

Variability in Measured Current Structure on the Southwest Continental Shelf of India

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ABSTRACT

Analyses of short duration current meter records collected in the coastal waters off Beypore on the southwest coast of India have been made to understand the tidal and non-tidal variability during premonsoon and summer monsoon seasons of year 2000. The region's tidal and non-tidal flows were described by means of time series displays, simple statistics, harmonic analysis, correlation coefficients and progressive vector diagrams. The non-tidal component of current was extracted using the X_0 filter. The study showed that the tidal currents were generally weak (<7cm/s) and dominated by tidal signals only in few records. Diurnal and semi diurnal constituents were found to be responsible for the rest of the variance. The signatures of the currents were different at the surface and bottom of the water column in the records collected during summer monsoon season, suggesting a baroclinic nature of motion, whereas the premonsoon records showed a barotropic nature. The stratification of the water column was strong during the summer monsoon season but was well mixed during the premonsoon season. There was a strong signature of diurnal solar forcing in the surface temperature records, which was totally lacking in the bottom records.

ADDITIONAL INDEX WORDS: Direct current measurements, tidal currents, southwest coast of India.

INTRODUCTION

The circulation pattern of the eastern Arabian Sea over the southwest continental shelf of India (inferred mostly by observations of physical and chemical properties of seawater) is reasonably well documented (SHETYE et al., 1990; MURALEEDHARAN et al., 1995; SHANKAR, 2000). Though these techniques provide estimates of mean and very low frequency circulation, direct current measurements are needed to determine the higher frequency time-dependent motion. For most of the Indian coastline, the current pattern in the near shore region, on shorter time scales, still remains poorly documented. However, a few in situ measurements were carried out using moored current meters, mostly confined to, off Bombay, Goa and Cochin (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).

Recently a number of research initiatives are on in the region to understand the complexity of processes in the wake of varied coastal development projects (ANONYMOUS, 1999a; ANONYMOUS, 2001; ANONYMOUS, 2002; DINESH KUMAR et al., 2004a; DINESH KUMAR et al., 2004b). Given the close proximity of the major population centers, it is not surprising that the topic of coastal ocean circulation is regarded as societal relevant. Motivating factor also include the effective utilization and preservation of coastal resources and observing and predicting its physical responses to ordinary and extreme events. Of equal importance are research efforts focused on the safety and navigation of commercial shipping operations.

With this background, current measurements were carried out during February/March 2000 and September 2000 off Beypore (11° 10'N; 75° 48'E) along the southwest coast of India. The fundamental goal of this study is to describe the tidal and non-tidal characteristics of surface and subsurface currents in the near shore waters. This information may

provide baseline data useful for any future coastal developmental activity in the region, even though the data records are short.

ENVIRONMENTAL SETTING

The coastal zone of southwest coast of India is characterized by a strip of barrier land, which separates the Arabian Sea from a chain of long irregular lagoons and estuaries. In synoptic view, the shoreline is seen as nearly straight and trending north-northwest to south-southeast. The continental shelf is very narrow in the south, which gradually broadens towards the north. The hydrography of the coastal waters is unique in several respects viz., the zone of strong upwelling as well as downwelling signatures.

The coast is exposed to seasonally reversing monsoon winds, which have an important bearing on the hydrography of the coastal waters. The winds are predominantly from the southwest directions during the southwest (summer) and northeast during the northeast monsoon period. The southwest monsoon winds are strong and remarkably steady, causing copious rainfall and resultant river discharge, primarily by orographic lifting of the moisture laden oceanic winds by the Western Ghats- another dominant geographic feature of the region.

Tides in the region are of mixed and predominantly semi-diurnal, the range of which increases to the north. During the summer monsoon season the coast bears the brunt of high waves causing severe erosion at several stretches.

MATERIALS AND METHODS

The study region and mooring stations are shown in Figure 1. Aanderaa RCM 7 recording current meters were deployed at the mooring sites. Data on currents (speed as well as direction) and temperature of varying durations were collected at the three stations viz. 1, 2 and 3, during premonsoon (February - May) and summer monsoon (June - September) seasons

of year 2000. The length of the current flow time series varied from a minimum of 6 days to a maximum of 14 days. Stations were located at a distance of less than 10 km from the shore. Details of these observations are given in Table 1. Eulerian and Lagrangian methods are used to describe the water movements. Currents at each station were resolved into east-west (u-component) and north-south (v-component) directions with the flow to the north and to the east being defined as positive. The data on current components as well as temperature were subjected to harmonic analysis to determine the amplitudes and phases of the tidal constituents (PUGH, 1987; EMERY and THOMSON, 1998). The tidal analysis (for the determination of the amplitudes and phases of the constituents) was carried out using the software of the Sea Level Center of the University of Hawaii and then the tidal series were reconstructed, using the obtained information of amplitudes and phases of the tidal constituents. The dates of full and new moon phases, which coincided with the period of observations were on 5th, 19th February, 6th, 13th March and 27th of September 2000 (ANONYMOUS, 1999 b).

The observed currents were de-tided using the X_0 filter (PUGH, 1987). Progressive Vector Diagrams (PVDs) were also constructed to present the cumulative speed and direction of flows at each mooring location.

RESULTS AND DISCUSSION

Sea Level

Before any discussion on the coastal currents are presented, it is essential to have a knowledge of tides prevailing in the study region, as they are known to be the major driving force for coastal currents. A detailed description of tide and sea level for the study region is available (SRINIVAS and DINESH KUMAR, 2002).

The amplitudes of the principal tidal constituents M_2 , K_1 , O_1 and S_2 were found to be 28.0, 20.3, 10.1 and 10.1 cm,

respectively. The mean spring range ($2(M_2+S_2)$) was 76.2 cm and the mean neap range ($2(M_2-S_2)$) was 35.8 cm. The type of tides at a given location can be determined using the Form Number, which is the ratio of the sums of the amplitudes of the diurnal constituents (K_1 and O_1) to that of the semi-diurnal constituents (M_2 and S_2). The tides are thus classified as mixed and predominantly semi-diurnal in nature, having a Form Number of 0.80. It's showed that the sea level variance is dominated mainly by tidal signals causing 89% of variance of the observed sea level. Based on these, the tidal variance can be considered to be greater than 90% during the two study periods covered in the present study viz. February-March and September.

Observed and predicted currents

The time series of current speeds at surface and subsurface levels at the various locations are presented in Figure 2. The mean current speeds were found to be higher during the summer monsoon season as compared to the premonsoon season as seen for station 2 and 3 (Table 2). During the summer monsoon season, the current speeds were stronger at the bottom than at the surface of the water column.

