

Nearshore currents along the Karnataka coast, west coast of India

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Abstract

Measured current data at 7 locations and the tide data at 3 locations during the pre-summer monsoon period along west coast of India is used in the study. The surface currents during March showed a predominant northward trend and during April it was towards south. Estimated tidal currents were upto 0.25 m s^{-1} with an average value of 0.08 m s^{-1} . Current tidal form number varied from 0.56 to 1 at different locations indicating currents are mixed predominantly semidiurnal. M2 and S2 tidal current constituents rotated clock wise at all locations. Near surface, the alongshore current was 2.6 to 5.9% of the alongshore wind and near bottom, it was 1.9 to 3.6% of the alongshore wind.

Key Words: Coastal currents, Harmonic constants, tidal heights and currents, sea level, atmospheric forcing, wind induced current, Arabian Sea

1. Introduction

Currents in the coastal waters are influenced by tides and as the distance from the coast increases, the currents are influenced by large scale near surface flow in the open sea. Observed coastal currents consist of wind-driven (Ekman), tidal, surface wave and geostrophic flows. The contribution of each of the above depends on the geographic location, continental slope and the coastal orientation. The circulation patterns along the west coast of India are studied mostly by observations of physical and chemical properties of seawater (Shetye et al., 1990; Muraleedharan et al., 1995; Shankar, 2000; Rao et al., 2008). Results based on direct current measurements, mostly confined to off Mumbai, Goa, Beypore and Kochi are also reported (Varkey, 1980; Shenoi et al., 1988; Unnikrishnan and Antony, 1990; Mathew et al., 1991; Shenoi and Antony, 1991; Antony and Shenoi, 1993; Hareesh Kumar and Mohan Kumar, 1996; Hareesh Kumar et al., 1996; Anilkumar and Dineshkumar, 2002; Dineshkumar and Srinivas, 2007; Shetye et al., 2008). A number of numerical studies have emphasized the importance of local and remote forcing for the circulation in the Arabian Sea (Bruce et al., 1994; Shankar and Shetye, 1997; Bruce et al., 1998; Shenoi et al., 2004). A detailed examination of the mechanisms forcing the seasonally reversing, trans-basin monsoon currents in the open ocean was presented by Shankar et al. (2002). Based on the observations made off Goa, Shetye et al (2008) found that during March-April, the West India Coastal Current (WICC) was forced both remotely and locally at periods exceeding 10 days; at periods less than 10 days, the WICC was locally forced.

Erosion and shoreline changes are observed at few locations along the Karnataka coast. Since information on nearshore currents along the coast is not available, currents were measured at 7 locations covering the coast of Karnataka state. In the present study we have examined the variations of the currents covering 200 km along the Karnataka coast, west coast of India based on the measured data for 30 days period during March-April 2008. The objective of the study is to identify the tidal and non-tidal currents at different locations along the Karnataka coast and study the relationship between wind, sea level and currents.

1.1 Study area

Coastal segment along the study region is bounded by Western Ghats in the east and the Arabian Sea in the west. The continental shelf off Karnataka has an average width of 80 km. The coastline at Karwar is inclined 24° to the west from the true north. Bathymetry is relatively simple with depth contours aligned approximately parallel to the coastline. Depth contours of 20, 50, 100 and 200 m occurs at 10, 30, 75 and 100 km off Karwar and 12, 48, 90 and 108 km off Malpe (Figure 1). Coastline at Honnavar and Malpe are inclined 17° to the west from the true north. There are a few islands off the coast, the major group being St. Mary's Island, 4 km off the coast near Malpe. The rivers joining the Arabian Sea along the Karnataka coast are Kali, Gangavali, Aganashini, Sharavathi, Hangarkatta and Gangolli. Sand bars are seen in most of the estuaries. The coast is exposed to seasonally reversing monsoon

winds, with winds from the southwest direction during the southwest (summer) monsoon period (June to September) and from the northeast during the northeast (winter) monsoon period (October to January). The southwest monsoon winds are strong and the annual rainfall is 3 m. Tides in the region are mixed and are predominantly semidiurnal and the range of which slightly increases to north. The average monthly sea level at Karwar varies from 1.06 m in September to 1.3 m in January. The average tidal range at Karwar is 1.58 m during spring tide and 0.72 m during neap tide.

2. Materials and methods

The current measurements were carried out using the RCM9 self-recording current meters (Aanderaa Data Instruments, Norway) at 7 locations C1 to C7 (Table 1). Current data was collected at every 10 minutes interval for a period of one month during March-April 2008. The RCM9 speed sensor has an accuracy of $\pm 2\%$ of the recorded speed. The current speed range is 0 to 3 m s⁻¹. The accuracy of current direction is $\pm 5^\circ$. The resolution is 0.35°. Temperature is measured by a thermistor fitted into a stud in current meter, which extends into the water. The accuracy of temperature sensor is $\pm 0.05^\circ\text{C}$. The range is -0.64 to 32.87°C and the resolution is 0.1% of selected range.

Along with the current meters, Valeport Tide gauge (Valeport Limited, UK) was deployed to collect the sea level data at locations C1, C3, C5 and C7. Sea level data was collected at every 10 minutes interval for one month period during March-April 2008. The Valeport tide gauge at location C1 was towed away from the moored location by fishing vessels and could not be traced at the moored location and hence the data could not be recovered.

All directions use the oceanographic convention and show the direction towards which the wind or current is moving. Currents at each station were resolved into zonal (u -component) and meridional (v -component) directions, with the flow to the east and to the north being defined as positive. The sea level and current components were subjected to harmonic analysis to determine the amplitudes and phases of the tidal constituents (Emery and Thomson, 1998; Pugh, 1987). Tidal analysis was carried out using standard harmonic method, where a finite set of cosine functions with frequencies at the known astronomical forcing frequencies were fitted to the data using the least square method. Tidal Analysis Software Kit, TASK (Bell *et. al.*, 2000) developed by the Proudman oceanographic laboratory, UK was used for the analysis. Analysis was done with 24 independent constituents and 8 related constituents recommended for one month data of tides and currents. Removal of tidal component from the current observations leaves residuals that include contributions from direct wind forcing, indirect wind forcing, surface waves and horizontal and vertical density gradients (Prandle, 1997). The residual zonal and meridional current components at Karwar, Honnavar and Malpe were rotated counter clockwise by 25° , 17° and 17° respectively to obtain cross shore and alongshore components.

Reanalysis data of zonal and meridional components of wind speed at 10 m height at 6 hourly intervals from NCEP / NCAR (Kalney *et.al.*, 1996) was obtained for the point (12.5° N; 72.5° E) close to the

study area to know the influence of wind on sea level and currents. These data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at <http://www.cdc.noaa.gov/>. Relationship between wind forcing and near surface and near bottom response was studied by linear regression analysis.

The temperature sensor of the current meter was used to obtain the sea water temperature at different depths at locations C1 to C7.

