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# Estimation of water circulation in Otsuchi Bay, Japan inferred from ADCP observation

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**Abstract**— In order to understand the seasonal water circulation system of Otsuchi Bay, direct current measurements were taken by using bottom-mounted Acoustic Doppler Current Profilers (ADCPs) during two periods, from October 2003 to March 2004 and from May 2004 to October 2004. During the first observation period, a remarkable estuary-type vertical circulation was observed. An anti-clockwise circulation, flowing into the bay along the northern coast and out along the southern coast was dominant during the second observation period. It was found that this clear seasonal variation was generated by both seasonal changes of wind and tide-induced residual current.

**Key words:** Otsuchi Bay, water circulation, ADCP, residual current, Sanriku coast

## Introduction

The demand of coastal aquaculture for seaweed and shellfish has recently increased in the coastal seas of northern Japan (Fig. 1). Evaluation of the carrying capacity in coastal waters is crucial for the sustainable exploitation of biological productivity (Furuya et al. 2002). Information on the water circulation in the bays is necessary for evaluating the reliability of the numerical model of the carrying capacity.

Otsuchi Bay is one of the bays on the Sanriku ria coast of northern Japan (Fig. 1). The Bay opens onto the North Pacific. The length and width of the bay are around 7 km and 2–4 km, respectively. Three rivers—the Unosumai, the Otsuchi and the Kotsuchi—flow into the bay and the total influx is about 3–35 $m^3 s^{-1}$ (Anbo et al. 2005). The International Coastal Research Center (hereafter ICRC, former Otsuchi Marine Research Center), of the Ocean Research Institute at the University of Tokyo, is located at the center of the northern coast of Otsuchi Bay. Basic oceanographic and meteorologic data (e.g. sea water temperature, wind speed etc.) have been accumulated since 1977 from the routine observation system at the ICRC (Otobe et al. 2004, 2005) and a variety of observational data from the bay have also been collected by many researchers. Based on the data, physical-biological coupled numerical models for Otsuchi Bay have been developed for the study of coastal material cycles, including aquaculture (Kawamiya et al. 1996, Kishi et al. 2003).

The first long term observation of seasonal variations in water flow using moored current meters was made by Shikama (1980) at Otsuchi Bay on the Sanriku ria coast. He moored current meters for one year, from December 1977 to December 1978, at the center of the bay where the water depth was 38 m and the analyzed results showed two dominant patterns of water flow. First, the seaward outflow of the surface water passes over the landward inflow of denser, more saline, water from outside the bay. This circulation is caused by westerly wind stress and is considered to be prominent in winter and spring when west to northwest winds prevail. Second, an inflow of surface water over an outflow of deeper water is observed frequently in summer. Both circulation patterns can be seen, depending on the difference in water density between inside and outside the bay (Shikama 1980, 1986, 1990).

There are few studies of water circulation in bays other than Otsuchi Bay on the Sanriku ria coast. Okazaki (1994) reported the water circulation in three bays—Miyako Bay, Toni Bay, and Hirota Bay (Fig. 1)—based on the results of moored current observations. He showed the following results for the individual bays. 1) The vertical circulation was predominant over tidal flow in Miyako Bay during December 1985 to January 1986. An anti-clockwise circulation was also observed in the bottom layer. 2) In Toni Bay, a stronger anti-clockwise circulation in October than that in November

1984 was caused by the intermittent intrusions of the internal tidal waves into the bay. 3) Hirota Bay is nearly rectangular and a large bay on the Sanriku coast. Current observations were carried out in autumn 1991 and the following summer, and circulations of sea water were clearly anti-clockwise in the bottom layer for both observation periods.

However, there have been few reports regarding three dimensional water flows in the bays on the Sanriku ria coast, because of the difficulty of mooring observation in the sea areas where fishing activity is a serious concern. Recently, the Trawl Resistant Bottom Mount (TRBM) platform has been developed for Acoustic Doppler Current Profiler (ADCP) observation. Therefore, we performed a continuous, long period observation of water circulation in Otsuchi Bay using an ADCP mounted in a TRBM (Otobe, 2004).

In this report, we present the residual current data for the whole year and for all layers, from surface to bottom, collected by an array of three ADCPs deployed at the center and across the main axis of the bay, and discuss the seasonal variations in water circulation.

