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A Mid-Depth Front Separating the South China Sea Water and the Philippine Sea Water

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In order to understand the influence of the South China Sea (SCS) water on the Kuroshio, and to study the dissolved carbonate system, we participated in six WOCE cruises aboard R/V Ocean Researcher 1. The areas studied were the northeast South China Sea and the West Philippine Sea near the Luzon Strait. Temperature, salinity, pH, alkalinity and total CO_2 were measured. Our data indicate that, although the Kuroshio and the SCS waters flow in and out of the Luzon Strait near surface, the SCS water seems mainly to flow out of the SCS at mid-depth. There exists a "mid-depth front" near 122°E between 350 and 1350 m in all seasons and years that we studied. The water mass between 350 and 1350 m east of the front belongs to the West Philippine Sea proper water, while on the west is the mixed water of the South China Sea and the West Philippine Sea.

1. Introduction

The Kuroshio (Black Stream) is the most important western boundary current in the North Pacific Ocean and the study of its water characteristics is important for various aspects of oceanography. With higher salinity and temperature notwithstanding, the Kuroshio is not a stream with solid boundaries. Consequently, the characteristics of the Kuroshio water are not drastically different from that of the West Philippine Sea (WPS).

The South China Sea (SCS) waters below 2500 m are quite homogeneous and have the same property as the WPS water at 2500 m. The SCS waters above 2500 m, however, are quite different from that in the WPS because the former has intensive upwelling, large river input and short residence time (Wyrtki, 1961; Han *et al.*, 1980; SOA 1988a, b; Han and Lin, 1992; Gong *et al.*, 1993; Chen and Huang, 1995). The Luzon Strait with the deepest sill at 2500 m form a connection between the WPS and the SCS (Liu and Lin, 1988). Similar to the loop current between the straits of Yucatan and the straits of Florida in the Gulf of Mexico, the Kuroshio has been known to enter the Luzon Strait (Chu, 1972; Nitani, 1972; Fan and Yu, 1981; Fan, 1982, 1984; Wang and Chern, 1987a, b). Shaw (1989, 1991) reported the intrusion of Kuroshio water into the sea southwest of Taiwan in late summer. The intrusion is intensified in winter and ceases by late spring when SCS waters again enter this region.

The SCS water has also been reported to flow out from the Luzon Strait and enters into the WPS (Wyrtki, 1961; Chu, 1972; Nitani, 1972; Wu, 1991; Gong *et al.*, 1993). The outflowing SCS water is unlikely to flow eastward to a great distance as it would be blocked by the northward flowing Kuroshio. Unlike the previous studies that look mainly at the surface waters, this study concentrates on the intermediate water. We will investigate whether the outflowing SCS water can be traced and how far eastward the outflowing SCS water gets to.

