Current distributions in the southern East China Sea in summer

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Abstract. Current measurements using a shipboard acoustic Doppler current profiler (ADCP) and two satellite-tracked buoys, together with conductivity-temperature-depth (CTD) casts, were carried out over the continental shelf in the southern East China Sea in July 1995. Two transects for ADCP measurements were defined and divided into segments of ~56 km. In order to remove diurnal and semidiurnal tidal flows from observed flows, four round-trip ADCP surveys were conducted along each segment over diurnal tidal periods of ~24 hours and 50 min. The outflow through the Taiwan Strait, i.e., the Taiwan Current, with velocities of 35–40 cm s⁻¹, was clearly observed to flow northeastward along the coast of China. The volume transport was estimated as at least 1 Sv. The Taiwan Current probably increased width and decreased velocity in the central East China Sea. Bifurcation into two branches of the Taiwan Current shown by previous studies was not observed. Another current entering onto the continental shelf northeast of Taiwan, i.e., the Kuroshio Branch, was found with velocities > 15 cm s⁻¹ in the surface, and it helped to make an anticyclonic eddy. The main portion of the Kuroshio Branch flowed northeastward along the 100 m isobath, with a volume transport of ~0.3 Sv. The Taiwan Current was clearly separated from the Kuroshio Branch by the area of very weak or southward (reverse) flows.

1. Introduction

The formation of the Tsushima Current has long been studied by many oceanographers, and the Tsushima Current was considered as a branch of the Kuroshio northwest of Amami Oshima [Uda, 1935; Nitani, 1972] or an extension of the Taiwan Current [Beardsley et al., 1985; Fang et al., 1991]. However, both interpretations have been refuted by Lie and Cho [1994] on the basis of observations with satellite-tracked buoys and conductivity-temperature-depth (CTD) casts, and it is now generally thought that the Tsushima Current originates not from a single current but from the confluence of several currents. Katoh et al. [1996] carried out current measurements with a shipboard acoustic Doppler current profiler (ADCP) over the continental shelf of the central East China Sea in the summers of 1991 and 1994 (Figure 1) and concluded that the Tsushima Current is formed between 30° and 31°N by the confluence of the following currents: (1) a current along the 100 m isobath, labeled 1; (2) east/south-eastward currents over the seabed shallower than 90 m, labeled from 2 to 5; and (3) a current separating from the Kuroshio and entering onto the continental shelf northwest of Amami Oshima, labeled 6. They suggested that current 1 starts from the seas northeast of Taiwan and that currents 2–5 start from the outflow through the Taiwan Strait, i.e., the Taiwan Current. In order to verify this supposition, the current distribution in the southern East China Sea must still be clarified, and it is necessary to confirm the existence of a current different from the Taiwan Current in the seas northeast of Taiwan.

In the southern East China Sea it is well known that the Kuroshio water intrudes onto the continental shelf northeast of Taiwan. Chern and Wang [1990, 1992a, b] carried out intensive measurements for clarifying the circulation northeast of Taiwan, and they found important facts about the Kuroshio intrusion as follows: (1) The intrusion of the Kuroshio subsurface water is a persistent feature, but that of the Kuroshio surface water is absent in summer and (2) the variation of the Kuroshio intrusion is closely correlated with that of the outflow from the Taiwan Strait. Hsueh et al. [1992, 1993] showed that a part of the Kuroshio overruns the shelf break and penetrates northward as a shallow surface current in April 1989, but the observations in August 1991 yield no evidence of a surface Kuroshio overrun. From these studies it was clarified that the Kuroshio surface water does not directly intrude onto the continental shelf northeast of Taiwan in summer. Such a current entering onto the continental shelf northeast of Taiwan, as detected from the Kuroshio water, was termed the Kuroshio Branch [Inoue, 1974; Kondo, 1985]. They surmised that the Kuroshio Branch flows northward at 123°–123.5°E up to near 30°N, but its structure

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is poorly understood owing to the lack of direct current measurements. Akamatsu [1977] analyzed hydrographic data and found that the Kuroshio water mixed somewhat with the coastal water enters onto the continental shelf northeast of Taiwan and extends northeastward along the 100 m isobath. This suggests that the Kuroshio Branch flows along the 100 m isobath and is continuous with current 1. Chuang and Liang [1994] showed from current measurements with a mooring array that the shelfward current velocity over the shelf break northeast of Taiwan fluctuates widely over short periods, meaning that the Kuroshio Branch is highly variable.

