



WIND INDUCED CURRENT AND ITS IMPACT ON TIDALLY FORCED WATER CIRCULATION PATTERN IN A CORAL REEF AREA OF SOUTHWEST JAPAN

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Abstract: Present study was conducted in the coastal region of Ishigaki Island, southwest Japan to analyze possible driving forces of water circulation which is crucial to the understanding of coastal ecosystems. Data were collected through the deployment of oceanographic instruments in and outside the reef. The time series of current velocities indicates that Shiraho coral reef is characterized by an almost regular and controlled water circulation under calm wind condition. Tidally forced oceanic water entered the reef through prominent channel and finally drained out through the southern part of the study area. In the offshore area, tidal currents during flood tide and ebb tide were nearly parallel to the north-south stretch of the reef. Data from Ishigaki Meteorological Observatory indicated that local wind can be an important factor in driving currents both in and outside the reef area. Though the wind field of the region was characterized by both north and south wind, the current field was more strongly influenced by north wind than the south wind. North wind developed a dominant south current inside the reef with a significant temperature drop during winter. During summer, northerly wind contributed to the development of south current in the offshore area as north-south component of wind and current showed the existence of low frequency density peaks. As dominant force came from north wind, no strong peak was seen in the east-west (cross-shore) component of wind and current.

Key words: Ishigaki Island, Shiraho coral reef, tidal current, wind, water circulation

Introduction

Research on coastal water circulation dynamics in tropical and subtropical waters has received considerable attention in the recent past because the hydrodynamic processes determine the short- and long-term sustainability of marine coastal ecological systems (Swenson and Chuang, 1983; Wolanski, 1986; 1994; Kruyt and van der Berg, 1993). The main forcing functions responsible for coastal circulation are astronomical tide, river discharge and meteorological forcing of which wind is important (Joseph and Kurup, 1987; Denes and Caffrey, 1988; Pylee *et al.*, 1990). The strength and therefore the significance of each of the above forcing mechanism vary depending on a wide range of topographic, hydraulic and meteorological controls (Hansen and Rattray, 1965, 1967; Chandrakanth *et al.*, 1987). Coral reefs typically occur along continental or insular shelves exposed to energetic oceanographic and meteorological phenomena. Community structures, production rates and exchange or dispersal of materials in coral reef areas are found significantly influenced by water circulations (Yamano *et al.*, 1998; Kraines *et al.*, 1998; Andrews and Pickard, 1990; Hamner and Wolanski, 1988; Smith, 1984). Circulations in reef areas may have a significant

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effect on nutrient supply by determining the thickness of the stagnant boundary layer (Bilger and Atkinson, 1995, 1992; Atkinson and Bilger, 1992). The description of water circulation pattern is therefore crucial to the understanding of ecosystem dynamics.

Many researchers e.g., Shepard and Inman, 1950; Harrison and Krumbein, 1964; Sonu and Johannes, 1971; Davis and Fox, 1972; Nummedal and Finley, 1978 have explained the effect of wind on offshore current. According to Sverdrup *et al.* (1942), whether stationary or moving, every wind system will create currents. Meteorological events act on water systems through atmospheric pressure gradients and wind (Le *et al.*, 2000). Andrews and Pickard (1990) concluded that reef circulation is mainly driven by wind, tide and by wave overtopping the reef crest. The significance of wind on circulation in coral reefs in a deep atoll lagoon was analyzed by Atkinson *et al.* (1981). For water circulations in platform reefs, the importance of wind was shown by authors like Frith (1981), Frith and Mason (1986), and Pickard (1986). Pickard (1986) studied the effects of wind and tide on upper layer currents at Davis Reef and Great Barrier Reef. He showed that the circulation on the reef flat is significantly influenced by wind direction. The author estimated the ratio of wave overtopping component to wind driven component and found that wind contributes 60% of the total on shallow reef flat. Present study analyzes the impacts of wind on water circulations both in and outside the reef.

Field observation methods

Study area: Southeast part of Ishigaki Island (24° 19'-37' N, 124° 4'-21' E) was the location of the present study (Fig. 1a). Ishigaki is an island in the Ryukyu Islands (from about 123° E to 129° E and from 24° N to 27° N), southwest Japan. The climate of the Island is subtropical. Fringing reefs are present around the Island. Shiraho hamlet lies on the southeastern coast of the Island. Shiraho reef is subjected to wind driven swells both in summer and winter and semidiurnal tides are dominant in the region. Shiraho reef is about 700 m wide in the north and about 850 m wide in the south and it is about 1300 m from north to south (Nakamori *et al.*, 1992). Field observations were made both in and outside the reef areas and over a stretch of about 8 km along the shore and about 8 km into the open ocean. Depths of water at the sensors' locations outside the reef area were 52 m to 230 m while in the reef area the maximum depth was about 3 m. Reef areas were connected with the open ocean through reef gaps namely "Tooru-guchi, Ika-guchi, Moriyama-guchi and Bu-guchi. Southern part of the reef area was comparatively shallow which is known as "Watanji" that becomes exposed to the air during low tide (Fig. 1b).