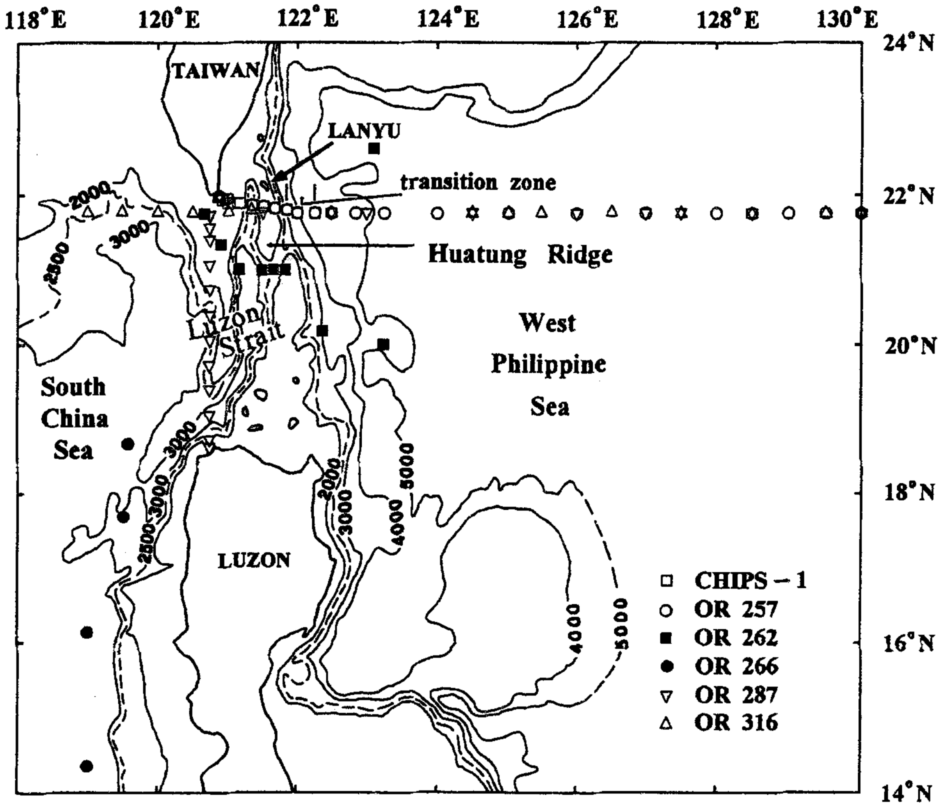

Fig. 1. Study area and station locations.

Table 1. Position and dates of the cruises.

No.	Cruise	Dates	Area
1	CHIPS-1	May 22–June 1, 1985	WPS
2	OR 257	Oct. 11–18, 1990	PR 20
3	OR 262	Nov. 17–22, 1990	WPS
4	OR 266	Dec. 16–30, 1990	PR21, SCS
5	OR 287	June 23–July 11, 1991	PR 20, PR21
6	OR 316	May 7–16, 1992	PR 20

WPS: West Philippine Sea.
SCS: South China Sea.
PR 20: WOCE Pacific Repeated Line 20.
PR 21: WOCE Pacific Repeated Line 21.

2. Study Area

We participated in 6 cruises of R/V Ocean Researcher 1 for WOCE PR 20 (World Ocean Circulation Experiment Pacific Repeated Line 20) and PR 21. PR 20 is across roughly 21°45′ N between the southern tip of Taiwan and 130°E; PR 21 is across roughly 120°43′ E from the southern tip of Taiwan to the Northern tip of Luzon (Fig. 1). The CHIPS-1 cruise was between May 22 and June 1, 1985 (Liu *et al.*, 1987). The 257th cruise (OR 257) was a part of the PR 20. It occurred between 11 and 18 Oct., 1990.

OR 262 was a WOCE test cruise between 17 and 22 Nov., 1990. OR 266 occurred between 16 and 30 Dec., 1990, as a part of PR 21, but occupied a few stations west of Luzon. OR 287 occupied PR 20 and PR 21 between 23 June and 11 July, 1991. OR 316 occupied PR 20 (119°N to 130°N) between 7 and 16 May, 1992, but extended a little west of Taiwan (Table 1). The station locations mentioned in this report are given in Fig. 1. Details of the cruises are given in Liu *et al.* (1987, 1991) and Chen *et al.* (1993a, b, c).

