La mer 30: 213–221, 1992
Société franco-japonaise d'océanographie, Tokyo

# On the distribution of bottom cold waters in Taiwan Strait during summertime

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**Abstract:** The general behavior of a stratified current flowing into Taiwan Strait has been studied from CTD and ADCP surveys conducted in the summer. Spatial distributions of hydrographic parameters have provided significant clues for illuminating the effect of topography on flows in the strait. Cold and saline waters in the northern Taiwan Strait mainly appear in the west, for example, but not at the eastern portion of the strait. A northwestward protruded, underwater cold and saline water tongue at north of Peng-hu also always exists. The tongue, being likely a permanent feature appearing from the spring to the autumn, is caused by flow separation due to topographic effects of the Chang-Yuen sand ridge on the incoming stratified currents. Surface waters, being lighter than bottom waters, are able to flow over the ridge. Bottom waters, however, are forced to turn northwestward along the depth contour and enter into the western strait. Field ADCP measurements have suggested the total transport of the latter to be of the order of 0.2 to 0.3 Sv in the summer.

## 1. introduction

Upwelling phenomena observed in Taiwan Strait (TS) have recently drawn particular attention (e. g. CHEN *et al.*, 1982; CAI and LENNON, 1988; XIAO, 1988; LI and LI, 1989). Previous investigators have reported upwelling phenomena being frequently seen along the west bank of TS during summertime. One of the two major upwelling centers was found on the northwest side of Formosa Banks. The other was found near Hai-tang Island in northern Fuchien. These phenomena have been repeatable, seasonal processes. Wind stress, ocean circulation and bottom topography have all been relevant to the behavior of upwelling in TS.

Some topics appearing in the above-mentioned literatures, however, are incomplete. The blocking effect exerted by the shallow Formosa Banks to incoming stratified currents from the South China Sea (SCS), for example, was ignored by most of these authors (except LI and LI, 1989). The topography used by CAI and LENNON (1988) for their numerical examinations was oversimplified. Additionally, important features of both Peng-hu Channel and the submarine ridge north of Peng-hu were also absent in their modeling. The real situation has still remained obscure, even though LI and LI (1989) showed that the source of upwelled cold waters in TS comes from the northern SCS and they postulated three possible conduits for them.

Upwelling in TS is a significant process for the strait dynamics. The path as well as the flux of upwelled cold waters are also of central importance to local hydrography. General features of upwelling phenomena in TS were descriptively reported in previous literatures. The detailed mechanisms, e.g. the topographic adjustment of a stratified current after it entering TS and its responses to prevailing winds are, however, not clear. The adjustment process is emphasized here, and some of our surveys in TS during the past several summers are reported. The purpose of this paper is to explore the general behavior of a stratified current entering the rugged TS during a calm wind condition. Some of the above-mentioned ambiguities, e.g. the persistency, possible paths and volume transport of the cold inflow in TS are expected to be cleared up by the data acquired during field surveys. The methodology is briefly discussed in section 2.

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The characteristics of transect profiles and plane contours of hydrographic parameters are described in section 3. The ADCP measurements are reported in section 4. The topographic effect induced by a submarine ridge in TS on the incoming stratified current is addressed in section 5. Conclusions are presented, after the discussion of some relevant topics for future studies, in section 6.

## 2. Data and methodology

Field data of both CTD and ADCP, which were acquired from several summer cruises of the R/V Ocean Researcher I (ORI) during 1988 and 1989 (Table 1), were used for exploring the behavior of bottom waters in TS. An NBIS CTD with 32 Hz sampling rate was used on each station for monitoring the vertical profiles of temperature (T) and salinity (S) in real time. The CTD group was requested during each cast to descend the CTD underwater unit as close (within 2 m) to the seabed as possible. This was done since the property of the bottom water is of central importance to later analysis. In addition to the CTD casts, a shipborne RDI 150 kHz ADCP was used in each cruise (except ORI 161) for detecting the velocity of water flowing underneath the keel of the ship during the voyage. The ADCP was set in the bottom tracking mode with 4 m bin length and a 5 minutes sampling interval.