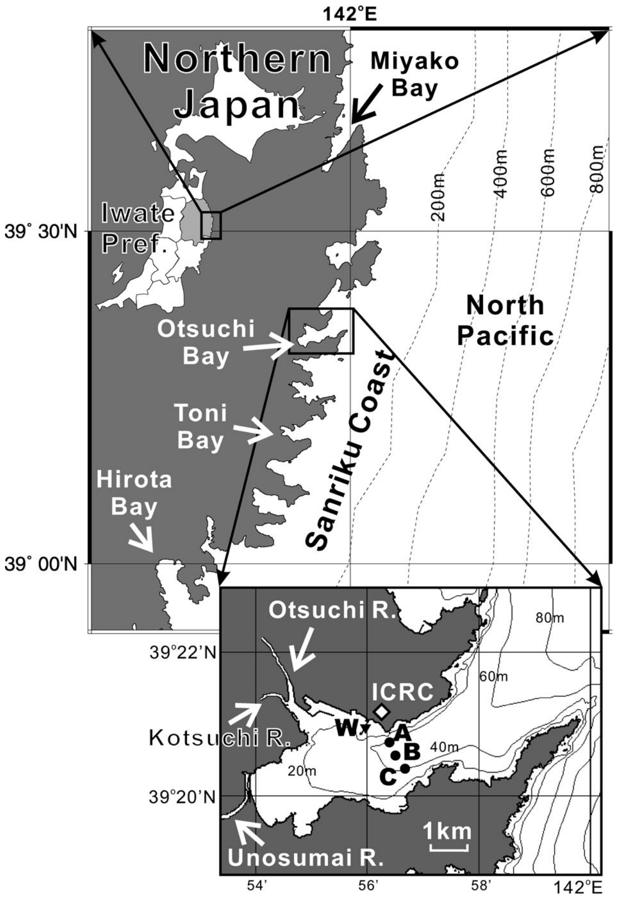


**Fig. 1.** Map of the observation site and the location of observation stations. A, B and C indicate the stations of ADCP (●) and W indicates wind velocity observation station (▼). Location of ICRC (International Coastal Research Center, Ocean Research Institute, the University of Tokyo) given by white (◇).

## Method

### Observations

Three ADCPs were moored on the seabed at the center of Otsuchi Bay during two periods, from October 2003 to March 2004 and from April 2004 to October 2004. Three ADCPs were positioned with approximately uniform spacing across the main axis of the bay. These positions are named as Station A, Station B, and Station C from the northern coast, respectively (Fig. 1). The locations, depths of each observation station, and observation periods are summarized in Table 1.

The ADCPs used in this study were RD Instruments Model Work Horse Sentinels (600 kHz, accuracy ±0.5% of the water velocity) with temperature sensors (accuracy ±0.2°C). The ADCPs were mounted in TRBMs (Model AL-200) manufactured by Flotation Technologies, which have double axis gimbals keeping the ADCP vertically-oriented and an acoustic recoverable system (Benthos, Inc. Model M-867-A, Acoustic Releaser). Near-surface data are usually not available because of contamination from echoes scattered back from the sea surface. However, the surface data of the current are important for estimating water mass flux. Therefore, in order to confirm the availability of the surface data obtained by ADCP, an electromagnetic current meter (Alec-Electronics Co., Ltd. Model ACM-8M) was attached about 1 m beneath the surface on a light buoy mooring rope of aquaculture at about 50 m north of both Stn. A and Stn. C. At Stn. B, the current meter could not be moored, unfortunately,

**Table 1.** Summary of mooring positions, depths and observation periods.

| Station | Position | | Depth (m) | Observation Periods |
|---|---|---|---|---|
| | Latitude | Longitude | | |
| A | 39°20′42.2″N | 141°56′22.4″E | 40 | 2003/10/08–2004/03/03<br>2004/04/21–2004/10/28 |
| B | 39°20′32.2″N | 141°56′28.4″E | 42 | 2003/10/08–2004/03/03<br>2004/04/21–2004/10/28 |
| C | 39°20′23.2″N | 141°56′39.4″E | 41 | 2003/10/08–2004/03/03<br>2004/04/21–2004/10/28 |

as it was right on the shipping route in the bay. We found a good correlation between near-surface current data from ADCP and that of the electromagnetic current meters. (Onishi and Otobe 2006). Hence, we are using near-surface ADCP data in the present analysis.

### Data processing

The velocity time series data collected at the three stations from bottom to surface with a vertical interval of 1 m, as well as bottom temperatures, were obtained every 10 minutes during the entire course of the observation periods. Over 80% of percent-good data were used, indicating a threshold level obtained from four beams of ADCP. The data gaps in the time series were linearly interpolated in time. The hourly mean values were calculated from six data points taken at 10-minute intervals, including two before and three after the designated time. The current directions obtained by a magnetic compass equipped with ADCP were corrected using -7 degree geomagnetic declination. Original current data were broken down into tidal components and residual components using a 48-hour tide-killer filter (Hanawa and Mitsudera 1985). The daily mean velocity vectors were calculated from the residual components of the hourly data, then the monthly mean velocity components ($\bar{u}$, $\bar{v}$), their variances ($u'$, $v'$), and their standard deviations ($\sigma_u$, $\sigma_v$) were calculated using the daily components ($u$, $v$). The major and minor fluctuation widths ($F_{Ma}=u'\cos\theta+v'\sin\theta$, $F_{Mi}=-u'\sin\theta+v'\cos\theta$) for the monthly mean vectors ($\vec{V}$) were also calculated, where $\theta$ indicates the direction of fluctuating major axis. To discuss flow stability, we calculated the kinetic energy of mean flow per unit mass $\overline{KE}=0.5(\bar{u}^2+\bar{v}^2)$, and the eddy energy per unit mass $KE=0.5(\sigma_u^{\,2}+\sigma_v^{\,2})$.