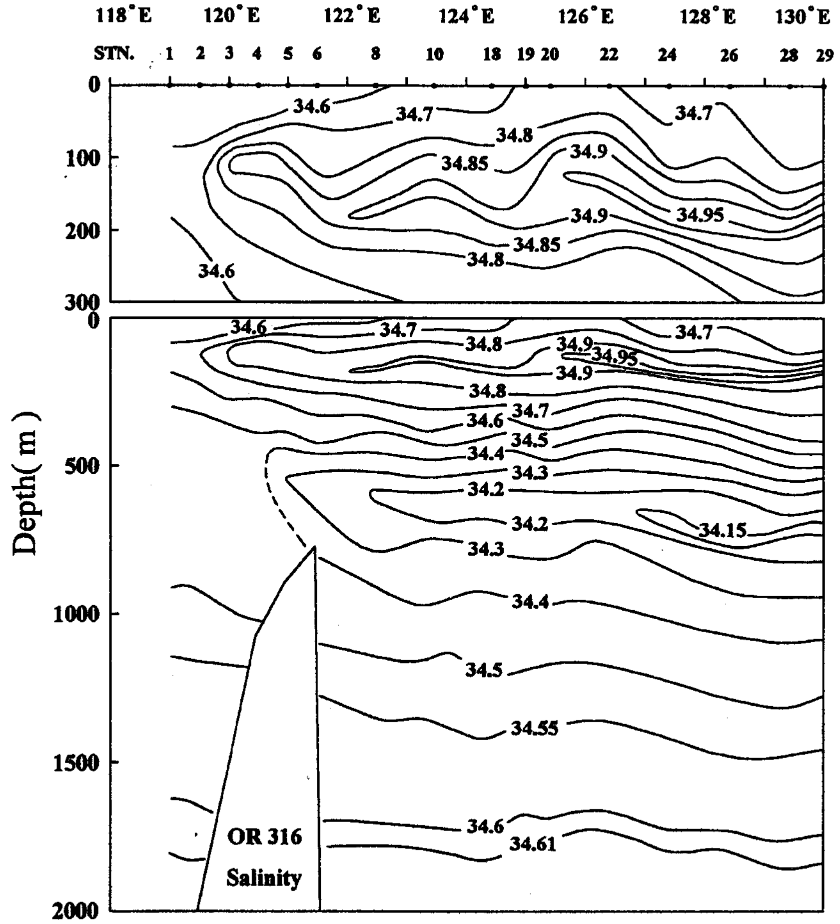

Fig. 2. The salinity cross-section based on the OR 316 data.

3. Experimental Method

Continuous temperature and salinity (conductivity) profiles and discrete water samples were obtained by a Seabird CTD-Rosette (SBE-11) assembly fitted with eleven 2.5-l Niskin bottles. Discrete salinity (S) samples were taken in order to check the accuracy of the CTD data. pH was measured at 25 ± 0.05°C by a Radiometer PHM-85 pH meter using a GK 2401C combination electrode. The US National Institute of Standards and Technology 4.006, 6.863 or 7.400 buffers were used for calibrating the electrode. The precision was better than ±0.003 pH unit (Huang, 1993).

The potentiometric alkalinity (TA) and total CO_2 (TCO_2) were measured by a PC-controlled automatic titration system composed of a Radiometer PHM-84 pH meter, a GK 2401C combination electrode, an ABU 80 autoburet, a titration cell and a temperature-controlled water bath set at 25 ± 0.05°C. The end points were determined by the Gran Function with a precision of 3 μmol/kg for TA and 6 μmol/kg for TCO_2, respectively (Bradshaw *et al.*, 1981; Chen *et al.*, 1993a, b, c). The coulometric method was also used to measure TCO_2 on the OR 316 with a precision of 2 μmol/kg (Chen *et al.*, 1993c). The potentiometric TCO_2 data are used in this paper.