The observed and predicted (tidal) currents (u-component and v- component) are presented in Figure 3 and 4 and related statistics are presented in Table 3. The steadiness was found to be high at all the stations, except for station 3 (at 2.0 m depth) during September. Steadiness was reported to be quite high at surface and subsurface depths along the east coast of India during February-May (NARASIMHA RAO and PRABHAKARA RAO, 1989).

The v- component of currents at all the stations dominated to that of u-component in terms of mean and standard deviation. The surface and bottom currents had quite different directions, as is evident at station 2 and during the summer monsoon season (Table 2). This mean vertical shear

could be due to the horizontal density gradients that occur in the region during this season.

However, this was not seen for the u- component for the above stations for the same period. The time series of the v- component of currents at the surface and bottom showed very high correlation, which was not seen in the case of the u component. The mean alongshore flow is stronger than the cross-shore flow, as reported earlier along the west coast (HAREESH KUMAR and MOHAN KUMAR, 1996; SHENOI and ANTONY, 1991). The alongshore flow can be quite strong at surface and subsurface levels, for a station off Cochin (depth 95m) during May-June, 1992, the mean value reaching about 60 cm/s at 30 m depth.

The variance explained in the case of data presented in Figures 4 c and 4d was 67%, for Figures 4 e and 4f, it was 19% and for Figures 4 g and 4h, it was 27%. In the case of u- component, the variance was less than 3% in all the three cases. The correlations in the above three cases were found to be positive. Premonsoon season is a period of minimal freshwater discharge, which could probably be the reason for the high correlation observed (Figures 4 c and 4d). The average annual freshwater discharge into the system is estimated as $4066 \times 10^6 \text{ m}^3$, for which 87.9% occurs during the summer monsoon season and 0.6% during the premonsoon season, and the rest (11.5%) during postmonsoon season (ANILKUMAR and DINESH KUMAR, 2002). The summer monsoon is a period of copious rainfall, which results in a very heavy river discharge. The substantial river discharge during the period cause density stratification, which in turn result into different signatures of the non-tidal currents at the surface and bottom levels. The enhanced river discharge cause stratification in a narrow subsurface layer effectively isolating the deeper layer, as reported elsewhere (ZAVIALOV et al., 2002)

SHENOI and ANTONY (1991) showed that the correlation coefficients in the case of alongshore flow at various depths

off Goa were higher than the cross-shore flows, suggesting that the cross-shore current fluctuation field Goa as baroclinic. When the correlations between the surface and bottom currents are high, a similar variability occurs at the two levels, as seen for station 2 during February-March, indicating a barotropic nature of motion. However, the relative importance of different forcing mechanisms may be different for the two velocity components (ZAVIALOV et al., 2002).

The role played by bathymetry is not clear in the above-mentioned relationship. The effects could be less for the v-component and more for the u-component, as relatively sharp gradients in the x direction and comparatively lesser gradients in the y direction.

The mean direction of the observed currents at the surface and bottom at stations 2 and 3, during the summer monsoon season were found to be quite different (Table 2). A difference of 146° in mean direction between surface and bottom was seen at station 2 and 125° at station 3, respectively. The surface currents have a southerly orientation, whereas the bottom currents have a northerly orientation. The currents at station 2 during premonsoon season, however, did not show any conspicuous change in direction at the surface and bottom. The difference in average direction between the surface and bottom currents is found to be only 13° .

The surface currents during February-March as well as September showed a southward movement. SHENOI and ANTONY (1991) also reported that the mean alongshore flows along the west coast of India were southward during March-May. The alongshore components of large-scale circulation also indicate a southerly component during March - September and a northerly component during November - January (SHETYE and SHENOI, 1988; SHENOI and ANTONY, 1991; SHANKAR, 2000).

The amplitudes of the diurnal and semi-diurnal bands of the tidal currents are presented in Table 3. The amplitudes of the diurnal and semi-diurnal currents were all generally much less than 7 cm/s. For stations 2 and 3 during summer monsoon, the diurnal amplitudes strongly dominated the semi-diurnal amplitudes for the u and v- components at the surface as compared to the bottom, suggesting baroclinic nature of the tides. The percentage of variance accounted by the tidal currents varied from 3 to 51%, suggesting the complex nature of the circulation patterns. Had the tides been the major forcing factor, the percentage variance accounted would have been much higher. At station 1, during the summer monsoon, the tidal signatures were very poor (less than 10%). This could be due to the station's close proximity to the freshwater zone of resulting from river discharge.

The Root Mean Square deviations between the observed and predicted currents were found to be higher in the case of the v-components as compared to the corresponding u-components. In general, there is some agreement in terms of crests and troughs between the observed and predicted series. However, the variance explained is not much, the maximum being 51%. Diurnal and semi-diurnal constituents were together responsible for a high variance of the observed currents, but not in all the series. The phase and amplitude information of all the tidal constituents have been used for the prediction purposes. The regular and predictable tidal movements of the coastal sea are continuously modified to a greater or lesser extent by the effects of the weather. The relative importance of tidal and non-tidal movements depends on the time of the year. The meteorological, hydrological and oceanographic forcing could be predominating during the summer monsoon season as compared to the premonsoon season.

Non-tidal currents

The time series of the non-tidal currents are presented in Figures 5 and 6, for the u and v- components, respectively.

The results are similar to that presented for the observed data in several respects. The v-component of currents at all the stations dominates that of the u-component, in terms of mean and standard deviation (Table 4). The surface and bottom have quite different directions, as is evident in the case of stations 2 and 3 during southwest monsoon season. This was, however, not seen for the u-component at these two stations during the same period. The time series of the v-component of currents at surface and bottom showed very high correlation, which was not seen in the case of the u-component. The variance explained in the case of data presented in Figures 6 c and 6d was 96%, where as in Figures 6 e and 6 f, it was 36% and in Figures 6 g and 6 h, it was 28% (in the case of the u-component, the variance was less than 3% in all the three cases). The correlations in the above three cases were found to be positive. The mean direction of the currents at the surface and bottom at stations 2 and 3, during summer monsoon season were found to be quite different (Table 4). A difference in the mean direction between surface and bottom of 139° was seen at station 2 and 163° at station 3, respectively. The surface currents have a southerly orientation, whereas the bottom currents have a northerly orientation. The currents at station 2 during premonsoon, however, did not show any conspicuous change in direction at the surface and bottom as the difference being 14° . From the above discussion, it is clear that the tidal and non-tidal currents are largely similar.