Sensor deployment: Observations were conducted during 2001 (from August 10 to October 27) and 2002 (from February 7 to March 25). As Fig. 1b shows six locations were selected outside the reef area (stations Off1-Off6) and seven stations in the reef (Re1-Re7). Acoustic Doppler Current Profilers (ADCPs) were set at offshore stations (Off1-Off6) to collect depth profiles of horizontal velocity. Acoustic frequencies of the ADCP were 500 to 600 kHz. ADCP recorded current at every 10 minutes and 1 meter depth intervals over the entire depth. For time series measurement of current velocities Compact Electro Magnetic Current Meters were also deployed at reef stations (Re1-Re7) with the aid of moored buoys. Reef currents were measured at 10 minutes intervals at around middle depth. Ishigaki Meteorological Observatory supplied data on solar radiation, atmospheric temperature, precipitation, wind velocity, atmospheric pressure, and sea vapor pressure. All these data were analyzed and compiled using different programs and software.

Results

Reef currents influenced by oceanic inflow: Figure 2 shows that when the tide in the offshore (station Off.1) started rising, tidal water entered into the reef. Offshore water flowed into the reef through station Re1 with southeast direction. This current continued flowing through station Re1

for a maximum period of 3 hours with gradual propagation toward the southern part of the reef area. After passing station Re2 tidal current advanced toward station Re7 with southeast direction at stations Re2 and Re7 and southwest direction at stations Re3 through Re6. During the period of tidal rise, almost unidirectional current was measured in the reef for a short period on a semidiurnal frequency. Figure 2 indicates that water circulations in the reef area were represented by northwest current at stations Re1, Re2 and Re5, southwest current at stations Re6 and Re7 and a dominant east current at stations Re3 and Re4 other than the short period semidiurnal current that followed nearly uniform directional pattern.

Reef currents induced by wind: The average velocity of north wind was higher in comparison to south wind during the observations (Fig. 3a). When north and northwest wind blew with a velocity of more than 5 m/s, it brought a sudden change in the regular water circulation pattern inside the reef (Figs. 3b and 3c). A dominant north wind increased the wave height considerably (Fig. 3d) and influenced the current of the reef area to flow toward the south with a significant velocity. When north wind prevailed it caused a sudden fall in atmospheric temperature that eventually caused a significant water temperature drop in the reef area (Figs. 3e and 3f). Results show that south wind with comparatively higher velocity (more than 10 m/s) was capable of developing current in the region. Five important periods are selected and discussed below considering the degree of significance of wintry wind on sea waves that break down on reef edge and finally influence the current field inside the reef.

- (a) 14:00 to 22:00 on February 2 (Fig. 4): North wind with a velocity of around 5 m/s led to a south current at stations Re3 through Re6. No current data were recorded from stations Re1, Re2 and Re7.
- (b) 06:00 to 15:00 on February 19 (Fig. 5): With a velocity of 5-7 m/s north wind dominated the wind field and the principle current direction at stations Re2, Re3, Re6 and Re7 were toward the south. Current directions at stations Re4 and Re5 were both toward the north and south.
- (c) 04:00 to 21:00 on February 24 (Fig. 6): North wind induced south current at stations Re2 to Re3, and Re5 to Re7. Data showed northwest current at stations Re1 and Re4.
- (d) 04:00 to 15:00 on March 14 (Fig. 7): As it was south wind with a velocity of 5-10 m/s north current was recorded in the reef areas at stations Re2 through Re6. Station Re7 experienced both north and south currents while station Re1 was mainly characterized by northwest current.
- (e) 18:00 on March 17 to 02:00 on March 18 (Fig. 8): Current vectors show a principle south current for all the stations except Re1 where current vectors indicate northwest flow pattern as usual.

Tidal current in the offshore region: Depth averaged current vectors both during flood tide and ebb tide were found to be nearly parallel to the north-south stretch of the reef. When the tide was rising, depth averaged south and southwest currents prevailed in the region while for a dropping tide, current directions were toward the north and northeast. Harmonic tidal analysis of 8 principal tidal constituents (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 and M_m) indicated that M_2 and S_2 tidal components mainly influenced the general circulation pattern outside the reef area.

Current induced by wintry wind in the offshore region: Though the depth averaged tidal currents in the offshore area mainly flowed toward the south and north during flood tide and ebb tide respectively, a careful examination of the depth profile of horizontal current indicates that local wind also induced current in shallow water region. Figure 9 shows horizontal velocity distributions for station Off1 starting from 5 m below the surface down to 50 m depth with a depth interval of 10 m. Velocities are shown for 04:00 to 21:00 on February 24 where north-south component (Fig. 9a) indicated the formation of south current in the surface layer with the gradual transmission toward the bottom. Velocity of east-west current (Fig. 9b) was significantly lower in

comparison to north-south current. As northerly wind blew (Fig. 6) during winter, a prominent south current was developed outside the reef area.

