

Waves and currents in tide dominated location off Dahej,
Gulf of Khambhat, India

V. SANIL KUMAR* AND K.ASHOK KUMAR

Ocean Engineering Division

National Institute of Oceanography

(Council of Scientific & Industrial Research)

Dona Paula, Goa 403 004 India

*email: sanil@nio.org

Tel: 0091 832 2450 327 Fax: 0091 832 2450 604

Abstract

Based on measurement of waves, currents and tides off Dahej in Gulf of Khambhat, the hydrodynamics is studied. Estimated tidal constituents shows that primary lunar semi-diurnal constituent M2 was the strongest constituent and the amplitude was found to be around 4.5 times strong as that of the major diurnal constituent K1. Currents were predominantly tide induced with speed upto 3.3 m/s and were towards north-northwest during flood tide and south-southeast during ebb tide. Residual cross shore and alongshore current was found to be varying with the corresponding change in the cross shore and alongshore wind speed. Influence of tidal current was observed in most of the wave statistical parameters.

Key words: Tidal currents, wave-current interaction, significant wave height, residual currents

1. Introduction

The tidal range at Gulf of Khambhat is the largest along the Indian coastline. Unnikrishnan *et al.* (1999) developed a barotropic numerical model of the Gulf of Khambhat and surrounding areas to simulate tides in the Gulf and were successful in simulating the tidal amplification. Nayak and Shetye (2003) found that the semi-diurnal tides in the Gulf of Khambhat amplify about threefold from mouth to head, whereas the amplification of diurnal tides is much smaller. Due to the large tidal range, strong currents are observed in the Gulf. The currents at Gulf of Khambhat are not studied in detail due to lack of measured data.

Existence of waves and currents is a common feature in most of the marine environment and the interaction between these two is important in many aspects of both coastal and offshore engineering. The influence of currents on long term ocean wave climate was studied by Burrows and Hedges (1985) and shown the effects of currents on integrated wave parameters. When the currents are strong they will have a significant influence on wave propagation. When waves are propagating towards an oncoming current, current will tend to increase the steepness of the waves by increase in wave height and decrease in wavelength (Burrows and Hedges 1985). Wave period will be longer in following current and shorter in opposing currents. During the flood flow, the waves will be lengthened and the height will be reduced and during the ebb flow, the waves will be compressed and the height will be increased. A review of wave current interaction is given by Jonsson (1990). In reality both current and depth refraction are likely to take place producing a complex wave current field. Another way the current modifies surface waves is to change the wave energy by causing an exchange of energy between wave and current. Wave energy may be gained or lost to the current.

Masson (1996) studied the wave-current interaction in a strong tidal current (upto 2 m/s). Wolf and Prandle (1999) reviewed the possible interaction

mechanisms between waves, tides and surges and using measured data, the effect of depth and current changes particularly on waves and the effect of waves on tidal currents were examined. Guedes Soares *et al.* (2000) have confirmed that when a current meets a wave system, differences are observed in the distribution of the spectral energy of the waves. The wave–current interaction process in the Southern North Sea was studied by Osuna and Monbaliu (2004) using a coupling scheme which allows the synchronous data transfer between a wave and a tide/surge model. In most of the earlier studies currents were upto 2 m/s. In the Gulf of Khambhat, currents were more than 2 m/s and hence the interaction between waves and currents under such high currents were examined.

The objective of the present work is to study the characteristics of waves and currents under large tidal variations based on the measured data. The interaction between the wave and current are examined when the wave and current data are available simultaneously.

Description of study region: Gulf of Khambhat which is in the northern part of the Arabian Sea has a width of 80 km at mouth and funnels down to 25 km over the longitudinal reach of 140 km (Figure 1). Entire banks surrounding the Gulf are bordered with large tidal flats nested into numerous tidal creeks. Ambika, Purna, Kim, Tapti, Narmada, Mahe, Sabarmati and Dhadhar rivers discharge into the Gulf. Mal Bank is a prominent sand shoal present at northern part of the Gulf. Middle part of the Gulf is deeper with depth ranging upto 30 m. Seabed in most part of the Gulf remains in quasi steady state and it moves as sand bars with tides. Bhavnagar Port is located on the western part of the Gulf. Many offshore oil, gas and chemical terminals exist and new installations are planned between Hazira and Dahej on the eastern part of the Gulf. On the other hand, the tides in the Gulf remain the largest of the Indian coast with spring tidal ranges of around 9 m and resulting in strong currents. Due to strong flood and ebb tidal currents, the water remains always turbid with high bed and suspended sediment loads. Studies of sand waves in the

Gulf of Khambhat suggest formation under high-energy hydrodynamic conditions associated with the large tidal range (Vora et al. 1980). The sand waves, with the finer sediments concentrated at the crests, are derived from the coarse sediments supplied by the Narmada and Tapti rivers.

2. Materials and methods

2.1 Winds

Since measured wind data was not available for the study area, National Centre for Environmental Prediction (NCEP)/ National Centre for Atmospheric Research (NCAR) reanalysis wind data (Kalney et al. 1996) at six hourly intervals during May to November 2003 were used in the study. This reanalysis global wind data in $2.5^{\circ} \times 2.5^{\circ}$ grid was extracted over the study region.

2.2 Waves

Directional waverider buoy was used for the wave measurements. The buoy was moored at a location off Dahej ($21^{\circ} 45.63' N$ and $72^{\circ} 30.86' E$; Figure 1) where the depth is 24 m with respect to CD (Chart Datum). Data on the three-translational motions (vertical, north-south and east-west) of the deployed waverider buoy were recorded for 20 minutes duration at every one-hour interval from May to November 2003. Time series data were sampled at a frequency of 1.28 Hz and a Fast Fourier Transform of 8 series, each consisting of 256 data points, are ensemble averaged to give wave spectra with 16 degrees of freedom. High frequency cut off is set at 0.58 Hz with a resolution of 0.005 Hz and the low frequency cut off is 0.03 Hz. The heave is measured with a resolution of 1 cm and an accuracy of 3%. When the moored buoy follows the waves, the force of the mooring line may change resulting in a maximum error of 1.5% in the measurement of surface elevation. If the wavelength is less than 5 m, the buoy will not follow the wave

amplitude and hence waves with period less than 1.8 s will not be measured. The significant wave height (H_s) and the average wave period (T_{02}) were obtained from the spectral analysis. Mean wave direction was estimated based Kuik et al. (1998). The period corresponding to the maximum spectral energy density (E) is referred as peak period (T_p) and is estimated from the wave spectrum. Spectral width parameter (ϵ) is estimated from the spectral moments (Cartwright and Longuet-Higgins 1956).