The Taiwan Current flows northeastward off the coast of China and reaches the mouth of the Changjiang River [e.g., Guan and Mao, 1982; Pan et al., 1987; Su et al., 1994]. Pan et al. [1987] showed that the Taiwan Current flows along 50-100 m isobaths near the coast of China and bifurcates into two branches around 28°30'N. The onshore branch flows northeastward along 50-60 m isobaths and deflects eastward off the mouth of the Changjiang River. In general, the term "Taiwan Current" refers to the onshore branch. The offshore branch flows northeastward near the shelf break, after making an anticyclonic loop northeast of Taiwan. The existence of an anticyclonic eddy northeast of Taiwan in summer is reported by Guan [1986], Pan et al. [1987], and Hu [1994]. Pan et al. [1987] suggested that the occurrence of the anticyclonic eddy is related to the loop of the offshore branch. However, Guan and Mao [1982] did not refer to the existence of the offshore branch. These differing descriptions concerning the offshore branch suggest that it may exist intermittently rather than steadily. Given that the offshore branch occurs, its area of flow appears to be similar to that of the Kuroshio Branch northeast of Taiwan, but the relation between the two currents is not well known. In order to address these issues, it is necessary to clarify the downstream transition of the Taiwan Current from the Taiwan Strait.

The authors carried out extensive oceanographic observations in the southern East China Sea in July 1995. The present paper describes the current distribution in the southern East China Sea and discusses the characteristics of the Taiwan Current and the Kuroshio Branch.

2. Observation and Data Process

CTD and shipboard ADCP measurements were carried out over the continental shelf in the southern East China Sea on July 19–30, 1995 (Figure 1), aboard the R/V Kaito-Maru (Okinawa Prefectural Office of Education). CTD casts were made along transects K, A, and B, and ADCP measurements were collected along transects A and B.

The CTD used was an Alec Electronics Company Ltd. model AST-1000. Temperature and salinity were recorded with resolutions of 0.01°C and 0.01 practical salinity unit (psu), respectively. The intervals between CTD casts were ~9.3 km on transects A and B and ~19 km on transect K.

The ADCP installed on the R/V Kaito-Maru was a Furuno Electric Company Ltd. model CI-30 with a frequency of 130 kHz. Flow direction and velocity were recorded with resolu-
Figure 2. Diagram of the four-round trip ADCP survey during a diurnal tidal period of 24 hours and 50 min. Let $t_i (i=1, \ldots, 8)$ be a time of the $i$th passing over a station of $P$. Let $A_{t_i}$ and $B_{t_i}$ be diurnal and semidiurnal tidal flow components, respectively, at the time of $t_i$. Then, $A_{t_i} = -A_{t_{i+4}}$ ($i=1,2,3,4$) and $B_{t_i} = -B_{t_{i+2}}$ ($i=1,2,5,6$), since the lag between $t_i$ and $t_{i+4}$ is 12 hours and 25 min, and that between $t_i$ and $t_{i+2}$ is 6 hours and 12 min and 30 s. Hence the diurnal and semidiurnal tidal flow components can be canceled only through averaging eight raw data at $P$. 

