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Wind-Driven Vortex-Pair Flows in Funka Bay, Hokkaido in Early Summer

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Abstract

Coastal currents were observed to try to detect wind-driven vortex-pair flows at four stations in Funka Bay located southwest Hokkaido. In early summer, when southeasterly winds were dominant in the area, leeward currents were observed at 10 m depth at northwest and southeast mooring station (Sts. DA and OT) in the bay, while weak and stagnant currents at the innermost station (St. OS) were observed throughout the mooring periods. At the center of the bay (St. 30), there were mainly windward currents at 80 m depth, but strong northeastward currents were found at 20 m depth. Correlation coefficients between northwest components of the currents and southeasterly winds were of the same value for the two coastal stations of St. DA and St. OT, but the response time of the currents for the winds were different at their stations. These observations confirm that a wind-driven vortex-pair in the bay was generated by wind forcing.

Key words : Wind forcing, Vortex pair, Funka Bay

Introduction

Funka Bay is located southwest of Hokkaido, northern Japan, and is a site where scallops and kelp are widely cultivated. Moreover, the bay is an important nursery ground of walleye pollock in the northwest Pacific. Surface currents are important in the transport processes of scallop larvae, pollock eggs and kelp seeds. Circulation patterns in the bay also influence on sedimentation and resuspension processes in the coastal cultivated fields.

Marine observations in Funka Bay were first conducted by the Marine Observatory in 1933 (Marine Observatory, 1934). A clockwise eddy characterized by warm and low salinity water was observed in the bay basin in mid summer. Kashiwamura (1963) suggested that basin-wide circular currents change seasonally, that is, the circulation is clockwise in summer and counterclockwise in winter, based on two kinds of observations of current direction panel method and drift bottles. Furthermore, current direction determined by panel observations at seven stations inside the bay showed that coastal currents flowed to same direction off northeast and southwest coasts, and that these directions change seasonally (Hokkaido Development

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Bureau, Institute of Civil Engineering, 1967).

On the other hand, Ohshima and Miyake (1990) suggested that a wind-induced vortex pair occurred in the bay based on the results of a numerical experiment using a barotropic model with bottom topography. Miyake et al. (1998) reviewed some past works and concluded that seasonal changes of coastal currents are induced by monsoon winds. Namely, southeasterly winds drive northwestward coastal currents in summer, and northwesterly winds drive southwestward coastal currents in winter in the bay. They considered that seasonal winds generated a pair of vortex flows with opposite direction, seasonally.

In this paper, we first describe the characteristics of coastal currents at four stations, and present evidence for such a wind-induced vortex pair in the bay.

Observations

Funka Bay has a circular basin with a bowl-shape bottom, a maximum depth of which is about 95 m, and has a sill of about 85 m depth (Fig. 1). Direct current measurements were carried out off the coasts and at the center of the bay from May to June in 1997. Aanderaa current meters (RCM) were moored at 20 m and 80 m depth at the center of the bay (St. 30), and electromagnetic current meters (ALEC, ACM-8M) were moored at 10 m depth of St. DA, St. OT and St. OS in the bay (Fig. 1). Details of observation periods are shown in Table 1. Water temperatures and current vectors obtained every 10 minutes were averaged hourly and smoothed using a low-pass Gaussian filter with an 81-hour half power point to remove high-frequency fluctuations such as tides, internal waves and inertial oscillations.

We used atmospheric pressure difference between Urakawa and Hakodate to estimate the southeast component of the wind (Fig. 1). Considering the geostrophic wind in the bottom Ekman layer, the pressure difference between their two stations

