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Current on the Edge of the Continental Shelf Northeast of Taiwan

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ABSTRACT

Data from a cruise conducted at the end of spring 1992 is presented in order to investigate the spatial structure of the countercurrent and the origin of the upwelling along the edge of the continental shelf northeast of Taiwan. The current velocity was measured by a shipboard Acoustic Doppler Current Profiler (ADCP) along the transect to examine the mean-current field. Hydrographic measurements along each transit were also performed. Based on the data, we obtained the qualitative mean-current field and its associated water characteristics. The cruise track extended from the northern coast of Taiwan to the continental shelf of the East China Sea. The measured mean current field can be divided into three regions. From the northern coast of Taiwan to the Mien-Hwa Canyon, the water flowed southeastwardly from the shelf toward the sea. This outflow could have originated from the Taiwan Strait. The current abruptly changed direction when crossing over the Mien-Hwa Canyon. In between the Mien-Hwa and North Mien-Hwa Canyons, the countercurrent dominated and flowed generally along the isobath in a southwestward or westward direction. The countercurrent spanned the entire water column with a horizontal scale of approximately 40 km. Analysis of the CTD data indicated that the countercurrent originated from subsurface Kuroshio water. North of North Mien-Hwa Canyon, the flow was northward and had the same characteristic as the subsurface Kuroshio water. This indicated that the subsurface Kuroshio water transgressed the continental shelf of the East China Sea.

Additionally, the countercurrent water and the upwelling water were found to have the same characteristics as the subsurface Kuroshio water and, historically, both are permanent features. We conclude that the countercurrent is an important factor in the origination of the upwelling found in this area.

(Key words: Kuroshio, Countercurrent, Sb-ADCP)

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1. INTRODUCTION

The continental shelf northeast of Taiwan is a region of interaction among water from the Taiwan Strait, the Kuroshio, and the East China Sea. Many local phenomena, such as a permanent upwelling, are related to this interaction. In order to understand the dominant processes involved, the Kuroshio Edge Exchange Processes (KEEP) program was developed. One of its main objectives is to identify the origination of the permanent upwelling feature discussed here. This upwelling was firstly identified by Uda and Kishi (1974), and subsequently studied by Fan (1980), Chern and Wang (1989), Wong *et al.* (1991) and Gong *et al.* (1992). The cold, high-nutrient, upwelled water is an important factor in local primary productivity and fishery resources (Anon, 1988 and Chiu, 1991).

The seasonal temperature distribution at 50 m depth northeast of Taiwan is shown in Figure 1 (after Hwang and Tang, 1993). The data is from 6077 CTD casts collected from 1985 to 1991. Except in winter, a pool of cold water which migrates slightly from season to season is clearly present at the northeast tip of Taiwan. Chern and Wang (1989) found that the cold water originated from the subsurface Kuroshio water. They inferred that an on-shelf intrusion of Kuroshio was responsible for this feature. By examining the monthly variations of temperature, nitrate, and dissolved oxygen, Liu *et al.* (1992) mentioned that this upwelling was a permanent feature even in winter and that the presence of the pool of cold, upwelled water in winter was masked by the cooling of shelf water in that season.

However, data from a subsurface-moored Acoustic Doppler Current Profiler(ADCP) (Tang and Yang, 1993) showed that the on-shelf Kuroshio intrusion is not a permanent feature. The intrusion occurred one month after the northeasterly monsoon intensified and the intrusion was confined to the upper 150m. Their measured current data does not support a positive correlation between upwelling and the on-shelf intrusion. A positive correlation is also not supported by other existing current data. Chuang *et al.* (1993) analyzed the current data collected from 1989 to 1992 during the KEEP program. They found that the current along the edge of the continental shelf generally flows from the northeast to the southwest. Such a current prohibits the on-shelf intrusion of Kuroshio. The southwestward current persisted in a deeper layer(>150 m) and varied seasonally in the upper layer. Since this flow opposes the flow of the Kuroshio, Hsueh *et al.* (1993) named this current the countercurrent of Kuroshio. Using a two-layer analytical model, they found that the subsurface Kuroshio water, deflected by a shelf break along 25°40'N, could give rise to this countercurrent. Since the countercurrent is persistent, possibly formed from the subsurface Kuroshio water and possibly associated with the permanent upwelling, an investigation of the spatial structure of countercurrent was deemed crucial to understand the formation of the upwelling. To explore this hypothesis, a cruise was conducted to measure the current along the edge of the continental shelf northeast of Taiwan. Data from a shipboard ADCP, including Sea Surface Temperature (SST) was utilized. To assist in the removal of the effects of high-frequency current fluctuations, the cruise line was repeated seven times in three days. Additionally, the four hydrographic measurements were performed along each cruise track. The paper is organized as follows. Section 2 presents the field work and hydrographic measurements. The temporal variations of temperature distribution will be noted. The current structure, measured by the shipboard ADCP, is described in Section 3. A comparison between the presented data and the moored current data is made. Section 4 provides a discussion and summary.