2.3 Currents and tides

Aanderaa Doppler current meter (DCM12) was used for the current and tide measurements. DCM12 was fixed to a frame and was kept near the seabed. From October 2002 to April 2003, measurements were done at a location $21^\circ 39.82'$ N and $72^\circ 30.16'$ E (Figure 1) where the depth is 24 m with respect to CD. From July to October 2003, the measurements were done at a location $21^\circ 40.42'$ N and $72^\circ 30.62'$ E where the depth is 14 m. The DCM12 is current profiling instrument intended to be deployed in a fixed position on the seabed for obtaining vector averaged speed and direction of the current. In DCM12, current measurements were performed by four acoustic transducers emitting ultrasonic pulses towards the surface of the sea. Echoes from particles and organisms in the water were scattered back to the transducers. These echoes change frequency due to their movement in correlation with sea current and this frequency change is known as Doppler shift. The accuracy of the DCM12 current speed sensor is ± 3 cm/s and that of the direction sensor is $\pm 2^\circ$. Current direction mentioned in this paper is the 'from' direction similar to that of wind and wave, which is opposite to the normal convention for currents. The measured surface currents were only used in the present study. The water level was measured using the pressure sensor of the DCM12. Tide is estimated by removing the mean value from the measured water level.

All directions use the oceanographic convention and show the direction towards which the wind or current is moving. Currents 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. Current components were not rotated with respect to bottom contour or coast. Hence the cross shore currents are the u component and alongshore currents are the v component. 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. For studying the wave-current interaction, the tidal current at 24 m water depth during May to November 2003 was estimated using the tidal constituents obtained from the measured current data at 24 m water depth during October 2002 to April 2003. The non-tidal currents are referred as residual currents.

3. Results and discussion

3.1 Wind and waves

Wind speed varied from 0.1 to 12 m/s with an average speed of 3.5 m/s during 2002 and from 0.1 to 10 m/s with an average speed of 3.7 m/s during 2003. Wind direction was predominantly from the sector between north and east and from the sector between west and north except during the southwest monsoon period. During the southwest monsoon period the wind was from the sector between south and west with a mean direction of 230° (Figure 2). Daily pattern in the wind was diurnal with relatively strong wind in the afternoon than in the forenoon.

Variation of significant wave height (H_s) and the wind speed during the south west monsoon is shown in Figure 2 along with the variation of mean wave direction and wind direction. The wave direction was predominantly between

180 and 225°. H_s was less than 1.6 m during the southwest monsoon period with variations in wave height following the variations in wind speed. Whereas the H_s in the Arabian Sea will be more than 1.8 m during the southwest monsoon period (Kumar and Anand 2004).

3.3 Tides and currents

Tides

The estimated tidal constituents at 14 and 24 m water depth based on the measured data are presented in Table 2. The harmonic analysis of the tides shows that primary lunar semi-diurnal constituent M2 was the strongest constituent and the amplitude was found to be around 4.5 times strong as that of the major diurnal constituent K1. Amplitude of S2 was found to be around 32% of M2. Shallow water tidal effects are primarily represented by the M4 constituent and are the result of the friction and other local effects. Amplitude of M4 was 6.8% of M2 tide at both 14 and 24 m water depth.

Variation of predicted tides at 14 and 24 m water depth during July 2003 based on the measured tides is shown in Figure 3 and it shows that the tide at 14 m was slightly larger than that at 24 m water depth. Generally the shoaling depths will increase the tidal amplitude towards the coast until friction reverses this trend (Wolf and Prandle 1999). The increase in amplitude was due to shoaling towards the coast. The mean tidal range for the year 2003 at 14 m was 0.19 m larger than that at 24 m. Tidal form number (ratio of the amplitude of the main diurnal and semidiurnal harmonic water level) was 0.235 and 0.256 at 14 and 24 m indicating that the tides were semi-diurnal.

Currents

Maximum current speed of 3 m/s was recorded at 24 m water depth (Table 2) and 3.3 m/s at 14 m water depth (Table 3). Currents were predominantly tide

induced and the direction was towards north-northwest during flood tide and towards south-southeast during ebb tide. The flood current was stronger than the ebb current with reversing currents similar to that for estuaries. Around 40% of the measured u component of currents was due to tide and 88% of the measured v component of currents was due to tide. Cross shore currents were found to be negligible compared to the alongshore current (Tables 2 and 3). Based on the measured data, the estimated u and v component of tidal currents at 14 and 24 m water depth during July 2003 is shown in Figure 4. Alongshore tidal currents were found to be lower (average for year 2003 was 0.45 m/s) at 14 m water depth than that at 24 m water depth due to the modification of tidal currents by local bathymetry and nearshore. Tidal currents were found to be higher towards the mid channel (24 m water depth) than that towards the shore (14 m water depth). The distance between the two locations was 1363 m.

Amplitude of M4 current was 8.8% and 2.5% of M2 currents at 14 and 24 m water depths (Table 4). Which shows friction and other local effects affected the currents at 14 m than that at 24 m. Alongshore currents were found to be lagging behind the tide by 2.8 hr at 14 m water depth and by 2.4 hr at 24 m water depth.

3.4 Wind, wave, currents and tides

The residual u and v component current at 14 and 24 m water depth was found to be varying with the corresponding change in the cross shore and alongshore wind (Figures 5 and 6).

The direction of wind and current was compared with the mean wave direction (Figure 7A). The waves were predominantly from the sector between south and southwest. Hence the currents during the flood tide is taken as following current and that during the ebb tide is taken as opposing current. The alongshore current is also presented in Figure 7A. Variation of wave direction

over the entire frequency range shows that the difference in direction of current and wave was more than 45° during the following current (Figure 7B). When the waves were following the currents, the waves did not turn to the current direction. During the opposing current, the wave direction was almost in alignment with the currents and was around 180 to 200° . Wolf and Prandle (1999) had similar observation.

Peak period was found to be high during the following current (Figure 8B) and mean wave period was high for opposing current than that during following current (Figure 8C). Spectral width parameter was found to increase for the opposing current (Figure 8D) indicating the wave spectrum was broader when the currents were opposing. Spectral width parameter was found to be low (0.5 to 0.6) during high currents indicating the wave spectrum was narrow banded during high currents. When the current was in the wave direction, the wave steepness was found to be decreasing (Figure 8E). But there was no relative increase when the current was opposing the waves. The variation in significant wave height with current was not regular (Figure 8F). Wave current interaction will depend on the vertical distribution of current velocity. The mean tidal range varies from 4 m during neap tide to 9 m during spring tide and will result in change in water depth with time. The water depth will be increasing during the following current and decreasing during the opposing current and these changes are not considered in the present study.