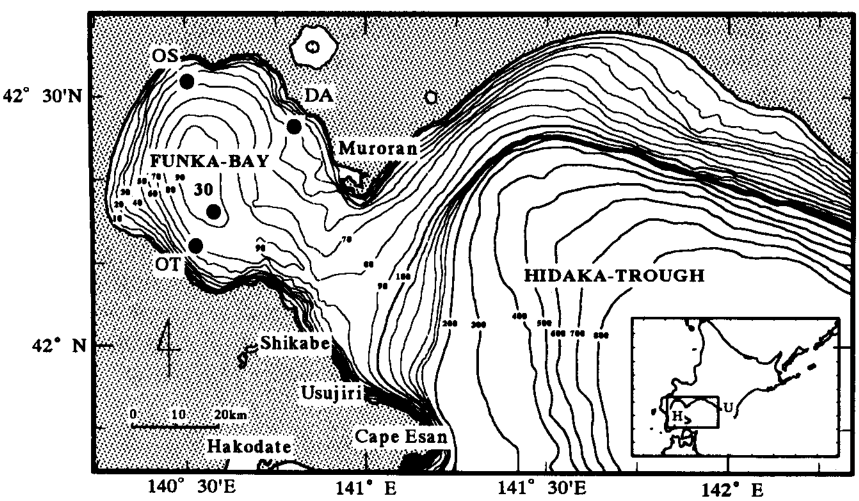

Fig. 1. Map of southern Hokkaido and locations of the observation sites.
●: Positions of current meter mooring
H: Hakodate U: Urakawa

Table 1. The observation periods and instrument depths of the current measurements in Funka Bay.

Data name	Station	Depth (m)	Period	Data number
DA-9705	DA	10	1 May-18 June	7056
OT-9705	OT	10	28 May-30 June	4896
TS-9705	OS	10	22 May-30 June	5760
F-9705U	30	20	1 May- 1 June 18 June-30 June	6480
F-9705L	30	80	1 May-15 June 18 June- 30 June	8496

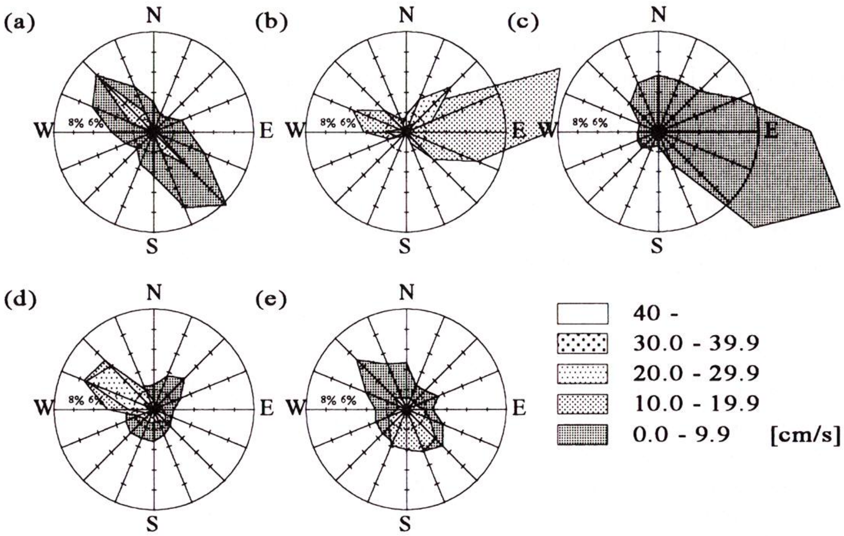

Fig. 2. Frequency distributions of the current direction at 10 m depth of (a) St. DA, (b) St. OT, (c) St. OS, (d) at 20 m depth of St. 30 and (e) at 80 m depth of St. 30.

corresponds to the wind along the major axis of the bay, which roughly means southeasterly wind (Yamamoto, 1976). Hourly atmospheric pressure data were quoted from the Annual Report of the Japan Meteorological Agency (1997). Time series of pressure difference were smoothed by the same method stated above.

Results

Characteristics of the currents at four stations

Frequency distributions of the current direction at 10 m depth of (a) St. DA, (b) St. OT, (c) St. OS, (d) at 20 m depth and (e) at 80 m depth of St. 30 are shown in Fig. 2. Northwest components of the currents which were a direction of major axis in the bay were dominant at Sts. DA, OS, and St. 30. But eastward currents which flowed to mouth of the bay were found at St. OT. The magnitudes of the currents at St. OT and at 20 m depth of St. 30 were greater than at the other stations.