### Wind data

Wind velocity data were obtained from the routine marine meteorological observation system (Otobe 1997) of the ICRC, at the middle point of the breakwater in front of this center (Fig. 1). We calculated the daily mean values of wind velocity from the original data observed at 10-minute intervals (Otobe et al. 2004, Otobe et al. 2005).

## Results

### First observation period (October 2003–February 2004)

At Stn. A, located on the northern side of the bay (Fig. 1), the current velocity of about 10 to 20 cm s$^{-1}$ with an eastward direction component was dominant in the upper layer above 10 m during the first observation period, from the fall to winter season (Fig. 2). The current speed decreased gradually with depth from the surface to the 10 m layer. In the layers deeper than 10 m, the current field changed as follows: The speed increased with depth and the velocity with an eastward component in the upper layer changed to one with a westward component. The prevailing wind was from the northwest with a speed of a few meters per second during autumn and increased in speed during the winter due to the winter monsoon. At Stn. B, just on the axis of the bay, the current field was approximately the same as that at Stn. A. At Stn. C, located on the southern side of the bay, the dominant current velocity in the upper layer, from the surface to 16 m deep, was 5 to 20 cm s$^{-1}$ and northeast in direction. The dominant currents in the upper layer flowing out from the bay to the ocean were similar to those observed at Stn. A and Stn. B. In the lower layer, below 20 m, the current direction changed, sometimes at intervals of a week to two weeks during this observation period, showing the reversals from southwestward (inflow) to northwestward (outflow) and vice versa. This phenomenon was not found at other stations.

### Second observation period (April 2004–October 2004)

At Stn. A, the current velocity in the upper layer above 10 m decreased to 5 to 10 cm s$^{-1}$ compared with the first observation period, and the direction of the current also changed to westward (inflow) until mid-September (Figs. 3). In the layers deeper than 10 m, except at the bottom layer, the current direction was approximately uniformly southwestward, showing an inflow. At Stn. B, the current field was approximately the same as that at Stn A. At Stn. C, the current velocity in the upper 2 m layer from the surface varied frequently in association with wind velocity. The velocity was very week in the middle layer, between 4 m and 18 m depth. In the layers deeper than 20 m, northeastward currents prevailed with the speed varying from 2 cm s$^{-1}$ to 5 cm s$^{-1}$ during this period.

The prevailing wind was southeasterly with the speed of a few meters per second during June and July. From late July to early August, a strong southerly wind was seen, caused by typhoons 200411 and 200412. The effect of the strong southerly wind was seen in the surface layer current, especially at Stn. C. After mid-September, the wind direction changed to northerly because of a monsoon.

### Monthly mean velocity and fluctuation

Monthly mean velocity vectors and ellipses of fluctuation at each station are shown in Fig. 4. The red (blue) arrow color indicates that the kinetic energy of the monthly mean velocity is larger (smaller) than the eddy kinetic energy.

During the first observation period, a stable large inflow was observed in the lower layer, from 20 m to the bottom, at Stn. A and Stn. B; however, at Stn. C, large inflows occurred intermittently in December and February (Fig. 4). During the second period, in comparison with the first period, a stable inflow was seen in the middle layer, from about 10 m to 30 m, at Stn. A and Stn. B, and the outflow appeared in the layer