Table 1. Period and measurement items of ORI cruises used.

| Cruise | Period | Items |
|---|---|---|
| 161 | 1988/ 6/ 7—6/10 | CTD only |
| 169 | 1988/ 7/27—7/30 | CTD and ADCP |
| 177 | 1988/ 9/ 1—9/ 6 | CTD and ADCP |
| 214 | 1989/ 6/13—6/16 | CTD and ADCP |

The kinematic bottom boundary condition for inviscid flows over a solid bottom, i.e. the free-slip condition, implies that the bottom surface is a three dimensional stream surface (YIH, 1979). Any isothermal, isohaline or isopycnal surfaces may be inferred here also to similarly be three dimensional stream surfaces according

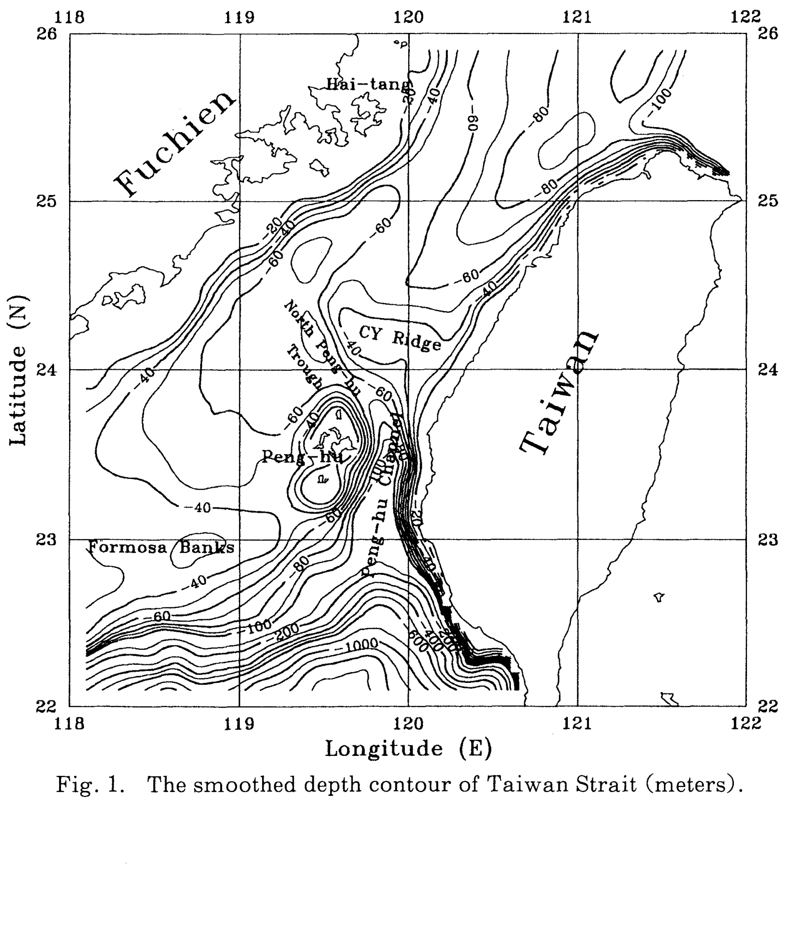


Fig. 1. The smoothed depth contour of Taiwan Strait (meters).

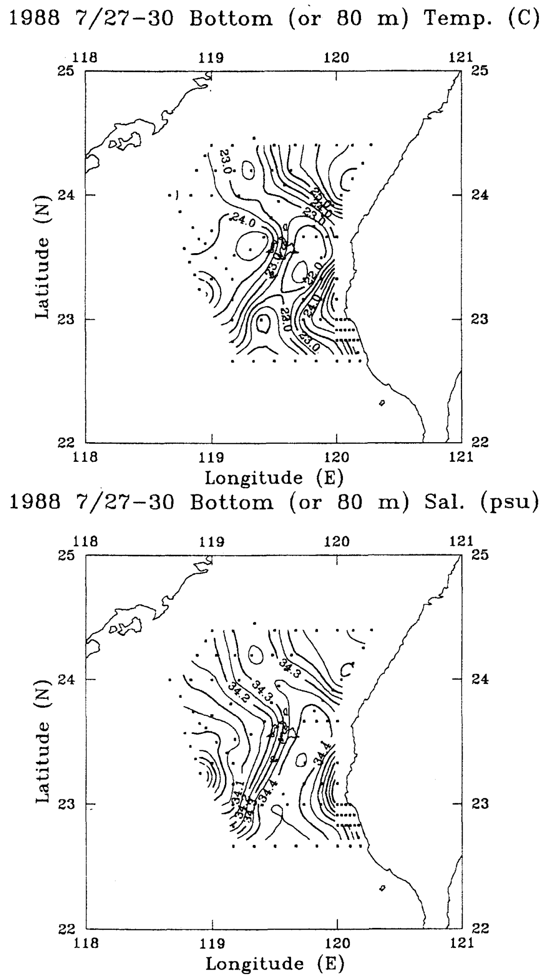


Fig. 2. Contours of T (℃, upper panel) and S (psu, lower panel) at 80 m depth or just above the bottom of TS during ORI 169, 1988 7/27–7/30.