3. Results

3.1 Sea level

During the measurement period, the maximum tidal range was 1.8, 1.9 and 2.1 m at Malpe, Kundapur and Honnavar (Kumar et al., 2011). Predominant tidal constituents were M2, S2, N2, K1, O1, Q1, J1 and M4 with constituent M2 having the highest magnitude followed by constituent K1. Based on the form number, which is the ratio of sums of the amplitudes of the diurnal constituents (K1 and O1) to that of the semidiurnal constituents (M2 and S2), tides are classified as mixed and predominantly semidiurnal in nature. The mean spring tide range is 1.41, 1.3 and 1.21 m at Honnavar, Kundapur and Malpe and the mean neap tide range is 0.66, 0.61 and 0.56 m (Kumar et al., 2011). Form number is found to increase from the north to the south along the coastline. Srinivas and Dineshkumar (2002) found the form number to be 0.80 for Beypore which is 270 km south of Malpe. The non-tidal sea level variation at all the three locations was similar and is mainly due to the v-component (meridional) of wind. When the wind from south was strong, a rise in sea level was observed and when the wind from north was strong, a fall in sea level was observed.

3.2 Currents

The measured current was upto 0.6 m s^{-1} with an average value of 0.2 m s^{-1} (Table 2). The v-component of current dominated the u-component at all the stations (Figure 2) which results in a large alongshore flow than the cross shore flow, similar to that reported earlier (Shenoi & Antony, 1991; Hareesh Kumar & Mohan Kumar, 1996; Dinesh Kumar and Srinivas, 2007). There was no significant variation in the currents measured at 20 m water depth and that measured at 10 m water depth (Figures 2 and 3). It is apparent that the surface currents are slightly stronger than the bottom and the strength of bottom v-component of currents was 80% of the respective surface current at Karwar and Honnavar. The estimated tidal currents were upto 0.25 m s^{-1} with an average value of 0.08 m s^{-1} (Table 2). The u and v component of tidal currents at 20 m water depth were maximum at south (Malpe) and were slightly reducing towards north and was minimum at Karwar (Table 2). At Karwar, the tidal current at 10 m water depth was higher than that at 20 m water depth since the current measurement location at 10 m water depth was close to the Kali river mouth. Tidal currents were relatively weak, accounting

for less than 10% of the total current variance in 20 m water depth and at around 12% at 10 m water depth.

The Tidal ellipse parameters were calculated based on Xu (2000) and found that the ellipse was largely aligned in the direction of depth contour (Tables 3 and 4). Constituents M2 and K1 have the highest magnitude of tidal velocities. The current tidal form number measured varied from 0.56 to 1.0 at different locations indicating currents are mixed. Amplitude of M2 major axis varied from 3.8 to 7.5 cm s⁻¹ along the Karnataka coast. M2 and S2 constituents rotated clock wise at all locations near surface and bottom and M2 tidal ellipses are oriented along shore. The alongshore component of residual current was found to vary with the residual water level (Figures 4 and 5). When the alongshore residual current was towards north, there was a rise in water level and when the current was towards south, there was a fall in water level. The cross shore component of residual currents near surface and bottom showed negative correlation at 20 m water depth indicating vertical shear (Figure 7A). The cross shore component of currents near surface and bottom was in opposite direction at Malpe showing stratification of water column at 20 m water depth. The alongshore component of residual current at surface and bottom showed high correlation with correlation coefficients ranging from 0.8 to 0.9 (Figure 7B).

The surface currents during March showed a predominant northward trend and during April it was towards south. The net movement was 5 cm s⁻¹ towards north at Karwar and was 6 cm s⁻¹ towards south at Malpe. At Honnavar and Kundapur, the net movement was negligible (Figure 8). Comparison of near surface currents with the winds shows that the residual along-shore current responds to varying alongshore wind forcing (Figure 9A). But the cross shore residual currents were not found to vary with the corresponding cross shore wind (Figure 9B).

3.3 Temperature

The average temperature varied from 29.1 to 29.6 °C (Table 5). The nearshore waters were slightly warmer than the offshore waters with increase in mean temperature of 0.2 °C. Mean temperature difference between surface and bottom at 20 m water depth is 0.1 and 0.3 °C at Honnavar and Malpe. The larger temperature difference between surface and bottom waters at Malpe shows the stratification of water. The fluctuations in temperature near surface had standard deviation of 0.34, 0.33 and 0.46 °C at Karwar, Honnavar and Malpe and the corresponding standard deviation near bed was 0.28, 0.25 and 0.29 °C.

4. Discussion

The study summarizes the results of the measurements carried out to study the tidal and non-tidal currents along the Karnataka coast based on direct current measurements. Study shows that the tidal currents were relatively weak, accounting for less than 10% of the total current variance in 20 m water

depth and at around 12% at 10 m water depth. The cross shore component of currents near surface and bottom was in opposite direction at Malpe showing stratification of water column at 20 m water depth. The larger temperature difference between surface and bottom waters at Malpe also indicates stratification of water. Wind induced flow in shallow coastal region may have considerable vertical shear associated with it. Davies (1981) observed that in German Bight a shallow region with depth below 35 m, under the influence of northerly winds, surface currents were essentially onshore, whereas bottom currents were offshore. A three dimensional model is required to reproduce the onshore surface current and offshore bottom currents. The alongshore component of residual current at surface and bottom showed high correlation with correlation coefficients ranging from 0.8 to 0.9.

Shenoi and Antony (1991) reported that the mean alongshore flows along the west coast of India were southward during March–May. Dinesh Kumar and Srinivas (2007) reported that surface currents during February–March at south-west coast of India showed southward movement. The alongshore components of large-scale circulation also indicate a southerly component during March–September and a northerly component during November–January (Shenoi and Antony, 1991; Shetye and Shenoi, 1988; Shankar, 2000). The present study shows that winds during March tend to drive water northward and during April drive southward. Wind induced currents based on laboratory studies by Wu (1983) and observations on Lake Huron by Churchil and Csanady (1983) is approximately 3% of the wind speed and nearly parallel to the wind direction. In the present study the alongshore currents near surface at 20 m water depth was 2.6 to 5.9% of the alongshore wind speed and near bottom it was 1.9 to 3.6 % of the alongshore wind speed. The mid depth currents at 10 m water depth was 2.7 to 4.4% of the wind speed. When the v-component of wind was towards north, onshore surface currents was observed. When the v-component of wind was towards south the surface currents were towards offshore and bottom currents were towards onshore at Malpe. During the measurement period, 97% of the variation in measured sea level was due to tide at Honnavar and Malpe and 96% of the sea level variation were due to tide at Kundapur which indicate that tides are responsible for most of the observed sea level variability along the Karnataka coast (Kumar et al., 2011).

5. Conclusions

The current measurements at 7 locations in the nearshore waters of the Karnataka coast shows that during the pre summer monsoon period, the current speed was upto 0.6 m s^{-1} with an average value of 0.2 m s^{-1} . The meridional component of current dominated the zonal component at all the stations and resulted in large alongshore flow than the cross shore flow. In the measured near surface currents, 4.3 to 7.3% of the v-component was due to the alongshore winds and near bottom it was 2.9 to 4%. Good correlation was observed between alongshore component of currents near surface and bottom. The cross shore component of currents near surface and bottom was in opposite direction showing stratification in water column at 20 m water depth off Malpe. The surface currents during March showed a predominant northward trend and during April it was towards south. The net movement was 5 cm s^{-1}

towards north at Karwar and was 6 cm s^{-1} towards south at Malpe. At Honnavar and Kundapur, the net movement was negligible. The estimated tidal currents were upto 0.25 m s^{-1} with an average value of 0.08 m s^{-1} . Study shows that the tidal currents were relatively weak, accounting for less than 10% of the total current variance in 20 m water depth and at around 12% at 10 m water depth. The current tidal form number varied from 0.56 to 1.0 at different locations indicating currents are mixed. M2 and S2 tidal current constituents rotated clock wise at all locations. Sea level data collected at 3 locations reveals that tides are responsible for most of the observed sea level variability along the Karnataka coast.

