Detailed Current Structures over the Continental Shelf off the San’in Coast in Summer

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We discussed the detailed current structures over the continental shelf off the San’in Coast in June 1988 and June 1989, using ADCP (acoustic Doppler current profiler) data, which were taken by the quadrirreciprocal method (Katoh, 1988) for removing tidal currents from observed currents. In waters northwest of Hagi ( Yamaguchi Pref.) and Hamada (Shimane Pref.), two mainly northeastward current cores were observed on each of transects. The offshore current core is baroclinic in relation to the bottom cold water with temperature below 10°C, and has velocities mostly between 0.5 and 0.8 kt (26 and 41 cm s⁻¹) at 20 m depth. The onshore current core, which is barotropic, has velocities between 0.3 and 0.5 kt (15 and 26 cm s⁻¹) at 20 m depth. In waters northwest of Izumo (Shimane Pref.), where the width of the continental shelf is narrow, it is difficult to distinguish between the two current cores, because the offshore core tends to join the onshore one. Estimating the magnitude of each term in the diurnally averaged equation of motion for about 3.3 nautical miles (6.1 km), we found that the orders of the inertia term and the gradient of tidal stress were 10⁻⁴ cm s⁻², and the order of the Coriolis force was 10⁻³ cm s⁻². Near the bottom northwest of Hagi and Hamada, two bands of countercurrents were found; one was slightly offshore of the intersection between the continental shelf and permanent thermocline, and the other was in the water colder than 5°C ridging on the continental shelf.

1. Introduction

In waters northwest of Yamaguchi Prefecture and Shimane Prefecture, which are called the “waters off the San’in Coast” in this paper, a rather wide continental shelf develops. Over this continental shelf, spawning and nursery grounds for many fishes exist (Uchida and Dotsu, 1958), and good fishing grounds are formed. Therefore, the waters over the continental shelf off the San’in Coast are very important for fishery in the southwestern region of the Japan Sea, and it is important to clarify the current structures in this area in order to understand the mechanism of transport of eggs and larvae and that of formation of fishing grounds.

Over the continental shelf off the San’in Coast, current measurements with mooring systems, current drogues, GEK (geomagnetic electrokinetograph) and ADCP (acoustic Doppler current profiler) have been carried out, and some important knowledge about current structures has been acquired. Ogawa et al. (1978) made measurements with current drogues in the Tsushima Strait and adjacent waters of Yamaguchi Prefecture, and they estimated the averaged velocity in the area as 0.3–0.9 kt (15–46 cm s⁻¹). Ogawa and Moriwaki (1985, 1986) made measurements with current drogues in coastal waters off Hamada, and they discussed the influence of wind on current fluctuation. Touju (1989) and Isoda and Murayama (1991) made measurements with
mooring systems in waters north of Mishima (Fig. 1) and off Hamada, respectively, and they clarified the features of current fluctuations. Isoda and Murayama (1990) made measurements with ADCP off Hamada and showed that two current branches existed throughout the year in the waters.

However, measurements with mooring systems have been hardly made at many points simultaneously mainly because of interference of trawl fishery. Number of current drogues which can be tracked simultaneously is not so many. Thus the measurement area with mooring systems or current drogues is limited. To the contrary, measurements with ADCP or GEK have been made widely, but tidal currents are not removed from observed currents in most cases. The velocity of currents over the continental shelf off the San’in Coast is at most 1.0 kt (51 cm s⁻¹), as shown by Ogawa et al. (1978). On the other hand, tidal currents with velocities of not less than 0.5 kt (26 cm s⁻¹), which are smaller than those in the Tsushima Strait (1.0–1.5 kt; Odamaki, 1989), were observed off the San’in Coast (Katoh, 1990b). Therefore, it is very difficult to find the characteristics of current structures without removing tidal currents from observed currents. For reasons mentioned above, there are few papers which discuss the horizontal and vertical structures of currents widely over the continental shelf off the San’in Coast.