The Progressive Vector Diagrams (PVDs) of the observed and non-tidal currents are displayed in Figure 7. For stations where data for the premonsoon and summer monsoon were available, it was seen that the surface currents and the bottom currents could show very different movement, as stated earlier. The PVDs generally show a strong northwest-southeast movement, which indicated flows parallel to the local shoreline. The range of movement and directions at surface and bottom, in x and y directions can be quite considerable,

as seen conspicuously in Figures 7 e and 7f and to a lesser degree in Figures 7 g and 7h. For the observed currents, the range of movement in the x and y directions at station 2, at the surface, during September were 14 and 32 km, and the same at the bottom were 39 and 85 km, respectively. For the observed currents, the range of movement in the x and y directions at station 3 during September were 10 and 40 km at the surface and at the bottom, these were 21 and 43 km. The paths traced out could also be quite different at the surface and bottom as seen in Figures 7 g and 7h. The PVDs constructed using the non-tidal current did not show much variation to that of the observed currents.

Temperature

The hourly time series of temperature at various depths are presented in Figure 8, for all the stations except at the bottom of station 2 for which temperature sensor failed during February-March. Time series of temperature showed comparatively higher variability at the surface, whereas in the bottom do not show such changes (Table 5). The movement of the time series of temperature was seen to be very different at the surface and bottom as revealed in Figures 8 e-h. In fact, the correlation between surface and bottom temperature at station 2, revealed a negative relationship with the variability explained at about 11% where as, at station 3, revealed a positive relationship with the variability explained of about 22%. The mean temperature difference between surface and bottom was around 2.5-3.0°C at both the stations. The bottom temperature records also showed comparatively lesser standard deviations, indicating strong stratification during the summer monsoon season. The time series of the temperature at the mid-depth and surface show peak values during late afternoon, which is lacking in the bottom records. Oscillations having semi-diurnal periods in the temperature at subsurface depths is reported higher than

that at the surface and attributed the same to internal tides (SHENOI et al., 1988).

The amplitude of surface temperature variability in the open ocean is quite small unlike in the sheltered and coastal areas. HAREESH KUMAR et al. (1996) reported the dominance of the diurnal cycle only in the surface layer whereas in the middle layer (50 m) and bottom (85 m) layers, the dominance was that of the semi-diurnal cycle during the premonsoon season for a station off Cochin, with a depth of 95m, at about 70 km from the coast. Within the mixed layer, diurnal variability of the incoming solar radiation and in the thermocline, internal waves with tidal periodicity were found to be the factors that control the temperature variability.

The time series of temperature at the bottom of station 2 and station 3 during September showed a variability of about 1°C, suggesting signatures of upwelling, an important oceanographic event, seen conspicuously off the southwest coast of India. The general hydrographic survey carried out in the region (spreading an area extending from 11°8'N-11°11'N and 75°42'E-75°49'E) during the period of the current meter observations, showed interesting results (ANONYMOUS, 2001). It's observed that during February, the temperature difference between surface and bottom waters was hardly 0.2 °C. The salinity also did not show much variability, the being about 0.5 PSU. On the other hand, during September, the temperature difference between surface and bottom was around 2.5 °C, the temperature at the surface being about 25.5 °C. The salinity showed much variability depth wise, with the difference between surface and bottom of about 3-4 PSU, the salinity at the bottom being uniformly high, about 34.6 PSU. The dissolved oxygen content at the bottom was also low during the southwest monsoon as compared to the premonsoon season, when the values were comparatively quite high and did not show much surface to bottom variability. The water column was thus well mixed during the premonsoon season and stratified during

the summer monsoon season. The low temperature, high salinity and low oxygenated waters seen during the summer monsoon season are signatures of upwelled waters, which are known to be important for the productivity of the region. This feature has been reported in the general hydrography off the southwest coast of India (MURALEEDHRAN et al., 1995; MURALEEDHRAN and PRASANNA KUMAR, 1996).

CONCLUSIONS

In the discussion above, we examined the information obtained from the in situ current measurements performed at the continental shelf waters of Beypore along the southwest coast of India. An attempt has been made to examine the tidal and non-tidal characteristics in the current variability which occurs over the nearshore waters.

The characteristics of the observed and tide-filtered currents were found to be quite different at the surface and bottom during the summer monsoon season. The signatures of the tides were not seen in the temperature records. There was a strong signature of diurnal solar forcing in the surface records, which was totally lacking in the bottom records.

The analyzed data records are limited, both in space as well as in time and therefore no attempt can be made to describe general circulation characteristics in a wider perspective. Moreover, the spectral broadening of tidally driven temperature and velocity variance into narrow band peaks, which can not be effectively resolved as variance at a selection of specific frequencies. This could be the reason for the low values of tidal variance explained for the components of velocity and temperature. However, the study may pave way for detailed investigations in future. Observations of longer durations similar to SHETYE et al, 1995 are to be taken up to resolve amplitudes and phases of all the diurnal and semi-diurnal constituents. This would enable extraction of the major semi-diurnal and diurnal constituents, which in turn can be used useful for predicting the currents, a not much

explored exercise, for the Indian coastal waters. Synchronous meteorological data, especially those on winds would be useful to understand their effects on the surface and subsurface currents. This would enable to have a better picture of the tidal and non-tidal variability with a link to the shelf region exchange processes.

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Table 1. Details of the current meter moorings.

Station Number	Depth w.r.t. Chart Datum (m)	Level of current meter (m)	Distance from the coast (km)	From	To	Number of days of data
1	5	2.0	1.2	0900 h 14/02/2000 0	0800 h, 28/02/2000	14
1	5	2.0	1.2	1200 h, 23/09/2000	1100 h, 29/09/2000	6
2	20	2.0	10.0	1100 h, 28/02/2000	1000 h, 13/03/2000	14
2	20	18.0	10.0	1100 h, 28/02/2000	1000 h, 13/03/2000	14
2	20	2.0	10.0	1100 h, 07/09/2000	1000 h, 15/09/2000	8
2	20	18.0	10.0	1100 h, 07/09/2000	1000 h, 15/09/2000	8
3	20	2.0	9.6	1100 h, 15/09/2000	1000 h, 23/09/2000	8
3	20	18.0	9.6	1100 h, 15/09/2000	1000 h, 23/09/2000	8