Statistics of the hourly mean currents are shown in Table 2. The along shore

Table 2. Statistics of the hourly-mean currents at four stations. The alongshore and crossshore components are expressed as $u(+u=315$ T northwest) and $v(+v=45$ T northeast). Mean components, mean speeds of the currents, mean velocity vectors and the standard deviations of each components are listed.

Data name	$\bar{u}$ (cm s^{-1})	$\bar{v}$ (cm s^{-1})	$\bar{V}$ (cm s^{-1})	$\bar{V}$ (cm s^{-1})	(deg)	σ_u (cm s^{-1})	σ_v (cm s^{-1})
DA-9705	1.31	−0.22	7.16	1.33	305	8.96	2.72
OT-9705	−0.67	7.38	16.19	7.41	50	9.65	11.40
OS-9705	−1.02	1.28	3.24	1.64	84	2.27	2.31
F-9705U	6.60	−3.50	12.93	7.47	287	11.10	6.88
F-9705L	−1.78	−1.41	9.19	2.27	173	7.48	6.56

and cross shore components are expressed as u $(+u=315$ T northwest) and $v(+v=$ 45 T northeast). The mean values are averaged over the observation periods. The mean speeds of the currents at St. OT and at 20 m depth of St. 30 are about 16 and 13 cm/s, which are greater than that at the other stations. While, the mean speeds of the currents at St. OS are very small of about 3 cm/s. Standard deviations of u and v components are greater than the mean values of their components at all stations. It shows that the fluctuating components of the currents were more dominant than the mean currents.

Coastal currents

Time series of (a) vector stick diagrams, (b) their northwest components, and (c) water temperature at 10 m depth are shown in Fig. 3 (at DA), Fig. 4 (at OT) and Fig. 5 (at OS), respectively. The periodic current reversals of the northwest and the southeast were obtained at St. DA (Fig. 3(a)). These reversals were along the local bottom topography (see Fig. 1). Water temperature increased from 5°C to 11°C for the measurements periods of two months. This trend is considered to be a seasonal variation. But we should focus here that water temperature increased when the currents were southeastward and decreased when flowing northwestward (Fig. 3(b), (c)).

Cross shore components of the currents were dominant during the periods of the first half at St. OT, since then flowed eastward (Fig. 4(a)). In this station, we used water temperature as a relative scale, because the water temperature data was not calibrated accurately. Water temperature increased during the southeastward currents and decreased during northeastward currents (Fig. 4(b), (c)).

We computed the cross correlation coefficients between the northwest components of the currents and the water temperature at Sts. DA and OT. Their cross correlation coefficients and the response time are shown in Fig. 5 and Table 3. The cross correlation coefficient at St. OT is high negative correlation of −0.71. The response time of the water temperature for the northwest components of the currents at St. OT is 7 hours. Similarly, this tendency is found at St. DA, but the correlation coefficients at St. DA is less than that at St. OT.

The magnitudes of the currents at St. OS were very small during the observation periods (Fig. 6(a)). This implies that a stagnation point of coastal currents may locate near St. OS, as was denoted by Ohshima and Miyake (1990).

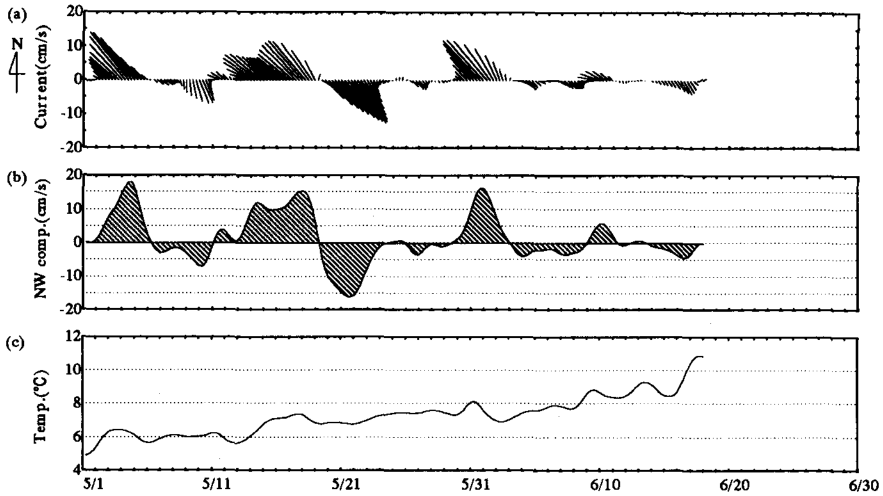

Fig. 3. Time series of (a) vector stick plots, (b) northwest components of the currents, and (c) temperature at 10 m depth of St. DA from May to June, 1997.