6. Acknowledgments

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7. References

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Figure Legends

Figure 1. Location of measurements (C1 to C7 are current measurement locations and sea level data collected at C1, C3, C5 and C7)

Figure 2. Time series variation of (a) residual water level at Honnavar, Kundapur and Malpe and (b) v component of wind speed (Kumar et. al. 2011)

Figure 3. Variation of measured zonal (u) and meridional (v) component of currents near surface and bottom at 20 m water depth off Karwar, Honnavar and Malpe

Figure 4. Variation of measured zonal (u) and meridional (v) component of mid depth currents at 10 m water depth off Karwar, Honnavar, Kundapur and Malpe

Figure 5. Variation of zonal (u) and meridional (v) component of residual currents near surface and bottom at 20 m water depth off Karwar, Honnavar and Malpe along with the residual water level (r)

Figure 6. Variation of zonal (u) and meridional (v) component of residual currents near mid depth at 10 m water depth off Karwar, Honnavar, Kundapur and Malpe along with the residual water level (r)

Figure 7. Variation of (A) cross shore residual currents near bottom with surface and (B) along shore residual currents near bottom with surface in 20 m water depth at Karwar, Honnavar and Malpe

Figure 8. Progressive vector plot of currents measured at (a) Karwar, (b) Honnavar, (c) Kundapur and (d) Malpe

Figure 9. Variation of (A) alongshore near surface residual current (v_r) with alongshore wind (B) cross shore near surface residual current (u_r) with cross shore wind at Karwar, Honnavar and Malpe