In this paper, the detailed current structures—mainly vertical ones—over the continental shelf off the San’in Coast in summer were discussed on the basis of data obtained by ADCP measurements in June 1988 and June 1989 with the R/V Kumamoto-Maru (380 ton, the Kumamoto Prefectural High School of Fisheries).

2. Observation Methods
The ADCP (JLN-612, Japan Radio Company Ltd.; frequency, 125 kHz) and STD (salinity-temperature-depth recorder; AST-1000, Alec Electronics Company Ltd.) measurements were carried out along transects A (only between stations A1 and A19), C and E on 22–30 June 1988,
and along transects A, B and D on 19–28 June 1989 (Fig. 1). No ADCP measurement was made between stations B19 and B24.

Depending on length of the transects, procedures of ADCP and STD measurements were decided as follows (Fig. 2). (1) In the case of transects D and E which length was about 30 nautical miles (56 km), ADCP measurements were made after STD measurements. (2) In the case of transects B and C which length was about 60 nautical miles (111 km), initial STD measurements and succeeding ADCP measurements were made along a half of a transect, and afterward the other ADCP measurements and final STD measurements were made along the other half of the transect. (3) In the case of transect A which length was about 90 nautical miles (167 km), ADCP and STD measurements were made by the same procedure as the case (2) along a two-thirds part

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Fig. 2. Procedures of ADCP and STD measurements. Solid circles on the left end line indicate STD stations. Lengths of the transects in (1), (2) and (3) are about 30, 60 and 90 nautical miles, respectively.
of a transect, and afterward STD measurements were made after ADCP measurements along the remaining one-third part of the transect.

With the ADCP used in this observation, it is possible to measure currents at three depths simultaneously. But the deepest depth of measurement must be less than about 70% of the sea bottom depth from measurement capacity of the ADCP. Thus the shallowest depth of measurement was fixed at 20 m, and the intermediate and deepest ones were adjusted depending on the sea bottom depth. Velocity relative to the sea bottom was measured at all observations owing to the shallow sea bottom. STD measurements were made at intervals of about 3.3 nautical miles (6.1 km). Collection and analysis of current data were made according to Katoh (1988).

3. Results and Discussions

3.1 Temperature and diurnally averaged current on vertical sections along the transects

Temperature sections and current vectors averaged for a diurnal tidal period (24 hours and 50 minutes) at three depths on the transects are shown in Fig. 3. When the length of the transect is longer than 30 nautical miles (56 km), the time of STD measurements in a part of the transect lags longer than a day from that in another part of the transect. Thus isotherms are contoured independently in each of sections where the time lag of STD measurements is within a day, and the limit of the section is indicated by a vertical line in Fig. 3. In this paper, a current averaged for a diurnal tidal period (24 hours and 50 minutes) is called the “diurnally averaged current”, and water with temperature below 10°C is called the “cold water”, referred to Yamasaki (1969) and Moriwaki and Ogawa (1988).

On each of transects A, B and C northwest of Hagi and Hamada, two current cores, where currents were relatively strong compared with surrounding parts, were observed. The velocity in the onshore current core was 0.3–0.5 kt (15–26 cm s⁻¹) at 20 m depth, but it was 0.1–0.2 kt (5–10 cm s⁻¹) below a depth of 80 m. Ogawa et al. (1978) estimated the velocity in summer in coastal waters off Yamaguchi Prefecture as 0.55 kt (28 cm s⁻¹), which was larger than the velocity measured in this time. On the other hand, the velocity in the offshore current core was mainly 0.5–0.8 kt (26–41 cm s⁻¹), and it was found to be more than 1.0 kt (51 cm s⁻¹) on transect A in June 1988. Therefore, the velocity in the offshore current core seems to be larger than that in the onshore one. The offshore current core was situated above the southern boundary of the cold water spreading on the continental shelf. The direction was almost uniform from the top to the bottom of measurements on each transect.