4. Conclusions

Tide at 14 m was larger than that at 24 m water depth with an increase of 0.19 m in the mean tidal range. The maximum current speed was 3 m/s with average value of 1 m/s at 24 m water depth and 3.3 m/s with average value of 0.8 m/s at 14 m water depth. Current direction was predominantly between north and northwest during the flood tide and was between south and southeast during the ebb tide. Alongshore tidal currents were found to be

lower (average was 0.45 m/s) at 14 m water depth than that at 24 m water depth. Residual cross shore and alongshore current at 14 and 24 m water depth was found to be varying with the corresponding change in the cross shore and alongshore wind.

During the opposing current, wave direction was turning towards the current direction and was almost in alignment with the currents and was around 180 to 200°. When the waves were following the currents, the waves did not turn to the current direction. Spectral width parameter was found to increase for the opposing current and was found to be low (0.5 to 0.6) during high currents. When the current was in the wave direction, the wave steepness was found to be decreasing. Peak period was found to be high during the following current and mean wave period was high during opposing current.

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Table 1. Tidal constituents off Dahej at 14 m and 24 m water depth

| Constituent | Speed (deg/hr) | 14 m water depth | | 24 m water depth | |
|-------------|-------------------|-------------------|----------------|-------------------|----------------|
| | | Amplitude (cm) | Phase (deg) | Amplitude (cm) | Phase (deg) |
| Z0 | - | 464 | - | 470 | - |
| Q1 | 13.3986609 | 6 | 9 | 7 | 26 |
| O1 | 13.9430356 | 30 | 357 | 31 | 6 |
| M1 | 14.4920521 | 2 | 31 | 2 | 62 |
| K1 | 15.0410686 | 63 | 3 | 64 | 6 |
| J1 | 15.5854433 | 4 | 53 | 4 | 65 |
| OO1 | 16.1391017 | 5 | 71 | 3 | 74 |
| MU2 | 27.9682084 | 9 | 122 | 6 | 81 |
| N2 | 28.4397295 | 68 | 307 | 74 | 309 |
| M2 | 28.9841042 | 300 | 329 | 281 | 328 |
| L2 | 29.5284789 | 12 | 339 | 33 | 324 |
| S2 | 30.0000000 | 99 | 5 | 91 | 6 |
| 2SM2 | 31.0158958 | 3 | 189 | 6 | 179 |
| MO3 | 42.9271398 | 5 | 153 | 4 | 157 |
| M3 | 43.4761563 | 4 | 57 | 3 | 94 |
| MK3 | 44.0251729 | 5 | 201 | 7 | 232 |
| MN4 | 57.4238337 | 10 | 151 | 10 | 150 |
| M4 | 57.9682084 | 20 | 164 | 19 | 167 |
| SN4 | 58.4397295 | 4 | 193 | 4 | 198 |
| MS4 | 58.9841042 | 14 | 213 | 13 | 215 |
| 2MN6 | 86.4079380 | 4 | 315 | 4 | 329 |
| M6 | 86.9523127 | 6 | 325 | 5 | 341 |
| MSN6 | 87.4238337 | 3 | 353 | 3 | 16 |
| 2MS6 | 87.9682084 | 7 | 21 | 5 | 30 |
| 2SM6 | 88.9841042 | 2 | 75 | 1 | 81 |

Table 2. Range and average values of measured current speed, u and v component and that estimated from the tidal current constituents near surface during different months at 24 m water depth

| Month and year | Measured | | | | Estimated from tidal current constituents | | |
|----------------|-------------|---------|------------|------------|---|----------|----------|
| | speed (m/s) | | u (m/s) | v (m/s) | Speed (m/s) | u (m/s) | v (m/s) |
| | Range | Average | Range | Range | Range | Range | Range |
| October 2002 | 0-2.9 | 1.2 | -1.0 – 0.8 | -1.9 – 1.7 | 0-2.2 | -0.3-0.3 | -1.8-2.2 |
| November 2002 | 0-2.9 | 1.2 | -1.0 – 1.0 | -3.0 – 2.4 | 0-2.4 | -0.3-0.3 | -2.2-2.4 |
| December 2002 | 0-2.8 | 1.3 | -1.0 – 1.0 | -2.8 – 2.4 | 0-2.7 | -0.3-0.4 | -2.2-2.7 |
| January 2003 | 0-2.8 | 1.2 | -0.9 – 0.9 | -2.7 – 2.7 | 0-2.5 | -0.3-0.4 | -2.1-2.5 |
| February 2003 | 0-3.0 | 1.3 | -1.0 - 0.9 | -3.2 – 3.5 | 0-2.7 | -0.3-0.4 | -2.4-2.7 |
| March 2003 | 0-3.0 | 1.4 | -1.0 - 1.0 | -2.9 – 3.2 | 0-2.6 | -0.3-0.4 | -2.4-2.6 |
| April 2003 | 0-3.0 | 1.2 | -0.9 - 1.0 | -2.5 – 3.3 | 0-2.1 | -0.3-0.3 | -2.1-2.2 |

Table 3. Range and average values of measured current speed, u and v component and that estimated from the tidal current constituents near surface during different months at 14 m water depth

| Month and year | Measured | | | | Estimated from tidal current constituents | | |
|----------------|-------------|---------|-----------|----------|---|----------|----------|
| | speed (m/s) | | u (m/s) | v (m/s) | Speed (m/s) | u (m/s) | v (m/s) |
| | Range | Average | Range | Range | Range | Range | Range |
| July 2003 | 0-3.3 | 0.92 | -1.5 -1.1 | -1.7-3.2 | 0-1.7 | -0.2-0.2 | -1.3-1.7 |
| August 2003 | 0-2.6 | 0.76 | -0.9 -1.1 | -1.5-2.6 | 0-1.8 | -0.2-0.2 | -1.5-1.8 |
| September 2003 | 0-1.8 | 0.66 | -0.9-1.1 | -1.7-1.7 | 0-1.8 | -0.1-0.2 | -1.4-1.8 |
| October 2003 | 0-2.1 | 0.61 | -1.5-0.9 | -1.7-2.1 | 0-1.9 | -0.2-0.2 | -1.6-1.9 |