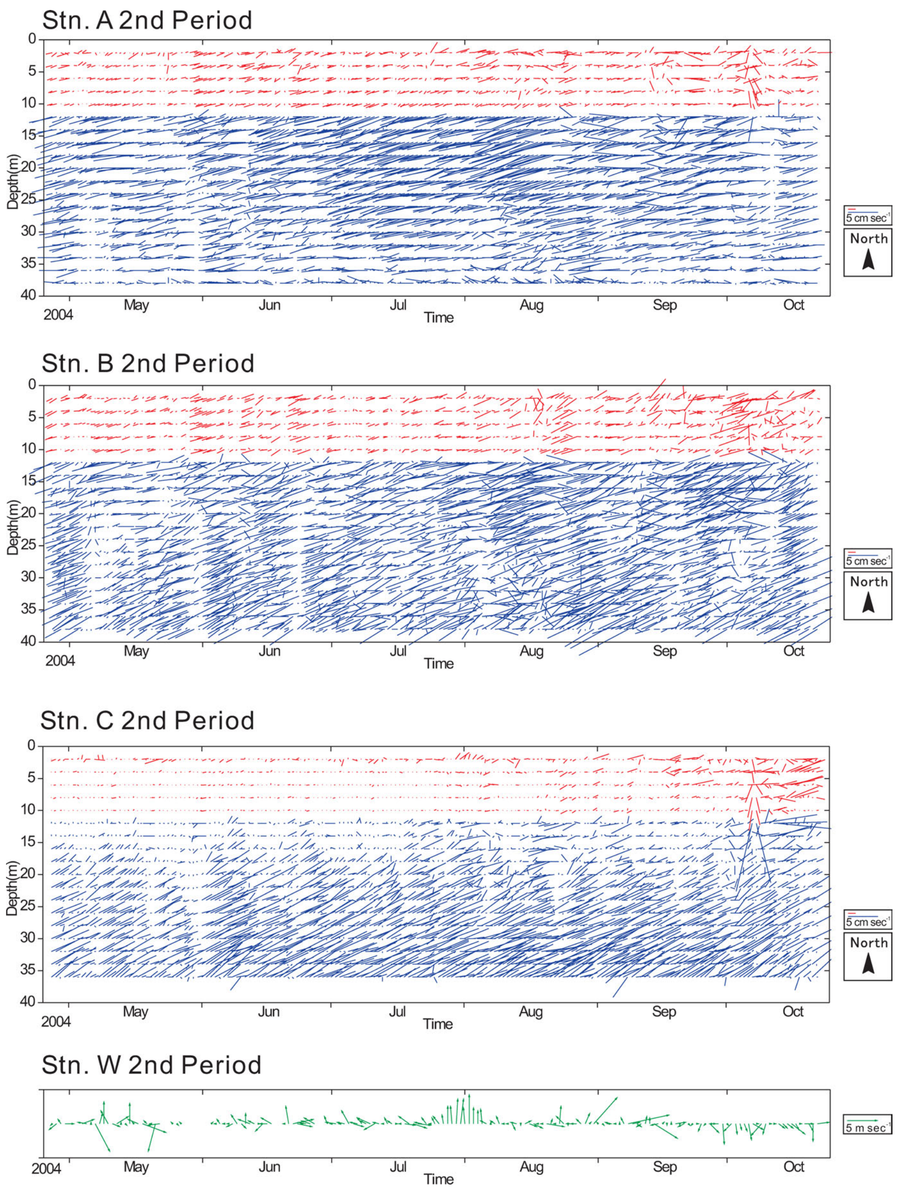


**Fig. 2.** Stick diagrams of daily mean residual current velocity at three stations (A, B and C) and the daily mean wind velocity (W) during the first observation period from October 2003 to February 2004. For convenience, the magnitude and the colors of arrows have been changed for depths below 10 m.

