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The Structure of the Tsushima Warm Current off the Wakasa Bay During 1995-96

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In order to clarify the current structure of the Tsushima Warm Current along the Japanese coast, the CTD and ADCP measurements were carried out during two cruises in May 1995 and June 1996 off the Wakasa Bay.

The Tsushima Warm Current along the Japanese coast had two axes above the thermocline, the nearshore axis was located within 30km from the coast, following the isobath of the 150m depth, and the offshore one well corresponded to the thermal front on the shelf break. Below the thermocline, a southwestward subsurface counter current were found although there are some discrepancies in the structure of the undercurrent between the geostrophic calculations and the results of the multi-level ADCP. This discrepancy might come from the presence of the strong thermocline where the ADCP system might be inaccurate.

1. Introduction

The Tsushima Warm Current along the Japanese coast (TWCJC) is characterized by the baroclinic instability and many meanders. Although the mean path of this TWCJC has been studied by many authors (Moriyasu, 1972; Ohwada and Tanioka, 1972; Naganuma, 1977; Yoon, 1982a, 1982b, 1991; Kawabe, 1982a, 1982b; Katoh, 1993, 1994, 1996), it has not been well clarified due to such strong variabilities.

Meanwhile, recent numerical experiments of the Japan Sea circulation suggest that the TWCJC is accompanied with the southwestward subsurface counter current (SSCC) around the shelf break (Yoon, 1991; Kim and Yoon, 1994; Seung and Yoon, 1995). However, the existence of the counter current has not been confirmed by the observations. The strong unknown tidal currents, in the shallow region, prevent us to see the residual steady flow in a snapshot observation, and the shallowness in the shelf region makes the geostrophic calculation inaccurate.

In order to clarify the current structure of the TWCJC and to detect the SSCC on the shelf break, the CTD and ADCP (Acoustic Doppler Current Profiler) measurements were carried out during two cruises in May 1995 and June 1996 off the Wakasa Bay.

2. Observations and Data

During two periods; 26 May to 8 June 1995 and 9 to 20 June 1996, we carried out the CTD and ADCP measurements along the two sections off the Wakasa Bay by R/V Kakuyo-maru (Nagasaki University) as shown in **Fig. 1**. The CTD (Mark IIIB, Neil Brown) and the ship-mounted ADCP (CI-30, Furuno Electric Company Ltd.) surveys were carried out along the line A in 27-31 May, and along the line B in 1-3 June 1995. In 10-13 June 1996, the CTD, the ship-mounted ADCP and the multi-level ADCP surveys were carried out along the line A. The multi-level ADCP is a function of a towed vehicle called Flying Fish, which measures CO_2, DO, temperature, salinity, depth, turbidity, chlorophyll, pH and current velocity in real time (Koterayama and Yamaguchi, 1994). The total length of the line A and the line B are about 90km and 133km, respectively. The number of the CTD stations is 13 along the line A and 19

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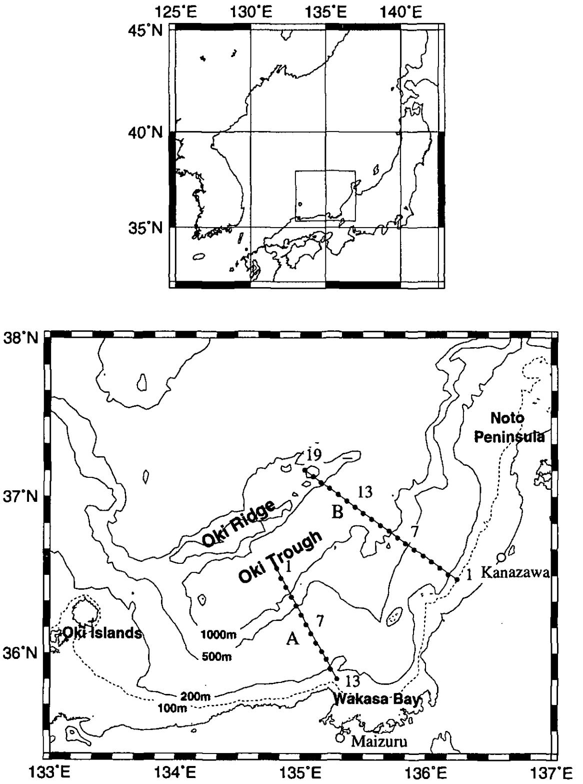