Table 4. Tidal current constituents at 14 m and 24 m water depth

| Constituent | 14 m water depth | | | | 24 m water depth | | | |
|-------------|---------------------|-------------|--------------------|-------------|---------------------|-------------|--------------------|-------------|
| | Cross shore current | | Alongshore current | | Cross shore current | | Alongshore current | |
| | speed (cm/s) | Phase (deg) | speed (cm/s) | Phase (deg) | speed (cm/s) | Phase (deg) | speed (cm/s) | Phase (deg) |
| Q1 | 0 | 154 | 2 | 10 | 3 | 304 | 1 | 302 |
| O1 | 2 | 169 | 2 | 239 | 4 | 260 | 6 | 267 |
| M1 | 1 | 81 | 1 | 317 | 1 | 324 | 1 | 313 |
| K1 | 2 | 147 | 8 | 310 | 6 | 135 | 24 | 295 |
| J1 | 1 | 52 | 1 | 234 | 4 | 25 | 3 | 346 |
| OO1 | 1 | 16 | 2 | 346 | 1 | 336 | 1 | 255 |
| MU2 | 6 | 64 | 11 | 46 | 4 | 179 | 7 | 57 |
| N2 | 2 | 46 | 18 | 247 | 1 | 259 | 40 | 244 |
| M2 | 3 | 203 | 103 | 249 | 11 | 45 | 165 | 262 |
| L2 | 4 | 302 | 12 | 304 | 1 | 253 | 29 | 258 |
| S2 | 4 | 53 | 28 | 285 | 3 | 300 | 49 | 312 |
| 2SM2 | 2 | 137 | 5 | 147 | 2 | 7 | 2 | 157 |
| MO3 | 1 | 69 | 2 | 102 | 3 | 267 | 4 | 90 |
| M3 | 1 | 173 | 2 | 27 | 2 | 151 | 3 | 42 |
| MK3 | 1 | 72 | 3 | 156 | 2 | 265 | 4 | 262 |
| MN4 | 1 | 18 | 4 | 134 | 2 | 126 | 6 | 150 |
| M4 | 2 | 80 | 9 | 145 | 1 | 294 | 4 | 161 |
| SN4 | 1 | 305 | 4 | 192 | 2 | 236 | 4 | 178 |
| MS4 | 2 | 108 | 7 | 217 | 2 | 311 | 8 | 239 |
| 2MN6 | 1 | 185 | 4 | 295 | 1 | 108 | 4 | 305 |
| M6 | 1 | 95 | 7 | 319 | 1 | 174 | 6 | 299 |
| MSN6 | 1 | 223 | 3 | 347 | 1 | 136 | 4 | 31 |
| 2MS6 | 1 | 169 | 8 | 0 | 1 | 249 | 5 | 11 |
| 2SM6 | 1 | 163 | 3 | 55 | 1 | 122 | 1 | 51 |