Table 2. Statistics of the observed currents

Station Number / Period	Level of current meter (m)	Observed current speed			U-component of current		V-component of current		Vector mean speed	Vector mean direction (°)	V(%)
		Mean	SD	Mean10	Mean	SD	Mean	SD			
1 (Feb, 2000)	2.0	10.6	5.2	23.5	4.4	4.7	-6.4	7.6	7.7	146	72.6
1 (Sep, 2000)	2.0	17.5	9.4	35.8	-7.0	4.2	15.4	9.5	16.9	336	96.6
2 (Feb-Mar, 2000)	2.0	8.7	4.7	20.2	2.3	2.7	-7.2	5.7	7.6	162	87.4
2 (Feb-Mar, 2000)	18.0	6.5	3.2	15.9	2.7	2.7	-4.5	4.1	5.3	149	81.5
2 (Sep, 2000)	2.0	10.5	5.2	27.4	-1.4	5.9	-6.6	7.6	6.7	192	63.8
2 (Sep, 2000)	18.0	17.8	2.5	22.6	-5.5	6.9	13.8	7.5	14.8	338	83.1
3 (Sep, 2000)	2.0	13.1	7.5	32.9	-1.2	5.9	-1.4	13.8	1.9	220	14.5
3 (Sep, 2000)	18.0	18.8	4.3	28.0	-2.7	10.5	9.7	12.8	10.0	345	53.2

Mean10 is the average of the maximum ten current speeds; V is the steadiness of the current

Table 3. Details of the semi-diurnal and diurnal currents

Station Number/ Period	Level of current meter(m)	u-component (cm s ⁻¹)		v-component (cm/s)		Tidal variance (%) Component	
		Diurnal	Semi- diurnal	Diurnal	Semi- diurnal	u	v
1 (Feb, 2000)	2.0	3.70	0.83	6.19	3.85	34	51
1 (Sep, 2000)	2.0	0.35	0.61	1.44	3.42	4	9
2 (Feb- Mar, 2000)	2.0	1.80	1.00	2.50	2.40	33	21
2 (Feb- Mar, 2000)	18.0	1.46	0.61	2.27	1.87	20	27
2 (Sep, 2000)	2.0	5.48	0.75	4.26	0.97	46	18
2 (Sep, 2000)	18.0	2.83	2.94	4.43	2.03	18	22
3 (Sep, 2000)	2.0	5.84	0.12	2.88	1.41	50	3
3 (Sep, 2000)	18.0	4.26	4.51	4.83	5.31	19	16

Table 4. Details of the non-tidal currents

Station Number/ Period	Level of current meter (m)	u-component of current		v- component of current		Non-tidal current	
		Mean	SD	Mean	SD	Speed (cm/s)	Direction (°)
1 (Feb, 2000)	2.0	4.6	1.5	-6.8	3.2	8.2	146
1 (Sep, 2000)	2.0	-6.9	3.2	15.6	5.5	17.1	336
2 (Feb- Mar, 2000)	2.0	2.5	1.1	-7.6	4.1	8.0	162
2 (Feb- Mar, 2000)	18.0	2.9	1.8	-4.7	3.0	5.5	148
2 (Sep, 2000)	2.0	-2.0	1.5	-6.0	3.7	6.3	198
2 (Sep, 2000)	18.0	-6.5	2.5	15.2	1.6	16.5	337
3 (Sep, 2000)	2.0	-1.0	2.0	-4.7	8.8	4.8	192
3 (Sep, 2000)	18.0	-0.7	7.5	7.9	9.4	7.9	355

Table 5. Details of the semi-diurnal and diurnal temperature variability

Station Number / Period	Level of current meter	Temperature (°C)				Tidal Variance (%)
		Mean	Standard deviation	Diurnal	Semi-diurnal	
1 (Feb, 2000)	2.0	28.84	0.43	0.20	0.07	16.21
1 (Sep, 2000)	2.0	27.89	0.71	0.19	0.10	4.91
2 (Feb-Mar, 2000)	2.0	29.20	0.29	0.22	0.02	30.33
2 (Feb-Mar, 2000)	18.0	--	--	--	--	--
2 (Sep, 2000)	2.0	25.54	0.89	0.53	0.06	18.34
2 (Sep, 2000)	18.0	22.44	0.13	0.02	0.01	6.79
3 (Sep, 2000)	2.0	25.31	0.79	0.40	0.12	14.37
3 (Sep, 2000)	18.0	22.65	0.24	0.05	0.02	0.55

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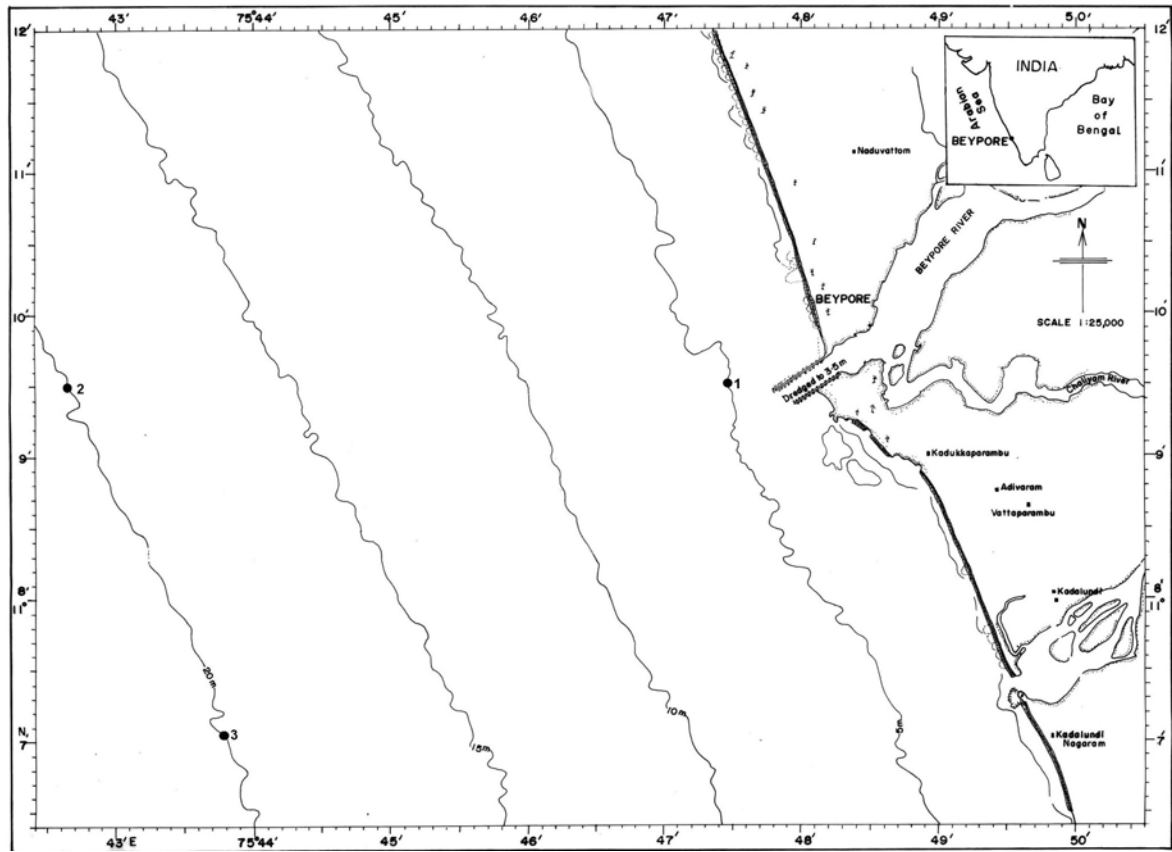