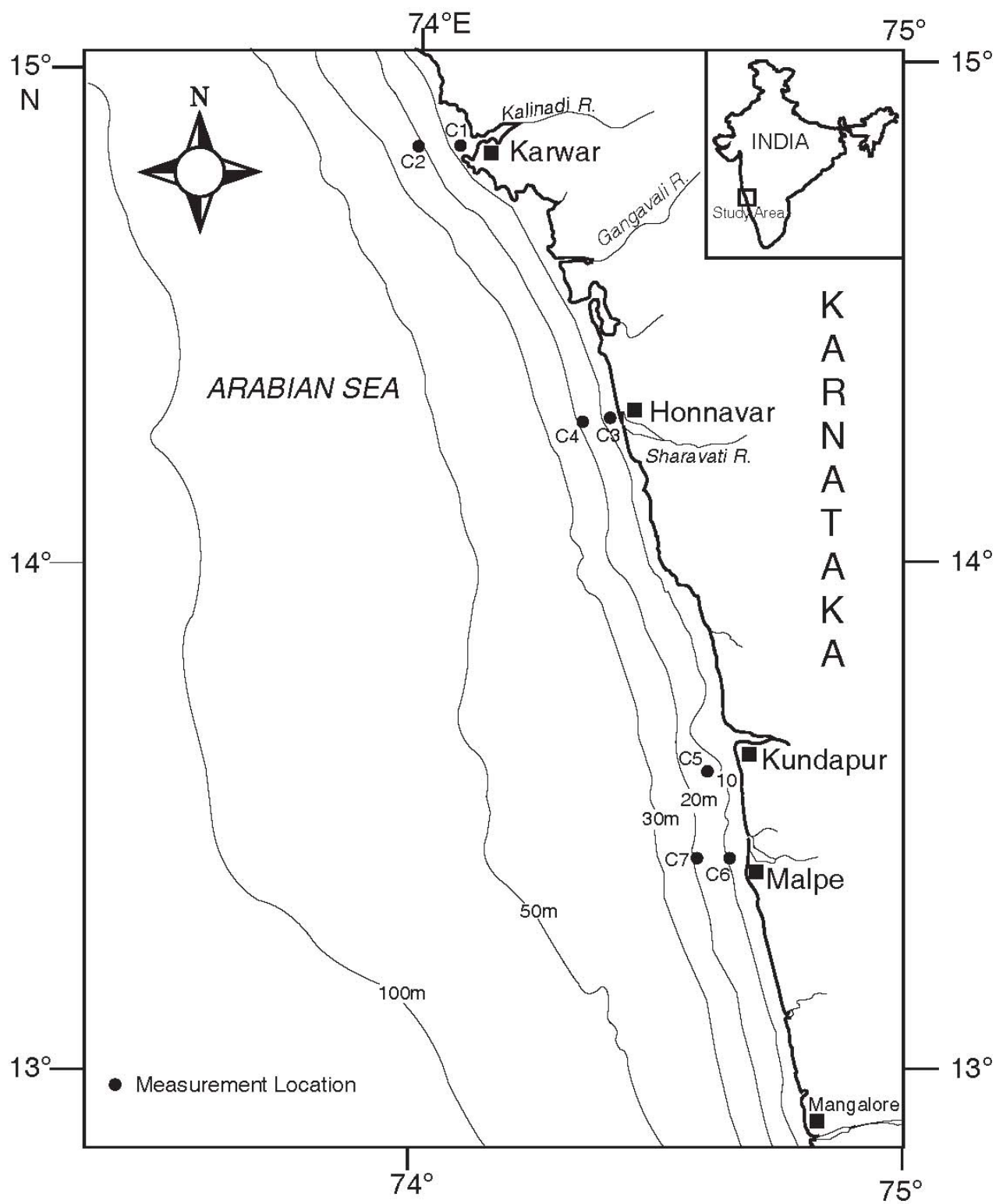


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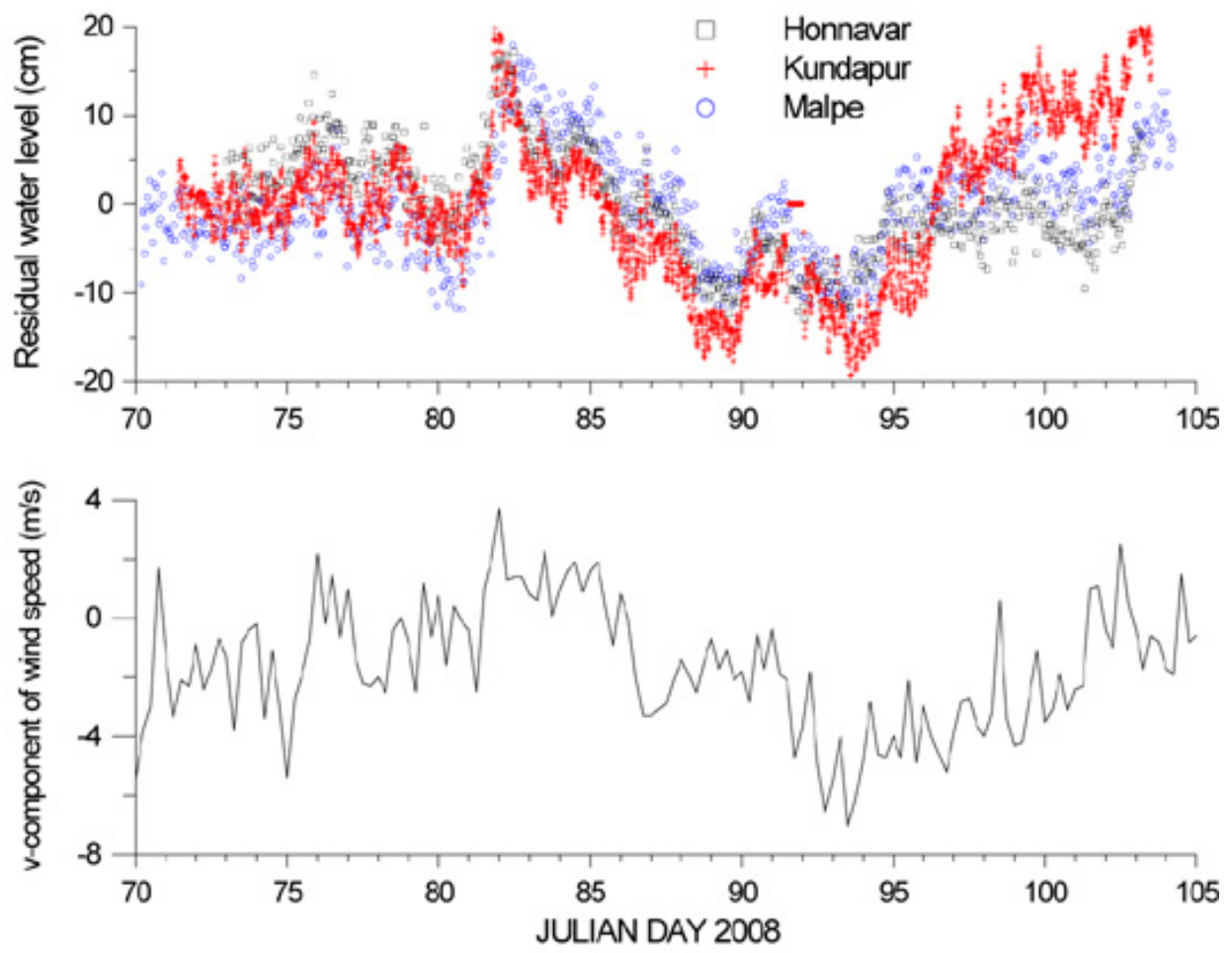


Figure 2. Time series variation of (a) residual water level at Honnavar, Kundapur and Malpe and (b) v component of wind speed (Kumar et. al. 2011)

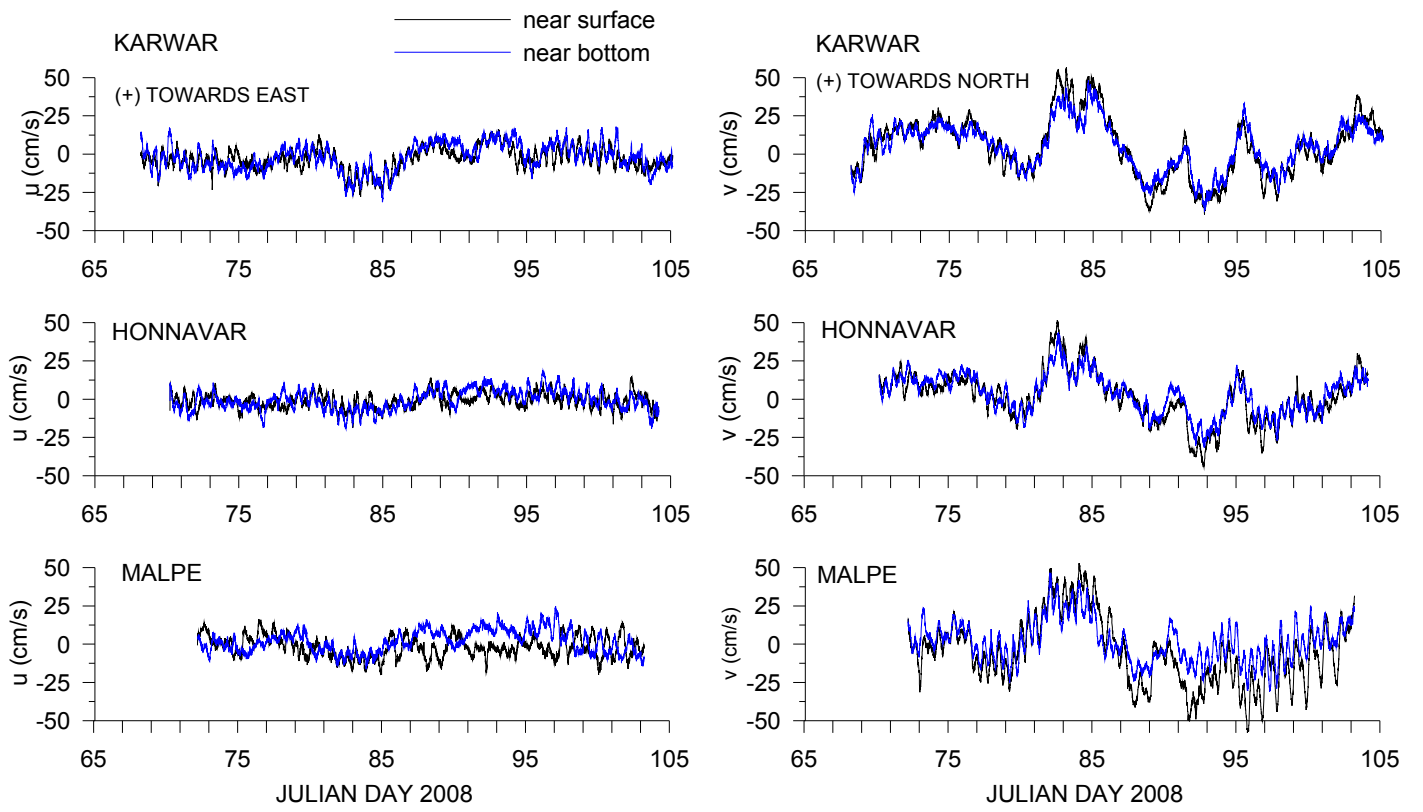


Figure 3. Variation of measured zonal (u) and meridional (v) component of currents near surface and bottom at 20 m water depth off Karwar, Honnavar and Malpe