Isoda and Murayama (1990) showed that the currents tended to divide into two branches throughout the year over the continental shelf off Hamada. Katoh (1990a) reported that two current cores were observed on a transect northwest of Hamada in August 1988. Judging from these results, we can conclude that two current cores exist often in summer off Hagi and Hamada.  

On transects D and E northwest of Izumo, where the width of the continental shelf was narrow, the cold water extended near the coast. Two current cores which were recognized off Hagi and Hamada likely came to join each other, and it was difficult to distinguish between the two cores there. The direction was almost uniform from the top to the bottom of measurements on each transect, while the velocity became smaller as the measurement depth was deeper.

3.2 Estimation of velocities at the surface and bottom

It is impossible to know velocities at the surface and bottom from ADCP measurements only.
Fig. 3. Vertical sections of temperature and diurnally averaged current vectors at three depths along the five transects with the R/V Kumamoto-Maru. In the observations along transects A, B and C, the time lag in STD casts between the left and right sections of a vertical line was longer than a day, and therefore isotherms were contoured independently of the adjacent section. Dates above station names indicate the period of ADCP measurements.

Thus the velocities, which are perpendicular to a section, were estimated by ADCP measurements and the assumption of geostrophic current together.

Let $X_1$ and $Y_1$ be the velocities at the shallowest depth of ADCP measurements derived from calculations of geostrophic current and from ADCP measurements, respectively (Fig. 4). Let $X_s$ be the velocity at the surface derived from calculation of geostrophic current. Then the velocity at the surface, $Y_s$, was estimated as follows,
\[ Y_s = X_s + (X_1 - X_1). \]

Let \( X_3 \) and \( Y_3 \) be the velocities at the deepest depth of ADCP measurement derived from calculations of geostrophic current and from ADCP measurements, respectively. Then the velocity at the motionless depth near the bottom, \( Y_b \), was estimated as follows,

\[ Y_b = Y_3 - X_3. \]

For calculations of geostrophic current, a motionless depth is tentatively settled near the bottom (in case water depth \( \leq 200 \) m) or at 200 m depth (in case water depth \( > 200 \) m).

3.3 Factors disturbing geostrophic balance

The velocity measured with ADCP is thought to be a sum of barotropic and baroclinic components. Thus, when subtracting the velocity derived from calculations of geostrophic current, which corresponds to the baroclinic component, from the velocity derived from ADCP measurements, this remainder corresponds to the barotropic one. Strikely speaking, the remainder corresponds to the velocity at the motionless depth settled tentatively for calculations of geostrophic current. Hereafter, the remainder is called the "reference-depth velocity". When currents balance geostrophically, the reference-depth velocities are suggested to be equal to each other among three depths of ADCP measurements at the same location, since the barotropic component is constant from the surface down to the bottom.

![Diagram](image)

**Fig. 4.** Vertical profiles of velocities based on ADCP measurements and calculations of geostrophic current. Ordinate and abscissa indicate depth and velocity, respectively. Open and solid circles indicate velocities derived from ADCP measurements and calculations of geostrophic current, respectively. Circles with a dot indicate velocities at the surface and near the bottom, estimated by these two methods combined together. Motionless depth was tentatively settled near the bottom (in case water depth \( \leq 200 \) m) or at 200 m depth (in case water depth \( > 200 \) m).
From the above consideration, it can be examined how diurnally averaged currents balanced geostrophically, through calculating differences between the maximum and minimum of the reference-depth velocities among three depths of ADCP measurements at each "basic bin", where a diurnally averaged current was calculated (Katoh, 1990b). The frequency distribution of the differences is shown in Table 1. The differences at 70% cases were no more than 0.2 kt (10 cm s⁻¹), and those at 39% cases were no more than 0.1 kt (0.5 cm s⁻¹). Therefore, diurnally averaged currents seem to have balanced almost geostrophically during the period of the present observations. However, there are six cases where the difference is more than 0.4 kt (21 cm s⁻¹), and the maximum of the difference is 0.71 kt (37 cm s⁻¹) (Table 2). The reasons for such a large difference are thought to be as follows. ① When a geostrophic current fluctuates due to some causes during a diurnal tidal period, the geostrophic balance is disturbed. ② In waters where velocities of tidal currents are different considerably among locations, the gradient of tidal stress becomes large. In such a case, a tidal residual current occurs (Yanagi, 1989), and the geostrophic balance is disturbed. ③ Values obtained from the quadrirreciprocal method (Katoh, 1988) with ADCP were averaged for a diurnal tidal period, while temperature and salinity data for calculations of geostrophic current were based on only one measurement. Therefore, the geostrophic balance is not affected between density distribution based on one measurement and the current distribution averaged for a diurnal tidal period, when density distribution changes considerably during a diurnal tidal period.