Figure 1. The study region with the current meter mooring locations.

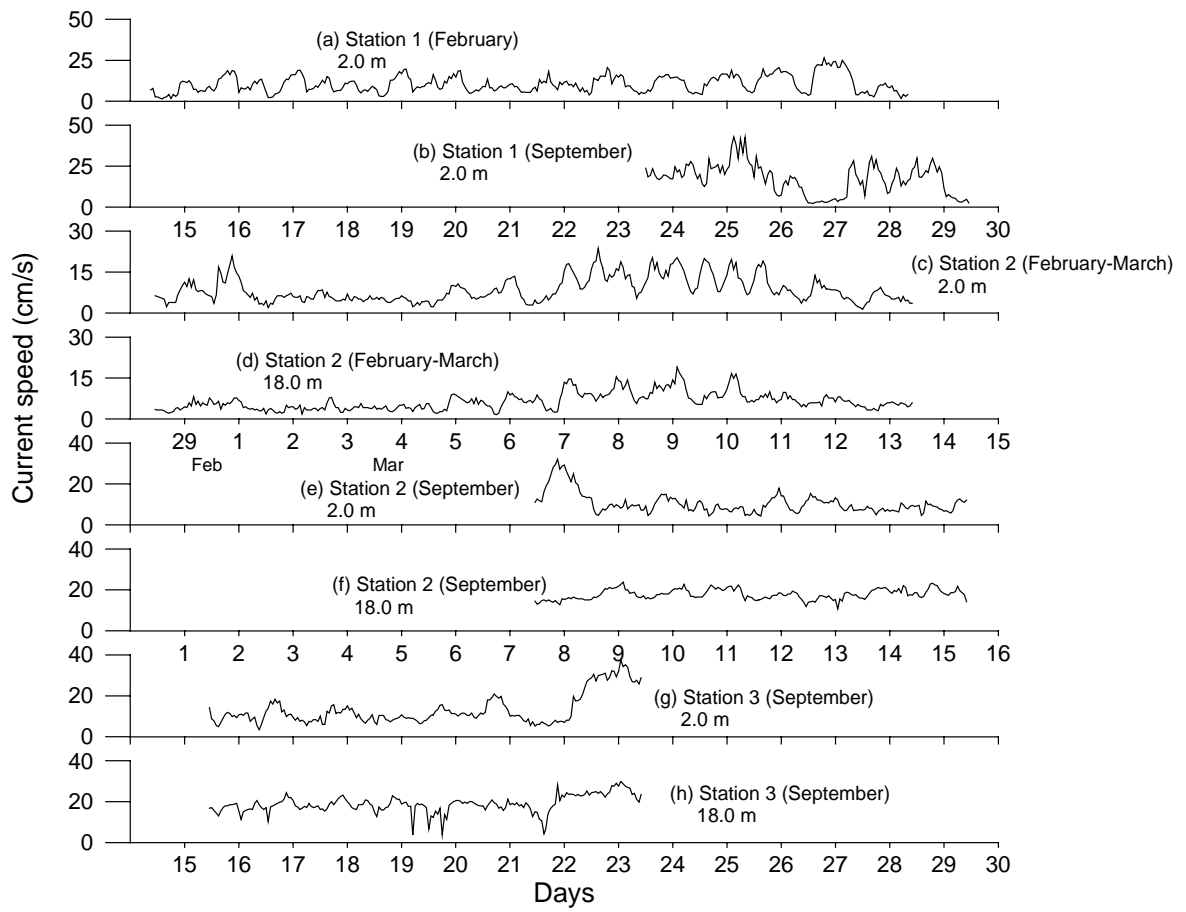


Figure 2. Variation of current speed during the period of observations.