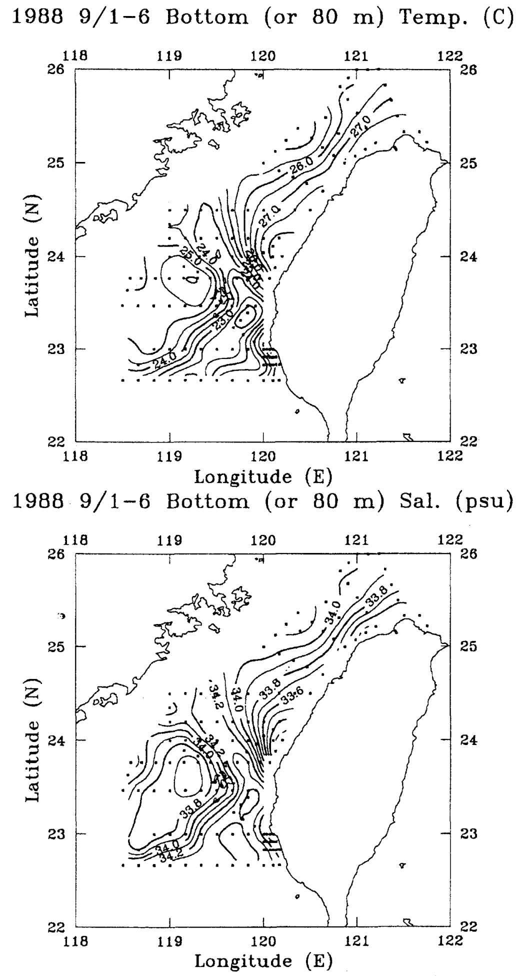


Fig. 3. Contours of T (℃, upper panel) and S (psu, lower panel) 80 m depth or just above the bottom of TS during ORI 177, 1988 9/1–9/6.

to the conservation of heat, salt and mass, if mixing is negligible and the flow is steady. The intersection of any two of these surfaces marks a streamline. This idea could be extended to a number of real situations. For example, isotherms (or isohalines and isopycnals) on the bottom surface may signify streamlines, if vertical profiles of either T or S are vertically uniform near the bottom and lateral mixing is negligible. The path and lateral boundary of cold flows on the bottom could be easily defined according to this argument. A core region composed by cold and saline waters could be determined here for each hydrographic section once the path and lateral boundary had been marked. Volume transport within the core would then be obtained from that determination and corresponding ADCP measurements.

## 3. Bottom topography and hydrographic patterns

An overview of the bottom topography of TS may be useful before addressing the hydrography. The submarine canyon (the Peng-hu Channel), that lays offshore of southwest Taiwan, is perhaps the most striking feature of the bottom topography of TS (Fig.1). The northwestward extension of the canyon is called the

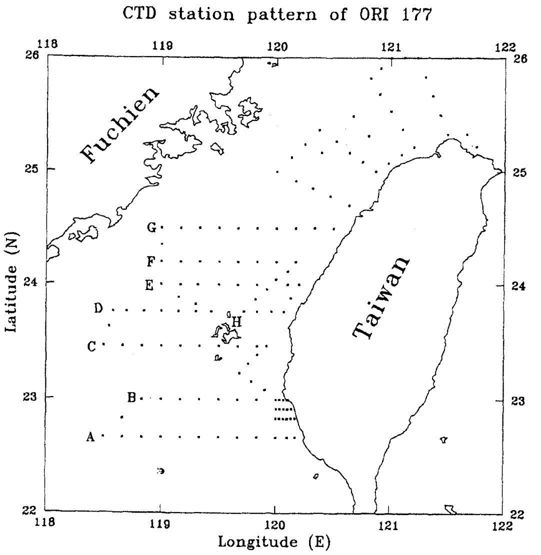


Fig. 4. The station pattern of CTD casts during ORI 177, 1988 9/1-9/6. Capital letters denote different sections. Sections A to G run from east to west. Only Section H runs from southwest to northeast.