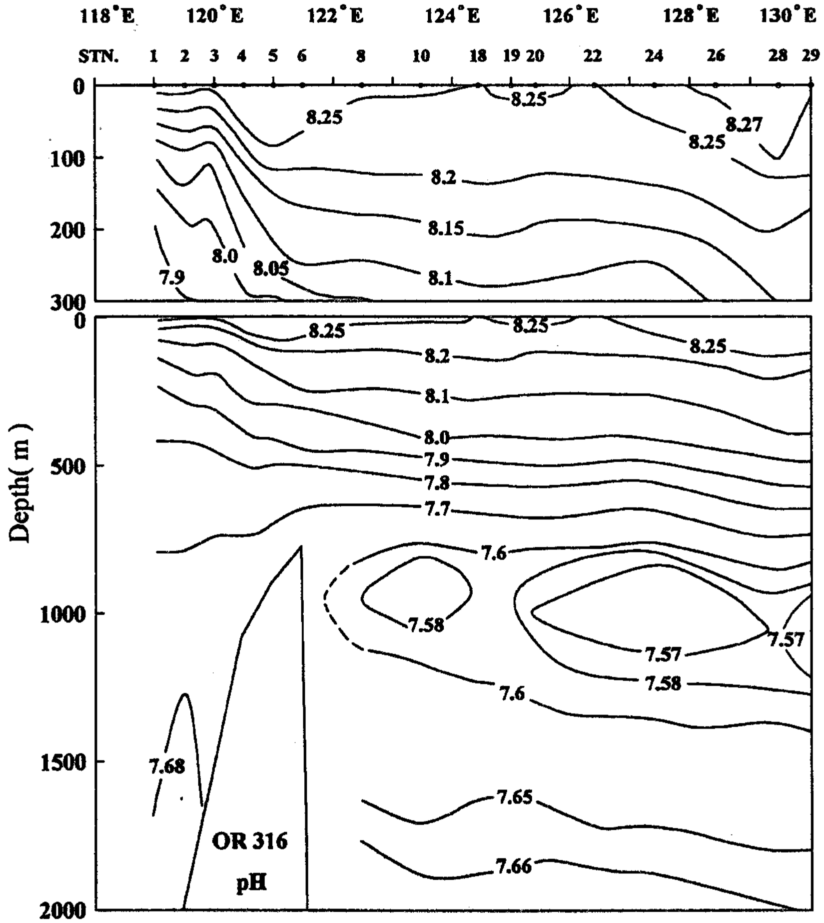

Fig. 3. The pH cross-section based on the OR 316 data.

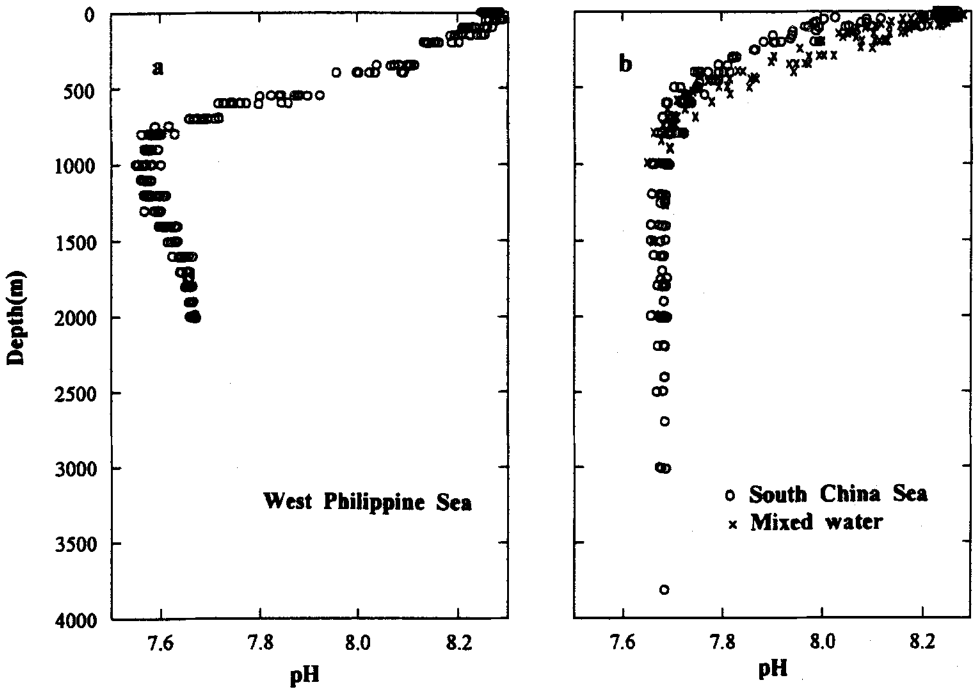

Fig. 4. The pH vertical profiles based on the OR 266, 287 and 316 data. Mixed water: Waters located between 120°43′ E and 121°50′ E.