Current induced by wind in the offshore region during summer: For summertime observation, current vectors at station Off4 are presented in Fig. 9 at depths starting from 5 m below the surface down to 53 m with an interval of 10 m. Wind and current vectors are presented in Fig. 9 from August 10 to October 27. Harmonic tidal effects composed by a bit of 8 major tidal constituents e.g., M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 and M_m (M_2 -principal lunar; S_2 -principal solar; N_2 -larger lunar elliptic; K_2 -luni-solar semidiurnal; K_1 -luni-solar diurnal; O_1 -principal lunar diurnal; P_1 -principal solar diurnal and M_m -lunar monthly) were subtracted from raw current data. After subtraction, the resultant velocities were smoothed through 25 hrs. The wind data also smoothed through 25 hrs. Wind vectors show a dominant north wind that produced south current in discrete layers. Current vectors also indicated that horizontal current responded to the wind speed considerably and current velocities gradually decreased from the surface toward the bottom layer with the subsequent fall in initial wind stress.

Power spectral analysis of wind and current data for Station Off4 data are presented in Fig. 11 where both the current and wind velocities were smoothed through 25 hrs. Before smoothing the current data, 8 major tidal components (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 and M_m) were subtracted from raw data. Spectrum graphs show low frequency velocity peaks. Low frequency (at 12.5 days interval) velocity peaks were found for north-south component of wind and current.

Discussions

According to the present study, Shiraho coral reef is characterized by an almost regular and controlled water circulation pattern under normal atmospheric condition. Incoming tidal waters and reef configurations played an important role to this characteristic circulation pattern. Figure 2 indicates oceanic water entered the reef through *Toruguchi* channel and after that it flowed toward *Watanji*, and finally drained out through the southernmost part of Shiraho reef. Yamano *et al.* (1998) and Nadaoka *et al.* (2001) pointed out that Shiraho Reef is characterized by a single water circulation unit, where the sea water comes in through the reef edge and drained into southern reef through the depression on *Watanji*. The driving force of the circulation comes from tidal oscillations and wave breaking effects that occur at the reef edge area. The authors did not mention the detail flow pattern and also the entry point of tidal water. Present study explained the issues of hydrodynamic environment that were not investigated properly in previous studies. Other than the inflow of strong tidal current, reef water followed distinct circulation pattern. Nakamori *et al.* (1992) discussed the role of arrangement of coral patches on the reef flat in reflecting this water circulation.

Though Shiraho reef is characterized by an almost regular and constant water circulation pattern, local wind is found to influence general circulation. Both north and south winds were present during the study however, north wind was found to drive currents in the reef during the winter season. Yamano *et al.* (1998) observed water circulation in Kabira reef of Ishigaki Island (located in the western part of the Island) and mentioned that northern-wind driven circulation was dominant in winter. Present study agrees with the findings of Yamano *et al.* (1998) however, the authors did not show the influence of southern wind in winter. Present study shows that south wind with a velocity of around 8-10 m/s can drive current in the reef area even in winter season. As it is already said *Toruguchi* channel played an important role to the inflow of offshore water inside the Shiraho reef, current velocity at station Re1 which is located near *Toruguchi* was always stronger than the rest of the measuring points. Since tidal force, reef gap and configuration of the reef channel mainly controlled the velocity and direction of current at station Re1, the influence of wind force was almost negligible there. Elsewhere, reef currents were sometimes found not to follow the speed and direction of wind due to the configuration of the reef channel. This is because

the above flow has the tendency to reverse when the wind stress drops (Tyler and Sanderson, 1996) and at the same time, other forces like tide, reef configuration try to counter the wind stress. Depth averaged tidal currents in the offshore area were dominated by alongshore direction where bathymetric features are assumed to play a vital role. The phenomena of tidal current in the study area were also discussed by Nadaoka *et al.* (2001). Beside the significance of tidal force, wintry wind was found to be an important factor contributing to nearshore current. Figure 10 indicates that the wind field was dominated by north wind that influenced current of the shallow offshore region to flow in a south direction. These results went a bit contrary to the findings of Yamano *et al.* (1998) who observed dominant southern wind-driven circulation in Kabira reef. It appears that this discrepancy comes from the difference of locations of Kabira and Shiraho reef. The depth profiles of current vectors are dominated by variability both in along-shelf direction and speed. This is because wind stress and along-shelf surface slope are the leading terms in depth-integrated along-shelf momentum balance, but bottom stress also plays an important role in the balance (Wong, 1999). Power spectral densities show that during summer, the wind field was dominated by northerly wind that contributed to the generation of south current. The results also indicate that both during summer and winter, the hydrodynamic environment of the study area was mainly dominated by northerly and southerly winds. As a result no strong density peaks were found in the east-west (cross-shore) component of horizontal current.

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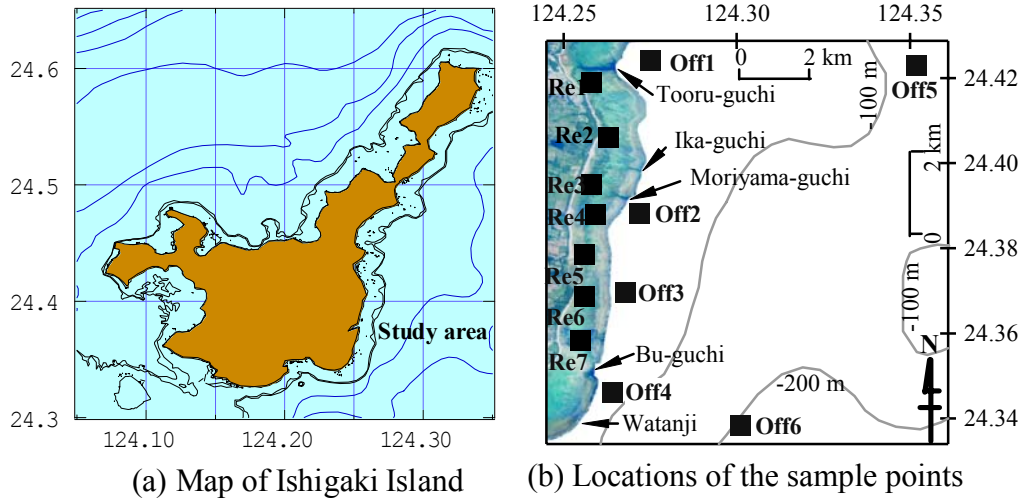