North Peng-hu Trough hereafter. It joins the Peng-hu Channel northeast of Peng-hu Islands and is also a principal part of the submarine trough system in TS. Three highlands, in addition, exist in TS, i.e. Formosa Banks, Peng-hu Islands and a southeast-northwest oriented ridge at north of Peng-hu (the Chang-Yuen sand ridge or CY ridge; WANG and CHERN, 1989). The CY ridge and its extension divide the southwest and the northeast TS roughly into two basins (the south basin and the north basin for later reference). All of these features are likely to influence the flow pattern and the hydrography of TS as well.

The spatial distribution of passive parameters, e.g. T and S, could be used, under certain conditions, to signify the pattern of bottom flows (Section 2). Figs. 2 and 3 are two typical examples. The depth of 80 m is selected arbitrarily to be an upper limit since the majority portion of TS is shallower than 80 m (Fig. 1). Data used for the drawings of Figs. 2 and 3 are either at 80m depth or just above the bottom if the water depth is less than 80m.

A cold and saline water tongue appearing at north of Peng-hu is striking and common to all

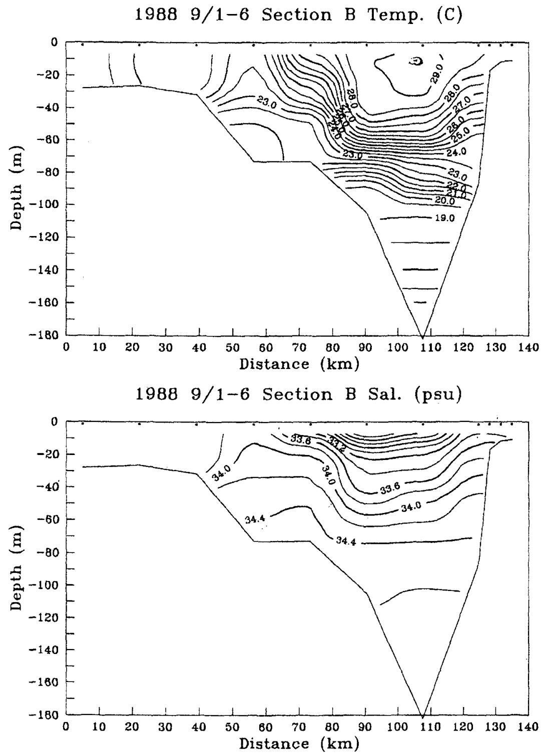


Fig. 5. Vertical transects of T (℃, upper panel) and S (psu, lower panel) along Section B of ORI 177.

summer cruises of Table 1. Cold and saline waters that compose the tongue stem from the east of Formosa Banks and extend into the Peng-hu Channel. They turn northwestward after passing Peng-hu and form a protruded tongue-like pattern (Figs.2 and 3). Two relatively warmer but less saline regions exist on both sides of the tongue. One is located at the north basin. The other occupies a significant portion of the south basin and Formosa banks (Fig.3). Lateral rims of cold waters are, interestingly, almost parallel to local isobaths of 70 m on the left or 60 m on the right. Topographicall steering is the primary mechanism leading to the observed apparent trajectory of cold waters. Bottom streamlines on the south slope of the CY ridge are, moreover, directed to the northwest in a divergent manner. They, however, turn clockwise and converge to the northeast after passing the ridge (Figs. 2 and 3). The anticyclonic turning and convergence of streamlines can be qualitatively attributed to the cross-isobath movement due to

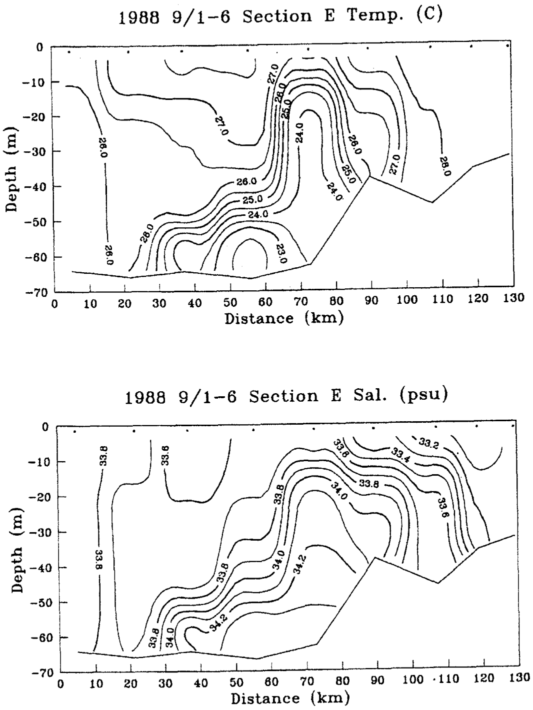


Fig. 6. Vertical transects of T (℃, upper panel) and S (psu, lower panel) along Section E of ORI 177.