At first, the factor ① will be examined. ADCP measurements through six diurnal tidal periods on transect A in July 1989 (Fig. 5) and those of anchored measurements in waters north of Mishima (Touju, 1989) and off Hamada (Isoda and Murayama, 1991) show that the directions in the current cores are between NNE and ENE and their fluctuations are very small. However, the velocities in the current cores fluctuate considerably. For example, the maximum velocity in

<table>
<thead>
<tr>
<th>Velocity (kt)</th>
<th>0.0–0.1</th>
<th>0.1–0.2</th>
<th>0.2–0.3</th>
<th>0.3</th>
<th>0.4</th>
<th>0.4–</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (%)</td>
<td>38.8</td>
<td>31.6</td>
<td>14.3</td>
<td>9.2</td>
<td>6.1</td>
<td></td>
<td>100.0</td>
</tr>
<tr>
<td>Accumulated</td>
<td>38.8</td>
<td>70.4</td>
<td>84.7</td>
<td>93.9</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>frequency (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Bins where the difference between the maximum and minimum of the “reference-depth velocities” among three depths was not less than 0.4 kt (21 cm s⁻¹) and values of the difference.

<table>
<thead>
<tr>
<th>Date</th>
<th>Bins</th>
<th>Difference (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 1988</td>
<td>C18–C19</td>
<td>0.64</td>
</tr>
<tr>
<td>June 1989</td>
<td>A12–A13</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>A14–A15</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>A16–A17</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>B9–B10</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>D8–D9</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Fig. 5 decreases suddenly from 0.7 to 0.4 kt (36 to 21 cm s\(^{-1}\)) between the fifth and sixth measurements. In such a case, the geostrophic balance is naturally disturbed.

In the next place, the factor \(\theta\) will be examined on the basis of current data obtained from this observation, on condition that the factor \(\Theta\) can be ignored.

The positive \(x\) axis is set in the NE direction along the coast line and the positive \(y\) axis is set in the offshore direction perpendicular to the \(x\) axis. The positive \(z\) axis and water level \(\eta\) are set vertically upward. When a geostrophic current does not fluctuate during a diurnal tidal period, velocity components in the direction of each axis are divided into diurnally averaged current components \((U, V, W)\) and tidal current ones \((U', V', W')\). Water level \(\eta\) was also divided into a diurnally averaged component \(\bar{\eta}\) and a tidal fluctuating one \(\eta'\). The equation of motion in the direction of the \(y\) axis which is averaged for a diurnal tidal period is written as follows;

\[
U \partial V / \partial x + V \partial V / \partial y + W \partial V / \partial z + fU = -g \bar{\eta} / \partial y + F_y + S_y, \tag{1}
\]

Fig. 5. Diurnally averaged current vectors at 20 m depth on transect A (between A1 and A10) from 14 to 21 July in 1989, adapted from Katoh and Teshima (1991).
where $f$ is the Coriolis parameter, $g$ is the acceleration of gravity, and $F_v$ is the eddy viscous force averaged for a diurnal tidal period. $S_y$ is the gradient of tidal stress, which is written as follows:

$$S_y = -U' \frac{\partial V'}{\partial x} + V' \frac{\partial V'}{\partial y} + W' \frac{\partial V'}{\partial z},$$  \hspace{1cm} (2)

where the over-bar indicates averaging for a diurnal tidal period.