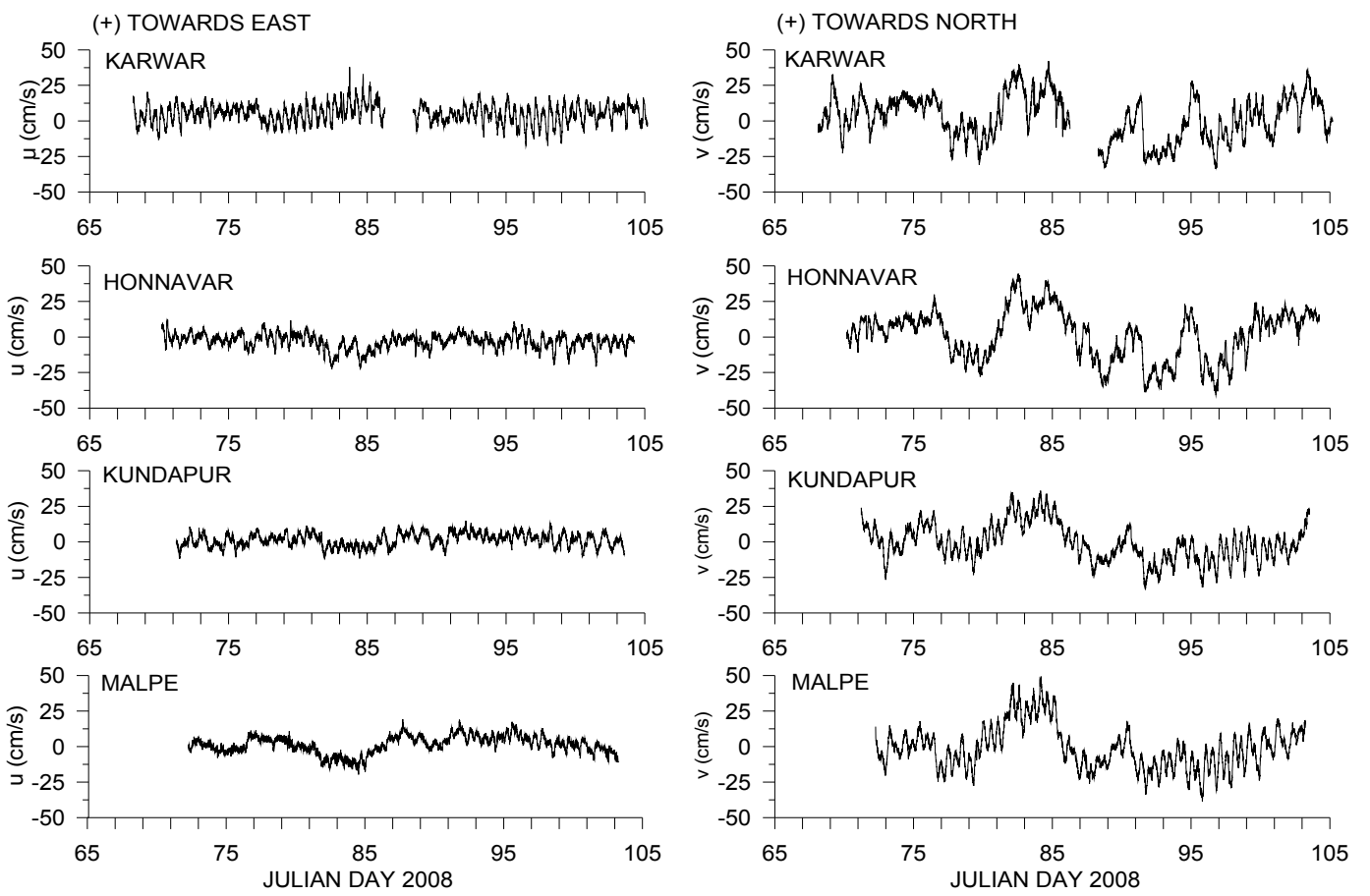


Figure 4. Variation of measured zonal (u) and meridional (v) component of mid depth currents at 10 m water depth off Karwar, Honnavar, Kundapur and Malpe

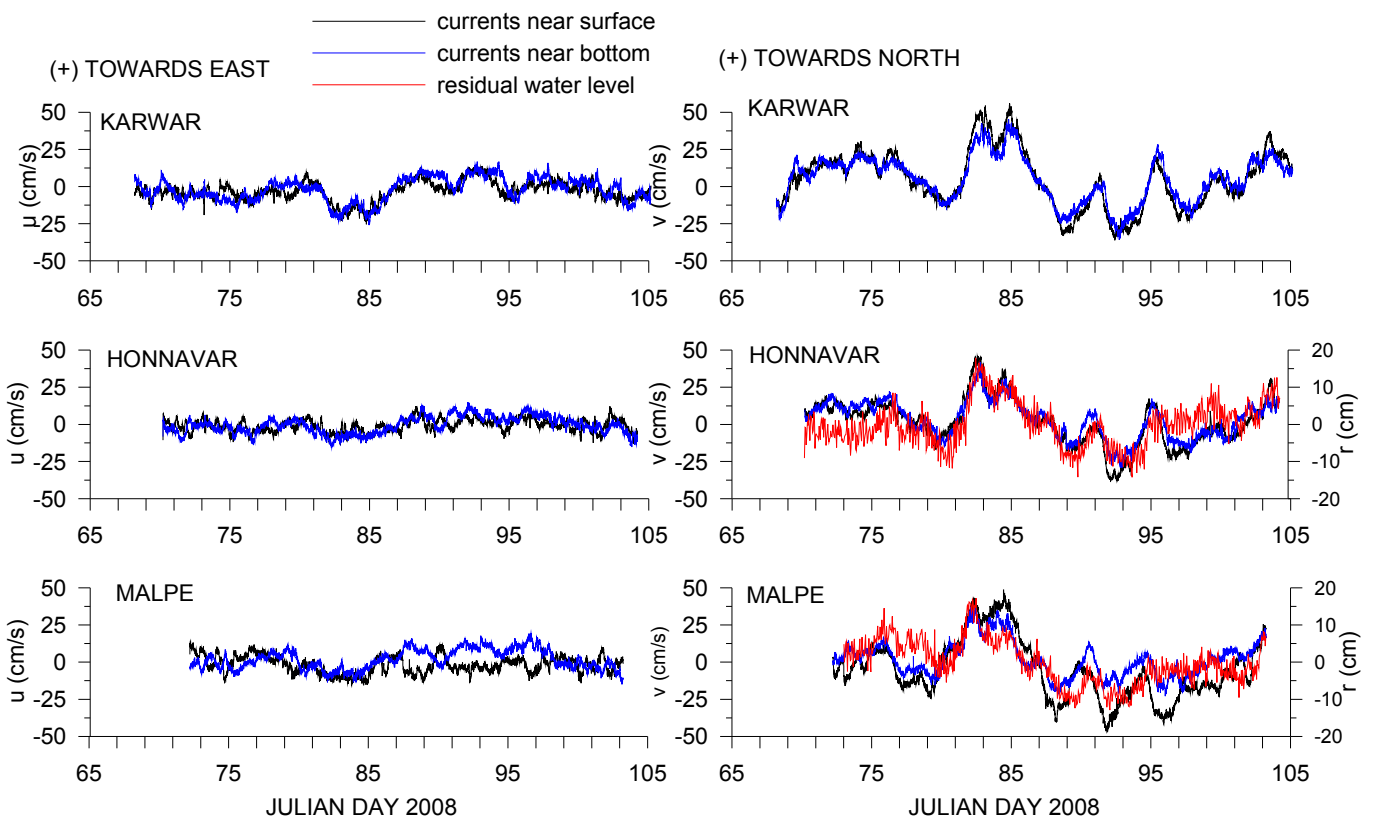


Figure 5. Variation of zonal (u) and meridional (v) component of residual currents near surface and bottom at 20 m water depth off Karwar, Honnavar and Malpe along with the residual water level (r)