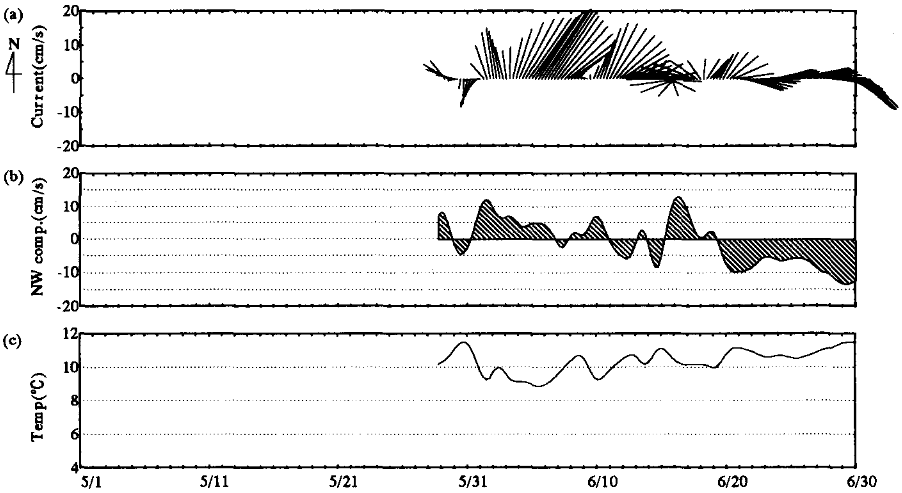

Fig. 4. Time series of (a) vector stick plots, (b) northwest components of the currents, and (c) temperature at 10 m depth of St. OT from May to June, 1997.

Currents at the center of the bay

Time series of (a) vector stick diagrams, (b) their northwest component, and (c) water temperature at St. 30 are shown in Fig. 7 (at 20 m depth) and Fig. 8 (at 80 m depth). Strong northwest currents were found in late June at 20 m depth and the magnitude reached about 30 cm/s (Fig. 7(a), (b)). These currents are considered to be due to basin-wide circulation reported by the Marine Observatory (1934). These basin-wide currents were partially reported by Nishida (1993) and Nishi (1997), based on the data of a ship-mounted ADCP and current meters.

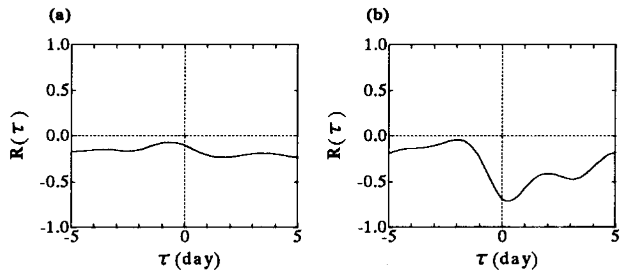

Fig. 5. Cross correlation coefficients between the northwest components of the currents and the water temperature at (a) St. DA and (b) St. OT.

Table 3. Cross correlation coefficients and the response time between the northwest components of the currents and the water temperature at St. DA and OT.