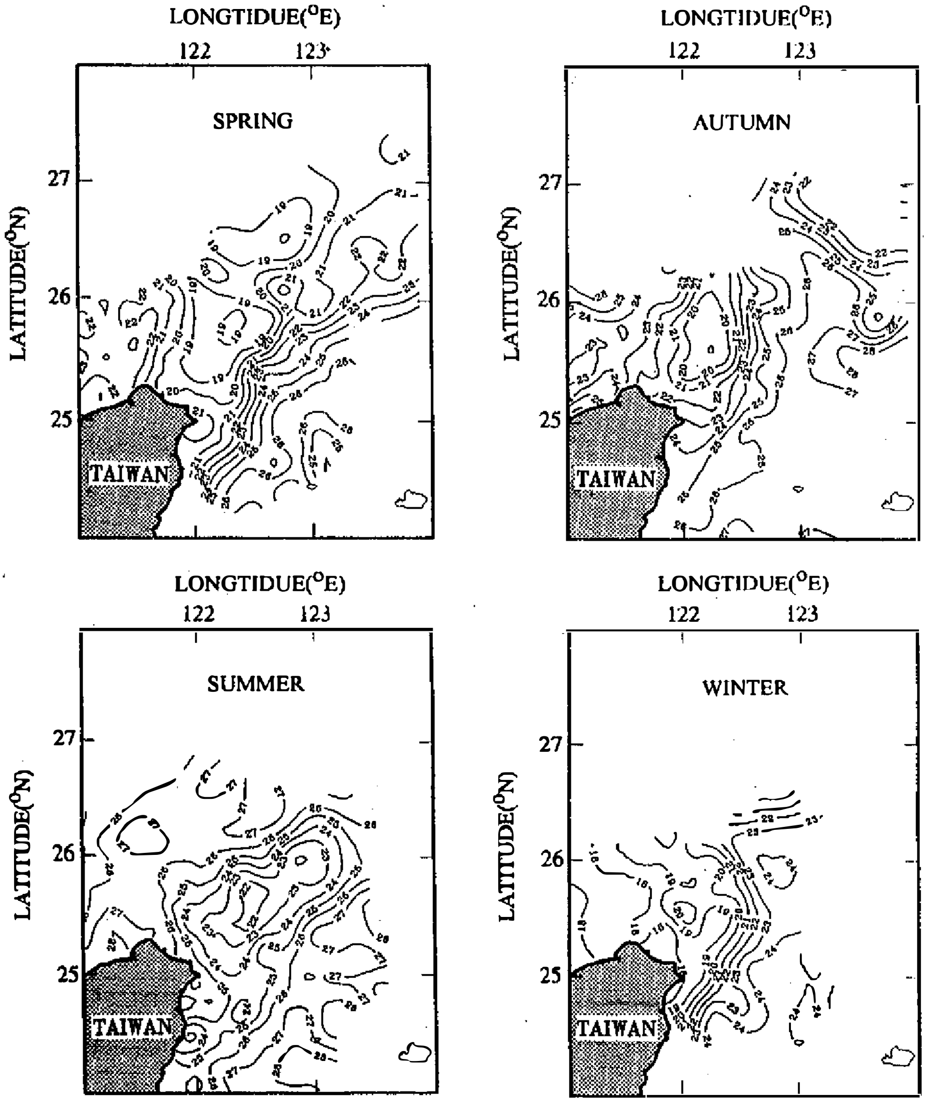

Fig. 1. Seasonal temperature distributions at 50 m depth northeast of Taiwan.

2. FIELD WORK AND HYDROGRAPHIC MEASUREMENTS

A cruise conducted from May 30 to June 2 of 1992 studied the spatial structure of current along the edge of the continental shelf northeast of Taiwan. The current velocity and its geographic position were obtained by using a 153 kHz shipboard ADCP and a Global Positioning System (GPS), respectively. Figure 2 shows the cruise track and the surrounding bathymetry. The length of the track is approximately 115 km. The cruise track crossed over two canyons, the southern canyon, the Mein-Hwa Canyon and the northern, North Mein-Hwa Canyon. The cruise track was repeated seven times in three days. The measured current data during the second track was biased due to operational difficulties. Two moored

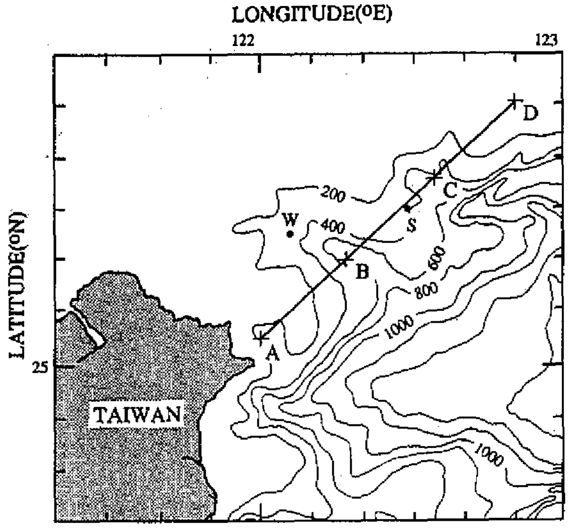

Fig. 2. The cruise track and its surrounding bathymetry.