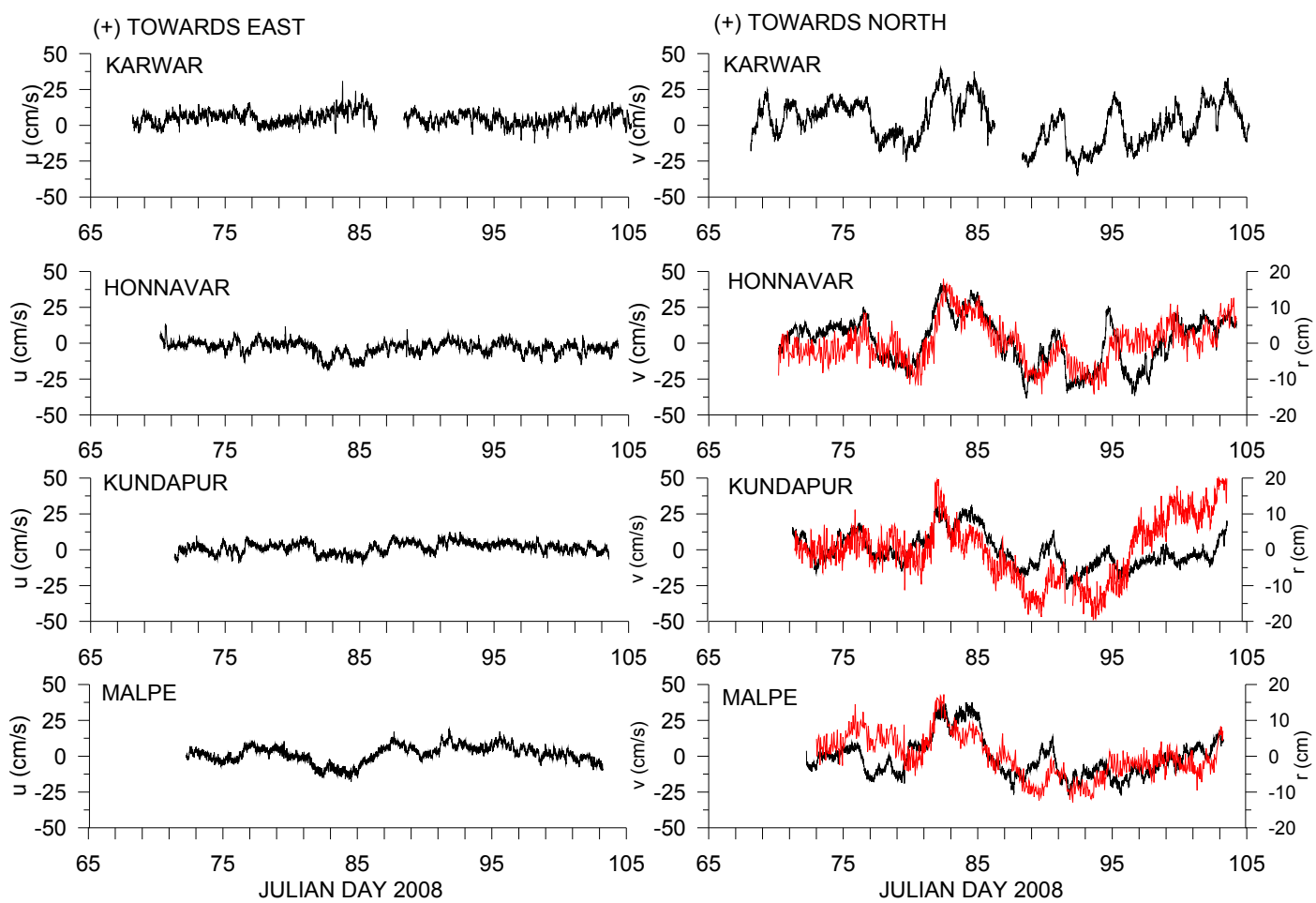


Figure 6. Variation of zonal (u) and meridional (v) component of residual currents near mid depth at 10 m water depth off Karwar, Honnavar, Kundapur and Malpe along with the residual water level (r)

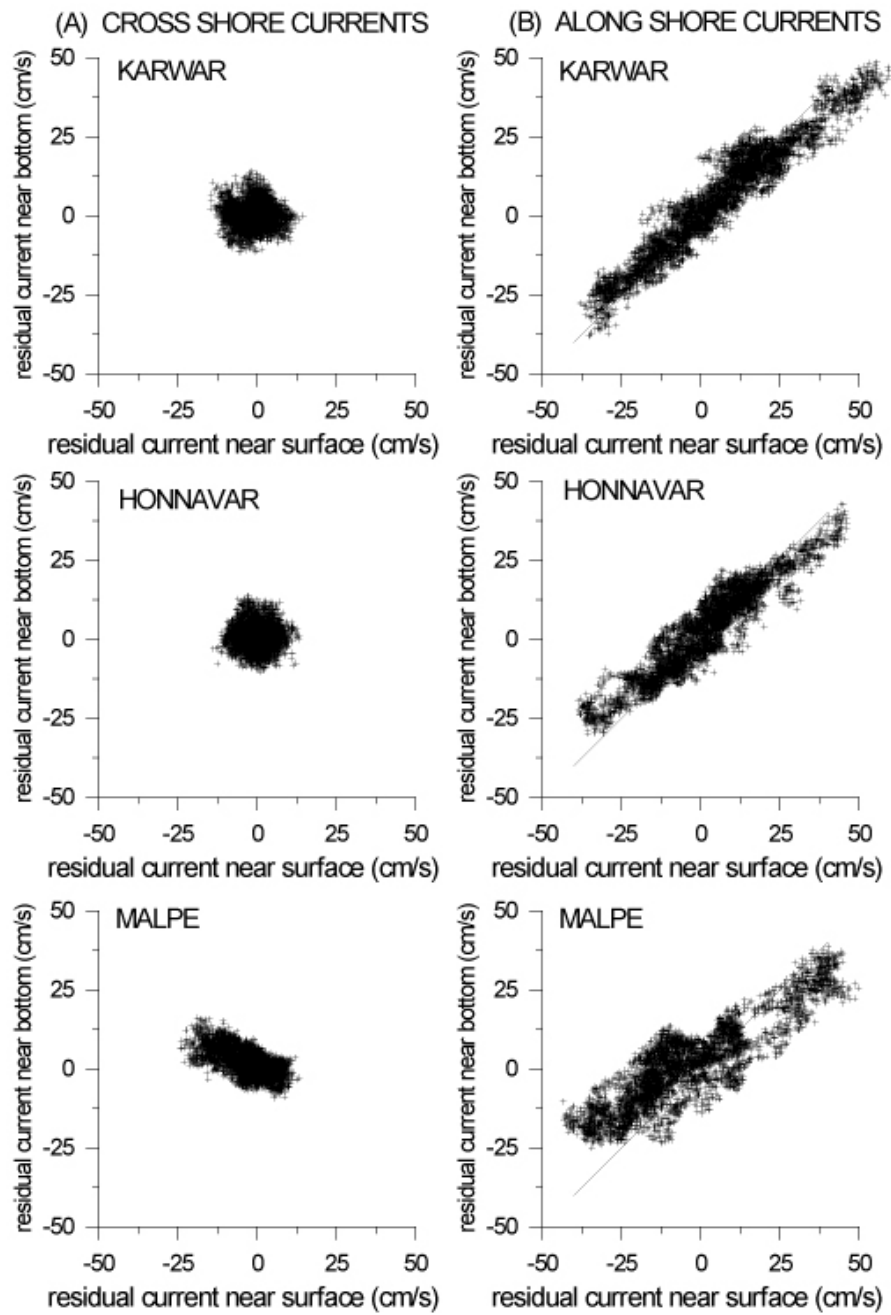


Figure 7. Variation of (A) cross shore residual currents near bottom with surface and (B) along shore residual currents near bottom with surface in 20 m water depth at Karwar, Honnavar and Malpe