Fig. 1 A map of the locations of the sections for the CTD and ADCP measurements with R/V Kakuyo-maru and the topographic feature. The observations were carried out along the line A in 27-31 May 1995 and in 10-13 June 1996, and along the line B in 1-3 June 1995.

along the line B, respectively. The depth for the measurements of the ship-mounted ADCP were 20, 70 and 150m along the line A, and 30, 80 and 150m along the line B. The measurements by the multi-level ADCP were carried out every 8m depth from 32m to 368m depth. The data within 30m above the bottom is dealt as missing where the total depth is less than 368m. The absolute current velocities were obtained from Stn. A8 to A13 of the line A and from Stn. B1 to B7 of the line B where the bottom-tracking was possible. Whereas, at the stations where the bottom-tracking was impossible, the absolute current velocities were calculated using the current velocities relative to the ship and the absolute ship velocities which are evaluated from the location data by the Global Positioning System (GPS). In order to remove the tidal currents, the ADCP surveys were made by the method of plying four times along the same sections during 24 hours 50 minutes (Katoh, 1993). The harmonic analysis was made to separate the mean current, the diurnal tidal current and the semi-diurnal tidal current for the raw data of both the ship-mounted and the multi-level ADCP by using the least square method (Isobe, 1992). The diurnally averaged current is obtained by taking an average for ADCP data of all surveys on each section after subtracting the tidal currents.

3. Results and Discussions

The vertical sections of the temperature and the salinity are shown in **Fig. 2**. The temperature distributions in **Fig. 2a**, **b** and **c** show the strong thermocline at about 150m depth, suggesting the northeastward baroclinic flow on the shelf break. While, as shown in **Fig. 2d**, **e** and **f**, the high salinity water (over 34.6 PSU) occupies the region above the thermocline on the shelf. It should be noted that the temperature increases abruptly about 2° C shoreward from Stn. A7 to A8 and from Stn. B7 to B8 in 1995. This phenomena seems to be caused by the time gap between the observations. Therefore the geostrophic current in these regions are not calculated.

The spatial distributions of the diurnally averaged current by the ship-mounted ADCP at the intermediate depth are shown in **Fig. 3**. The shaded arrow areas indicate the thermal fronts with the temperature between 8 and 13° C at the 100m depth which is referred from the report by the Japan Sea National Fisheries Research Institute (Nihonkai Gyo-Jyou Kaikyou Sokuhou). The velocity fields suggest the two northeastward current axes, the nearshore axis and the offshore one, off the Wakasa Bay. The current speed of the nearshore axis is about 30cm/s, and that of offshore one from 50 to 65cm/s. The nearshore current flows along around 150m isobath, while the latter flows corresponding closely to the thermal front, following roughly 500m isobath.

The trajectory of the surface drifter for the period from 6 June to 5 August, 1991 by Ishii and Michida (1996) is shown in **Fig. 4**. It indicates that the surface drifter flows on all the way