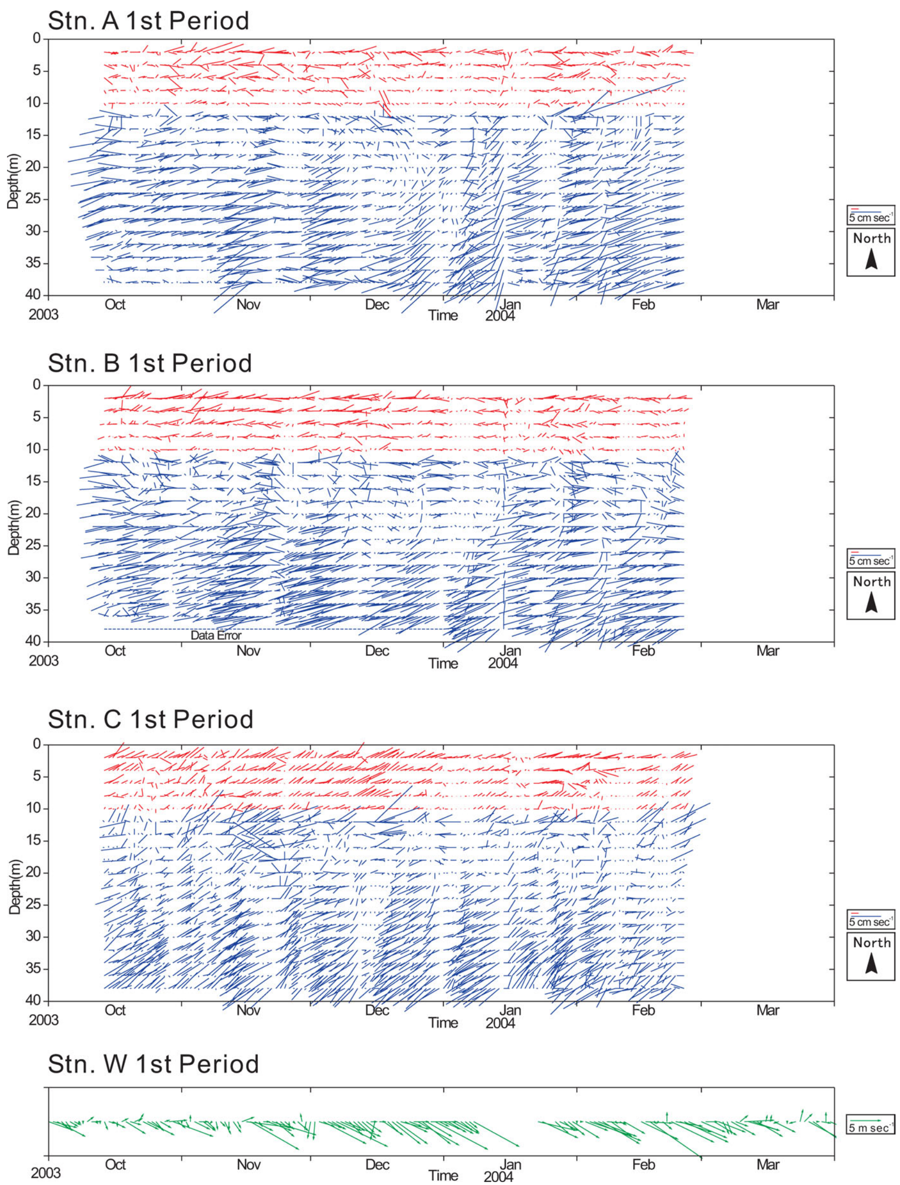


**Fig. 3.** Stick diagrams of daily mean residual current velocity at three stations (A, B and C) and the daily mean wind velocity (W) during the second observation period from March 2004 to October 2004.

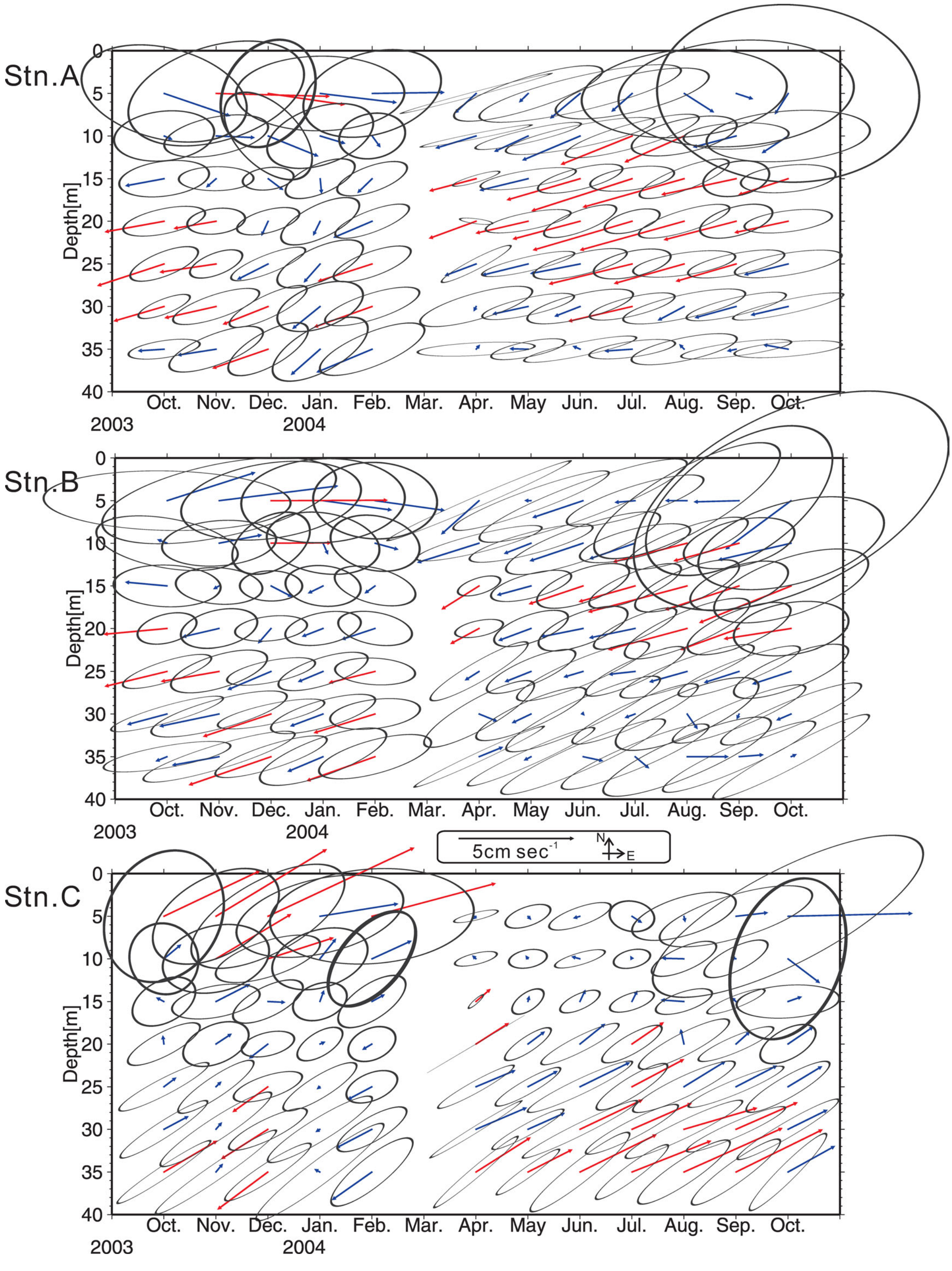


**Fig. 4.** Monthly mean velocity vectors and ellipses of fluctuation. The red (blue) arrow color indicates that the kinetic energy of the monthly mean velocity is larger (smaller) than the eddy kinetic energy.

lower than 30 m at Stn. B. At Stn. C, however, stable outflow was observed from the middle layer to the bottom layer throughout the second period.