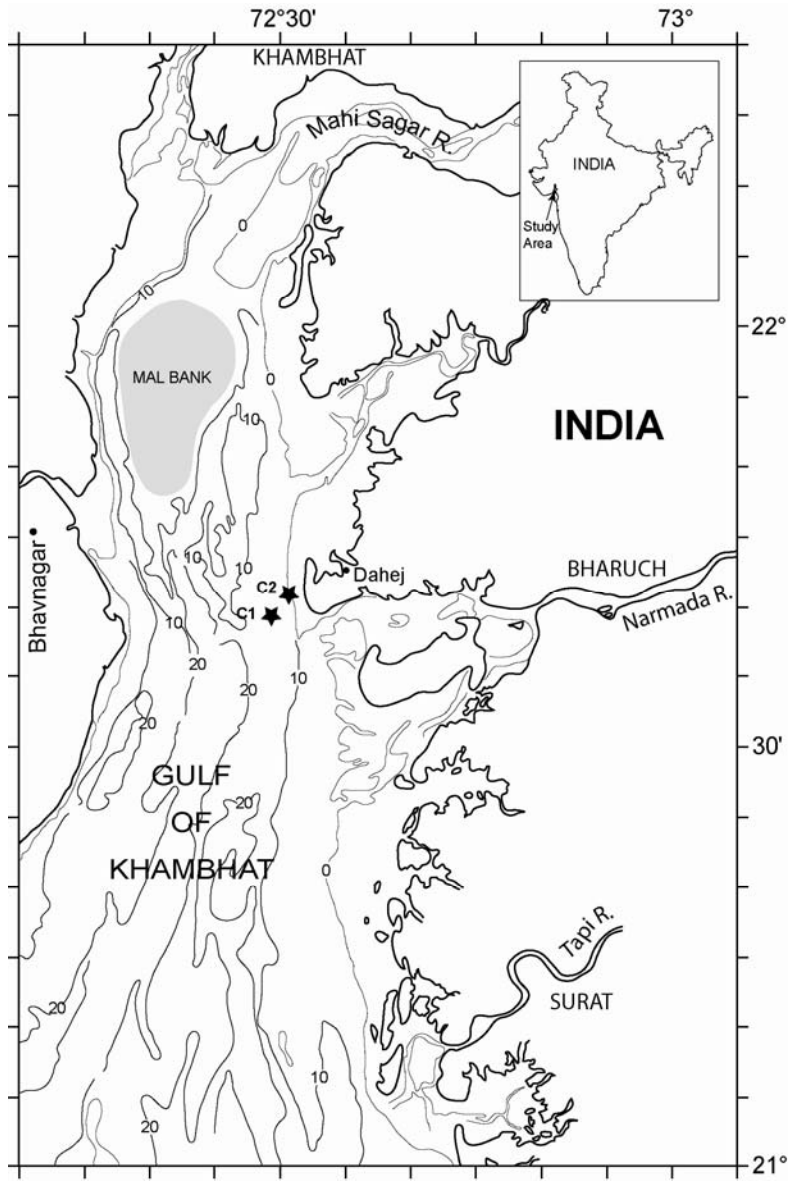


Figure 1. Map of the study area showing the measurement locations

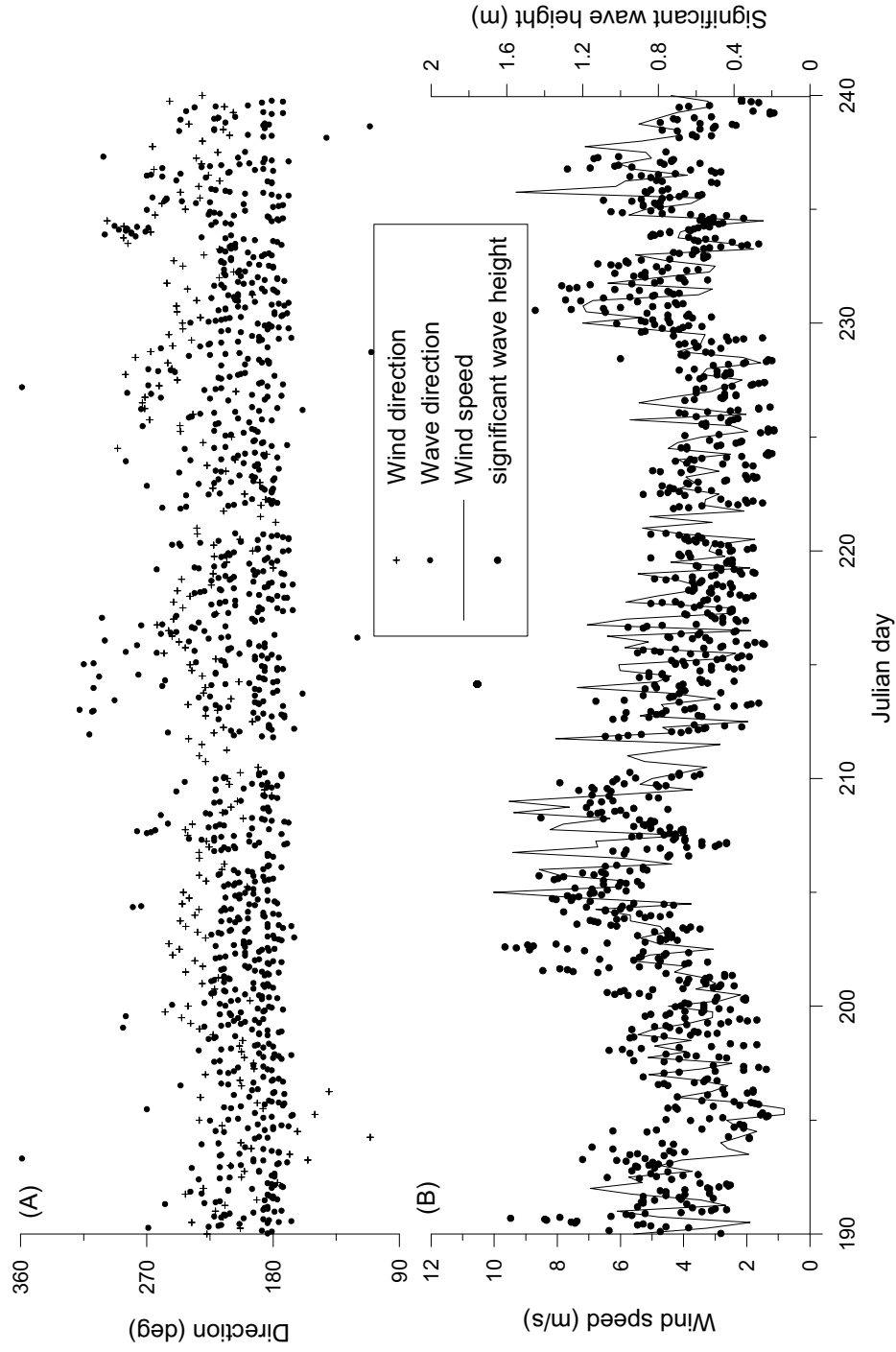


Figure 2. Variation of (A) wind direction and mean wave direction and (B) wind speed and significant wave height during southwest monsoon period

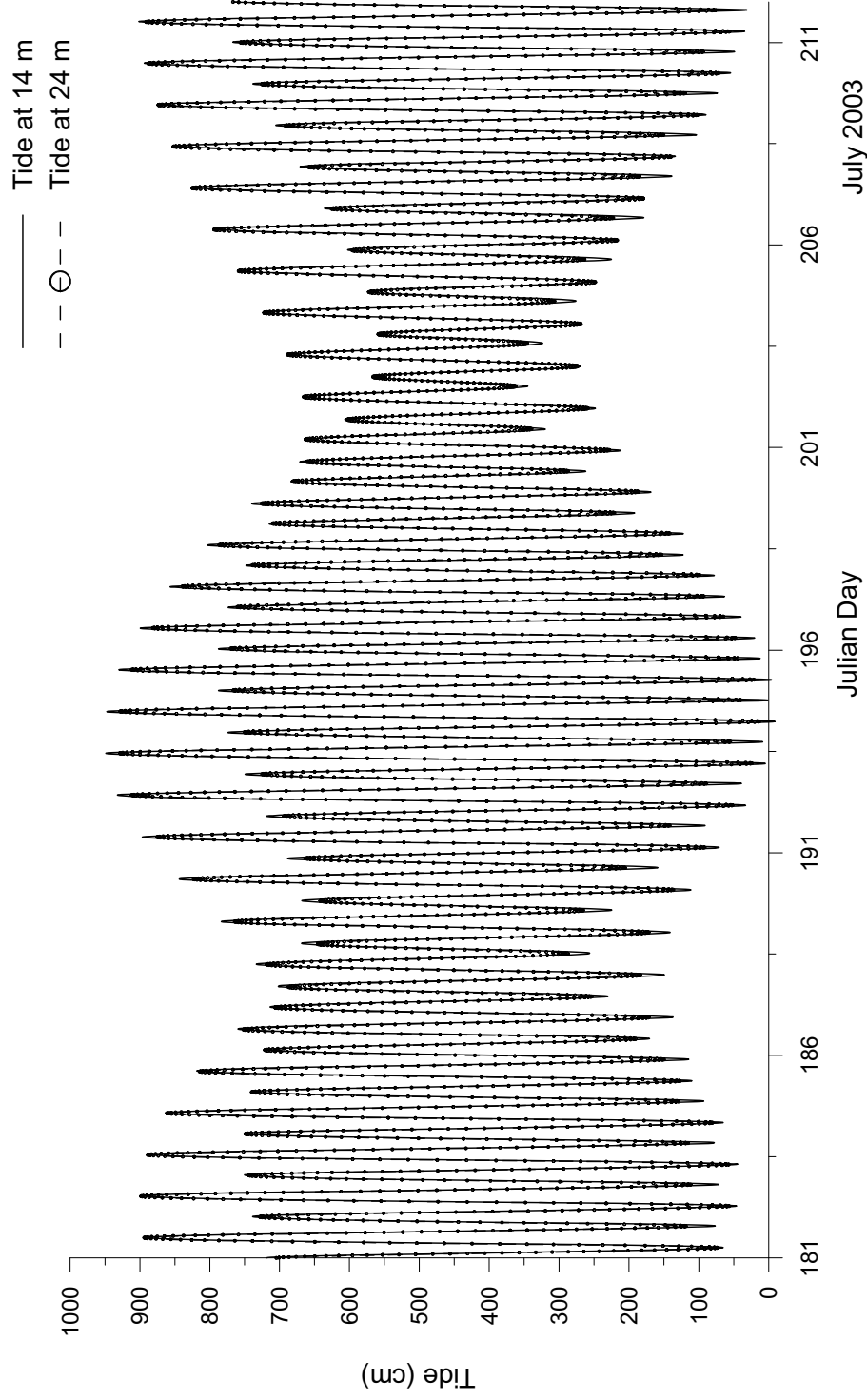


Figure 3 Plot of predicted tide at 14 and 24 m water depth during July 2003 based on the measured data. alongshore current.