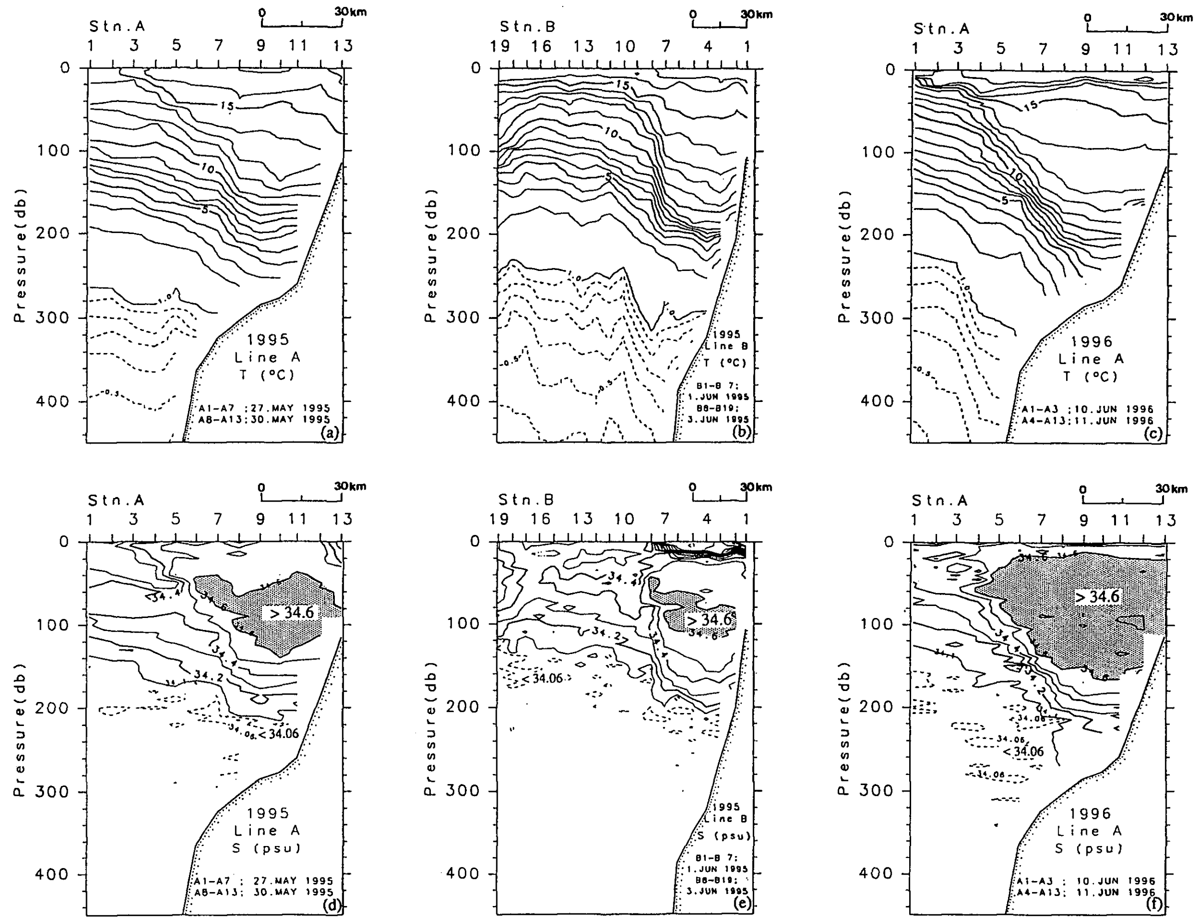

Fig. 2 Vertical sections of the temperature (upper) and the salinity (lower).

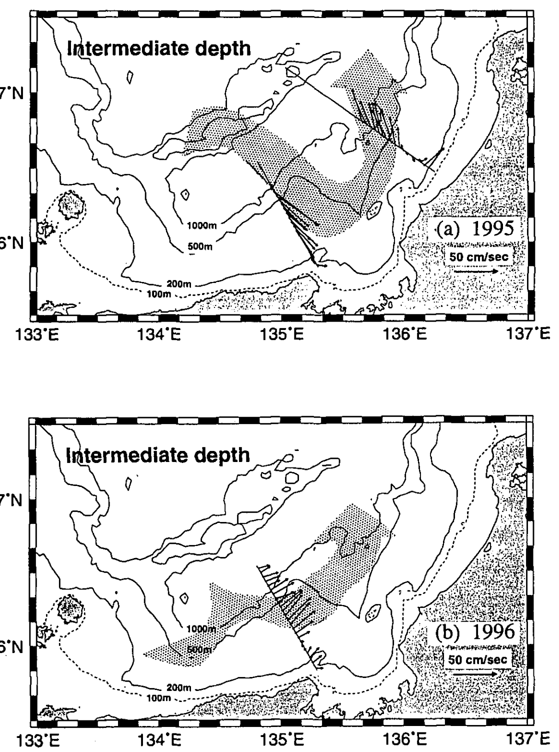

Fig. 3 Horizontal velocity fields of the diurnally averaged current obtained by the ship-mounted ADCP at the intermediate depth, 70m depth along the line A and 80m depth along the line B. Shaded arrow areas indicate the thermal front with the temperature between 8 and 13°C at the 100m depth (referred from the report by the Japan Sea National Fisheries Research Institute).

along the Japanese coast from the Tsushima Strait to Tsugaru Strait. They estimated that this current velocity off the Wakasa Bay were ranging from 30 to 40cm/s. It seems that the nearshore core off the Wakasa Bay observed by our observations well corresponds to this flow. Therefore it might be suggested that TWCJC is divided into two branches, one corresponding to the thermal front on the shelf break and the other flowing along the 150m isobath.