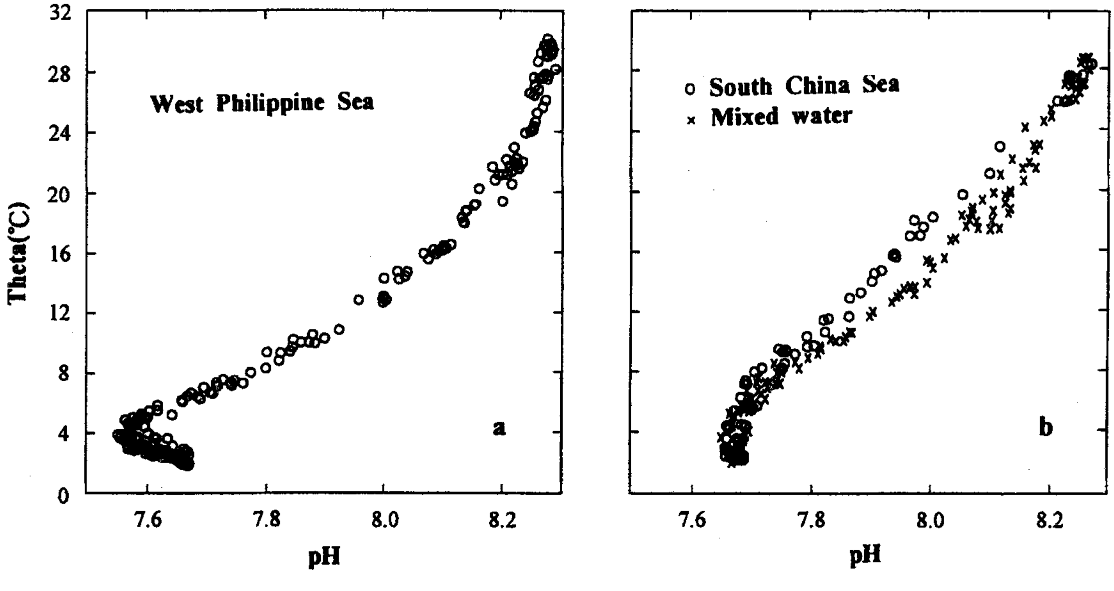

Fig. 5. The θ/pH diagrams based on the OR 266, 287 and 316 data. Mixed water: Waters located between 120°43′ E and 121°50′ E.

4. Results and Discussion

A typical salinity cross-section for PR 20 (OR 316) is shown in Fig. 2. There is a shallow salinity maximum centered at approximately 200 m at 130°E, shoaling toward west to roughly 100 m at 120°E. A minimum salinity core (the North Pacific Intermediate Water, NPIW) extends to a lesser degree across the Luzon Strait into the SCS. Intensive upwelling and vertical mixing tend to reduce the extreme signals in the SCS.

Figure 3 shows a typical pH cross-section for PR 20 (OR 316). The shallow pH contours tend to shoal towards west. The pH minimum east of the ridge (Huatung ridge, Huang *et al.*, 1992) is typical in the North Pacific Ocean (Chen *et al.*, 1986) but the signal disappears in the SCS. This is because the pH minimum core in the WPS, slightly deeper than NPIW, has received much end products of the organic carbon decomposition, thus increasing the acidity. On the other hand, the North Pacific Bottom Water (NPBW) and its deep return water (the Pacific Deep Water, PDW) have higher pH values at the source region and do not experience much organic carbon decomposition (Chen *et al.*, 1986). As a result, a pH minimum is formed at mid-depth in WPS. There is no NPBW in the SCS and the PDW influence is small. Intensive upwelling in the SCS further diminishes any remnant pH minimum from the WPS (Wyrtki, 1961).

Figure 4 shows typical pH vertical profiles in the WPS and SCS, respectively. The mid-depth pH minimum in the WPS stands out. Again the pH minimum in the WPS stand out in the θ/pH diagrams (Fig. 5) and in the plot of potential density vs pH (Fig. 6). On the other hand, a $NTCO_2$ ($NTCO_2 = TCO_2 \times 35/S$) maximum exists in the WPS but not in the SCS, as evidenced in the θ/$NTCO_2$ diagrams (not shown). Similar trend was also shown in the θ/AOU plot (Gong *et al.*, 1993).