In Eq. (1) the vertical velocity is very small, and thus the third term of the left side was ignored. The term of $F_v$ was ignored for simplicity. The order of magnitude of the horizontal pressure gradient force $g \frac{\partial \eta}{\partial y}$ is regarded as equal that of the Coriolis force $fU$. Therefore, the orders of magnitudes of $fU$, $U \frac{\partial V}{\partial x}$, $V \frac{\partial V}{\partial y}$ and $S_y$ were estimated as follows:

At first, the order of magnitude of $fU$ was estimated. The velocity components $U$ and $V$, which are perpendicular and parallel to the transect, respectively, are about 0.5 kt (26 cm s$^{-1}$), judging from Figs. 3 and 5. As $f$ is $8.3 \times 10^{-5}$ s$^{-1}$ in the observation area, the magnitude of $fU$ is

$$8.3 \times 10^{-2} \text{ s}^{-1} \times 26 \text{ cm s}^{-1} \sim 2.2 \times 10^{-3} \text{ cm s}^{-2}.$$

Next, the orders of the nonlinear terms of diurnally averaged current, $U \frac{\partial V}{\partial x}$ and $V \frac{\partial V}{\partial y}$, were estimated. The maximum variation of $V'$ in the direction of the $y$ axis was observed in June 1988 at the bin between stations A12 and A16, which length is about 10 nautical miles (18.5 km), and its value is more or less 0.5 kt (26 cm s$^{-1}$) (Fig. 3). The variation of $V'$ in the direction of the $x$ axis is significantly smaller than that in the direction of the $y$ axis, since currents in the observation area are nearly parallel to the coast line in most cases. Therefore, the nonlinear terms are at most

$$26 \text{ cm s}^{-1} \times 26 \text{ cm s}^{-1} / \left(1.85 \times 10^6 \text{ cm}\right) \sim 3.7 \times 10^{-4} \text{ cm s}^{-2}.$$

Finally, the magnitude of $S_y$ was estimated. In order to estimate $U'$ and $V'$ in Eq. (2) and their gradients, a diurnal variation of tidal currents on transect A in June 1988 is shown in Fig. 6. $W'$ in Eq. (2) was ignored, because it seems to be very small. As shown in Fig. 6, $U'$ and $V'$ are about 0.5 kt (26 cm s$^{-1}$), which is almost equal to $U$ and $V$. However, the variation of $V'$ in the direction of the $y$ axis is much smaller than that of $V$, and thus $S_y$ seems to be significantly smaller than the nonlinear terms of diurnally averaged current.

As mentioned above, the orders of magnitude of $U \frac{\partial V}{\partial x}$ and $V \frac{\partial V}{\partial y}$ are $10^{-4}$ cm s$^{-2}$ and that of $S_y$ is much smaller than these, while the order of magnitude of $fU$ is $10^{-3}$ cm s$^{-2}$. Therefore, tidal residual currents hardly influence the geostrophic balance in the observation area, and the factor 2 can be ignored.

At last, the factor 4 will be examined. The influences of change of the density distribution during a diurnal tidal period can not be clarified from this observation. However, it is suggested that the density distribution changes considerably during a diurnal tidal period over the continental shelf off the San'in Coast, on the basis of the result of temperature measurements which were made on a same transect twice for a diurnal tidal period (Yamaguchi Prefecture, 1987; Fig. 7).

Consequently, the fluctuation of velocity parallel to the coast line and the diurnal change of density distribution are the major factors affecting the geostrophic balance. Among the six bins shown in Table 2, the cold water was observed at the five bins except B9–B10 (Fig. 3). Judging
from this fact, it is probable that the distribution of the cold water changes considerably during a diurnal tidal period and that the geostrophic balance is disturbed by its change.