VACM currentmeters were deployed at W. A moored subsurface electric S4 currentmeter was also deployed at S. Their current data were used as a reference for the shipboard ADCP measurements. Four CTD stations, labeled by A, B, C and D, were designated along the track. The seven repetitions of the cruise track allowed seven CTD profiles to be obtained at Station B and C, and five and six profiles to be obtained at Station A and D, respectively. The SST along each transect was recorded by the temperature sensor of ADCP.

The vertical temperature profiles at A, B, C, and D are shown in Figure 3. At Station A, the depth of the mixed layer varied from 10 m to 50m. Beneath the mixed layer, the water temperature sharply decreased with depth to the bottom, where the largest temporal temperature variation was found. This implies that a flow with large horizontal temperature gradient dominated near the bottom. Such a flow may be related to a tidal current. A similar feature was also observed at Station B. At Station B, the depth of the mixed layer was generally less than at Station A. The thermocline varied from 30 m to 60 m. In this depth range, the temporal temperature variation was of comparable amplitude to the near-bottom variation. The vertical distribution of temperature at Station C was generally similar to that at Station B, except the temporal variation near the bottom was smaller. At Station D, the mixed layer almost disappeared. The temperature changed nearly uniformly from near-surface to the bottom. Differing from Station A and B, the temporal variation of temperature at Station D was small.

Utilizing the same data, Figure 4 shows the mean distribution of temperature as a function of depth and horizontal distance. The contour interval is 2°C. The isothermal depth was deepest at both ends of the transect and shallowest at Station B, close to the area of permanent upwelling. The SST was also measured along the transect by the ADCP temperature sensor. The results are shown in Figure 5. The coldest SST was found near Station B, but migrated from time to time, possibly corresponding to tidal motion. The warmest SST was at Station D.

Figure 6 shows the T-S curves at Station A, B, C, and D. Obviously, the water mass at Station A is different from that at the other three stations. In comparison with the study of

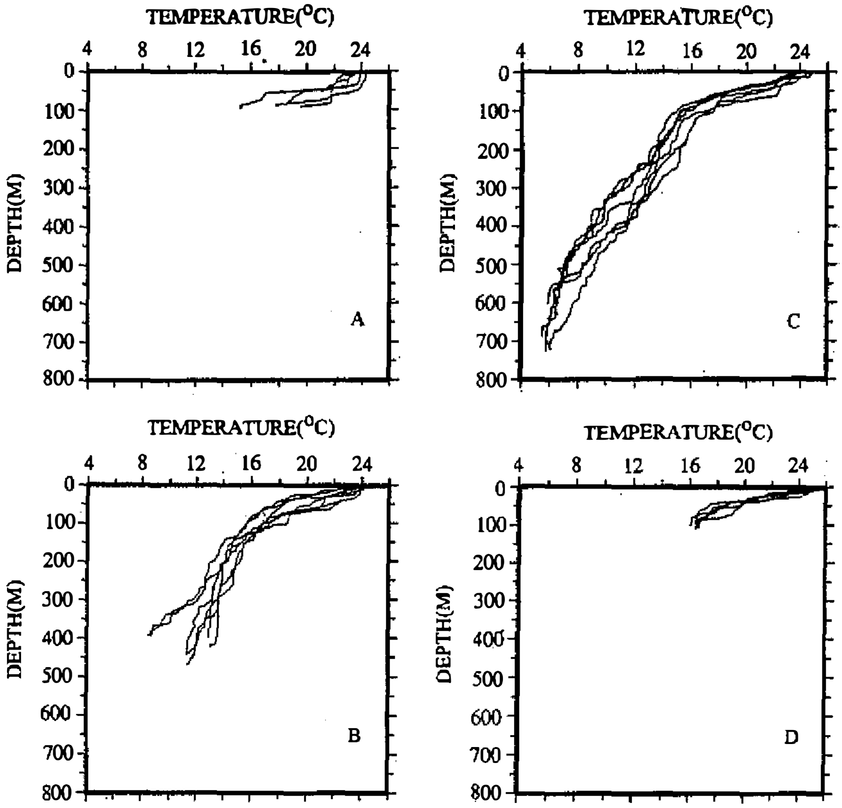

Fig. 3. Vertical temperature profiles at Stations A, B, C, and D.

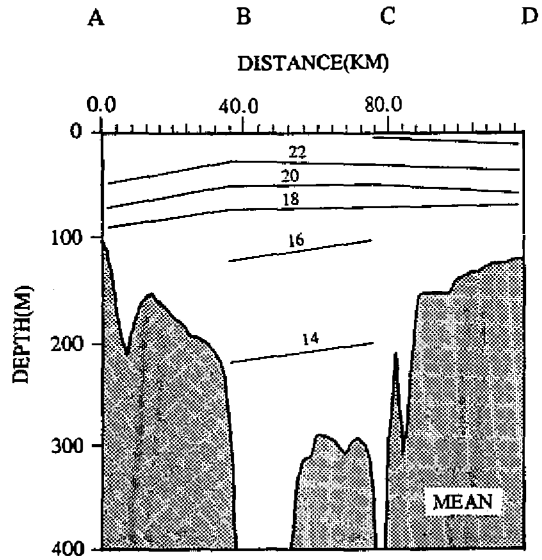

Fig. 4. Mean temperature distribution by seven cruise transits at Stations A, B, C, and D.