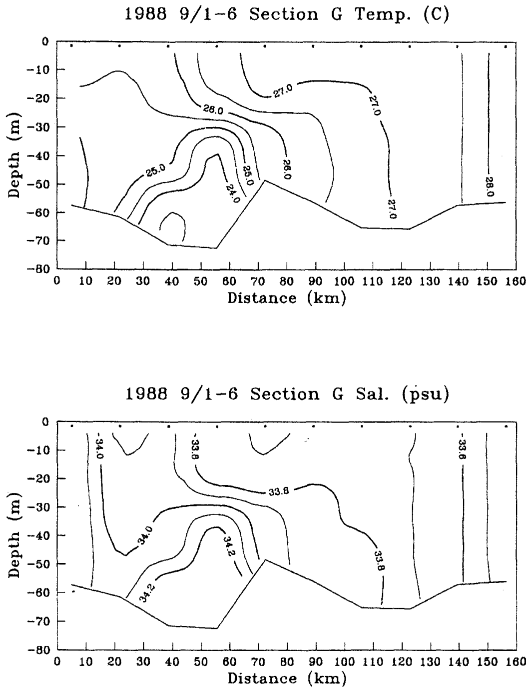


Fig. 7. Vertical transects of T (℃, upper panel) and S (psu, lower panel) along Section G of ORI 177.

waters flowing over the ridge. This flow pattern is dictated by the conservation of potential vorticity (NOF, 1979). The other warm region west of Peng-hu and north of Formosa Banks is also an interesting place. It unfortunately lies largely beyond the survey areas and must be the focus of future study.

The basic configuration of the tongue-like pattern is likely permanent from the spring through the summer to the autumn. This is reasonable since the basic aspects of the tongue-like pattern found in June, July and early September (as well as other two cruises in May of both 1988 and 1989 which are not included in Table 1) were approximately the same, but different from other winter cruises (WANG and CHERN, 1989). Therefore, a quasi-steady state assumption is acceptable. The cruise ORI 177 has been selected here for illustrating the details of the tongue. Several transects of T and S of ORI 177 shown in Fig. 4 are presented in Figs. 5–7. The water column is basically well-stratified in the Penghu Channel. It becomes, however, weakly stratified or uniform toward the west (Section B, Fig. 5). A different pattern is apparent at sections north of the CY ridge, where the water column is nearly uniform along the east bank, but more stratified toward the left bank of TS (Section G, Fig. 7). The action of near-bottom turbulence is not likely to be negligible there, considering the shallowness of the south basin and the vigorousness of tidal currents. An equilibrium between advective and detrainment processes is implied by the existence of a permanent tongue structure. The tongue-like pattern can not be maintained in the North Peng-hu Trough, unless a continuous supply of cold and saline waters exist in order to compensate the detrainment loss due to mixing. The existence of an undercurrent is implied by this.

## 4. ADCP measurements

Vertical sections of ADCP measurements during ORI 177 are presented in Figs. 8–10 for illustrating the spatial structure of the current field in TS. Corresponding hydrographic contours are

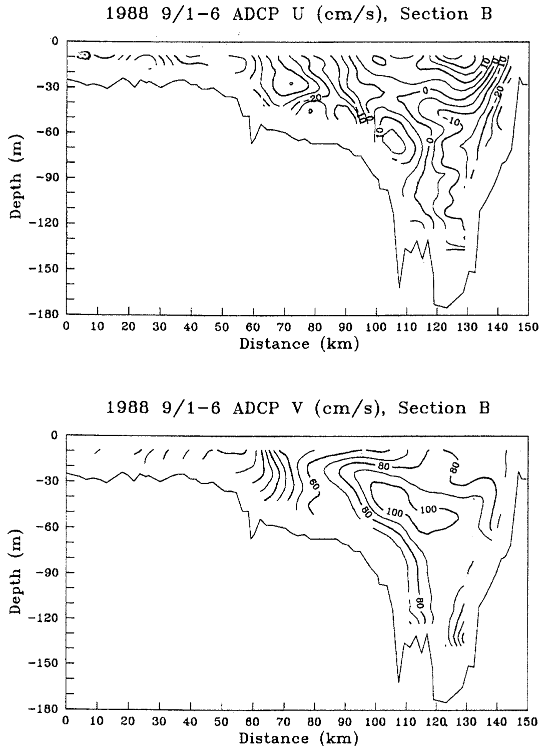


Fig. 8. Vertical transects of the eastward velocity component, U (cm $s^{-1}$, upper panel), and the northward velocity component, V (cm $s^{-1}$, lower panel), of ADCP measurements along Section B of ORI 177.