## Discussion

To understand the seasonal water circulation (residual current) system in Otsuchi Bay, direct current measurements were carried out by using bottom mounted ADCP during two observation periods. The first observation period corresponds

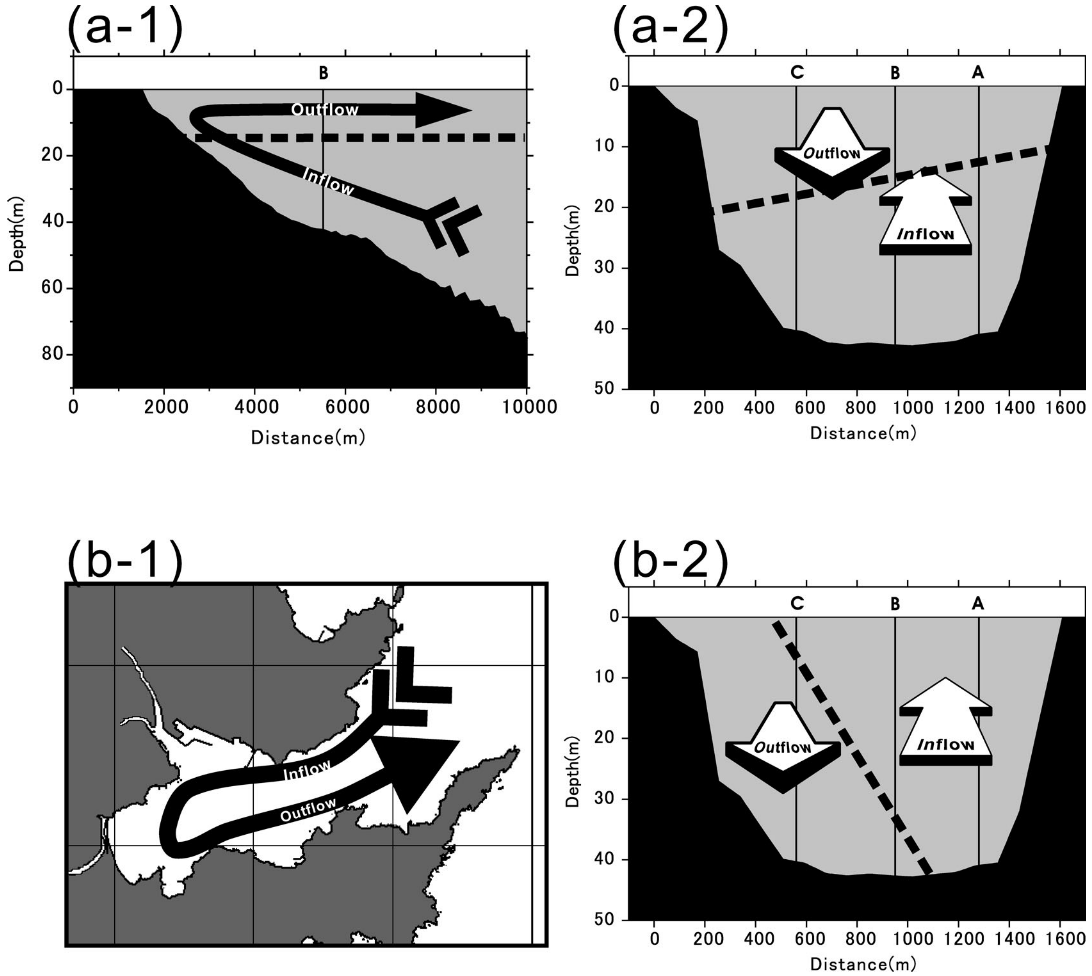


**Fig. 5.** Schematic view of water circulation in Otsuchi Bay. Flow sections along the main axis of the bay (a-1) and across at the center of the bay (a-2) during the first period, late-fall and winter. Horizontal distribution of water flow (b-1) and the vertical section across at the center of the bay (b-2) during the second period, spring and summer.

to seasons from mid-autumn to late-winter, when the winter monsoon, strong westerly or north-westerly winds prevail, and vertical mixing occurs and thermal stratification has been broken. The second observation period corresponds to the seasons of spring and autumn, when a southerly wind prevails and stratification is formed (Otobe et al. 2004, 2005). In other words, the two observation periods also correspond to cooling and heating seasons for sea water, respectively (Kutsuwada et al. 1988). During the first observation period or cooling season, the outflow in the upper layer and the inflow in the lower layer produced remarkable observations at all stations. However, the inflow in all layers of Stn. A, the northern part of the section, and the outflow in all layers at Stn. C, the southern part of the section, were observed during the heating season. Furthermore, inflow in the upper layer thicker than 30 m and outflow in the bottom thin layer were seen at Stn. B (Fig. 3 and Fig. 4). There are some differences in the vertical structures of residual current among the three stations, as mentioned above. These results suggest that the circulation pattern in Otsuchi Bay is categorized schematically, as shown in Fig. 5.