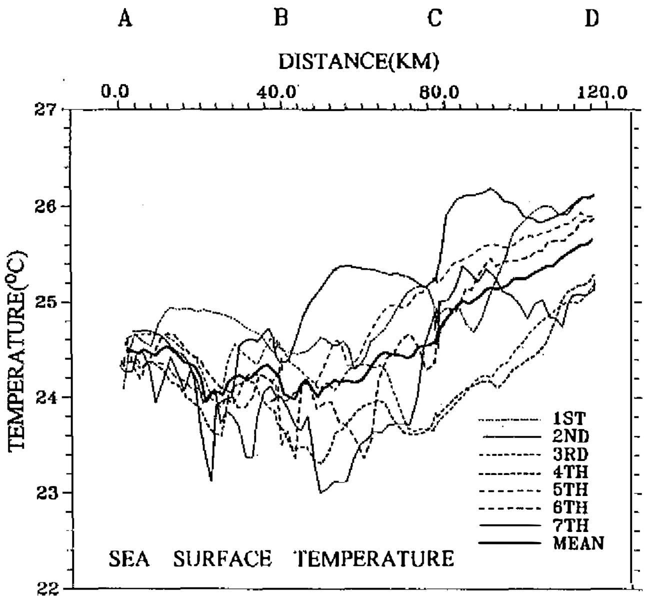

Fig. 5. The seven SST distributions and their mean along the transect.

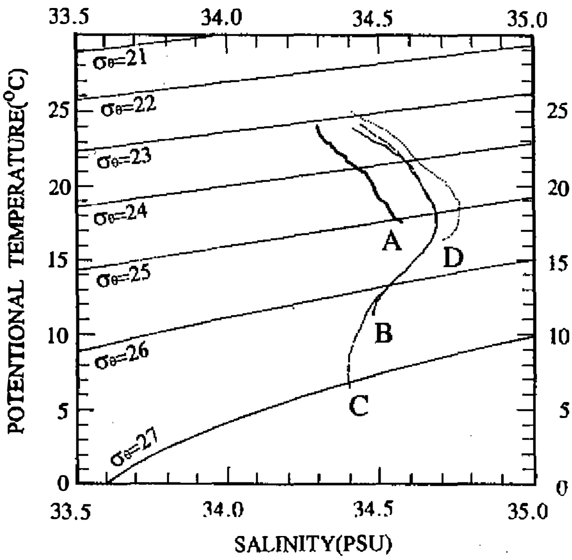

Fig. 6. T-S curves for Stations A, B, C , and D.

Chern and Wang (1989), the waters at Station A and D are similar to the continental shelf and subsurface Kuroshio waters, respectively. Between these two stations, the waters are mixed but substantially similar to the subsurface Kuroshio water rather than the continental shelf water. This is a clear evidence that the subsurface Kuroshio water does flow from the northeast to the southwest. On its way to the northeast, the subsurface Kuroshio water is slightly mixed with the shelf water. Close to the coast of Taiwan (Station A), the subsurface

Kuroshio became indiscernible. The abrupt disappearance of the subsurface Kuroshio water indicates that this water has either intruded onto the shelf or flowed out to the open sea in the area near Mien-Hwa Canyon.

3. CURRENT MEASUREMENT AND ANALYSIS

The current velocity obtained directly from the shipboard ADCP is relative. The ship velocity needs to be subtracted in order to determine the absolute current velocity. For the R/V Ocean Researcher I, there are two ways to estimate the ship speed. One is to use the GPS and the other is to use the ADCP itself. The first method is called the GPS mode. It requires time-averaging to reduce the random error (Smith and Morrison, 1989). The latter method is called the bottom tracking mode. It has a much smaller random error but is limited by water depth. Its maximum range is 500 m. Since the bottom tracking mode was available during most of this experiment, the GPS mode was not utilized.

For the bottom-tracking mode only, there are nearly 200 available measured profiles along each transit. Each measurement averaged over 120 pings. The ping interval and the measurement interval was one second and two minutes, respectively. Since the ADCP was installed 4 m below the surface and its blanking and bin lengths were set at 8 m, the first measurement for each velocity profile was at 12 m below the water. For current measurement, the maximum range of the 153 kHz ADCP is about 350 m. In order to further reduce the random error and enhance data representation, a spatial average is applied. Figure 7 shows the available measurements along each cruise track, and the spatial average interval (circa 10 km). To present the current field, the horizontal profile of the transect is divided into 13 intervals. The intervals are numbered (1~13) from the southwest end to the northeast (number 13 on the profile). This number system will be used on the spatial velocity distribution graph. The number of available measurements in each interval is not even, because of the irregular ship speed and lack of data when the water depth is over 500m.