Station	Depth (m)	Period	Cross correlation coefficient $R(\tau)$	Response time (hour)
DA	10	2 May-17 June	−0.23	40
OT	10	29 May-29 June	−0.71	7

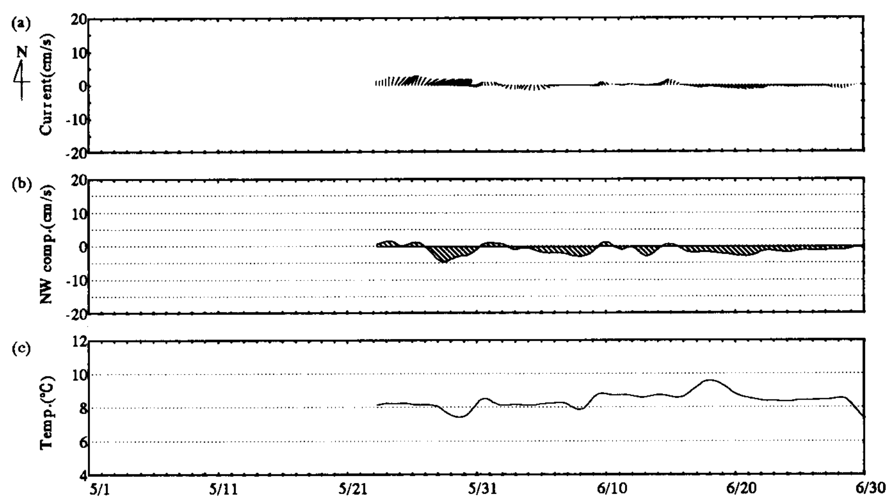

Fig. 6. Time series of (a) vector stick plots, (b) northwest component of the current, and (c) temperature at 10 m depth of St. OS from May to June, 1997.

In spite of the deeper depth, the magnitudes of the currents at 80 m depth were great (Fig. 8(a), (b)). In particular, strong southward currents were recorded on 4 May, 15 May, 25 May, 1 June and 10 June.

Discussion

Relation between wind and current

We examined the relation between southeasterly wind index and northwest

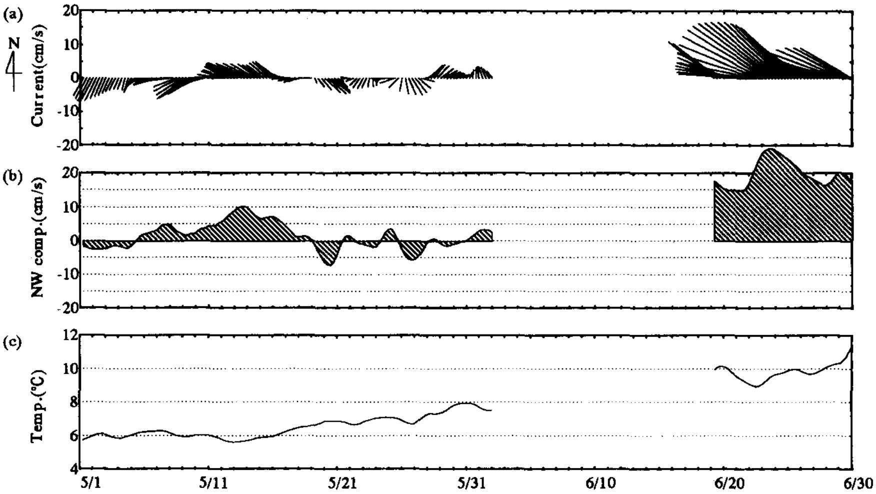

Fig. 7. Time series of (a) vector stick plots, (b) northwest component of the current, and (c) temperature at 20 m depth of St. 30 from May to June, 1997.