Currents at the surface and bottom will be discussed mainly on the case that currents balance almost geostrophically; in other words, the reference-depth velocities at three depths of ADCP measurements are almost equal to each other.

3.4 Vertical sections of velocity component in the two current cores

Figure 8 shows vertical sections of velocity component perpendicular to the transects, which derived from ADCP measurements combined with velocities at the surface and bottom estimated in Subsection 3.2. The characteristics of vertical distribution of velocity in the two current cores were discussed, on the basis of the vertical sections along transects A, B and C off Hagi and Hamada.

On transect A, the two current cores were recognized clearly in Fig. 8. The onshore one was centered between A5 and A10 in 1988 and between A6 and A7 in 1989; it was centered from the surface to 20 m depth in both years. The velocity at its center was about 0.3 kt (15 cm s$^{-1}$), and the area with velocities more than 0.2 kt (10 cm s$^{-1}$) extended to 60 m depth. On the other hand,
Fig. 7. Vertical sections of temperature around Mishima (Fig. 1) on 19-20 August 1985, adapted from Yamaguchi Prefecture (1987).
the offshore one was centered between A15–A16 in 1988 and between A16 and A18 in 1989; it was centered from the surface to 20 m depth like the onshore one. The velocity at its center was about 0.6–0.7 kt (31–36 cm s⁻¹), and the area with velocities more than 0.3 kt (15 cm s⁻¹) extended to 80 m depth. On transect B, the offshore current core was recognized between B15 and B17. However, the onshore one was hardly recognized, because the onshore current flowed nearly parallel to the transect. On transect C, the two current cores were observed between C3 and C5 and between C12 and C19. The velocity in the offshore one was significantly smaller than that on transect A.

The horizontal and vertical gradients of velocity in the offshore current core were larger than those in the onshore one in many cases (transect A in 1988, transects A and B in 1989). It means that the offshore current core is baroclinic and is influenced strongly by the cold water which

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**Fig. 8.** Vertical sections of velocity components (in kt) perpendicular to the transects shown in Fig. 1. The velocity components were derived from ADCP measurements and calculations of geostrophic current combined together. Shadow areas indicate southwestward countercurrents. The observations were carried out with the R/V Kumamoto-Maru in June 1988 and June 1989.
extends on the continental shelf (Fig. 3). On the other hand, the gradients in the onshore one were small, and the area with velocities between 0.2 and 0.4 kt (10 and 21 cm s\(^{-1}\)) extended from the surface to 60 m depth. Therefore, the onshore current core is more barotropic than the offshore one. The characteristics mentioned above corresponds well to those of two branches of Hamada reported by Ioda and Murayama (1990).

As to the path of the Tsushima Current, the “triple branch theory” and the “single meander path theory” are representative (Kawai, 1974). In the former, it is suggested that the “first branch” and “second branch” flow off the San’in Coast. Kawabe (1982a, 1982b) suggested that the first branch is a barotropic current controlled by the bottom-topography and that the second branch is a baroclinic one which flows along the intersection between the bottom and permanent pycnocline. Yoon (1982) showed that the first branch is a barotropic current controlled by the bottom-topography from numerical experiments, too. Judging from their positions and dynamic characteristics, we can conclude that the onshore and offshore current cores observed in this study correspond to the first and second branches, respectively.

### 3.5 Countercurrents near the bottom

As shown in Fig. 8, countercurrents were observed near the bottom at some bins. The differences between the maximum and minimum of the reference-depth velocities among three depths were at most 0.23 kt (12 cm s\(^{-1}\)) at the bin of C9–C10 in 1988 and at those of A15–A16, A18–A21, B12–B13 and B14–B17 in 1989 (Katoh, 1990b). Thus, the estimated distributions of velocity component in these five bins can be thought to reflect the actual ones.