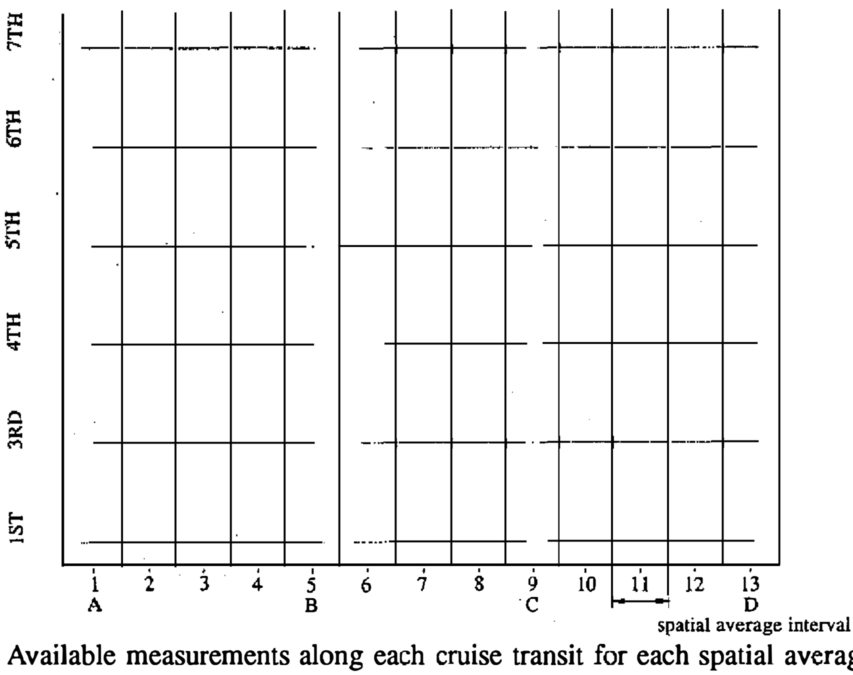

Fig. 7. Available measurements along each cruise transit for each spatial average interval.

Figure 8 shows the measured current velocity for six transits. Generally speaking, the current field can be divided into three regions. From the northern coast of Taiwan to the Mien-Hwa Canyon, where, except for transect 7, the southeast current predominated. The water flowed out from the shelf to the sea. The current velocity changed rapidly, from southeast to southwest or west, near the Mien-Hwa Canyon. This southwest or west current is a countercurrent of Kuroshio. It persisted (except for transect 6) between the two canyons. Over the North Mien-Hwa Canyon, the current turned northwestward and then further north. This implies that the subsurface Kuroshio water does not only form a countercurrent but also transgresses the continental shelf of the East China Sea. Although this current field was found in most measurements, it varied from time to time. In this current field, the tidal current was significant. Similarly, the subsurface-moored RCM currentmeter data collected at W, 20 km northwest of Station B (see Figure 9), showed that the mean current was smaller than the tidal current. Moreover, the velocity measured by the shipboard ADCP at Station B (marked by an asterisk) generally agreed with the moored currentmeter data.