Figure 1 Map of Ishigaki Island and locations of the sample points

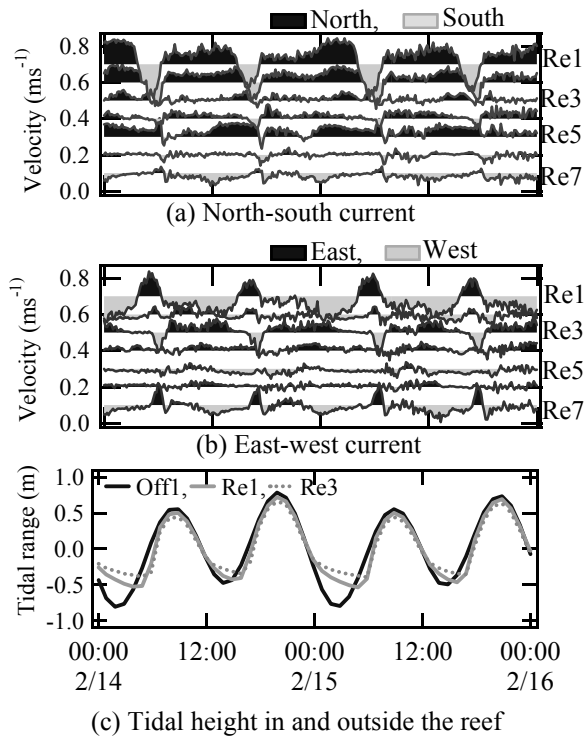


Figure 2 Horizontal current inside the reef, and tidal levels for reef and offshore areas