It is now apparent that the SCS water in a way is distinguishable from the WPS water in the 300 to 1500 m range and a front may separate these two waters. Indeed when the θ/S diagrams

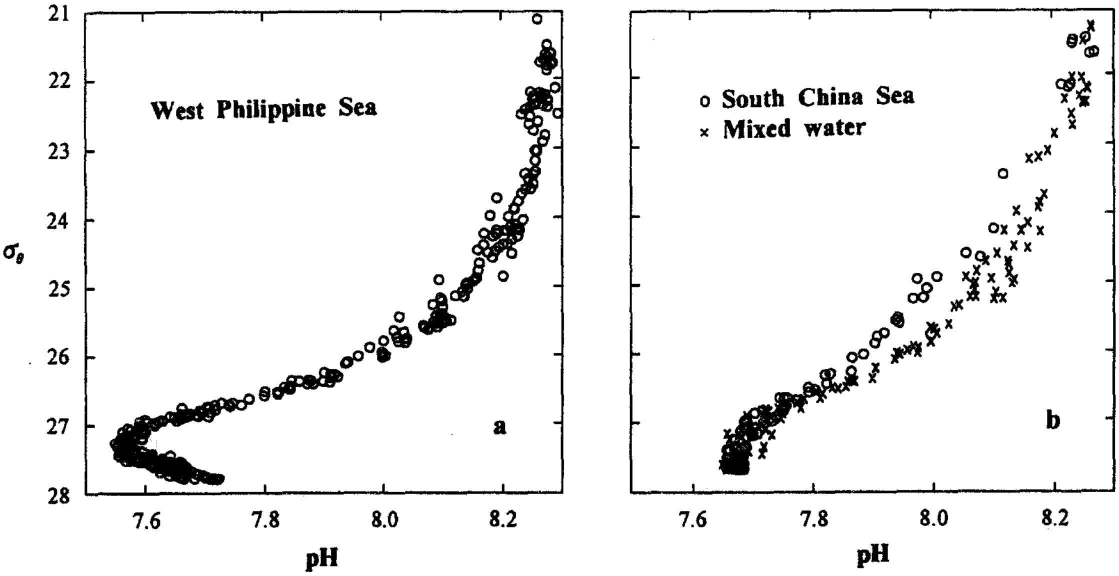

Fig. 6. Potential density vs. pH diagrams based on the OR 266, 287 and 316 data. Mixed water: Waters located between 120°43′ E and 121°50′ E.

are compared there exists a rapid transition in this depth range a little east off the southern tip of Taiwan.

In Fig. 7 we plotted selected θ/S diagrams based on the CHIPS-1 data. The typical SCS and WPS curves are marked as dashed lines based on OR 266 data in the northeast SCS and the WPS data near 130°E. The SCS water has lower salinity near surface than the near-surface salinity in the WPS. The salinity maximum and minimum are more distinctive in the WPS, i.e., the WPS has higher maximum salinity but lower minimum salinity. The water of S_{max} in the SCS has a potential temperature of about 16°C and a salinity of about 34.6 psu. The S_{max} water in WPS has higher potential temperature (21°C) and S (34.9 psu). The SCS S_{min} water has a potential temperature of about 8°C and a salinity of 34.45 psu. The WPS S_{min} water has lower potential temperature (7°C) and S (34.2 psu).

The θ/S curve at each station is shown as a solid line. The θ/S curves at STNs. 1–3 are similar to the SCS type. From STN. 4 on eastward, the near surface and the maximum salinity waters become closer to the WPS type. The water near the minimum salinity layer (350–1350 m)