Comparing the positions of these countercurrents with the vertical sections of temperature in Fig. 3, the countercurrents at the bin of C9–C10 in 1988 and at those of A15–A16 and B12–B13 in 1989 were closely situated in the slightly offshore side from the intersection between the continental shelf and permanent thermocline. At the bin of D4–D6, too, which corresponded to the position in the slightly offshore side from the intersection between the continental shelf and permanent thermocline, a countercurrent with velocity more than 0.6 kt (31 cm s\(^{-1}\)) was observed in 1989, even though the difference between the maximum and minimum of the reference-depth velocities among three depths were significantly large (0.34 kt, 17 cm s\(^{-1}\)). These facts imply that a countercurrent often occurs at the position in the slightly offshore side from the intersection between the continental shelf and permanent thermocline, and that it continued along the intersection in June 1989.

On the other hand, at the bins of A18–A21 and B14–B17 in 1989 the cold water with temperature below 5°C ridged up and coincides well with the positions of countercurrents (Fig. 3). Thus, we conclude that the countercurrents continued along the ridging water with temperature below 5°C. Accordingly, depth contours of the 5°C isothermal surface are shown in Fig. 9, in order to discuss the continuity of the countercurrents observed at the bins of A18–A21 and B14–B17. The depth of the 5°C isothermal surface was estimated by linear-interpolation. In Fig. 9, small dots indicate the stations where the cold water was not observed. Locations of the cold ridges at the bottom accompanied with the countercurrents were indicated by shaded areas, too.

Figure 9 shows that the 5°C isothermal surface is below a depth of 260 m nearly at 36°30’ N and 131°00’ E, and that a part of crowded contours laying in the direction of northeast and southwest intersect with transects A and B. The countercurrents at the bins of A18–A21 and B14–B17 prove to be situated close to the southern boundary of the 5°C isothermal surface. On the supposition that the countercurrents observed at the bins of A18–A21 and B14–B17 continued along the southern boundary of it, we concluded that they probably continued from the shaded
areas in Fig. 9 to the area nearly at 36°N and 132°E.

As mentioned above, two bands of countercurrents were observed in this study; one was situated in the slightly offshore side from the intersection between the continental shelf and permanent thermocline, and the other was situated in the part where water colder than 5°C swelled as a ridge. Isoda and Murayama (1990) reported that countercurrents, which were observed clearly near the bottom, existed between the two branches over the continental shelf off Hamada. Moreover, countercurrents were observed off Tajima Coast of Hyogo Prefecture, too (Matsuyama, 1990). Therefore, it is thought that countercurrents often occur over the continental shelf in the southwestern region of the Japan Sea. However, the relationship between the two bands of countercurrents or the formation mechanism remained to be solved in the future. In order to solve these problems, it is necessary to measure current directly near the bottom with mooring systems at many stations for a long term.

4. Conclusions

Main conclusions obtained in this study are as follows:

1) In waters northwest of Hagi and Hamada, two mainly northeastward current cores were observed on each of the transects. The offshore current core was associated with the bottom cold water and has a baroclinic structure with velocities mostly between 0.5 and 0.8 kt (26 and 41 cm s⁻¹) at 20 m depth. On the other hand, the onshore one has a barotropic structure with velocities between 0.3 and 0.5 kt (15 and 26 cm s⁻¹) at 20 m depth. The onshore and offshore current cores correspond to the first and second branches of the Tsushima Current, respectively.

2) In waters northwest of Izumo, where the width of the continental shelf is narrow, the
offshore core likely tends to join the onshore one. Thus it is difficult to distinguish between the two current cores there.

3) Estimating the magnitude of each term in the diurnally averaged equation of motion for about 3.3 nautical miles (6.1 km), we estimate the orders of the inertia term and the gradient of tidal stress as $10^{-4}$ cm s$^{-2}$, and the order of the Coriolis force as $10^{-3}$ cm s$^{-2}$.

4) Near the bottom northwest of Hagi and Hamada, two bands of countercurrents were found: one was slightly offshore of the intersection between the continental shelf and permanent thermocline, and the other was in the water colder than 5°C ridging on the continental shelf.

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