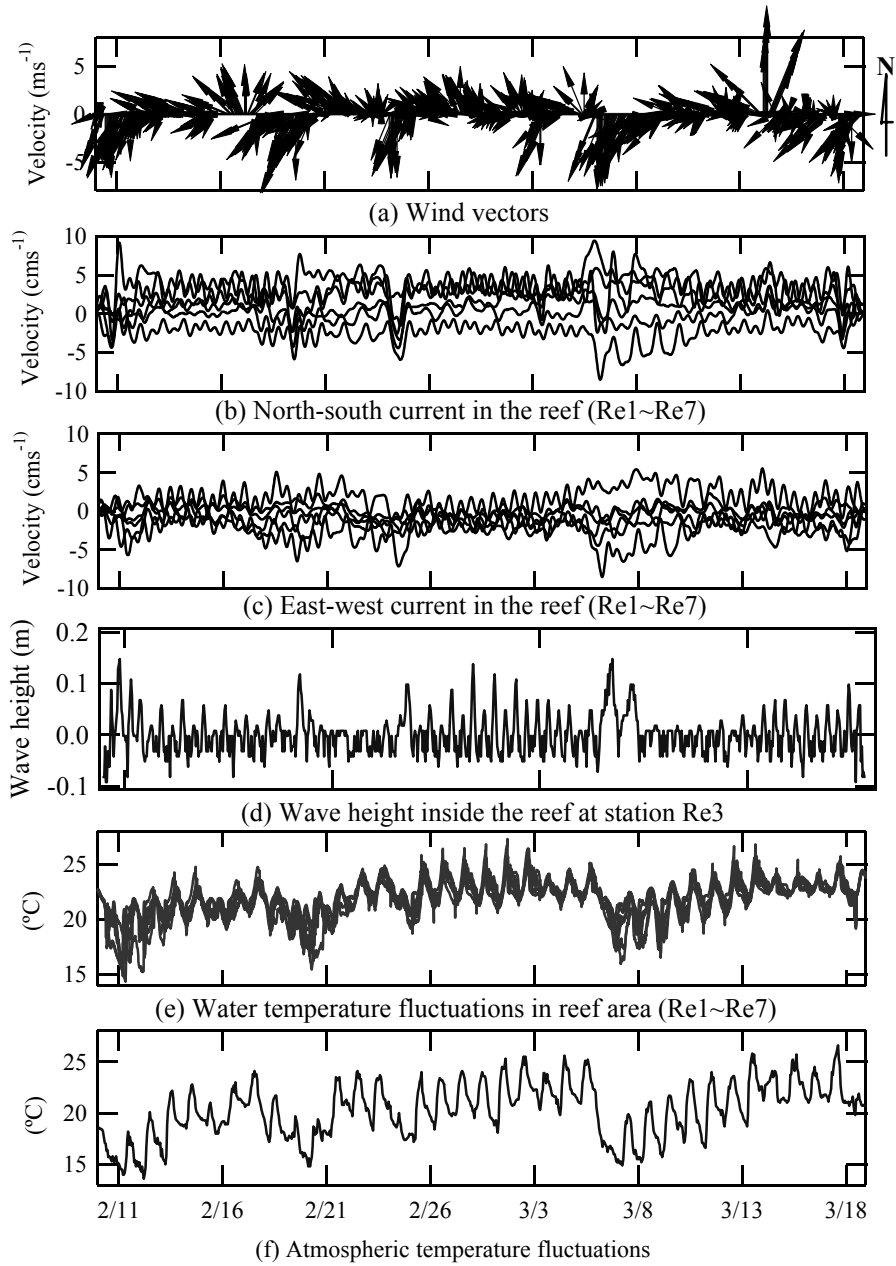


Figure 3 Wind vectors, atmospheric temperature, current, wave height and temperature in reef area

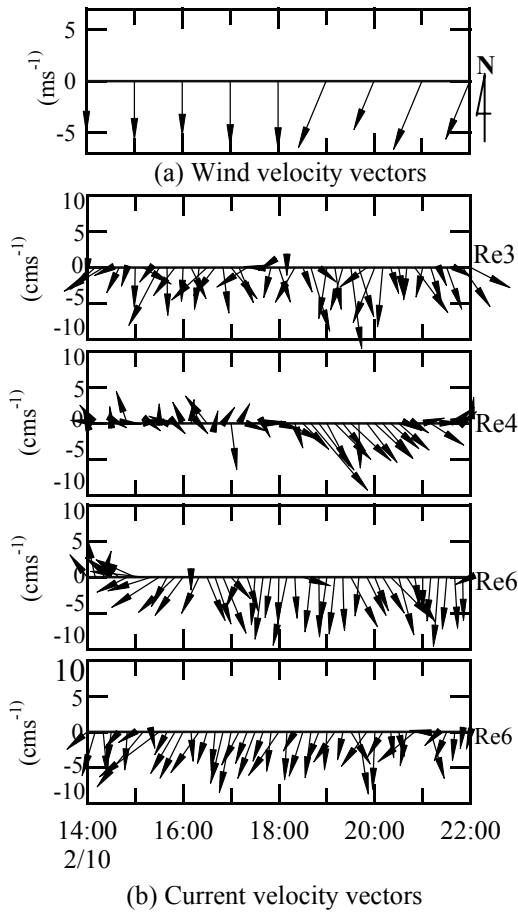


Figure 4 Wind and reef current vectors during 14:00 to 22:00 hours on February 10

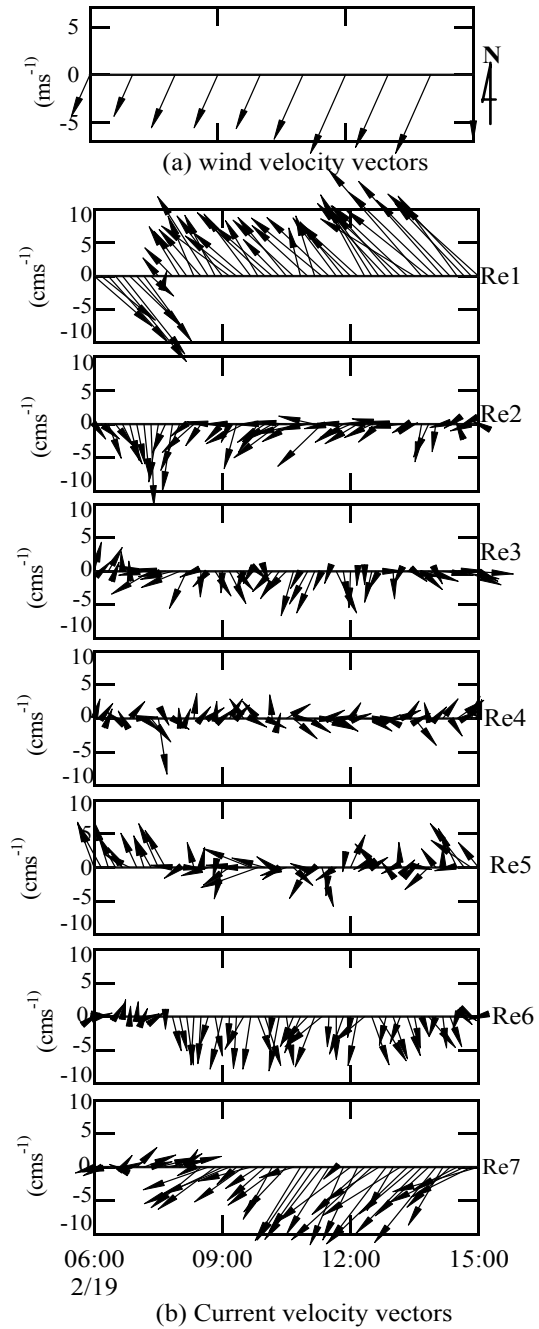


Figure 5 Wind and reef current vectors during 06:00 to 15:00 hours on February 19