The vertical structure of the velocity normal to the cross section of the line A obtained by the multi-level ADCP in 1996 is shown in **Fig. 5**. The area of positive value indicates the northeastward flow. Two current cores are clearly found above the thermocline. The nearshore core is located at the shallow steep slope (Stn. A11 to A13) and the offshore

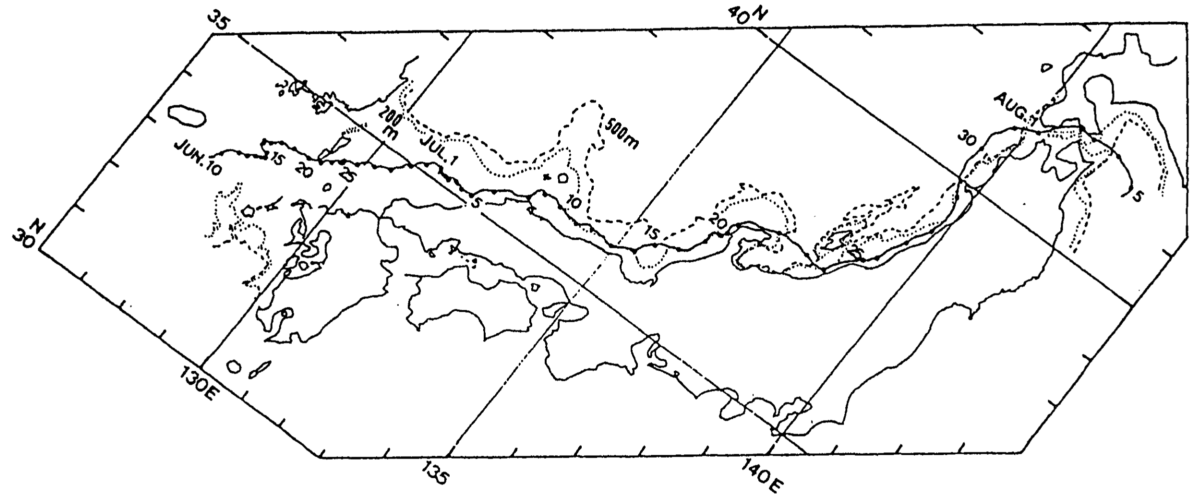

Fig. 4 Trajectory of the surface drifter for the period from 6 June to 5 August, 1991 (after Ishii and Michida, 1996). Solid circles mark the location of the first fix of every day. Dotted and dashed line represent depth contour of 200m and 500m, respectively.

one is located at the shelf break (Stn. A6 to A8). Between these two current cores, a counter current core can be found at the sub-surface level on the shelf with the maximum normal velocity of about 5cm/s.

The vertical structures of the geostrophic current are shown in **Fig. 6**. It is noted that the geostrophic calculations from Stn. A4 to A13 and from Stn. B1 to B10 refer to the diurnally averaged current obtained by the ship-mounted ADCP at the intermediate depth in 1995. While, the calculations from Stn. A1 to A4 and from Stn. B10 to B19 refer to the 1000m depth as a no motion level because the ADCP surveys were not carried out in the region. In 1996, the calculations refer to the diurnally averaged current by the ship-mounted ADCP at the intermediate depth along the whole line. It is found from the geostrophic current distributions along the line A (see **Fig. 6a** and **c**) that there is the SSCC on the shelf break with the maximum speed over 10cm/s. The SSCC is also found on the shelf along the line B. By comparing **Fig. 6c** with **Fig. 5**, we can see that the discrepancy between the structure of the geostrophic current and that of the flow measured by the multi-level ADCP increases below the 150m depth although the overall feature of the geostrophic current structure are similar to that measured by multi-level ADCP above the thermocline. The SSCC becomes more dominant in the geostrophic calculation.