Table 1. Starting and Finishing Times of CTD and ADCP Measurements on Transects K, A, and B in July 1995

<table>
<thead>
<tr>
<th>Transect</th>
<th>CTD Start</th>
<th>CTD Finish</th>
<th>ADCP Start</th>
<th>ADCP Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1-K8</td>
<td>July 19, 0846</td>
<td>July 24, 1036</td>
<td>July 19, 0831</td>
<td>July 24, 1038</td>
</tr>
<tr>
<td>A1-A7</td>
<td>July 19, 1931</td>
<td>July 24, 1036</td>
<td>July 19, 2339</td>
<td>July 24, 1558</td>
</tr>
<tr>
<td>A7-A13</td>
<td>July 23, 0505</td>
<td>July 28, 0822</td>
<td>July 23, 0943</td>
<td>July 28, 1236</td>
</tr>
<tr>
<td>A13-A19</td>
<td>July 19, 2354</td>
<td>July 28, 1236</td>
<td>July 23, 1427</td>
<td>July 28, 1722</td>
</tr>
<tr>
<td>B1-B7</td>
<td>July 29, 1326</td>
<td>July 26, 0120</td>
<td>July 29, 1722</td>
<td>July 26, 0112</td>
</tr>
<tr>
<td>B7-B13</td>
<td>July 28, 0822</td>
<td>July 27, 0210</td>
<td>July 28, 1236</td>
<td>July 27, 0712</td>
</tr>
<tr>
<td>B19-B25</td>
<td>July 26, 0120</td>
<td>July 27, 0208</td>
<td>July 26, 0120</td>
<td>July 27, 0208</td>
</tr>
</tbody>
</table>

Table 2. Velocities and Directions of the Diurnally Averaged Flows at Station B25, Obtained From the ADCP and Satellite-Tracked Buoy

<table>
<thead>
<tr>
<th>Period for Averaging Data</th>
<th>Start</th>
<th>Finish</th>
<th>Lapse, hour</th>
<th>Velocity, cm s$^{-1}$</th>
<th>Direction, degree($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCP</td>
<td>July 26, 0120</td>
<td>July 27, 0208</td>
<td>24.80</td>
<td>37</td>
<td>31</td>
</tr>
<tr>
<td>Buoy</td>
<td>July 26, 0821</td>
<td>July 27, 0759</td>
<td>23.63</td>
<td>36</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>July 26, 1258</td>
<td>July 27, 1427</td>
<td>25.48</td>
<td>35</td>
<td>43</td>
</tr>
</tbody>
</table>

Observations were stopped for 2 days after finishing ADCP measurements at section A1-A7 due to rough weather. Local time is used.
where $G_s$ is the geostrophic velocity at the surface. The volume transport ($T$) through a sector with a width of $d$ can be given as

$$ T = \frac{d}{2} \left[ \frac{1}{2} \left( V_1 + V_2 \right) H_{1-2} + \left( V_2 + V_3 \right) H_{2-3} + \left( V_3 + V_5 \right) H_{3-5} \right], $$

where $H_{1-2}$, $H_{2-3}$, $H_{3-5}$, and $H_{5-6}$ are the heights between the surface and the shallowest depth of the ADCP measurement, between the shallowest and intermediate depths, between the intermediate and deepest depths, and between the deepest and reference depths, respectively [Katoh et al., 1996].

### 3. Results

Vertical distributions of temperature, salinity, and diurnally averaged flows are shown in Figure 3. Using the above-mentioned values of $V_1$, $V_2$, $V_3$, $V_5$, and $V_6$ sections of velocities perpendicular to transects A and B are shown in Figure 4.
Figure 4. Sections of velocities perpendicular to transects A and B. The unit is cm s$^{-1}$. Shaded parts indicate velocities toward the south to the southwest.

Figure 3 shows that the current distributions at 20 m depth generally correspond with the temperature structure in the layer deeper than 50 m depth, and thus temperature at 60 m depth is taken in Figure 6a for investigating the continuity of currents. Figure 6 indicates the existence of an anticyclonic eddy, with temperature higher than 24$^\circ$C at 60 m depth and salinity lower than 34 at 20 m depth, in the southeastern portions of transects A and B, and it is confirmed by the similarity of the T-S diagrams among A8, B5, and B14 (Figure 5d). The vertical thickness of the anticyclonic eddy is estimated ~70 m, on the basis of the velocity section at
Figure 5. (a) T-S diagrams at K3, A2, A8, and A17 and (b) B5, B14, and B24 are shown. (c)-(d) Investigating similarities of T-S diagrams between A17 and B24, and those among A8, B5, and B14, respectively, are shown.