In general, the residual current is consistent with density current, tide-induced residual current, wind driven current, and the flow generated by their interactions (Unoki 1995).

Discharged water from three rivers flow into the bay head, and the Tsugaru Warm Current, a coastal boundary current, flows southward just off Otsuchi Bay (Hanawa 1984, Hanawa and Mitsudera 1987). Therefore, the density gradient from inside the bay (low density) to the bay mouth (high density) is maintained in both periods, at least in the surface layer, as shown in Fig. 6 and Table 2. The Rossby's internal radius of deformation for Otsuchi Bay is estimated at approximately 2 km. It is a comparable value to the effect of the Coriolis force on the seawater in Otsuchi Bay, with dimensions of about 2 km in its narrowest width and 7 km in length. So, the discharged water flows out along the southern coast (Fig. 6).

Figure 7 shows the seasonal scalar variations of residual current (low-pass filtered current) and tidal current (high-pass filtered current) during both observation periods. The

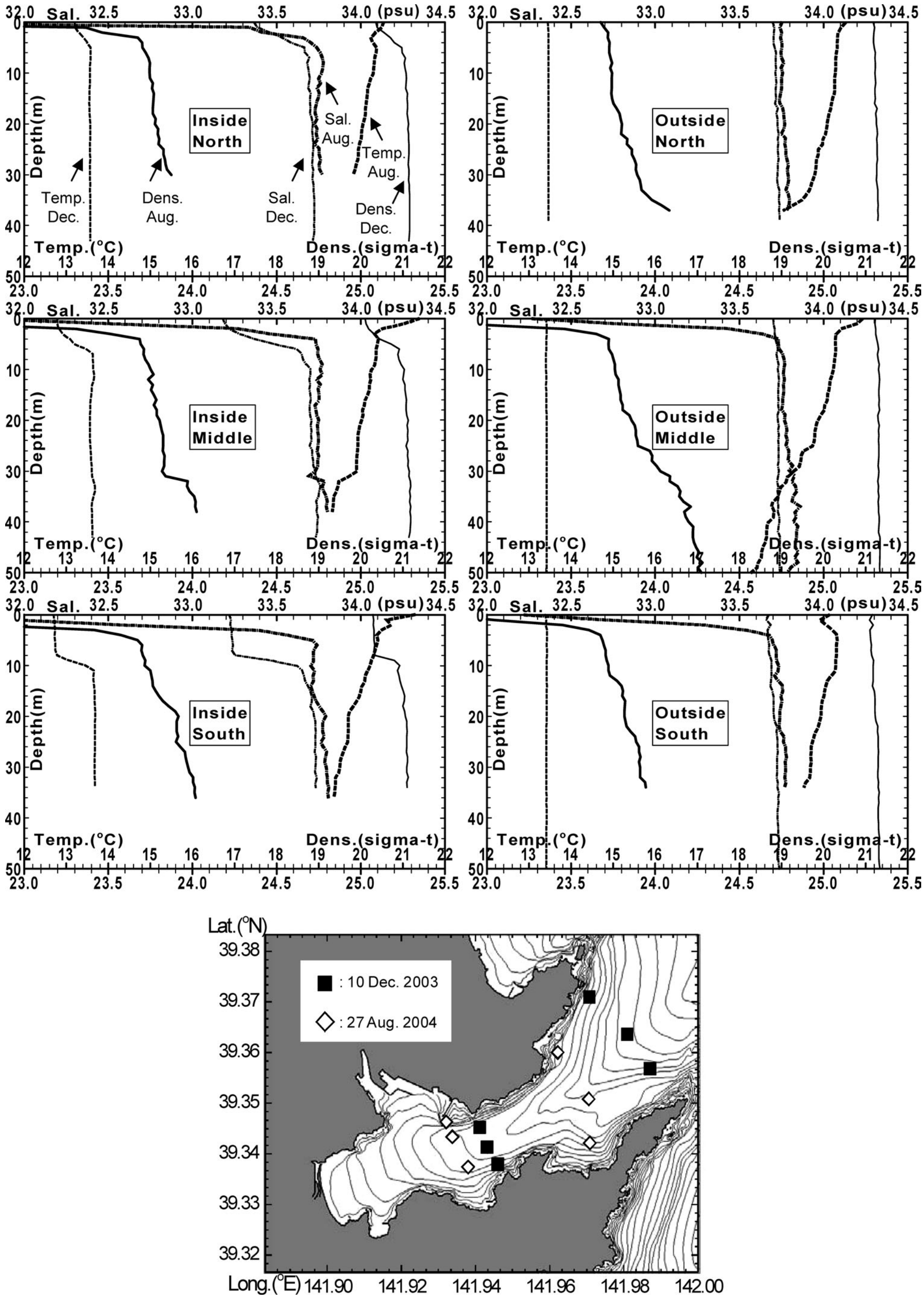


**Fig. 6.** Salinity, temperature and density (sigma-t) profiles obtained by STD and the locations of observation.

variation of the two currents seems correlative; the current speed of residual current is higher in summer than in winter, in association with tidal current speeds. These data suggest that the tide-induced residual current is induced in Otsuchi Bay and it will be remarkable in the summer season when the intrusion of internal tide waves from offshore occurs frequently (Okazaki 1990, Otobe et al. 1996).