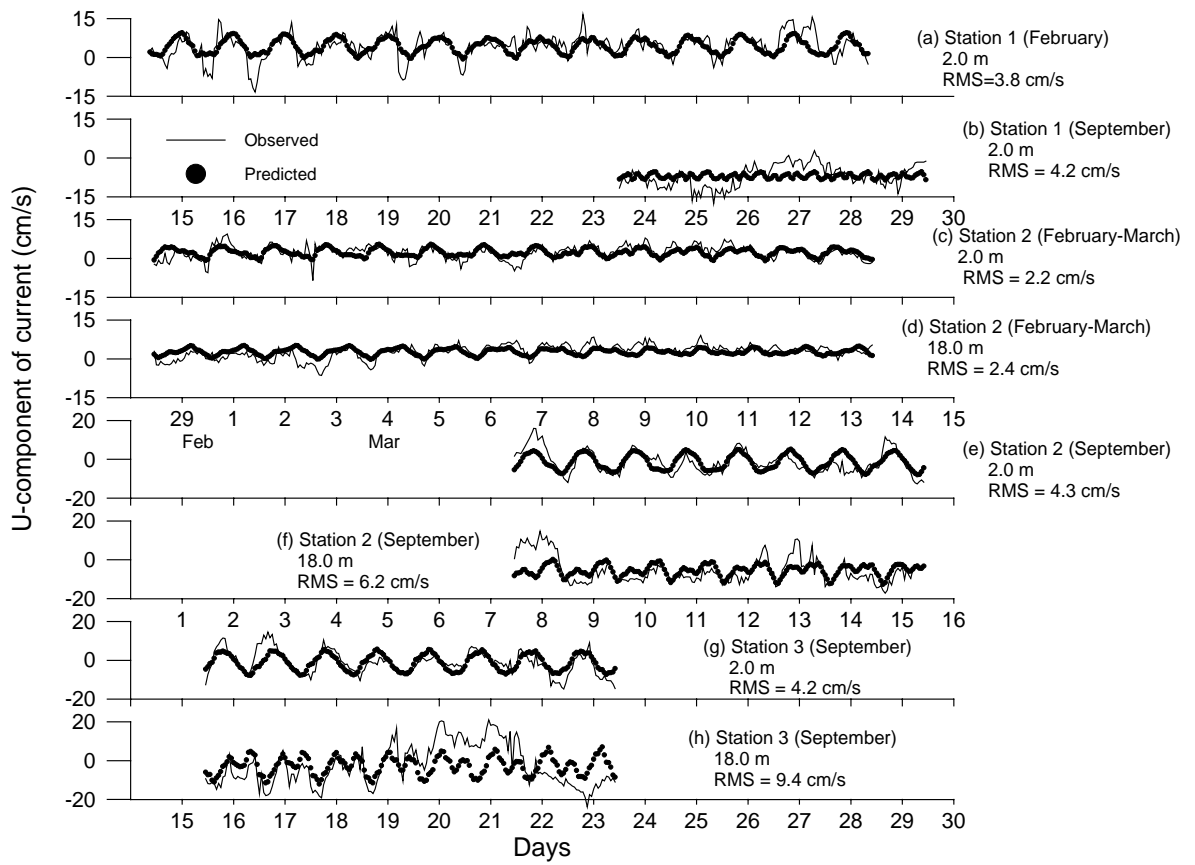


Figure 3. Variation of the observed and predicted u-Component of current during the period of observations.

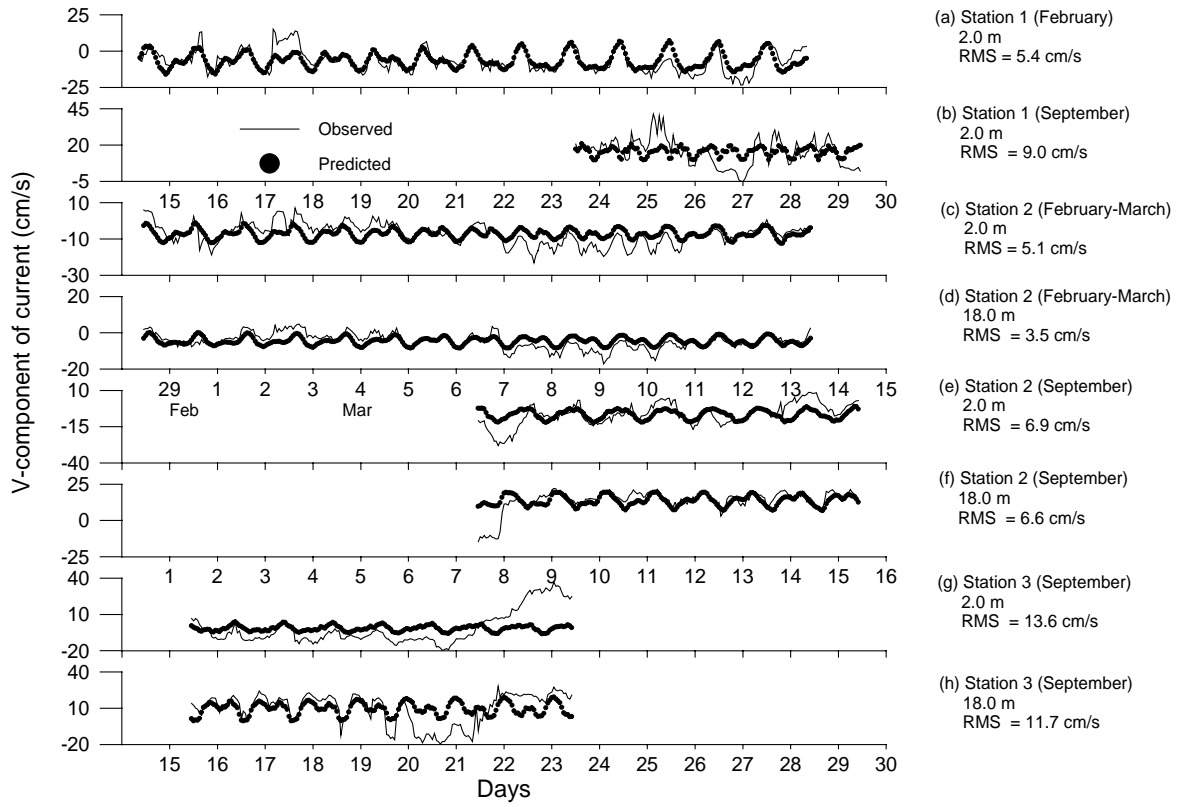


Figure 4. Variation of the observed and predicted v-Component of current during the period of observations.