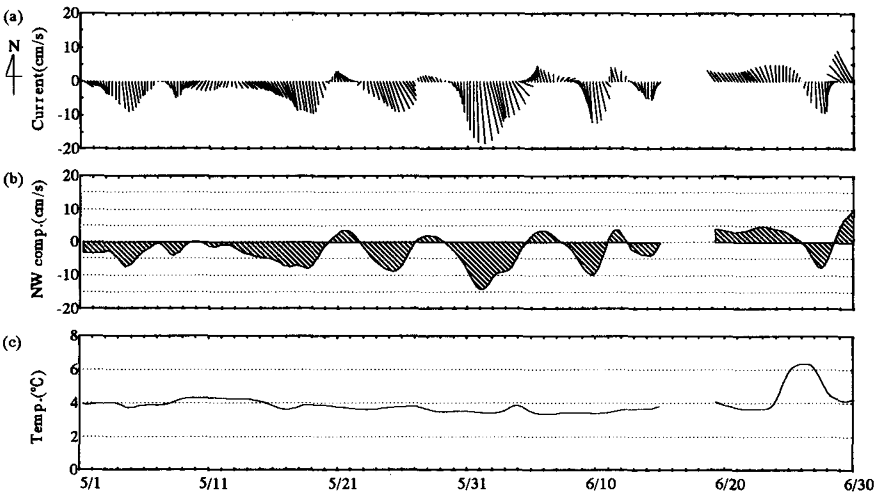

Fig. 8. Time series of (a) vector stick plots, (b) northwest component of the current, and (c) temperature at 80 m depth of St. 30 from May to June, 1997.

components of the currents. The response of the currents for wind index at 10 m depth of St. OS was clear (Fig. 10(c)). But their currents, however, were considered to caused by not the vortex pair but piling up, because St. OS located on the innermost part of the bay. The response of the currents at 20 m depth of St. 30 for the wind index was unclear (Fig. 10(d)), because the surface Ekman layer might have extended below 20 m depth and there was an effect of clockwise basin-wide circulation. Therefore we compared the southeasterly wind index with the northwest component of the currents at 10 m depth of Sts. DA, OT and at 80 m depth of St. 30 (Fig. 9(a), (b), (c) and (d)). The southeasterly wind indexes were plotted

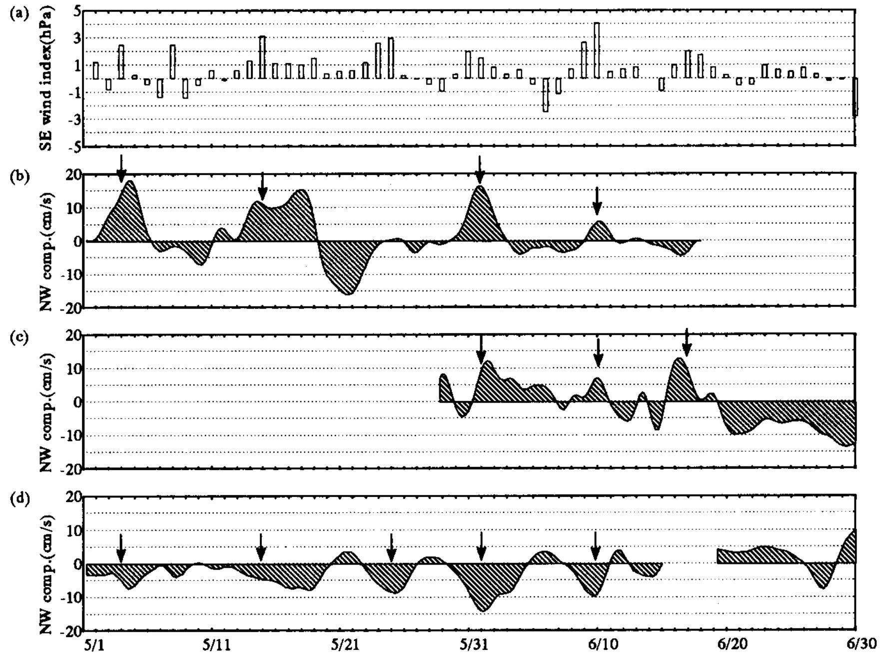

Fig. 9. Time series of (a) variation of the pressure difference between Hakodate and Urakawa and northwest components of the currents at 10 m depth of (b) St. DA, (c) St. OT and at 80 m depth of (d) St. 30 from May to June, 1997.