Figure 6. Diurnally averaged flows at 20 m depth and (a) temperature at 60 m depth and (b) salinity at 20 m depth.
NOAA-14/AVHRR infrared images of the sea surface temperature on (a) July 20 and (b) August 8 in 1995, prepared by the Japan Weather Association. Transects A, B, and K are shown by white lines. No data are in the dotted area due to clouds.

B3–B17 (Figure 4). The sharp front is formed in the southeastern margin of the anticyclonic eddy (Figure 6b). The area with temperature colder than 22°C at 60 m depth near Uotsuri Island shows the existence of a cyclonic meandering current (compare temperature section along transect K in Figure 3).

NOAA-14/advanced very high resolution radiometer (AVHRR) infrared images of the sea surface temperature on July 20 and August 8, 1995, prepared by the Japan Weather Association, are shown in Figure 7. Water colder than 28°C extends northeastward from the Taiwan Strait along the coast of China, and it passes near the northwestern ends of transects A and B. The extension of the cold water only near the coast of China confirms that the considerable northeastward current starts from the Taiwan Strait and that it is clearly separated from the north/northeastward current in the central portions of transects A and B. As observed on August 8, water warmer than 30°C passes through transect K and extends northeastward, and this extension is considered to be the area of flow of the Kuroshio. Moreover, water warmer than 29°C extends northeastward from the point at 28°N and 124°E; this indicates the existence of a current flowing northeastward parallel to the Kuroshio. It is noticeable that a cold water eddy is seen immediately northeast of Taiwan in August 8.

Trajectories of the satellite-tracked buoys released at B25 and C1 are shown in Figure 8. The northern buoy moves straight northeastward from B25 to X1 and then deflects eastward. The mean velocities from B25 to X1, X1 to X2, and X2 to X3 are 39, 34, and 25 cm s⁻¹, respectively. This shows that the current near B25 flows northeastward to X2 and eastward to X3 with decreasing velocity and that it reaches the area of current 2. However, the buoy released at C1 moves northward on average with spiraling and reaches Y1 near the middle of transect A; the mean velocity from C1 to Y1 is 7 cm s⁻¹. This shows that the northward flow of current C1, with high variability of velocity, contributes to the formation of the north/northeastward current in the central portions of transects A and B.

Volume transports in a width of ~19 km are shown in Figure 9. The volume transport at B17–B25, where the large northeastward current exists, is 0.81 Sv (1 Sv=10⁶ m³ s⁻¹). The difference of 0.33 Sv between the volume transport of 0.51 Sv at B9–B17 and that of 0.18 Sv at B3–B9 illustrates that the main portion of the north/northeastward current around B15 (see Figure 8) extends along the 100 m isobath and that the remainder extends toward the shelf break, helping to make the anticyclonic eddy.

4. Discussion

A strong northeastward current starting from the Taiwan Strait, with velocities of 35–40 cm s⁻¹ and a volume transport of 0.8 Sv, is clearly found near the coast of China. The position and direction of this northeastward current correspond to those found in the descriptions of the Taiwan Current in previous studies. Hence the northeastward current along the coast of China can be confidently regarded
Figure 8. Trajectories of the satellite-tracked buoys released at stations B25 and C1. The diurnally averaged flows at 20 m depth on transects A and B and in the central region of the East China Sea (see Figure 1) are also shown for reference. The buoy released at B25 passed X1 at 0236 on July 30, X2 at 1505 on August 2, and X3 at 1443 on August 4. The buoy released at C1 passed Y1 at 1523 on July 22.

as the Taiwan Current (Figure 10). It would appear that the western margin of the current is located on the continental side of B25, and thus the volume transport must be at least 1 Sv. The sudden deceleration of the buoy released at B25 north of 29°30'N (Figure 8) implies that the Taiwan Current increases its width and decreases its velocity in the central