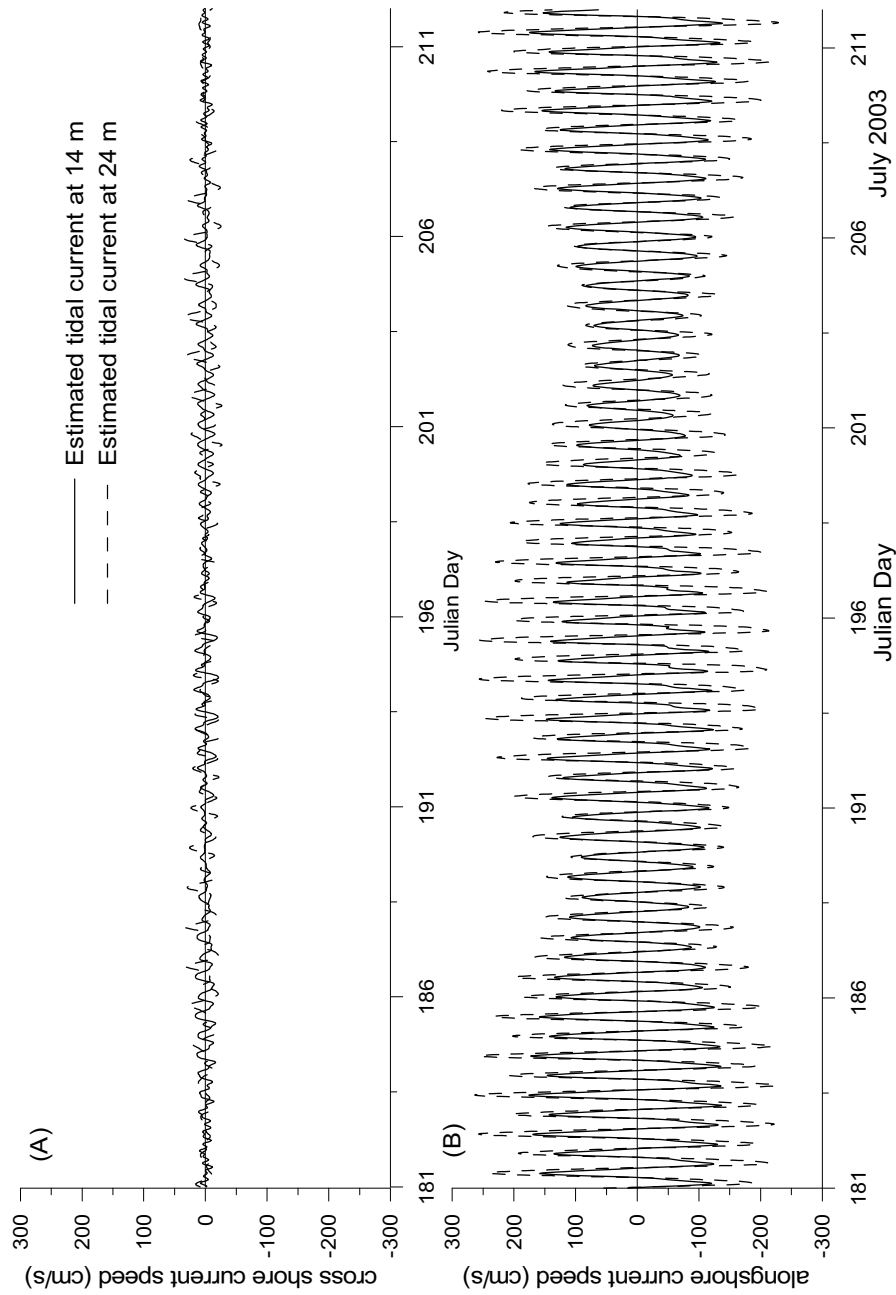


Figure 4. Plot of estimated tidal current at 14 and 24 m water depth (A) cross shore current (B) alongshore current during July 2003.