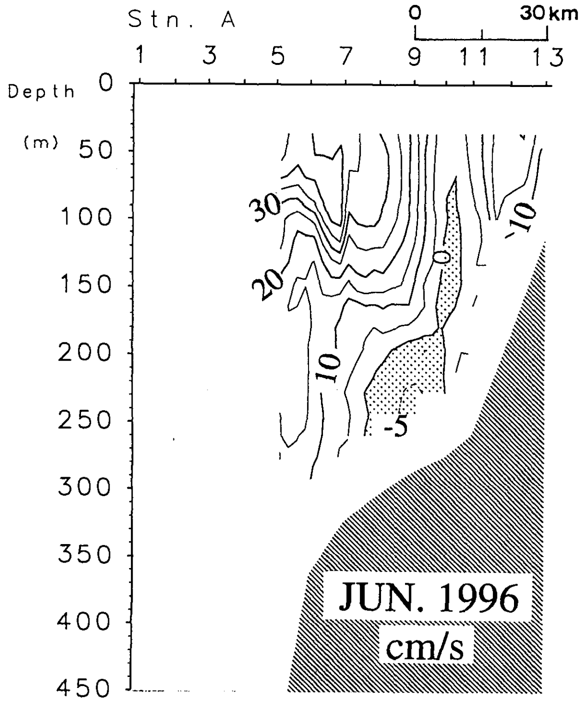

Fig. 5 Vertical structure of the diurnally averaged current normal to the cross section of the line A obtained by the multi-level ADCP in 1996. Shaded area indicates the southwestward flow.

In order to check the difference between them, the scatter diagram between the vertical gradient of the geostrophic current and that of diurnally averaged current by multi-level ADCP is shown in **Fig. 7**. The correlation coefficient is 0.81 and the Root Mean Square Error (RMSE) is 8.5×10^{-4} 1/sec above the 100m depth. The vertical profiles of the geostrophic current coincide

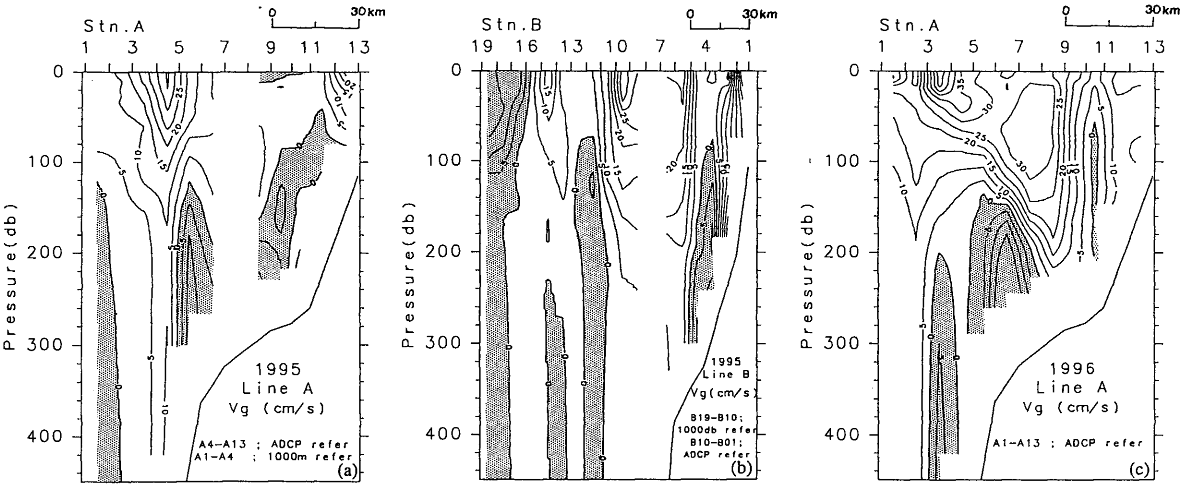

Fig. 6 Vertical structure of the geostrophic current. The geostrophic calculations in 1995 from Stn. A4 to A13 and from Stn. B1 to B10 refer to the diurnally averaged current normal to each sections obtained by ship-mounted ADCP at the intermediate depth, while the calculations from Stn. A1 to A4 and from Stn. B10 to B19 refer to no motion level at the 1000m depth, and in 1996 refer to the diurnally averaged current by ship-mounted ADCP at the intermediate depth on the whole line.

