents during summer monsoon based on ADCP and Ekman current computation. Zone 1 represents wind-driven Ekman forcing (Ek) as explained in Smitha et al. (2008), as the present study lacks observations in the region during summer. Zone 2 represents moderate northward flow with dominant remote forcing (*R*), zone 3 represents organized and moderate flow to the south dominated by remote forcing (*R*), and Zone 4 represents southward flow with dominant remote forcing. Blue arrows along the coast represent coastally trapped Kelvin waves (upwelling mode), and red arrows represent westward propagation of Rossby waves. Circulatory pattern in green arrows represents cyclonic gyre, Lakshadweep low. Arrows in gray represent the coastal surface current pattern observed from ADCP with size of the arrow varying according to the current strength

dominant role of remote forcing due to coastal Kelvin wave (McCreary et al. 1993; Shankar and Shetye 1997; Shankar et al. 2002) over the local wind forcing at the southern sector, in regulating the current structure.

To substantiate the indication on the presence of remote forcing along the shelf edge of SEAS, we analyzed monthly climatological SLA (1993–2009) derived from AVISO (http://apdrc.soest.hawaii.edu/) altimetry (Fig. 15). The negative value of SLA during summer monsoon along the southern part of western Bay of Bengal and eastern Arabian Sea shows propagation of upwelling mode of Kelvin waves. The high negative SLA (− 10 to − 15 cm) marked along SEAS during July–August month is related to the upwelling process over the area due to wind and propagation of coastally trapped upwelling mode Kelvin waves. Studies by Smitha et al. (2008) indicate clear zonation in the SEAS with regard to the intensity and forcing mechanism of the upwelling process during summer monsoon. They showed significant influence of alongshore wind in inducing the upwelling of the region, while the present study indicates that remote forcing does influence the current field along the shelf edge even in the southern sector (8–9° N).

Further north (9–13°N), the Ekman component (0.07 m/s) contributes 24% towards the total current (0.29 m/s) observed from ADCP, indicating 76% of the force due to remote forcing. Along 13–15°N, the Ekman (0.05 m/s) contributed 29% to the total current measured from the ADCP (0.15 m/s) indicating the role of remote forcing (71%). Earlier studies (Yu et al. 1991; McCreary et al. 1993; Shankar et al. 2002; Rao et al. 2010) explained that along the west coast of India, the sea level variations are strongly influenced by the propagation of remote forcing such as equatorial and coastal Kelvin waves around the rim of Bay of Bengal.