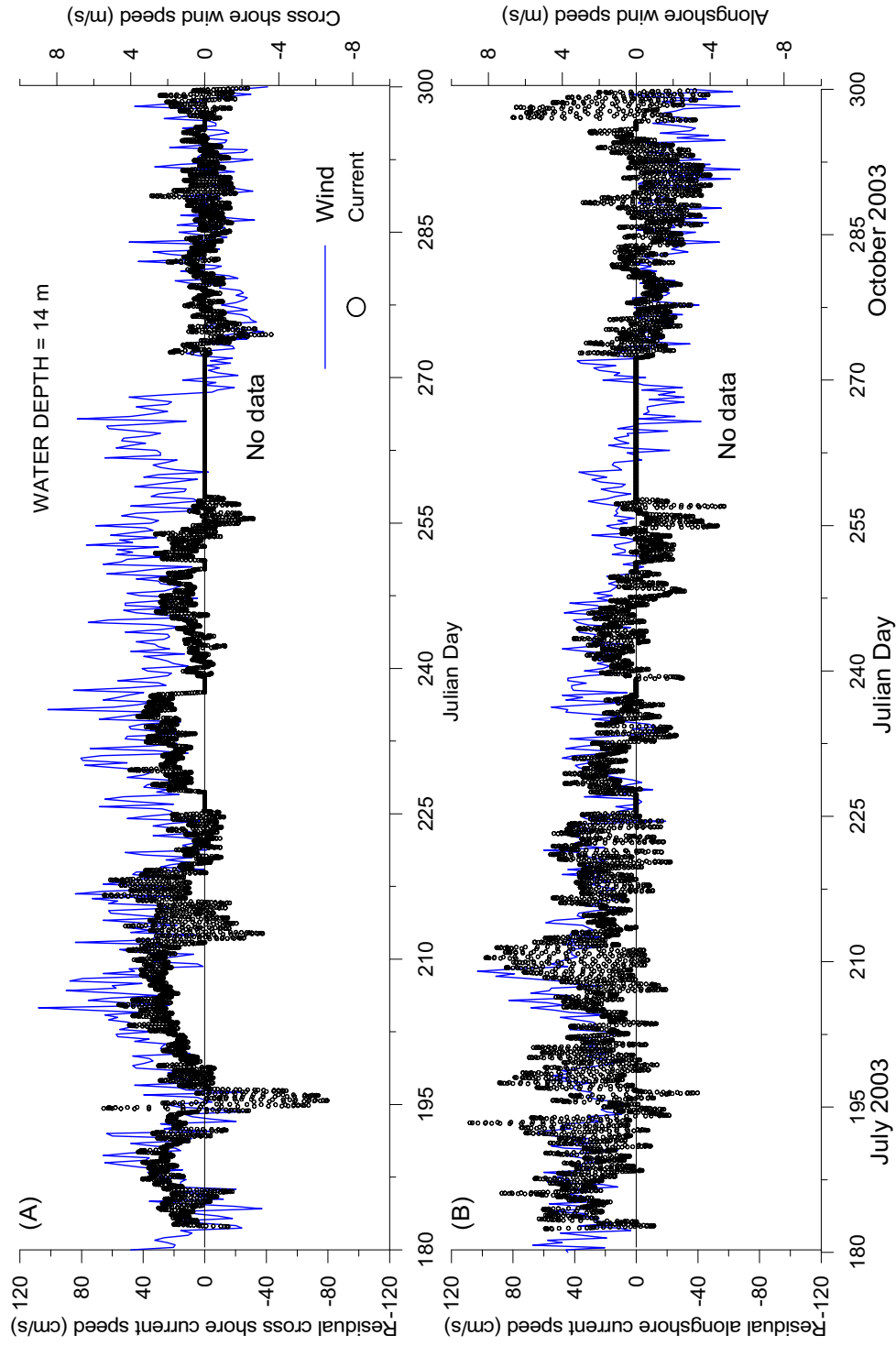


Figure 5. Variation of residual current at 14 m with wind speed (A) cross shore component (B) alongshore component.

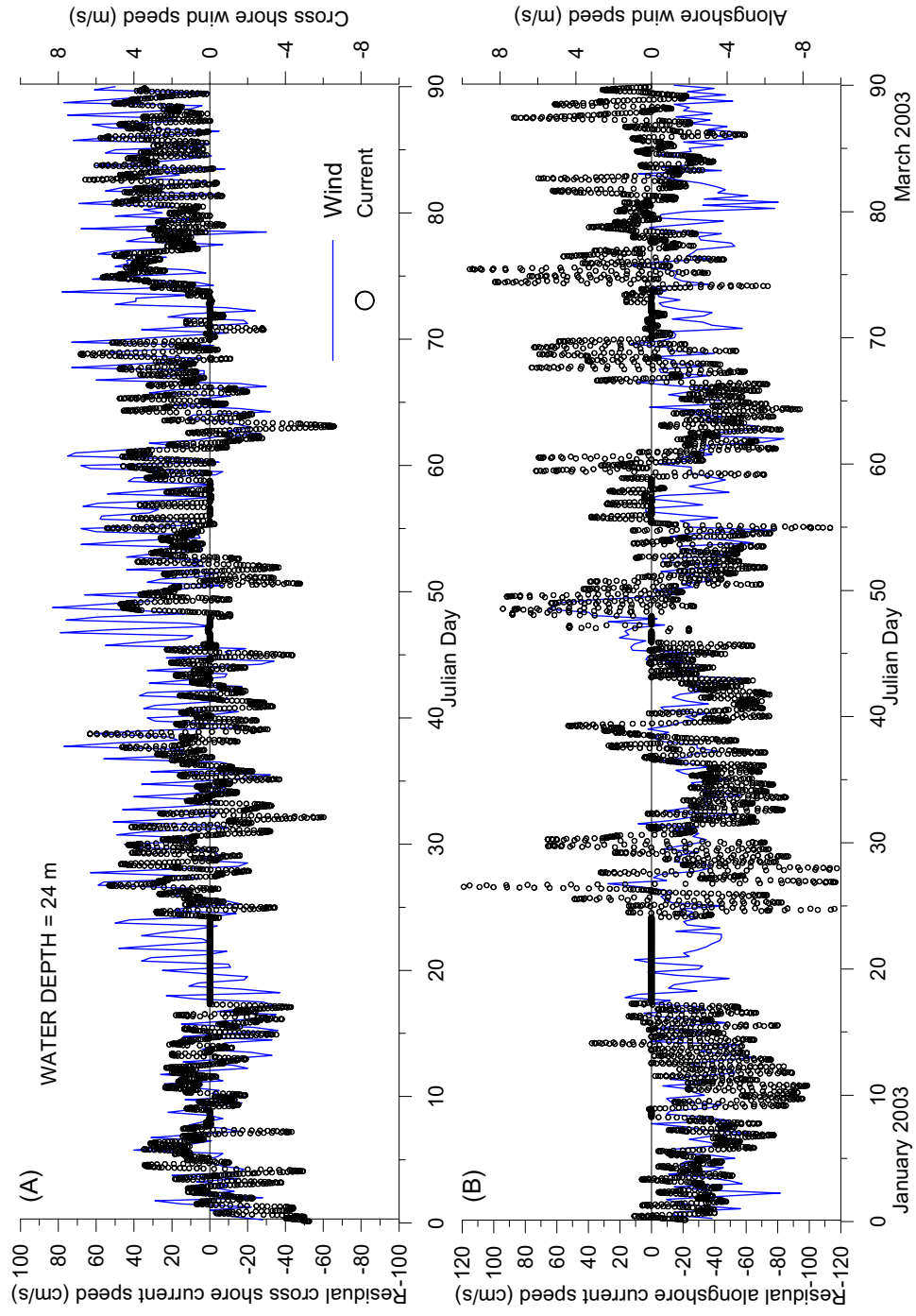


Figure 6. Variation of residual current at 24 m with wind speed (A) cross shore component (B) alongshore component.