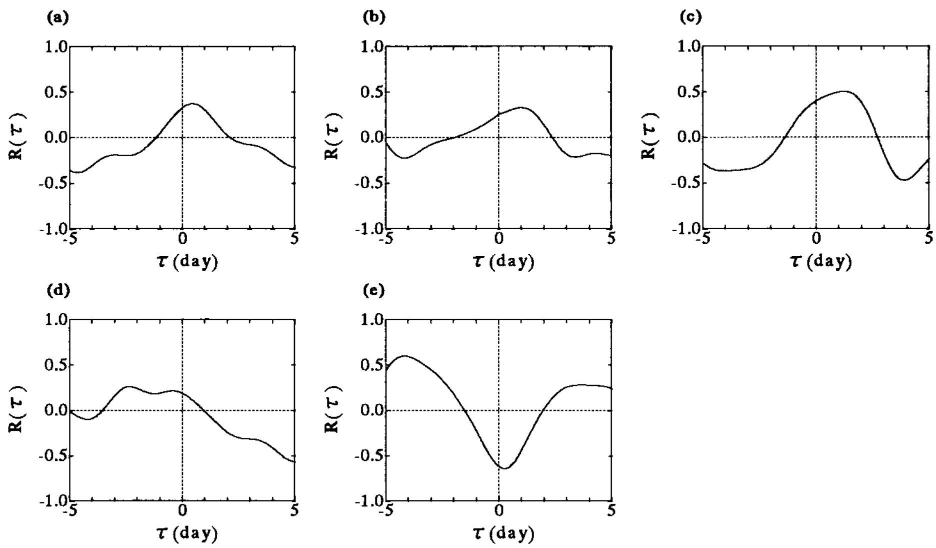

Fig. 10. Cross correlation coefficients between the variation of pressure difference and the northwest component of the current at 10 m depth of (a) St. DA, (b) St. OT, (c) St. OS, (d) at 20 m depth of St. 30 and (e) at 80 m depth of St. 30.

Table 4. Cross correlation coefficients and the response time between the variation of pressure difference and the northwest components of the currents at 10 m depth of St. DA, OT, OS, at 20 m and 80 m depth of St. 30.

Station	Depth (m)	Period	Cross correlation coefficient $R(\tau)$	Response time (hour)
DA	10	2 May-17 June	0.37	11
OT	10	29 May-29 June	0.33	24
OS	10	23 May-29 June	0.50	30
30	20	2 May-31 May	—	—
30	80	2 May-14 June	−0.64	6

daily.

During the southeasterly winds occurred on 3 May, 15 May, 1 June and 10 June, northwestward currents which reached about 15 cm/s arose at St. DA as shown by arrows in Fig. 9(a), (b). Similarly, northwestward currents also arose at St. OT on 1 June, 10 June and 16 June (Fig. 9.(a), (c)). All the currents at both stations flowed to the leeward direction. In these periods, southeastward currents arose in response to the southeasterly winds at 80 m depth of St. 30 (Fig. 9.(a), (d)). These currents were all windward ones. Thus, these current patterns off the coast (Sts. DA and OT) and at the bay center (St. 30) suggest that the vortex-pair flows were induced by the southeasterly wind forcing.

Cross correlation

Cross correlation coefficients between the southeasterly wind index and northwest components of the currents at 10 m depth of (a) St. DA, (b) St. OT, (c) St. OS, (d) at 20 m depth of St. 30 and (e) at 80 m depth of St. 30 are shown in Fig. 10 and Table 4. Positive correlations were found at 10 m depth of Sts. DA, OT and OS. The response of the currents for wind forcing was delayed for 11, 24 and 30 hours at Sts. DA, OT and OS, respectively. The correlation coefficients were 0.37, 0.33 and 0.50 at Sts. DA, OT and OS, respectively.

On the other hand, there is a negative correlation between the wind index and the flow at 80 m depth of St. 30. The response of the water for wind forcing was delayed for 6 hours. The correlation coefficient was significantly high value of −0.64. This implies that the vortex-pair flows are clearer in the interior region than in the surface layer.

Concluding Remarks

In the surface layer of coastal regions such as Sts. DA and OT, the currents were strongly affected by wind. Winds also affected at 80 m depth of St. 30. Wind-induced currents mainly arose at Sts. DA and OT, but the currents associated with clockwise circulation were clearly found at 20 m depth of St. 30 in June. Therefore, an interaction between wind-induced currents and density-driven currents is important in these basin-wide currents.

As a result, it is confirmed that a wind-driven vortex pair was generated in the Funka Bay. But, it is difficult to separate the purely wind-driven currents from the actual currents in the bay, because the actual currents include some density-driven currents, propagations of some waves and local disturbances.

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