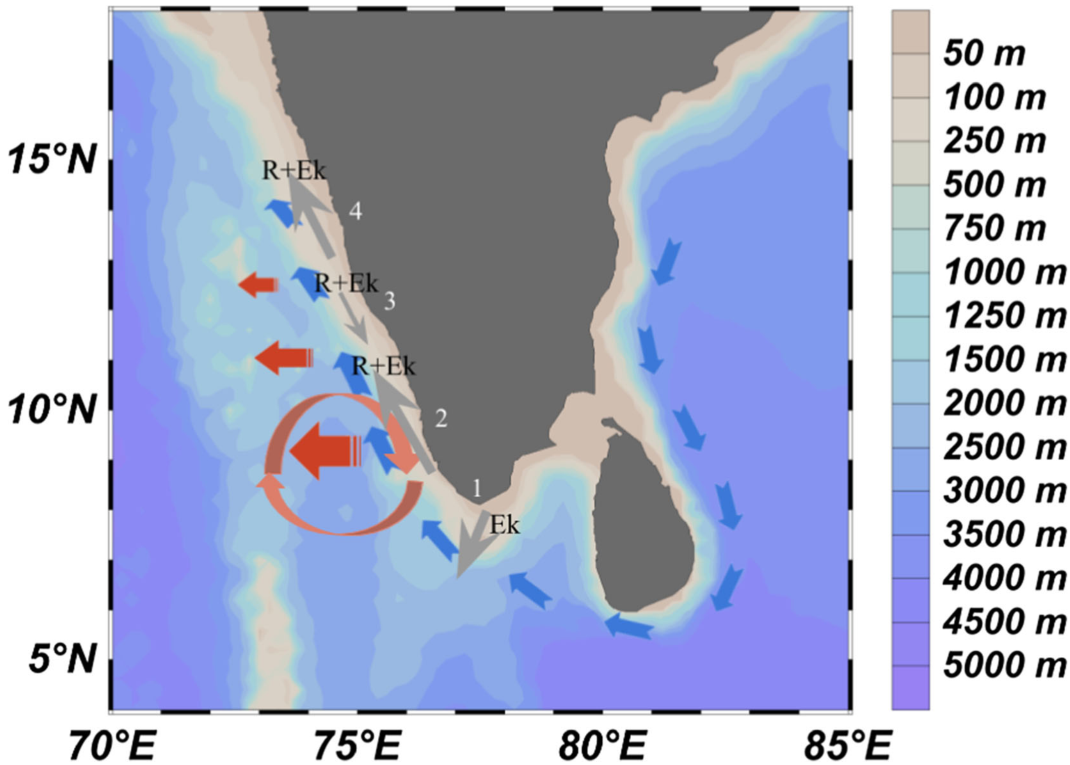

Fig. 17 Schematic representation of different zones of currents during winter monsoon based on ADCP and Ekman current computation. Zone 1 represents strong south-southwesterly Ekman component (Ek), zone 2 represents moderate northward flow with dominant remote forcing(*R*) (leaving a narrow inactive zone after zone1), zone 3 represents moderate northward flow except between 11 and 12° N (weak southward flow) with dominant role of remote forcing (*R*) (associated with weak westward component), and zone 4 represents moderate northward flow with dominant remote forcing. Arrows (in blue) along the coast represent coastally trapped Kelvin waves (down welling mode), and red arrows represent westward propagation of Rossby waves. Anticyclonic gyre/Lakshadweep high is marked as circulatory flow pattern. Arrows in gray represent coastal current at the surface observed from ADCP, with size of the arrow varying according to the current strength

Recently, studies by Suresh et al. (2016) accounted the winds near the southern tip of India and east of Sri Lanka contribute to 60%, and wind variation from the rest of the Bay and the equator contributes for 20% and 10%, respectively, towards the sea level variability along the west coast of India. The above results indicate the strong influence of remote forcing in the shelf hydrodynamics processes of SEAS during the summer monsoon as recorded in the present study.

North and northwestward flow was dominant during winter observations except between 7–8° N and 11–12° N where it was southwestward. The geostrophic current pattern shows that the survey track is in the eastern periphery of the warm core eddy or Lakshadweep high (Shankar and Shetye 1997) in the region (Fig. 2b, marked area). Earlier studies report that the surface current pattern observed are directed poleward as a part of WICC (Shetye et al. 1991; Prasanna Kumar et al. 2004), while the present observations record the modification of the pattern in the shelf edge due to the prevailing eddy. The *u* component shows a westerly dominant flow up to 104-m level whereas *v* component shows northerly dominant pattern except at southern sector up to 104 m.

During winter, overall, ADCP derived total currents and the Ekman current (Table 3) showed less influence of wind on the current field throughout the study area except in the southernmost (7–8° N) sector. ADCP current value at 7–8° N is 0.33 m/s, and the Ekman current (0.19 m/s; contributing 57% of the total) values indicates that the wind has a major role over remote forcing (43%), in the generation of current over the region. However, along the 8–9° N sector, ADCP shows moderate current of 0.40 m/s. Ekman current found is very feeble (0.02 m/s), while contribution due to remote forcing shows higher percentage (95%). This indicates flow is mainly geostrophic in the 8–9°N sector. ADCP shows the average current speed of 0.35 m/s and 0.62 m/s at 9–13° N and 13–15° N sector, where the contribution from Ekman current (0.02 m/s and 0.05 m/s) were weak, indicating the dominance of the remote forcing (94.4% and 92% respectively) on the current generation. Hence, along the 9–15° N sector, the remote force dominates over Ekman forcing. Strong currents are recorded along the 13–15° N sector which is more or less comparable with the observation made by Amol et al. (2012). The positive SLA about 10–15 cm in the climatological mean (Fig. 15) during October– November along the rim of BoB indicates propagation of coastally trapped downwelling Kelvin waves, and it travels all along eastern Arabian sea during November to February (Rao et al. 2010). Hence, the role of remote forcing along the shelf edge of SEAS during winter monsoon is well evident from the climatology of SLA as well.