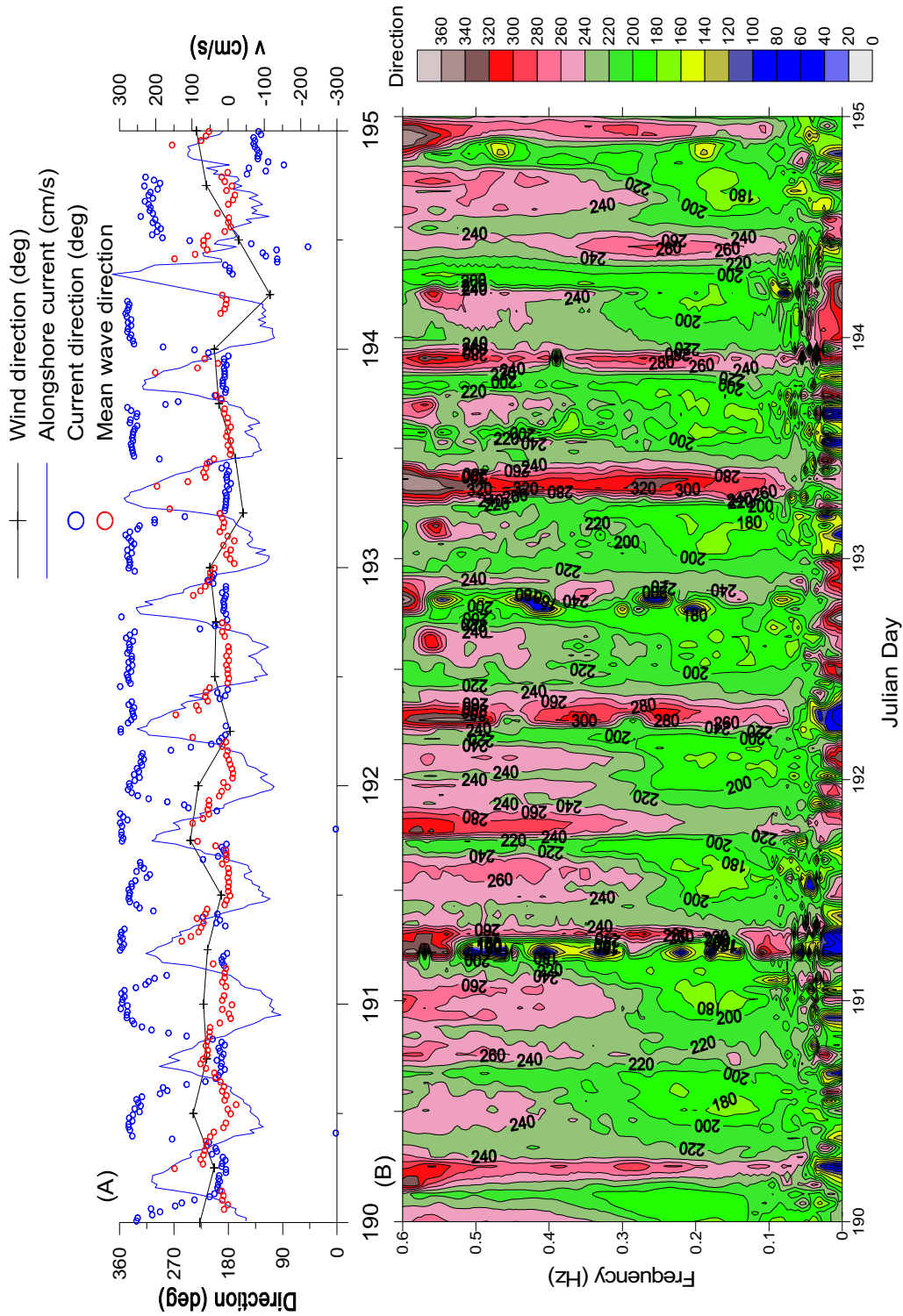


Figure 7. Plot of (A) current direction, mean wave direction, wind direction and alongshore current (B) plot of mean wave direction with frequency.

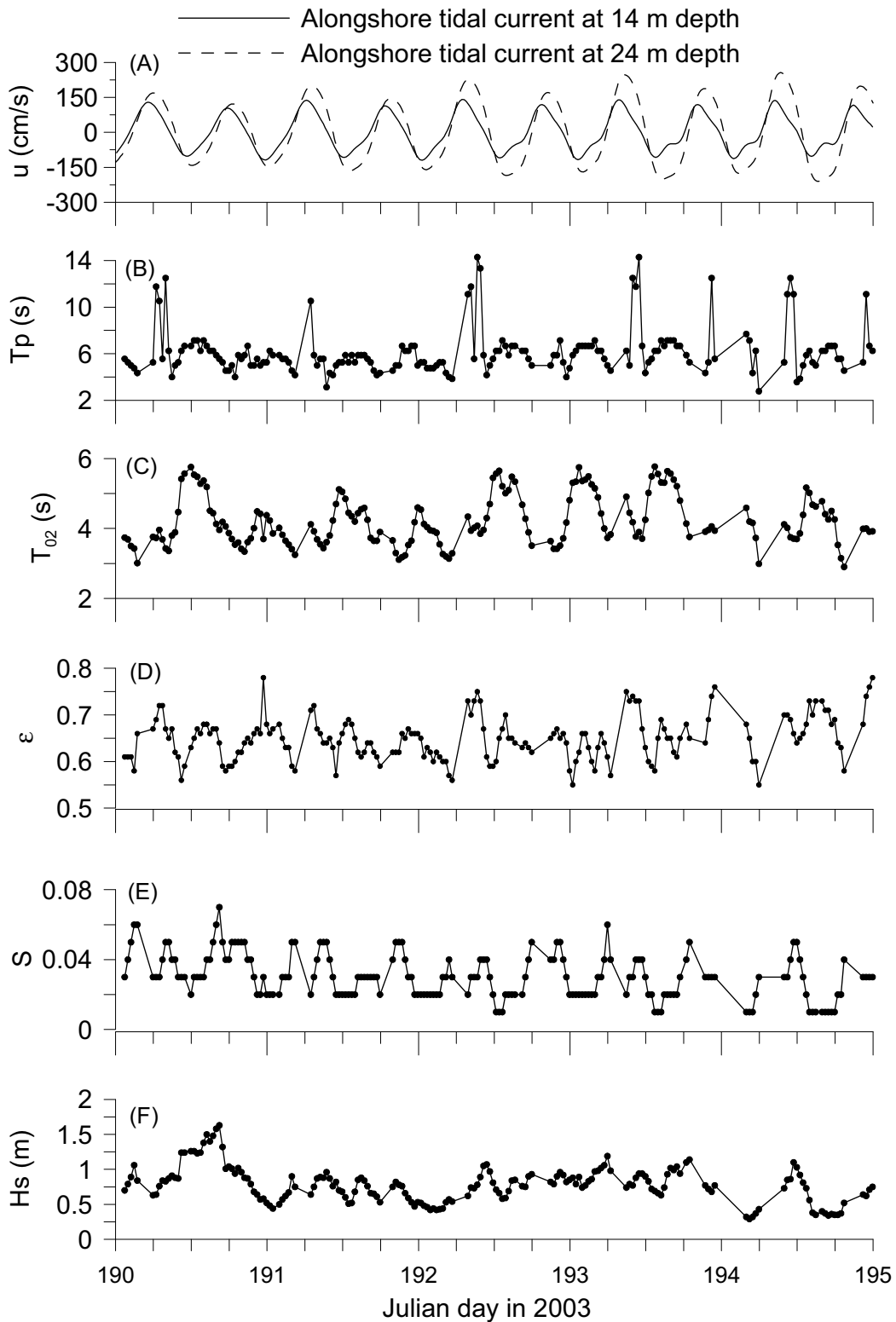


Figure 8. Plot of (A) Alongshore tidal current at 14 m and 24 m water depth, (B) peak period, (C) mean wave period, (D) spectral width parameter (E) wave steepness (F) significant wave height