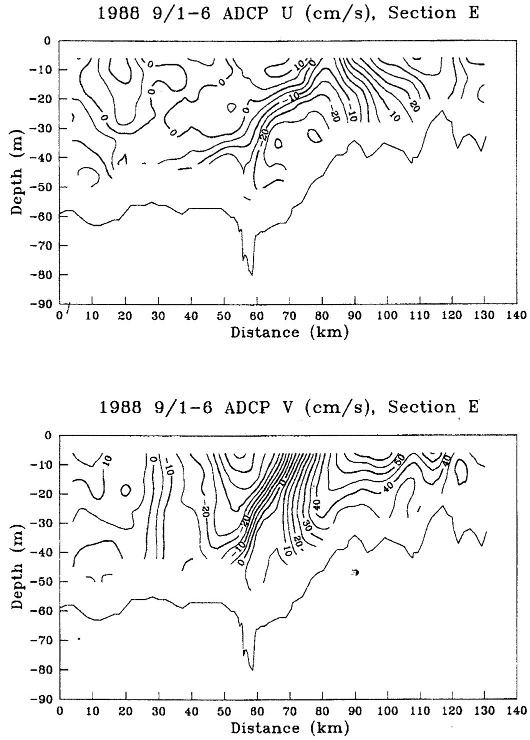


Fig. 9. Vertical transects of U (cm $s^{-1}$, upper panel) and V (cm $s^{-1}$, lower panel) of ADCP measurements along Section E of ORI 177.

shown in Figs. 5–7. Tidal currents are not feeble within the survey area. Aliasing induced by tidal variation is therefore embedded within these measurements. An apparent current, with a strength of the order of 80–120 cm $s^{-1}$, is shown by ADCP surveys (Figs. 5–7). It is along the eastern edge of the plateau which is composed by Formosa Banks and Peng-hu Islands. The current flows through Peng-hu Channel toward the CY ridge in the upper layer. The direction of the current changes from ENE (Section A) to NNE (Sections B and C), then to NNW (Section H) in front of the CY ridge. The current veers on and after passing the ridge from NE (Section E) to ENE (Section F). Its strength is significantly reduced. The axis of the stream, on the other hand, shifts more toward Peng-hu Island as it approaches the end of Peng-hu Channel. The uphill slope of the CY ridge is encountered by the flow there. A cyclonic turning with positive vorticity is then presented in Sections A to C. An anticyclonic veering associated with negative vorticity, however, successively occurs in Sections H, E and F. An undercurrent is, additionally, found in the lower layer to be flowing northwestward along the North Peng-hu Trough (Sections E and F; the former is shown in Fig. 9). The undercurrent veers to the northeast at a further downstream section to coincide with the orientation of local isobath (Section G, Fig. 10). In comparison with corresponding hydrographic patterns, a close correlation between the undercurrent and the cold water core is found; e.g. the zero contour of the eastward velocity component along Section E (Fig. 9, upper panel) roughly agrees with the isoline of either 26.5℃ or 33.7 psu (Fig. 6). Similar features are observed in other sections.

Tidal currents are significant in TS; the amplitude of the lunar principal, $M_2$ constituent, is approximately 70 cm $s^{-1}$ in the Peng-hu Channel (CHUANG, 1985). Tidal currents cause aliasing