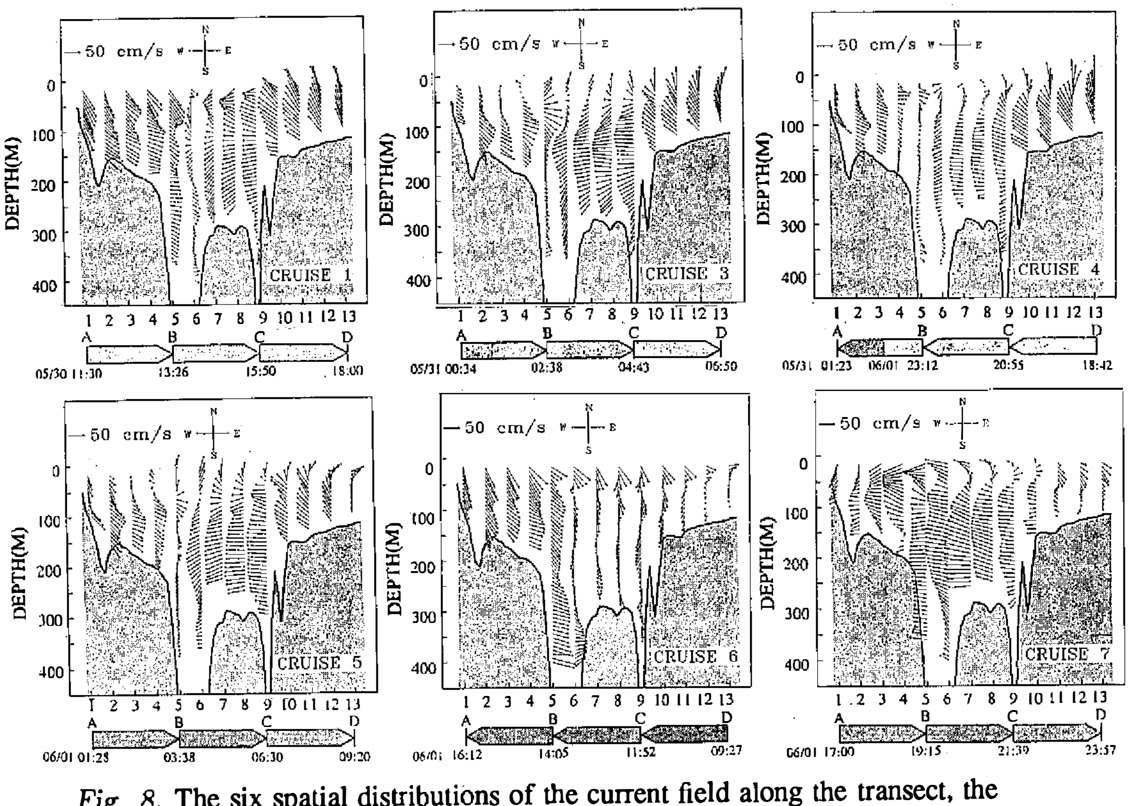

Fig. 8. The six spatial distributions of the current field along the transect, the shaded arrows beneath each diagram indicate the ship direction and its arrival schedule at the four CTD stations.

To further investigate the mean current field, we assumed that the tidal signal would be filtered out by averaging over the six measurements (Geyer and Singnell, 1990). Figure 10 shows the mean current distribution and vertical average velocity. South of the Mien-Hwa Canyon, the water flowed from the shelf toward the sea. The flow velocity was 30-40 cm/sec. The vertical shear velocity was small. The current abruptly changed its direction (from southeast to southwest or west) as it crossed the canyon. The countercurrent dominated between the two canyons with a horizontal scale of approximately 40 km and a maximum velocity between 150m and 200m depth. The countercurrent's amplitude was smaller in the surface layer than in the deeper ocean, perhaps a response to the southwesterly wind. North of the North Mien-Hwa Canyon, the current gradually turned from westward to northward. This mean current field is quite similar to earlier observations. Figure 11 shows the mean velocity of mooring-measured, mean current data (from Chuang *et al.*, 1993) collected during the KEEP program. Although the speed of shipboard ADCP measurement is generally higher than that of moored current data, the current directions agree. This indicates that the present measurements, at least qualitatively, represent the mean current field on the edge of the shelf northeast of Taiwan.

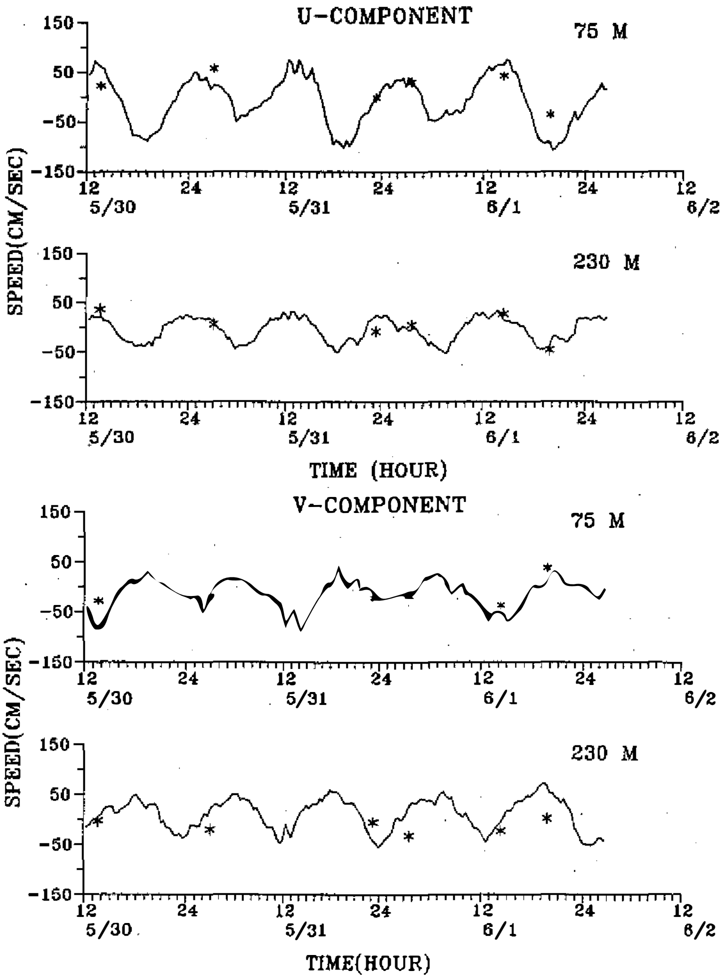

Fig. 9. The time series of U and V components of RCM currentmeter data at 75 m and 230 m depth at Station W. Measured ADCP data at Station B is indicated by "*".