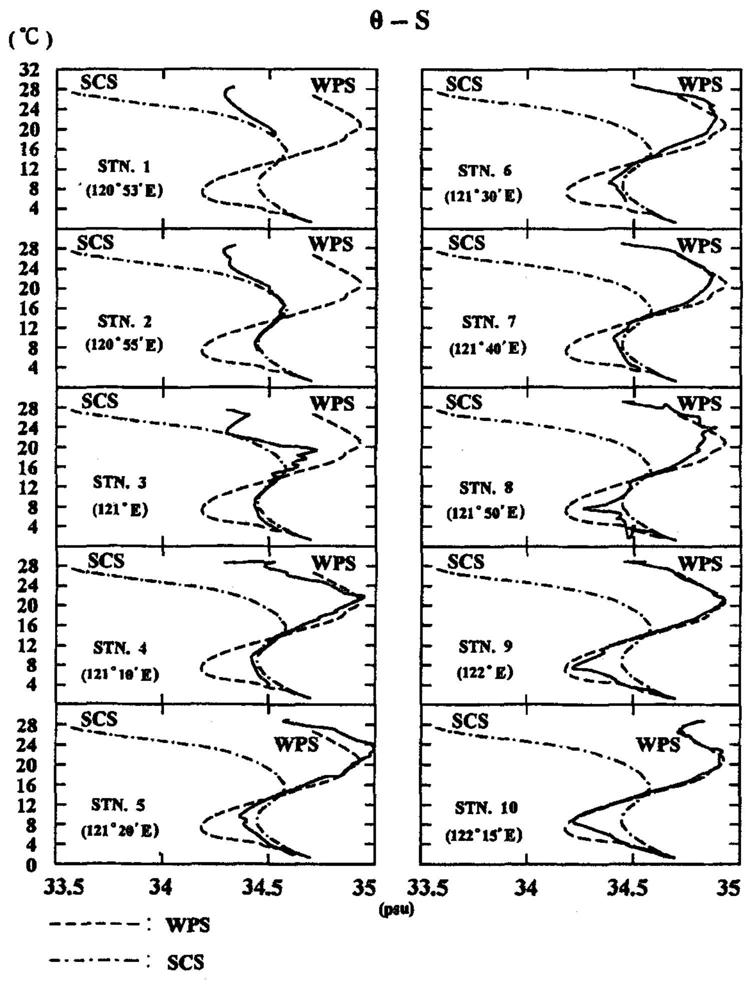

Fig. 7. The θ/S diagrams based on the CHIPS-1 data.

remains closer to the SCS type until reaching STN. 7. East of STN. 7 the S_{min} layer becomes the WPS type. The transition was near 121°50′ E on the continental slope east of the ridge (Huang, 1993). Data from other cruises also indicate that the transition occurred near 122°E. The pH and $NTCO_2$ data (Figs. 4–6) confirm the transition.

Few investigators have studied the intermediate water near the Luzon Strait. Wyrtki (1961) reported that the WPS intermediate water between 400 and 900 m enters the SCS in summer based on the sea level data. In winter the SCS intermediate water flows out of the SCS. This suggestion is inconsistent with our data as we clearly see the SCS intermediate water in our study area west of 122°E. This water has to be coming out of the SCS in all seasons.

Nitani (1972) reported that a fairly strong intermediate water (near the S_{min}) enters into the SCS along the northern coast of Luzon in the summer of 1965 based on geostrophic calculations. The intermediate water in the SCS flows out to WPS along the southern coast of Taiwan after complicated meandering in the Luzon Strait. Our data are consistent with this observation. Gong *et al.* (1993) also supported the notion that the outflow is mostly in the SCS intermediate water based on oxygen and nutrient data.

It should be pointed out that the Kuroshio transport is concentrated between 121° and 123°E at about 21°N, extending to 1000 m depth (Chen *et al.*, 1994). The outflowing SCS water seems to form the western part of Kuroshio at mid-depth. This explains why the western part of the Kuroshio east of Taiwan has a comparatively higher salinity at the S_{min} layer (Nitani, 1972).

5. Conclusion

A mid-depth front between 350 and 1350 m encompassing the S_{min} layer seems to exist near 122°E above the continental slope. East of it the water mass belongs to the WPS, on the west is mainly the SCS water. The outflowing water from the SCS is prevented by the Kuroshio from flowing further eastward. As a result, the SCS water joins the Kuroshio and forms the left-hand part of Kuroshio at intermediate depth.

Acknowledgements

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