East China Sea, which is well consistent with the distribution pattern of the weak and separated currents 2–5 shown in Figure 1. The eastward deflection and deceleration of the Taiwan Current around 30°N is also able to be seen in Fang et al. [1991], which shows the transport density in summer based on historical current data from 24 hours anchored ships. However, another north/northeastward current, with velocities larger than 15 cm s⁻¹ in the surface, observed in the central portions of transects A and B is clearly separated from the Taiwan Current. This current probably starts over the shelf break west of Uotsuri Island, taking into account the existence of the sharp front in the southeastern margin of the anticyclonic eddy (Figure 6b) and the northward trajectory of the buoy released at C1 (Figure 8). The current which enters onto the continental shelf northeast of Taiwan and flows northward is named the Kuroshio Branch [Inoue, 1974; Kondo, 1985], and thus the north/northeastward current can be regarded as the Kuroshio Branch (Figure 10).

Salinity of surface water transported by the Kuroshio Branch is low (<33.8), whereas that of subsurface water is relatively high (Figure 3). This indicates that the Kuroshio surface water does not directly intrude onto the continental shelf in summer, and it is well consistent with the conclusion of Chern and Wang [1992a] and Hsueh et al. [1993]. The origin of the surface water is not determinate from the present observational data, but it is attractive that low-salinity water (<33.8) is not observed in the area of the Taiwan Current; this implies that the low-salinity water originates from an area close to Taiwan. Wang and Chern [1992] observed in summer of 1988 that salinity is lower in the eastern side than in the western side of the Taiwan Strait, and Chern and Wang [1989] showed that the surface cyclonic circulation closely northeast of Taiwan tends to drive waters from the Taiwan Strait into the Kuroshio surface layer. Taking into account these descriptions and the occurrence of

Figure 9. Volume transports through unit sections with widths of ~19 km along transects A and B. Numerals indicate total volume transports through the sections between two adjacent dots.
the cold water eddy closely northeast of Taiwan (Figure 7b), it is likely that low-salinity water distributed immediately west of Taiwan is driven seaward and intrudes onto the continental shelf northeast of Taiwan, mixed with the Kuroshio surface water.

The Kuroshio Branch divides into two parts near the 100 m isobath (Figure 10). The main portion flows northeastward with a volume transport of ~0.3 Sv, and it is most likely continuous with current 1 along the 100 m isobath in the central East China Sea, with a volume transport of ~0.4 Sv [Pan et al., 1996], judging from their positions and directions shown in Figure 8. It is strongly supported by the northeastward extension of warm water (>29°C) parallel to the Kuroshio (Figure 7b). These results confirm the view proposed by Akamatsu [1977] that the Kuroshio Branch extends northeastward along the 100 m isobath.

In the seas northeast of Taiwan, we cannot identify the offshore branch of the Taiwan Current making an anticyclonic loop [Pan et al., 1987], but the Kuroshio Branch is observed instead (Figure 10). This indicates that the Taiwan Current did not bifurcate into two branches in July 1995. The difference of the current distribution between Pan et al. [1987] and the present study seems to be closely related to the high variability of the Kuroshio Branch, which is indicated by the trajectory of the buoy released at C1 (Figure 8) and the measurements with mooring-array by Chuang and Liang [1994]. Chern and Wang [1992b] showed that the strength of the Kuroshio Branch is inversely correlated with that of the Taiwan Current, responding to fluctuation of southwestern winds. Hence it is very important to monitor the fluctuations of the Taiwan Current and the Kuroshio Branch, in order to clarify the correlation between the two currents and the variability of the Tsushima Current as well.

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References


Chern, C.-S., and J. Wang, The influence of Taiwan Strait waters on the circulation of the southern East China Sea, La mer, 30, 223-228, 1992b.


Hsueh, Y., C.-S. Chern, and J. Wang, Blocking of the Kuroshio by the continental shelf northeast of Taiwan, J. Geophys. Res., 98, 12,351-12,359, 1993.


Kondo, M., Oceanographic investigations of fishing grounds in the East China Sea and the Yellow Sea, I, Characteristics of the mean temperature and salinity distributions measured at 50 m and near the bottom (in Japanese with English abstract), Seikai-ku Suisan Kenkyusho Kenkyu Hokoku, 65, 1-17, 1992.


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