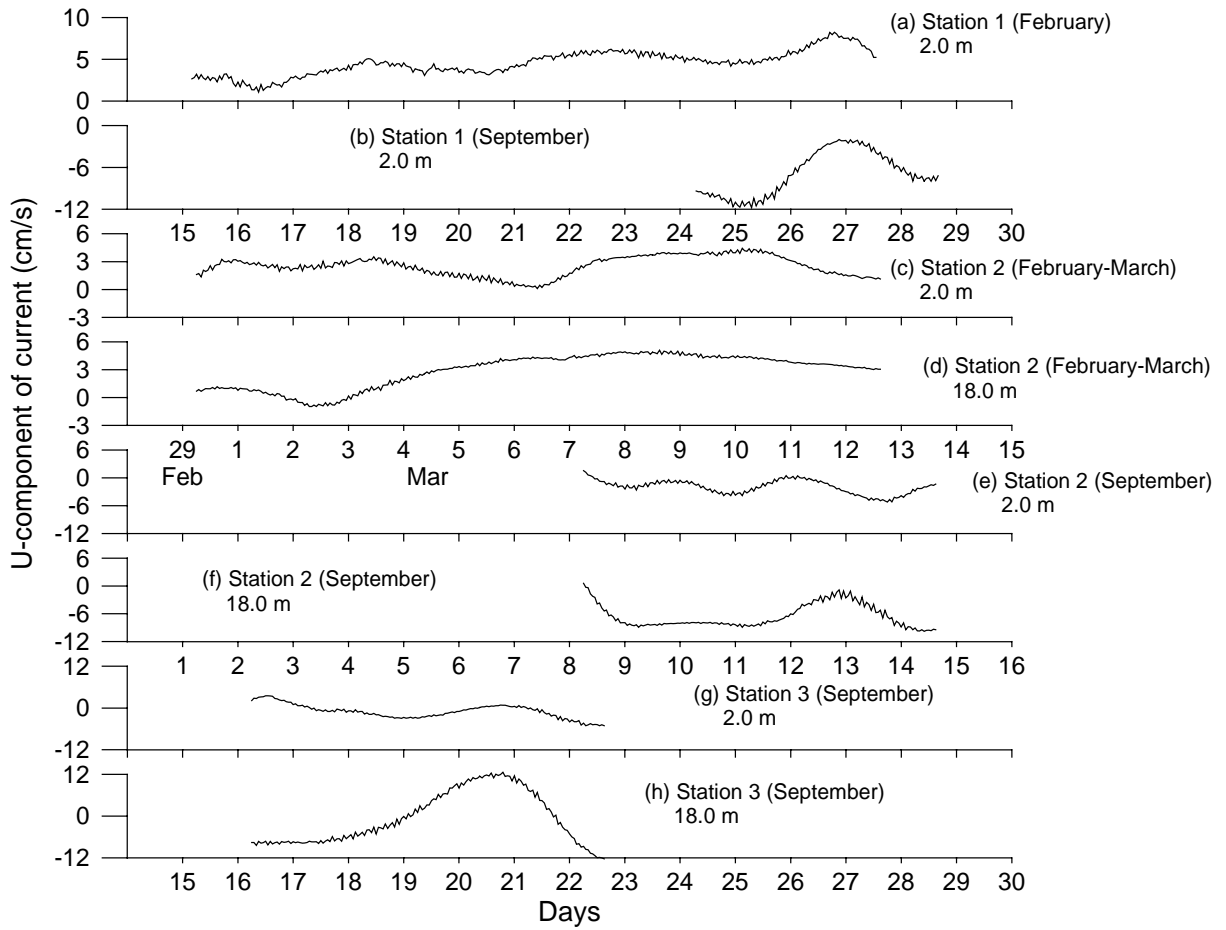


Figure 5. Variation of the filtered u-component of current during the period of observations.

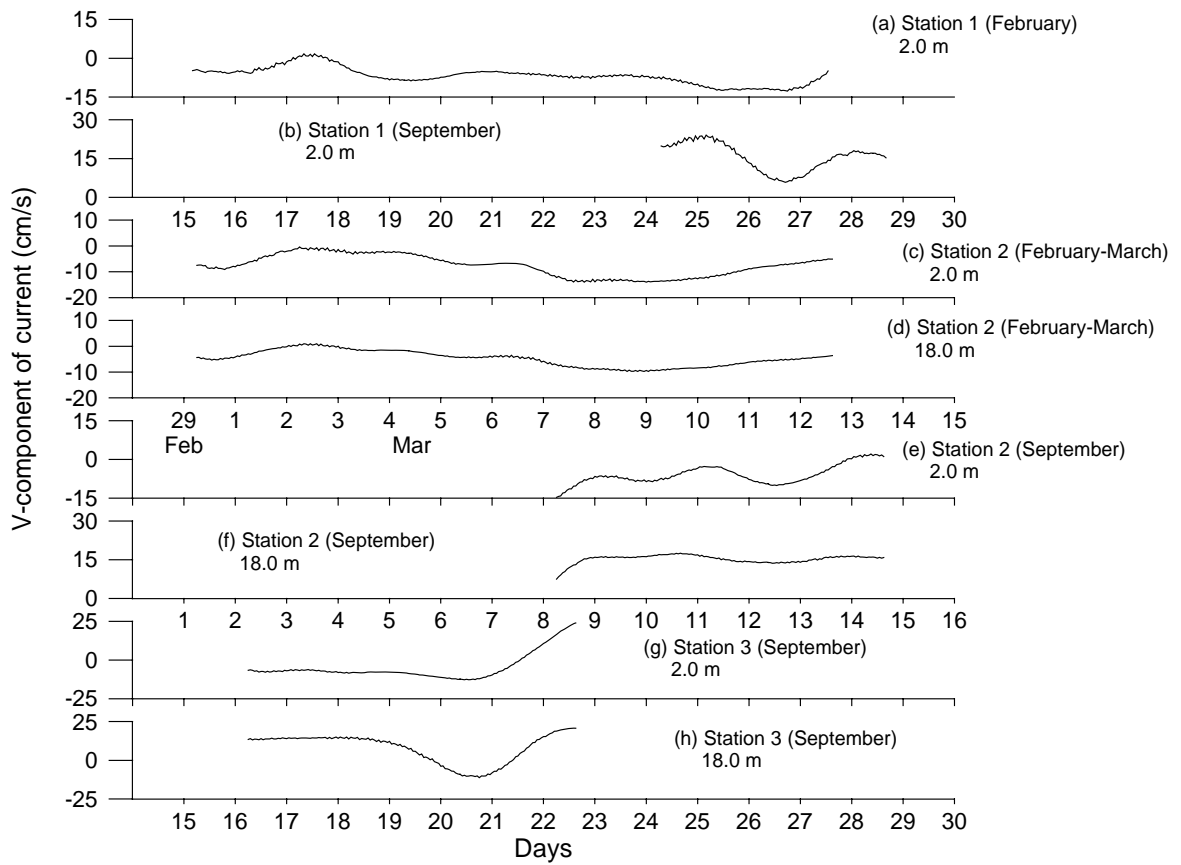


Figure 6. Variation of the filtered v-component of current during the period of observations