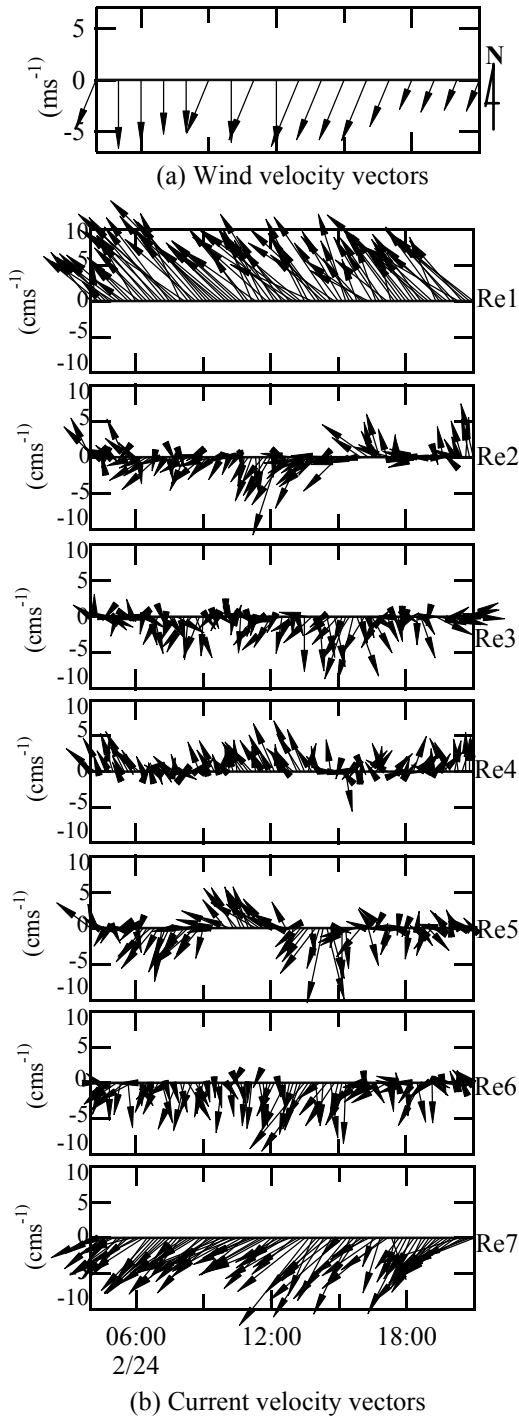


Figure 6 Wind and reef current vectors during 04:00 to 21:00 hours on February 24