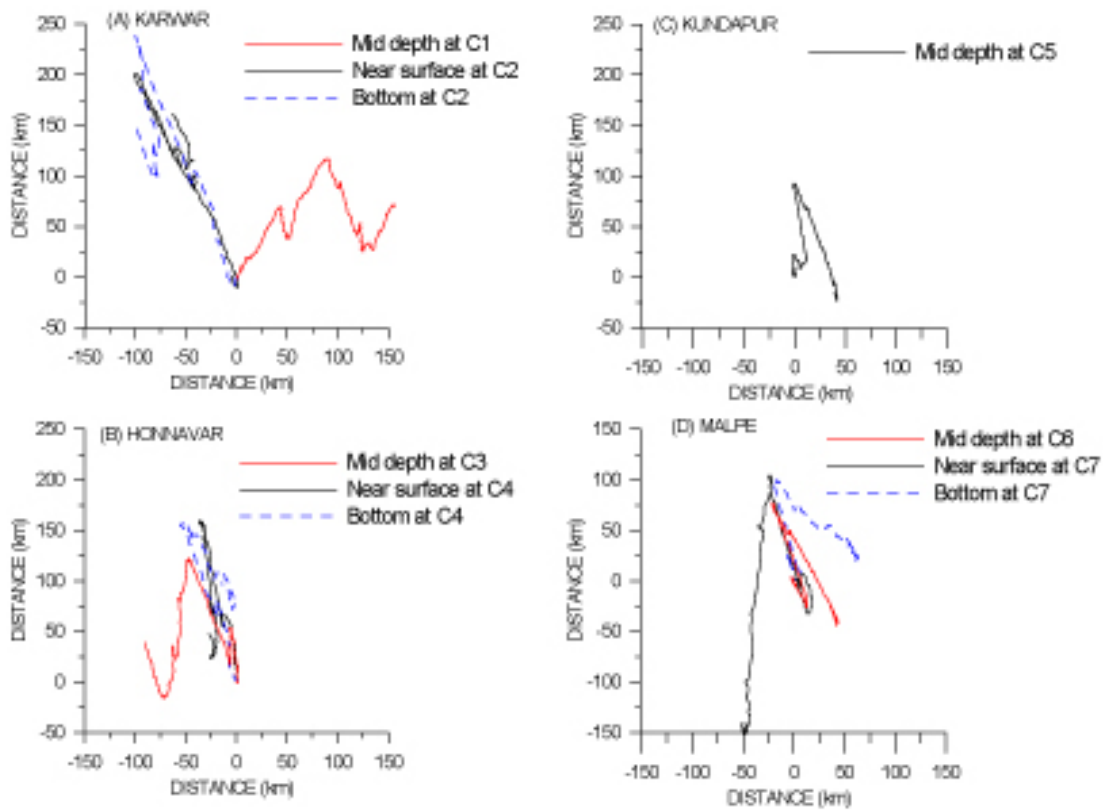


Figure 8. Progressive vector plot of currents measured at (a) Karwar, (b) Honnavar, (c) Kundapur and (d) Malpe

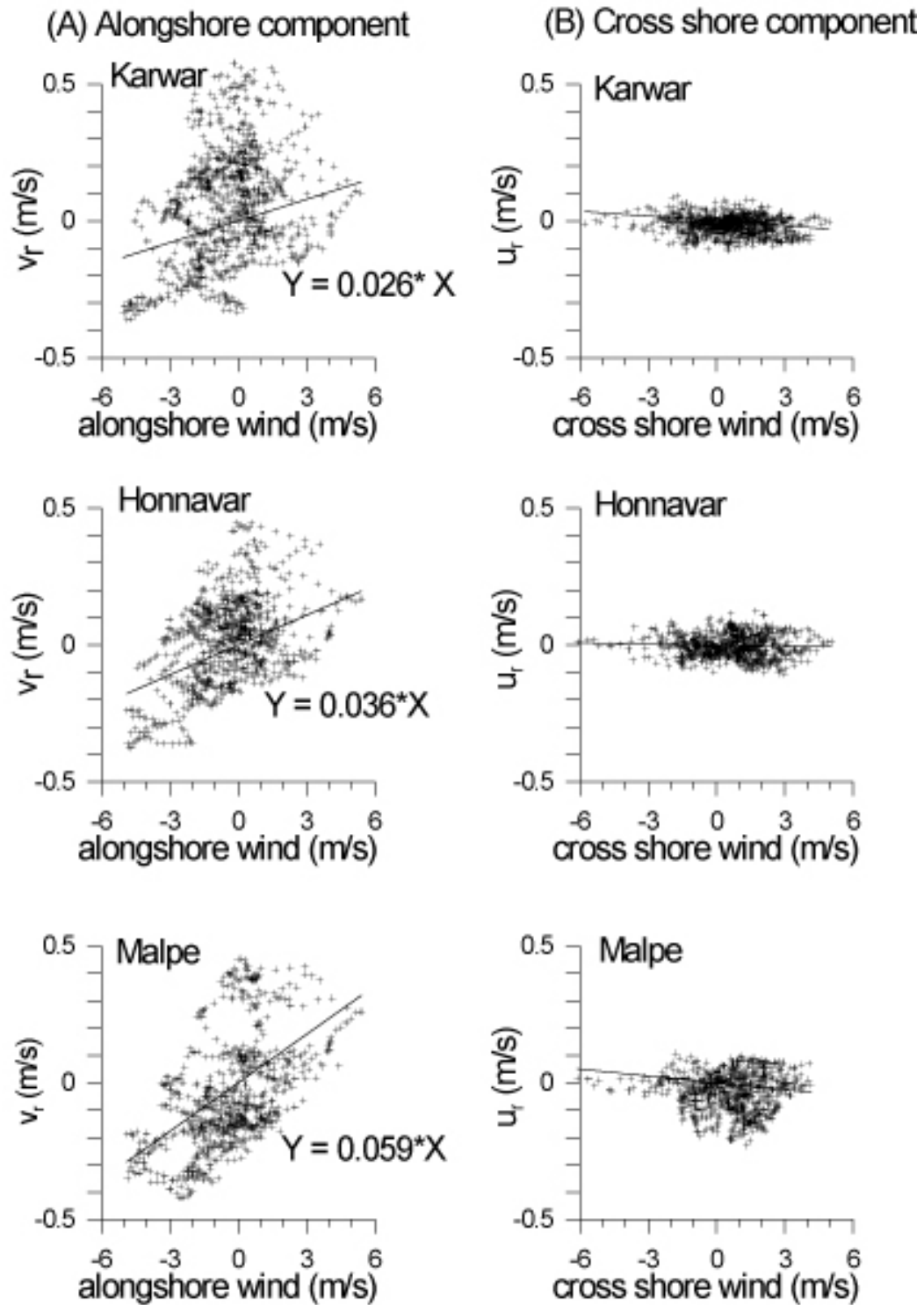


Figure 9. Variation of (A) alongshore near surface residual current (v_r) with alongshore wind (B) cross shore near surface residual current (u_r) with cross shore wind at Karwar, Honnavar and Malpe

Table 1. Locations considered in the present study along with period of measurement and measurement depth.