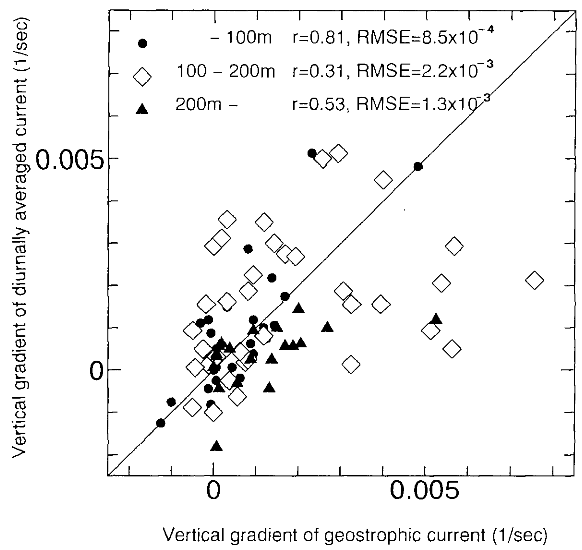

Fig. 7 The scatter diagram between the vertical gradient of the geostrophic current and that of diurnally averaged current obtained by multi-level ADCP. Closed circles, open rhombuses and closed triangles indicate the values from 32 to 100m depth, from 100 to 200m depth and from 200m to the deepest depth where the ADCP system was measured, respectively.

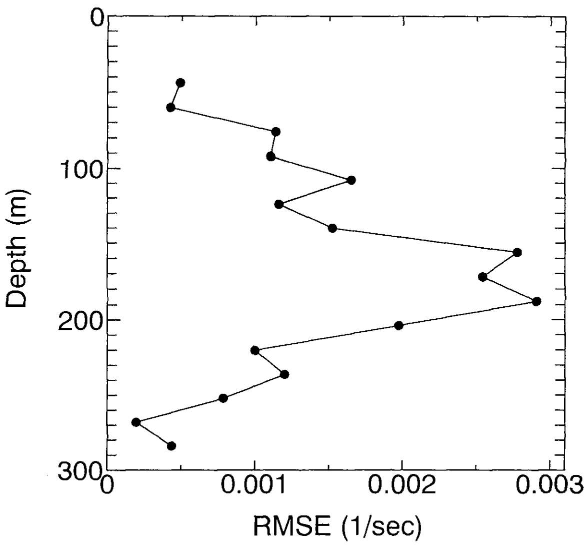

Fig. 8 Vertical profile of the RMSE evaluated from the difference between the vertical gradient of the geostrophic current and that obtained by multi-level ADCP.

with those by the ADCP from 32 to 100m depth. However, the discrepancy around 100 to 200m depth becomes large. The RMSE is evaluated from the difference between the vertical gradient of the geostrophic current and that of multi-level ADCP (**Fig. 8**). A peak is found around 170m depth, where the strong thermocline was located (see **Fig. 2c**). The strong density change, at the thermocline, might affect the reflection and transmission of the sonic waves. Therefore, It might be suggested that the ADCP system is inaccurate around the strong thermocline.

4. Summary

The Tsushima Warm Current along the Japanese coast is clearly divided into two branches above the thermocline off the Wakasa Bay, the nearshore axis flows along the 150m isobath with the velocity over 30cm/s, and the offshore one well corresponds to the thermal front with the value ranging from 50 to 65cm/s, following the isobath of 500m depth. The direct current measurement by the multi-level ADCP and the geostrophic calculation suggest that there is a southwestward counter current core under the surface flows with the maximum velocity normal to the section over 5cm/s. The correlation between the ADCP measurement and the geostrophic calculation is high enough above the thermocline, where correlation coefficient is 0.81, and the RMSE is 8.5×10^{-4} 1/sec. However, below the thermocline, the discrepancy between the two structure becomes large. This might come from the presence of the strong thermocline where the ADCP system might be inaccurate.

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