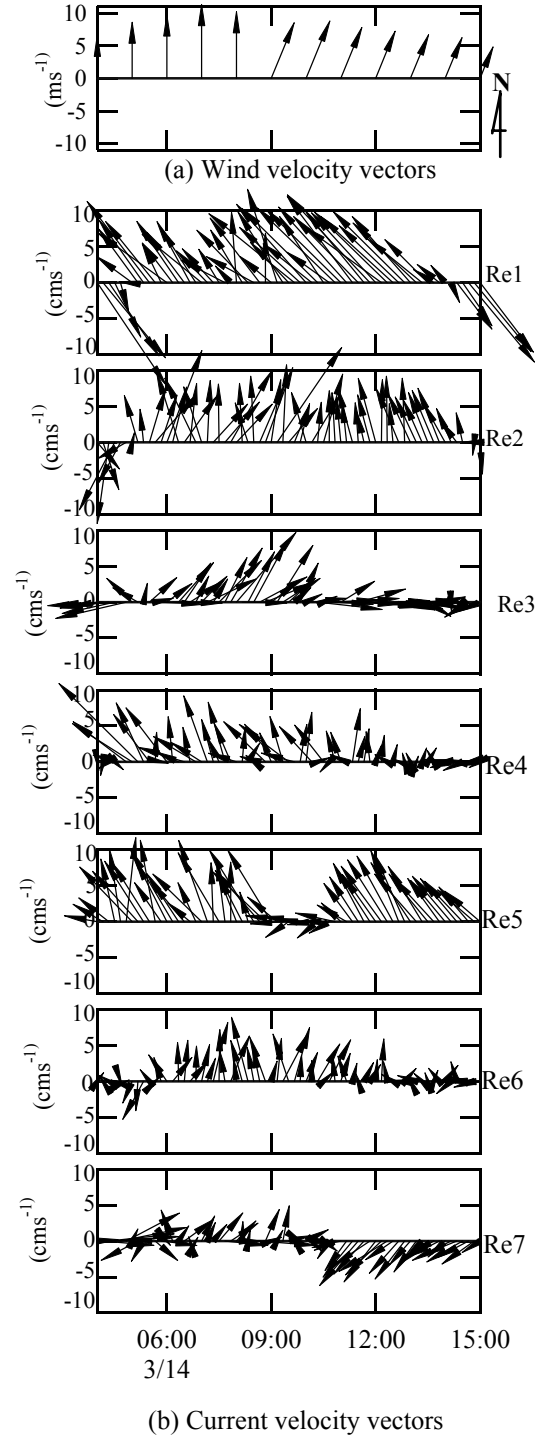


Figure 7 Wind and reef current vectors during 04:00 to 15:00 hours on March 14

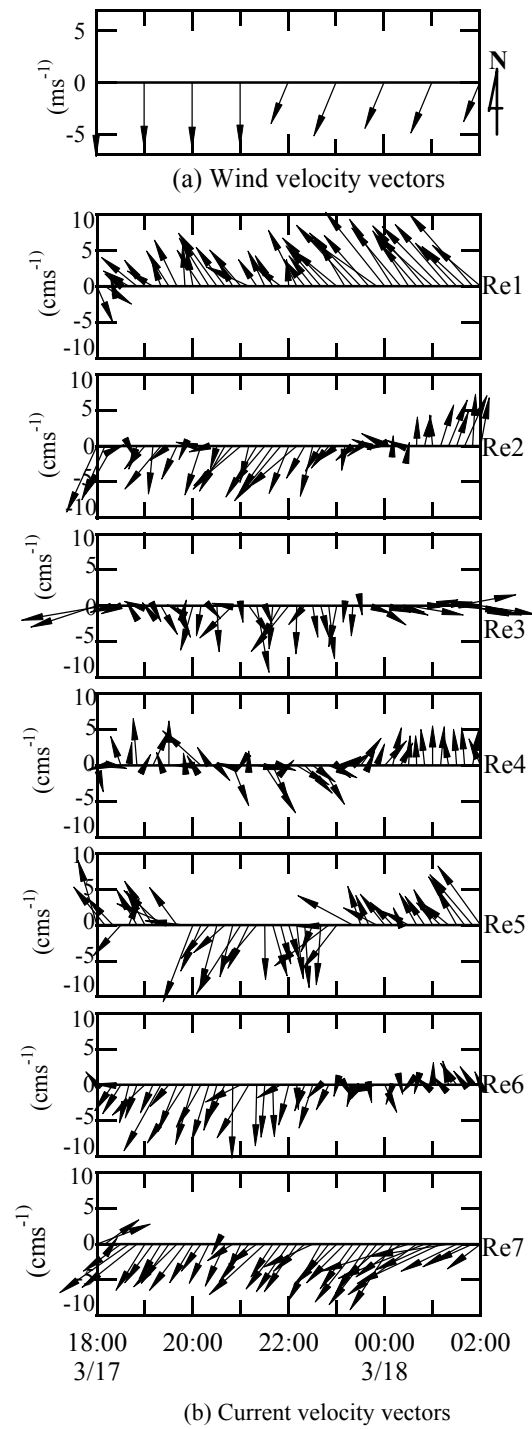


Figure 8 Wind and reef current vectors during 18:00 hour on March 17 to 02:00 hour on March 18