Sr No.	Location	Latitude	Longitude	Water depth (m)	Measurement depth from surface (m)	Period of measurement
1	Karwar (C1)	14° 49.452'N	74° 04.943'E	10	4.5 (mid depth)	9 March 2008 to 15 April 2008
2	Karwar (C2)	14° 50.270'N	74° 00.263'E	20	7.5 and 15 (near surface and bottom)	9 March 2008 to 15 April 2008
3	Honnavar (C3)	14° 18.265'N	74° 23.407'E	10	4.5 (mid depth)	11 March 2008 to 14 April 2008
4	Honnavar (C4)	14° 18.276'N	74° 19.062'E	20	6.5 and 14 (near surface and bottom)	11 March 2008 to 14 April 2008
5	Kundapur (C5)	13° 36.154'N	74° 37.923'E	10	5 (mid depth)	12 March 2008 to 13 April 2008
6	Malpe (C6)	13° 18.539'N	74° 40.384'E	10	4.5 (mid depth)	13 March 2008 to 13 April 2008
7	Malpe (C7)	13° 18.593'N	74° 36.867'E	20	4 and 15 (near surface and bottom)	13 March 2008 to 13 April 2008

Table 2. Range of current speed measured at different locations along with the measured u and v component of current and that estimated due to tide

Location	Water depth (m)	Measurement depth (m)	Measured current speed (cm s ⁻¹)		Estimated tidal current speed (cm s ⁻¹)		Measured U (cm s ⁻¹)		Measured V (cm s ⁻¹)		Tidal U (cm s ⁻¹)		Tidal V (cm s ⁻¹)	
			Range	Average	Range	Average	Min	Max	Min	Max	Min	Max	Min	Max
Karwar	10	4.5	0-59	16	0-17	7	-17	38	-34	42	-11	12	-13	14
Karwar	20	7.5	0-59	18	0-10	4	-28	16	-39	57	-8	8	-10	8
Karwar	20	15	0-52	16	0-11	4	-31	18	-38	48	-8	10	-7	6
Honnavar	10	4.5	0-48	16	0-12	5	-23	12	-41	45	-8	5	-12	9
Honnavar	20	6.5	0-52	14	0-13	4	-19	15	-44	52	-5	6	-13	9
Honnavar	20	14	0-44	13	0-11	4	-19	19	-32	44	-7	8	-8	8
Kundapur	10	5.0	0-36	12	0-16	5	-12	15	-34	36	-7	6	-16	13
Malpe	10	4.5	0-50	14	0-19	6	-20	19	-38	49	-5	4	-19	17
Malpe	20	4.0	0-58	20	0-25	8	-20	16	-58	53	-8	9	-25	19
Malpe	20	15.0	0-47	14	0-20	6	-16	25	-31	47	-6	9	-15	18

Table 3. Harmonic amplitude of tidal current ellipse for surface and bottom currents in 20 m water depth at Karwar, Honnavar and Malpe, where M is the major axis (cm s^{-1}), E is the eccentricity (negative sign indicates the ellipse is traversed in clockwise direction), N is the direction of major axis

Constituents	Karwar (surface)			Karwar (bottom)			Honnavar (surface)			Honnavar (bottom)			Malpe (surface)			Malpe (bottom)		
	M	E	N	M	E	N	M	E	N	M	E	N	M	E	N	M	E	N
Q1	0.9	-0.2	82	1.0	0.2	285	0.9	0.0	105	0.8	0.3	302	1.5	-0.4	107	0.5	0.3	79
O1	0.4	0.3	32	1.0	-0.5	205	0.6	-0.5	29	1.2	-0.4	1	3.7	-0.4	272	2.6	-0.2	251
K1	4.8	-0.2	280	2.8	0.4	353	2.8	0.1	264	3.5	-0.1	9	7.0	-0.5	286	3.3	0.3	221
J1	1.1	-0.1	296	0.7	-0.3	251	1.1	-0.6	312	1.3	-0.1	229	1.6	-0.3	327	0.9	0.4	219
N2	1.1	-0.4	66	1.1	-0.4	58	0.5	-0.4	84	1.3	-0.2	48	1.7	0.2	85	1.8	0.0	73
M2	4.1	-0.5	33	4.1	-0.5	32	3.8	-0.1	49	5.6	0.0	41	7.5	-0.2	76	7.5	-0.1	77
S2	1.4	-0.9	27	1.5	-0.8	17	1.6	-0.1	223	2.3	0.0	36	2.9	0.0	78	3.0	-0.3	79
M4	0.2	0.8	25	0.5	0.2	353	0.4	0.1	47	0.1	-0.3	43	0.5	-0.2	88	0.3	-0.1	52

Table 4. Harmonic amplitude of tidal current ellipse for mid depth currents in 10 m water depth at Karwar, Honnavar, Kundapur and Malpe , where M is the major axis (cm s⁻¹), E is the eccentricity (negative sign indicates the ellipse is traversed in clockwise direction), N is the direction of major axis

Constituents	Karwar			Honnavar			Kundapur			Malpe		
	M	E	N	M	E	N	M	E	N	M	E	N
Q1	1.8	0.1	83	1.1	-0.5	114	0.9	-0.1	125	0.9	0.0	123
O1	1.0	0.5	68	1.2	0.3	136	1.9	0.2	288	2.2	-0.1	277
K1	4.3	0.4	271	4.2	0.3	286	3.5	0.8	276	5.2	0.1	280
J1	1.4	0.1	251	1.6	-0.1	284	1.0	0.4	253	1.4	0.2	295
N2	1.8	-0.5	66	1.4	-0.1	64	2.1	-0.2	93	1.9	0.0	106
M2	5.9	-0.6	23	3.8	-0.3	55	5.2	-0.3	73	6.8	-0.1	89
S2	2.6	-0.8	55	1.6	-0.6	50	2.3	-0.4	82	2.5	-0.4	95
M4	0.5	-0.5	47	0.4	-0.5	308	0.5	-0.4	59	0.3	-0.1	94

Table 5. Range and average value of temperature at different locations

Location	Water depth (m)	Measurement depth (m)	Temperature (°C)		
			Range	Average	Standard deviation
Karwar	10	4.5	28.6-30.9	29.4	0.39
Karwar	20	7.5	28.3-30.2	29.2	0.34
Karwar	20	15.0	28.5-29.7	29.2	0.28
Honnavar	10	4.5	28.7-31.1	29.6	0.47
Honnavar	20	6.5	28.6-30.5	29.4	0.33
Honnavar	20	14.0	28.7-30.3	29.3	0.25
Kundapur	10	5.0	28.5-31.2	29.4	0.43
Malpe	10	4.5	28.2-31.0	29.4	0.53
Malpe	20	4.0	28.4-31.0	29.4	0.46
Malpe	20	15.0	28.4-29.7	29.1	0.29