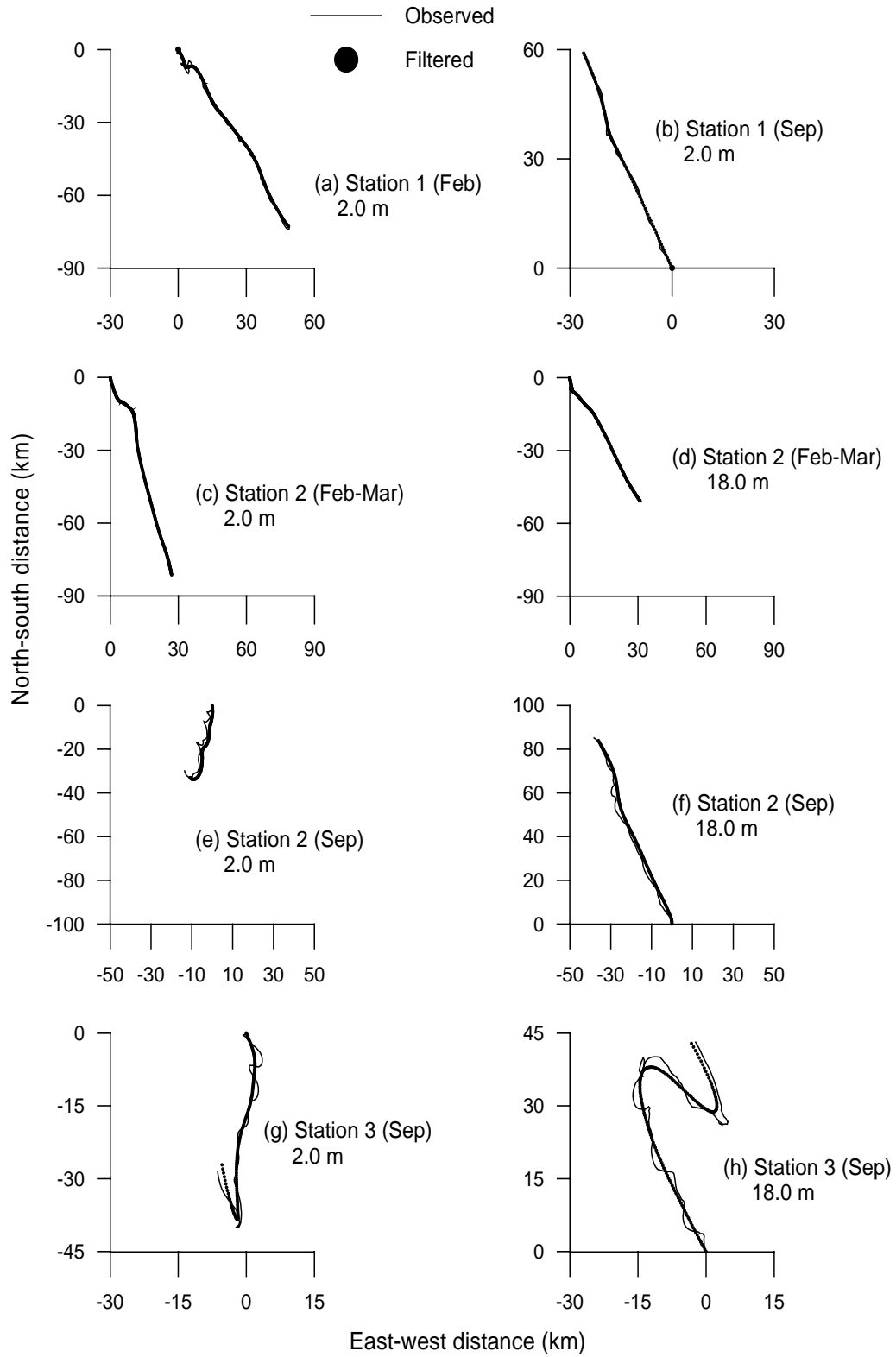


Figure 7. Progressive vector diagrams of observed and filtered currents during the period of observations

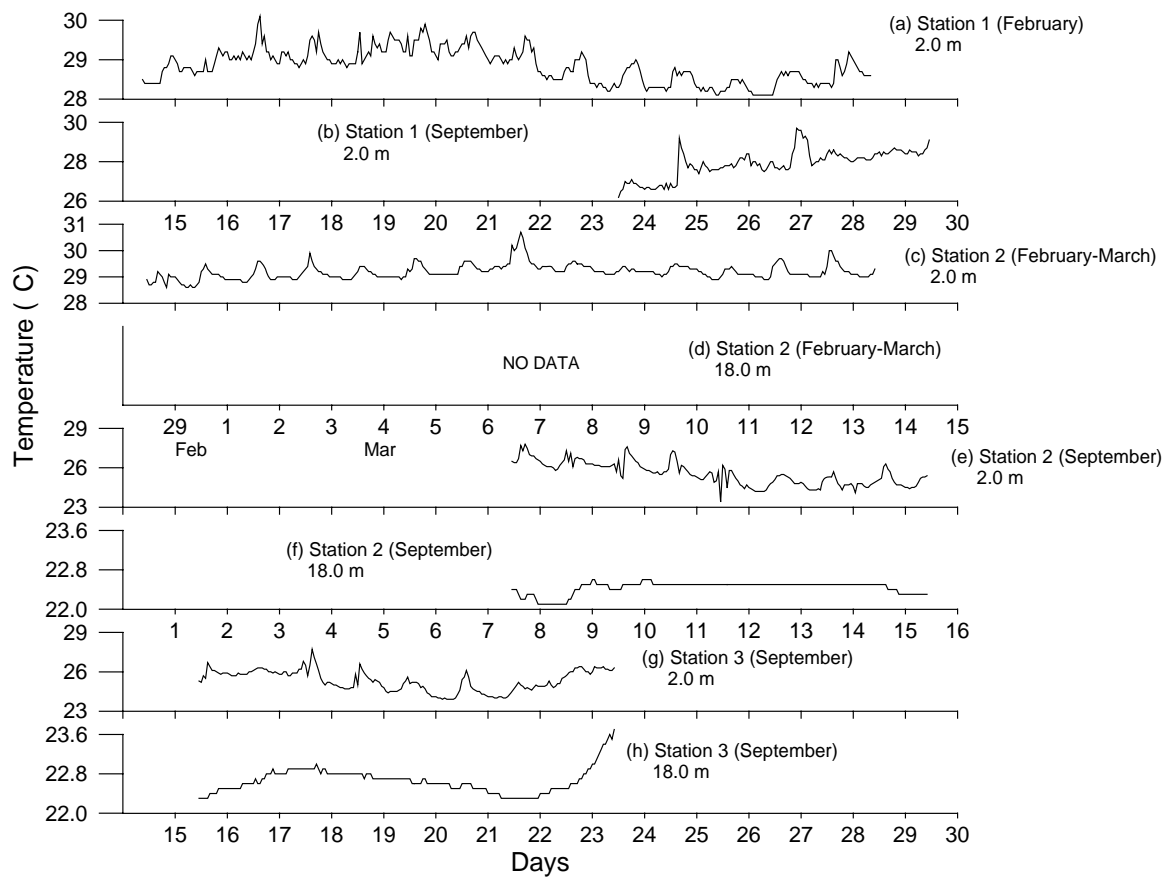


Figure 8. Variation of temperature during the period of observations.