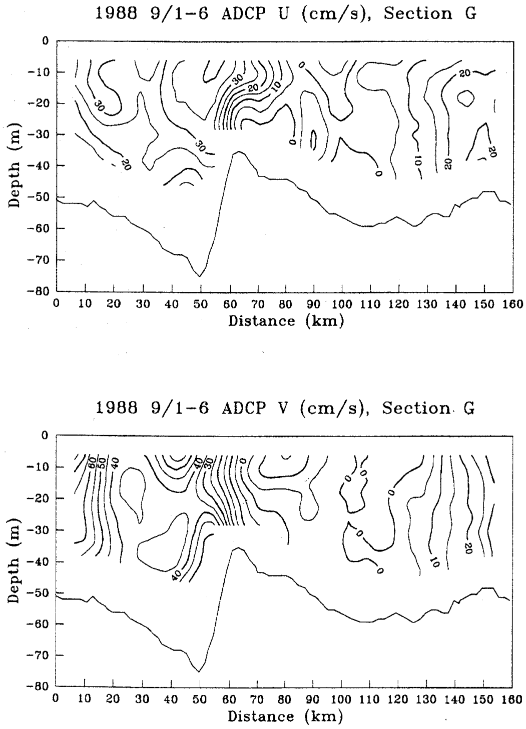

Fig. 10. Vertical transects of U ($cms^{-1}$, upper panel) and V ($cm\ s^{-1}$, lower panel) of ADCP measurements along Section G of ORI 177.

in ADCP measurements since they fluctuate periodically. Removing tidal influences from ADCP data is feasible if a precise tidal current prediction is provided. Another method is to take average over profiles from repeaed observations.

The procedure for the estimation of volume transport is straightforward. A common isoline of either T or S is first selected here from transect diagram of T or S as the bounding surface for defining the core of the cold water along the stream. The surface of 34.1 psu (and therefore 25.0℃) is chosen from hydrographic sections of ORI 177 to be the bounding surface. The velocity component normal to the section is next calculated from ADCP measurements. Extrapolation is carried out to fill in the blanked layers above the bottom. The volume transport is then estimated after integrating the normal velocity over the core area. The estimations are respectively 0.1, 0.4, 0.5 and 0.2 Sv for sections from E to H. A mean value of approximately 0.3 Sv is obtained for ORI 177. The validity of this procedure depends on the streamwise length scales for both the cold current and the tidal current, which must be much larger than the extent of the survey area. The values obtained remain tentative estimations because of poor knowledge of the length scales.

Table 2. The estimated volume transport of the cold current

| Cruise No. | Transport (Sv) | Note |
|---|---|---|
| 169 | 0.2 | Average of 4 sections |
| 177 | 0.3 | Average of 4 sections |
| 214 | 0.2 | Average of 3 sections |

Similar calculations for other cruises, but based on different criteria of T and S, have been made. Results are presented in Table 2.

Obtaining the exact quantity of volume transport is not an easy task. The validity of the foregoing estimations, however, could be judged indirectly by cross-checking with other observations such as measurements of moored current meters. The mean velocity of the near-bottom current at the north end of Peng-hu Channel was reported to be approximately 32 cm $s^{-1}$ during the 1984 summer (CHUANG, 1986). The value 30 m × 40 km is perhaps not an unreasonable estimation for the cross-sectional area of the undercurrent. By supposing the core pattern and the seasonal mean current remain roughly the same in different summers, a transport of 0.4 Sv is then obtained. This value is consistent with those shown in Table 2. The estimates obtained above seems to be robust, and the transport of the cold current in the summer is believed to be of the order of 0.2 to 0.3 Sv.

## 5. Topographic effect

The formation of a permanent undercurrent in TS could be interpreted in terms of flow-topography interactions. The phenomenon may be considered here from two points of view. For a rotational, steady and inviscid stratified flow under Boussinesq approximation, a quantity of

$$\frac{p}{\rho_0}+\frac{1}{2}u^2+g'z$$

is constant along a streamline, where $p$ represents the departure from hydrostatic pressure; $\rho_0$ is the reference density at the free surface $z=0$; $u$ is the water speed; and $g'$ is the reduced gravity (PHILLIPS, 1977). The width of the CY ridge is approximately 40 km (Fig.1), and we estimate $g' = 10^{-2}$ m $s^{-2}$ and layer thickness of both surface and bottom waters to be 50 m from typical density profiles in Peng-hu Channel. These give the baroclinic Rossby deformation radius for the flow to be 10 km, much less than the scale of the CY ridge. The bottom flow in the vicinity of the CY ridge is then likely to be quasi-geostrophic.