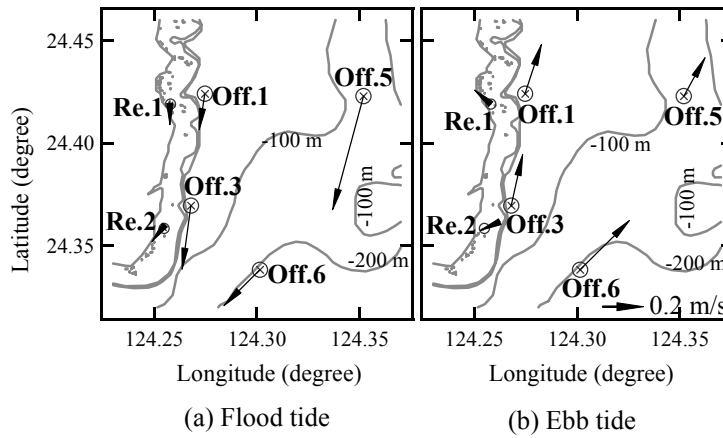


Figure 9 Current vectors for reef and offshore region

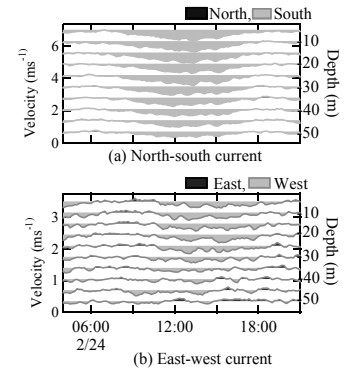


Figure 10 Depth profile of horizontal current at station Off1

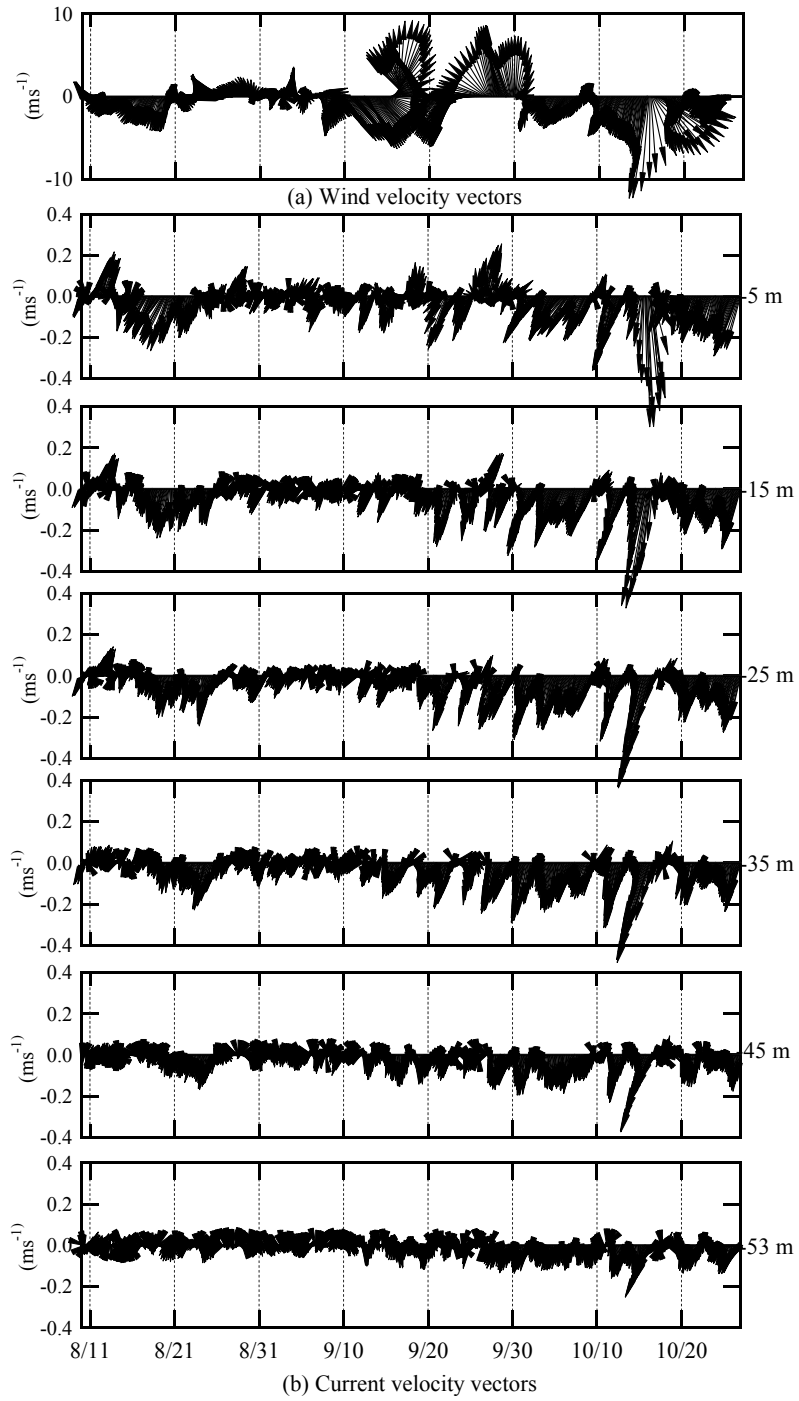


Figure 11 Wind vectors and vertical profile of current vectors at station Off4

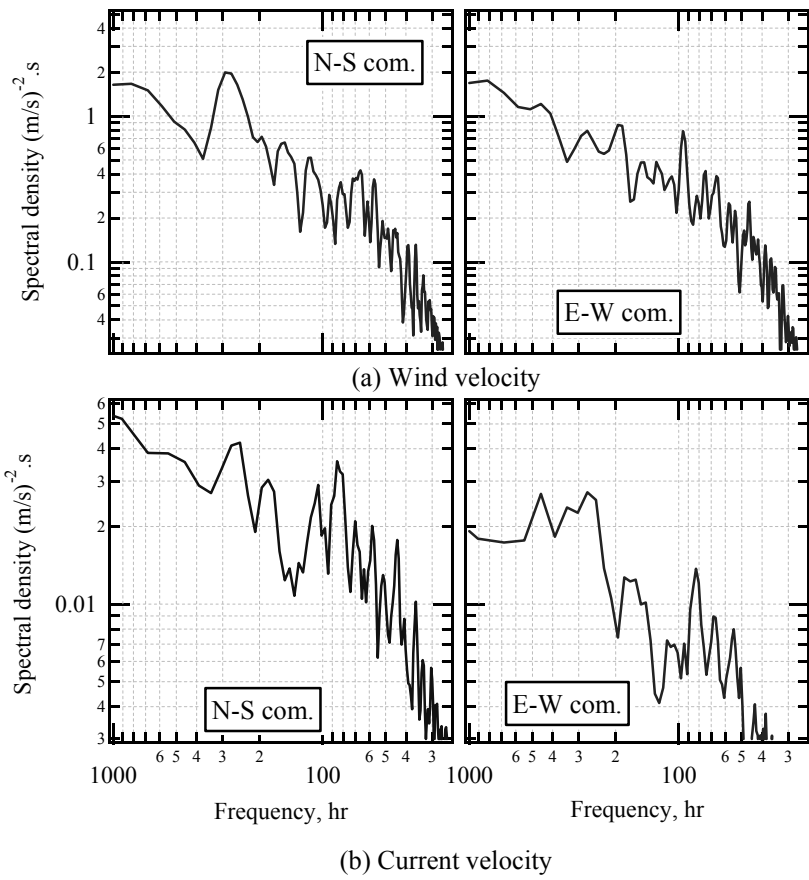


Figure 12 Power spectral densities for wind and offshore current (station Off4)