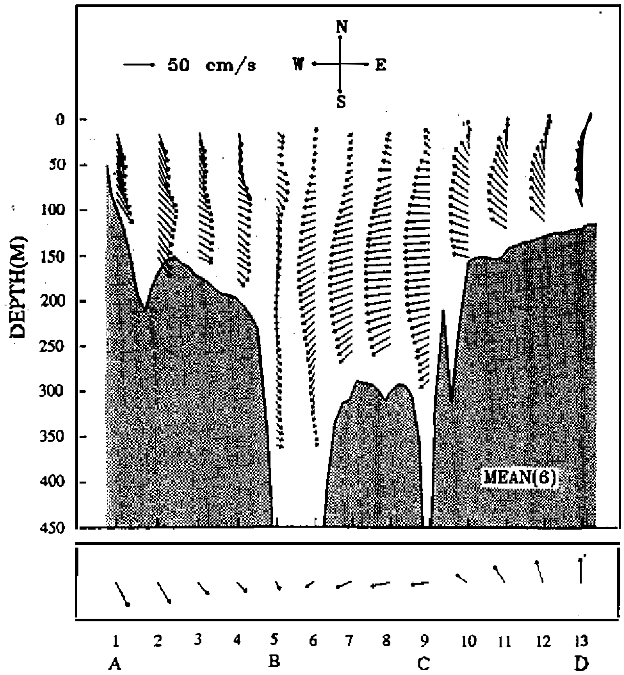

Fig. 10. The mean current distribution with the average vertical velocity shown below the graph.

A hypothesis is presented here. As the Kuroshio approaches the steep shelf break, along 25°40'N, part of its subsurface water is deflected and upwelled (Hsueh *et al.*, 1993). This water either runs over to the continental shelf (such as at Station D) or forms a Kuroshio countercurrent. This countercurrent is generally confined to the region near the shelf edge . As the countercurrent crosses the Mien-Hwa Canyon, a significant volume intrudes onto the shelf, resulting in upwelling. Since the countercurrent is persistent (Chuang *et al.*, 1993), the upwelling is also persistent. South of the Mien-Hwa Canyon, the countercurrent never reaches the coast of northern Taiwan due to interaction with outflow from the Taiwan Strait (Chern and Wang, 1989) near the shelf area of the Mien-Hua Canyon.

4. DISCUSSION

In order to examine the accuracy of the shipboard ADCP measurements, an S4 currentmeter was moored to monitor the current velocity during the experiment. The vertical excursion of the S4 data was large (maximum value around 150m) and attributed to improper mooring design. However, the obtained velocity data can still be referenced to the shipboard ADCP. Data obtained from the S4 currentmeter and the ADCP for similar depths as the ship passed the mooring location are compared in Figure 12. It shows a reasonable agreement between the two instruments, reconfirming the applicability of the shipboard ADCP measurements.

To investigate the mean current field, the semi-diurnal tidal current (which has a significant effect in this area) needs to be removed. In this study, we assumed that the tidal signal is removed by averaging the measurements over the six transits. The assumption is

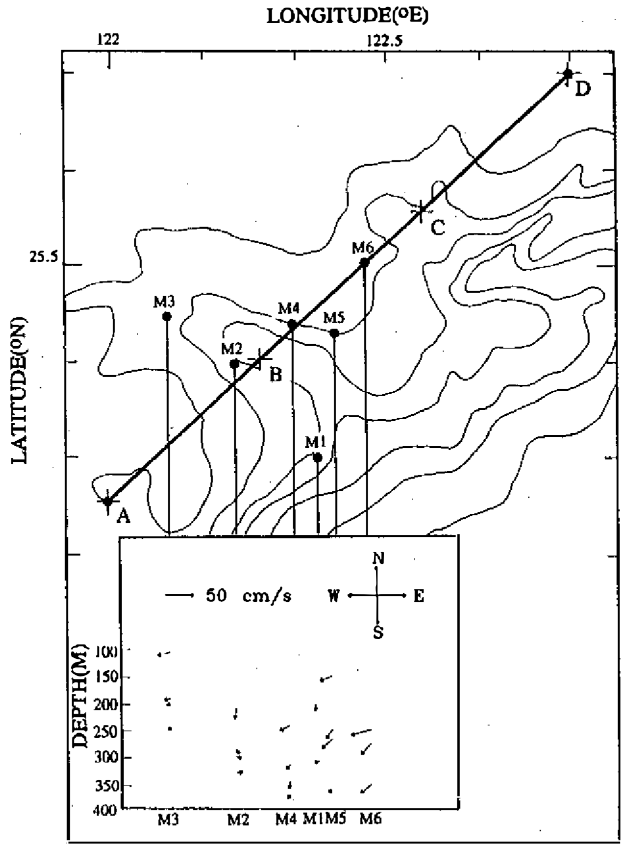

Fig. 11. Profile of the moored mean current data during the KEEP program (data from Chuang *et al.*, 1993).

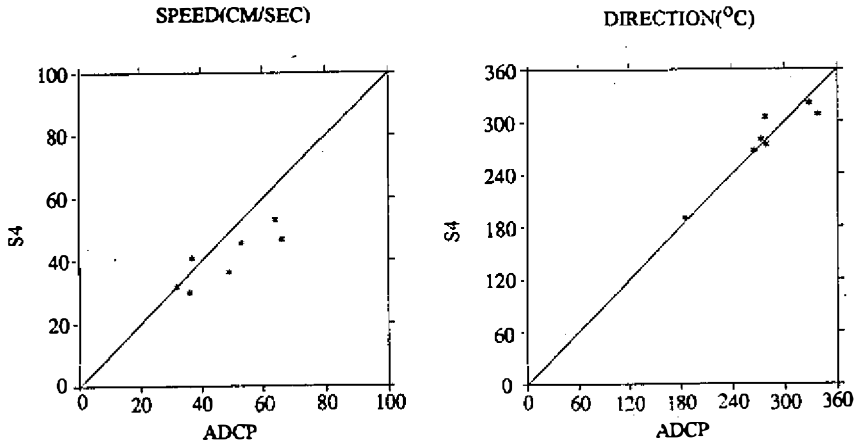

Fig. 12. Direct comparison of current speed and direction from the S4 currentmeter and the ADCP data.