Both isobars and isopycnals are equivalent to streamlines for a geostrophic flow. The latter then has to precisely follow the depth contour. The variation of pressure along a streamline is likely to be negligible if the flow is quasi-geostrophic, as compared to a variation of other terms in the Bernoulli invariant. Cross-isobath motions along a streamline basically involve the conversion of kinetic energy to potential energy. The criterion for quasi-geostrophic bottom currents which can not overpass the CY ridge is then likely to be

$$\frac{1}{2} V_0^2 < g' \Delta z,$$

where $V_0$ denotes the velocity of bottom flows at the entrance of the channel; $\Delta z$ is the elevation difference between the top of the ridge and the base plane. Substituting g', $V_0 = 32$ cm $s^{-1}$ (CHUANG, 1986) and $\Delta z$ (about 40 m (Fig.1)) into the inequality, the bottom flow in Peng-hu Channel is considered not energetic enough to surmount the CY ridge; flow separation has to occur. The most suitable destination for the subsurface heavy water can be expected from the bottom topography (Fig. 1) to be the North Peng-hu Trough, which provides an optimum path to the cold inflow. The process of topographical steering dictates that separated subsurface waters flow northwestward along the trough and form a cold and saline tongue there. The deflection of bottom current exports cold and saline waters from the Peng-hu Channel toward Fuchien coast. This deflection initiates the laterally asymmetric density distribution found in downstream sections at the northern TS.

Light fluids aloft can easily overpass the CY ridge. This is in contrast to the underlying subsurface heavy waters in the Peng-hu Channel. When the surface layer water escapes from the channel and encounters the CY ridge, the water column expands laterally due to the widening of the water body and is compressed vertically due to the reduction of water depth. Both effects cause the current system to enter into a state of adjustment. Surface waters are assumed, for simplicity sake, to be homogeneous and the incoming current is assumed uniform, geostrophic and hydrostatic at the entrance of Peng-hu Channel. The situation is then geometrically and dynamically analogous to that studied by NOF (1978). A critical Rossby number $Ro_C$ considered by NOF is of central importance to the adjusting flow pattern. A subcritical flow associated with an anticyclonic turning of streamlines appears on the ridge if the flow Rossby number $Ro > Ro_C$ (NOF, 1978, Fig. 3b). A supercritical flow emerges if $Ro < Ro_C$. Flow separation occurs, in this case, at the right wing of the current facing downstream (NOF, 1978, Fig. 4b).

The flow widens by a factor of about 2, from the CY ridge to Peng-hu Channel (Fig. 1). The initial thickness and the later reduction of thickness for the surface water are respectively 60 m and 20 m if the isothermal surface 26.0℃ is arbitrarily selected as the lower boundary of the upper layer. $Ro_C = O(0.4)$ is then achieved according to NOF's (1978) formula. A critical inflow velocity $V_{0C} = 48$ cm $s^{-1}$ is obtained with the width of Peng-hu Channel assumed to be 20 km. The velocity of upper layer currents during summertime in Peng-hu Channel usually exceeds this value (Fig. 8). No lateral separation then occurs on the CY ridge. The situation may signifieantly change in other seasons due to the weakening of northward flows. Flow separation is apparently unavoidable in winter. It may cause a southward flow region to the east of the CY ridge (WANG and CHERN, 1989).

## 6. Discussion and concluding remarks

A quasi-permanent, cold and saline undercurrent is found from previous CTD and ADCP measurements; it flows steadily along the North Peng-hu Trough then enters the western TS during summertime. The existence of this undercurrent appears to answer a number of questions on the source and path of cold waters in TS. This, however, is still insufficient for interpreting the appearance of cold waters at northwest of Formosa Banks (LI and LI, 1989). The problem could be solved in terms of a study of WHITEHEAD (1985).

The coast of Fuchien is assumed, for simplicity sake, to be vertical and the bottom of the south basin is flat. The situation is dynamically similar to that analyzed by WHITEHEAD (1985), if the undercurrent is uniform both horizontally and vertically at the entrance of North Peng-hu Trough and the upper layer is motionless under a rigid-lid approximation. More than 85 % of the total volume transport will turn to the right, and the remainder 15 % to the left. This occurs due to the angle between the axis of the cold stream and the coastline of Fuchien being approximately 30°. The remaining 15 % may be theoretically expected to export cold and saline waters to the offshore of south Fuchien. What has actually occurred has yet to be determined and perhaps be the focus of future study.

The general behavior of currents in TS has been studied, based on CTD and ADCP surveys in TS during previous summers. The stratified incoming current in the Peng-hu Channel is found separating vertically in front of the CY ridge. Waters in the upper layer overrun the ridge. Subsurface heavy waters, however, turn to the northwest and form a permanent cold and saline water tongue protruding toward Fuchien coast during summertime. The volume transport of the cold current is estimated to be 0.2–0.3 Sv from ADCP measurements.

## Acknowledgments

This work was sponsored by the National Science Council, the Republic of China, Grant No. NSC90-0209-M002A-19.

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