Based on the above observation on hydrography and current structure prevailed over the shelf edge, a schematic representation of different zones is prepared and depicted for summer (Fig. 16) and winter (Fig. 17). Figure 16 shows that during summer, southernmost part (zone 1, the present analysis is from 8° N to northwards), currents are strong and controlled by wind-driven Ekman forcing (Smitha et al. 2008), whereas zone 2 (8–9° N) the area of moderate northward flow and remote forcing is having dominant role over Ekman in the current generation. Zone 3 (9–13° N) represents organized and moderate southward flow dominated by remote forcing than Ekman and zone 4 (13–15° N) also represents moderate southward flow with dominant role of remote forcing over Ekman in the current structure.

During winter monsoon (Fig. 17), zone 1 represents strong south-southwesterly currents, and role of Ekman component (Ek) has major role along with remote forcing in triggering/maintaining the current. Zone 2 (8–9° N) represents moderate northward flow with predominant role of remote forcing (*R*) over current generation, zone 3 (9–13° N) represents moderate northward flow except between 11 and 12° N (southward) with dominant role of remote forcing (*R*) over current generation, and zone 4 represents moderate northward flow with dominant remote forcing. This result is in agreement with the inference of Amol et al. (2012) based on the coastal-trapped wave (CTW) theory calculation that the presence of remote forcing seen all the times on the shelf off the Indian west coast.

Conclusions

Present study addresses high-resolution vertical current structure in the SEAS shelf during summer and winter monsoons. Surface current pattern during summer (winter) shows dominant equatorward (poleward) flow in the study area except south of 9° N (8° N), where the flow is in opposite direction. The comparison between ADCP and Ekman currents during the summer and winter showed the contribution of remote forcing which is more dominant when the local winds are weak. The study documents the complimentary role of remote forcing versus local forcing in the generation of shelf currents. It was noted that even when local winds are strong, the role of remote forcing were significant. Apart from this, the study also describes seasonal variability in the shelf hydrodynamics and found to be influenced by moderate upwelling during summer and intrusion of low saline BoB water and mesoscale eddies during winter.

The result of the present study point out the need for current observation in good spatiotemporal resolution to understand the shelf circulation, the mesoscale feeding to the current dynamics, and in fine tuning the modeling approach to address the ecosystem dynamics of west coast of India. Also being the merging zone between the productive coastal and normally oligotrophic oceanic systems, understanding the regional current patterns in the shelf area is significant in regard to the biogeochemistry of the region and to identify the trajectory of the microscopic organism including the phytoplankton, zooplankton, and fish egg/larvae.

The study addresses sub-regional scale variations in the forcing governing the hydrodynamics and current structure, and put forward that, in spite of the difference in seasonal oceanic response and ultimately the ecosystem impact, the boundaries and forcing parameters of influence for this demarcation are similar during summer and winter seasons. The shelf edges and the associated hydrodynamics play an important role in modulating the intake of the ecosystem, through retention and biological flux. However, this part of the area between the productive coastal and normally oligotrophic oceanic systems is normally least prioritized. Being the boundary of these two different zones, the hydrodynamics and flow pattern in detail are of concern, to substantiate any modeling effort to explain the interactions within and between the ecosystems.

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