Here we consider three components of the currents to describe the seasonal change of circulation in the Bay: the density current driven by buoyancy flux from river discharge, tide-induced residual current, and wind-driven current. The first component, the density-driven current that is an essential part of estuary convection in the Bay, should exist throughout the year, because fresh water from rivers is supplied steadily and the two-layer structure in the Bay, which is maintained though the thickness of the upper layer, varies seasonally. The second component, the tide-induced residual current, also plays a certain role in circulation by having more of an influence upon it in summer as shown in Fig. 7. The third one, the wind-driven component, is so dominant in winter, when the strong monsoon winds blow continuously, that other components become relatively insignificant, and

**Table 2.** Mean density in the layers from surface to 2, 5 and 10 m deep at inside section, at outside section in the bay and difference of them.

| December 2003 | Inside Section | Outside Section | Difference |
|---|---|---|---|
| 0–2 m | 25.082 | 25.296 | 0.214 |
| 0–5 m | 25.104 | 25.297 | 0.192 |
| 0–10 m | 25.152 | 25.301 | 0.149 |
| **August 2004** | **Inside Section** | **Outside Section** | **Difference** |
| 0–2 m | 22.756 | 23.139 | 0.383 |
| 0–5 m | 23.061 | 23.326 | 0.265 |
| 0–10 m | 23.363 | 23.508 | 0.146 |

(sigma-t)

this seems to strengthen the estuary circulation. On the other hand, it is negligible in summer when the wind is weak and unstable, particularly in comparison with tide-induced residual current.

The circulation observed in Otsuchi Bay that is described in the present study agrees with the results of Shikama (1980) and Okazaki (1994), which were mentioned in the introduction.

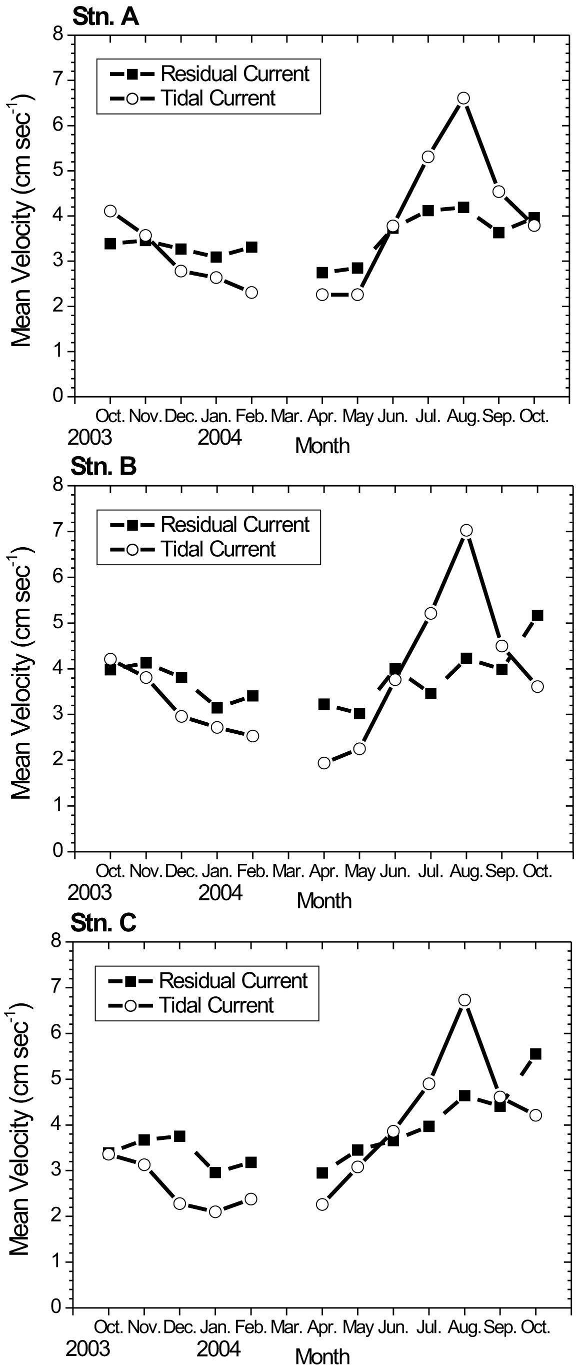


**Fig. 7.** Time series of scalar variations of residual current (low pass filtered current) and tidal current (high pass filtered current) during both observation periods.

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