examined as follows. A semi-diurnal tide can be expressed as

$$V_i = A \sin(ft_i + \theta)$$

where V_i and A are tidal current and amplitude, respectively, f is semi-diurnal tidal frequency, and θ is the associated phase. Here, t_i is the ith-time when the ship passed the measured point, and θ is assumed to be independent of space. Averaging over the six measurements, the percentage of the tidal signal which has been removed is only a function of θ. It can be defined as

$$P(\theta) = [1 - \frac{(\sum_{i=1}^{N} V_i)/N}{A}] \times 100\%, N = 6$$

If the tidal signal is perfectly removed, the value of P is 100%. To examine all the possibilities, Table 1 lists the "best" and "worst" conditions. The difference between these extremes is large, indicating that the tidal phase has to be determined in order to confirm the quality of mean current field. Using the subsurface moored RCM current data at W, the tidal phase is computed. Between the two canyons, over 70% of the tidal signal has been removed. Therefore, the countercurrent is properly characterized. On an average, 65% of the tidal signal is removed over the whole domain. This indicates that the mean current field is qualitatively represented in our measurements but cannot be quantified with adequate certainty.

Table 1. The quality percentage of mean current field with tidal signal removed.

Station Interval number	A 1	2	3	4	B 5	6	7	8	C 9	10	11	12	D 13
The percentage of the best(%)	100	100	100	100	100	100	100	100	100	100	97	99	99
The percentage of the worst(%)	44	25	28	45	44	64	74	79	70	45	35	29	27

Furthermore, a least-squared-error fitting method was applied to separate the semi-diurnal tidal and mean currents. Since there are only 6 measurements at each point, the maximum degree of freedom of a least-squared-error fit is 6. With 100% of error, to fit a mean value and a sinusoidal curve require one and three degrees of freedom, respectively. Therefore, only the semi-diurnal tidal and mean current were considered. The other components of motion, such as the diurnal and quarterly-diurnal tidal currents, were treated as the noise. This treatment will not significantly affect the fitting result since the moored current data at W indicated that the semi-diurnal tidal is much larger than the others. The mean current, obtained from this fit, agrees with the previous result, which simply took the average of 6 measurements. Meanwhile, the calculated tidal phase is nearly uniform along the cruise track. It provides an evidence for the assumption that θ is independent of space. Such agreement reconfirms that the mean current is at least qualitatively represented in Figure 10.

The on-shelf Kuroshio intrusion occurs seasonally in the KEEP area. Tang and Yang (1993) found that it is positively correlated with sea level at Keelung. When the intrusion occurred, the sea level dropped abruptly at Keelung and the countercurrent in the upper ocean disappeared. During the cruise discussed here, the sea level at Keelung was relatively high, implying that the Kuroshio did not intrude onto the shelf during this period and that the countercurrent would predominate at most depths. The obtained current field agrees with this inference.

5. SUMMARY

A cruise was conducted from May 30 to June 2 of 1992 to measure the current along the edge of continental shelf northeast of Taiwan. The length of the cruise track was approximately 115 km. The current velocity was measured by a shipboard 153 kHz ADCP. The cruise track was repeated seven times in order to examine the mean current field. Measurements were also made at four hydrographic stations along each transect to understand the properties of the current field.

The tidal current was large over the entire transect. Either the mean hydrographic or current fields was seriously biased by the tidal signal. Averaging over the six measurements, a qualitative mean-current field was obtained. This mean-current field can be divided into three regions. From the northern coast of Taiwan to the Mien-Hwa Canyon, the water flowed from the shelf to the sea. The current was southeastward. This outflowing water could have originated from the Taiwan Strait. The current abruptly changed direction when it crossed over the Mien-Hwa Canyon. The countercurrent dominated between the Mien-Hwa and the North Mien-Hwa Canyons and flowed basically southwestward or westward. Since the countercurrent flow and the upwelling waters had characteristics similar to the subsurface Kuroshio water and both exist permanently, it is evident that the upwelling originates from the countercurrent. North of North Mien-Hwa Canyon, the flow gradually turned from westward to northward. The water also had characteristics similar to the subsurface Kuroshio water. This indicates that the subsurface Kuroshio water transgresses the continental shelf of the East China Sea.

The present study re-confirms the existence and the spatial structure of the Kuroshio countercurrent on the edge of the shelf northeast of Taiwan. The countercurrent spanned the entire water column and its horizontal scale was approximately 40 km. All the measurements indicated that the current generally flowed along the isobath. The upwelling water was of subsurface Kuroshio current origin and the Mien-Hwa Canyon is critical for the formation of this permanent feature.

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