

## The Chemical Hydrography of the South China Sea West of Luzon and a Comparison with the West Philippine Sea

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(Received: January 16, 1992; Revised: August 31, 1992)

### ABSTRACT

The Chemical hydrography of the South China Sea west of Luzon observed in December, 1990 is reported and compared with that observed in the West Philippine Sea in October, 1990. The purpose is to understand the difference between the SCS water and its precursor, and how such change could be attained. The existence of salinity maximum and minimum in the South China Sea and the resemblance between the deep waters of the two seas reflected the influence of water intrusion from the West Philippine Sea to the South China Sea. On the other hand, distinctions in the water properties above 1500 m were found between the two seas. The subsurface water (100-600 m) of the South China Sea west of Luzon was considerably colder than that of the West Philippine Sea, and more enriched in nutrients and depleted in oxygen relative to the water of the same temperature in the western Philippine Sea. The situation was reversed in the intermediate water (600-1500 m). The salient features of our observations were supported by historical data. The chemical distinction between the two seas could be used to distinguish water masses in the interfacial zone. The much colder and nutrient-richer subsurface water and the uniformity in water properties in the South China Sea may be attributed to vertical mixing as well as upward advection, which was possibly related to rather rapid turnover of the deep water.

### 1. INTRODUCTION

The South China Sea (SCS) is the largest body of water in the Asiatic Mediterranean Sea. Its central part is a deep basin exceeding 4000 m in depth. The Luzon Strait between Taiwan and Luzon is the only important channel for the exchange of its deep water with the western Philippine Sea (WPS) in the open Pacific Ocean (Sverdrup *et al.*, 1942). All the other channels connecting with the surrounding oceans are either shallow or narrow.

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Because of the high sedimentation rate, the SCS provides well-preserved high-resolution sedimentary records of the past marine environment, and, therefore, is an important site for paleoceanographic studies (Andree *et al.*, 1986; Wang and Chen, 1990; Ku *et al.*, 1991; K.J. Hsu, personal communication, 1991). In order to interpret the paleo-records accurately, the present marine conditions and the controlling processes, especially the water exchange between the SCS and the open Pacific, must be thoroughly investigated.

Distinctive temperature-salinity relationships were found in the WPS and the SCS (Ninomiya, 1972). Based on hydrographic observations near the entrance of the SCS, Wyrki (1961) asserted that all waters above the sill depth of the Luzon Strait enter the SCS. More detailed hydrographic analysis depicted water intrusion from the WPS into the northern South China Sea in selected layers of the upper water column (Fan and Yu, 1981; Shaw, 1989; 1991). Wyrki (1961) made a model calculation to show that the water exchange between the two seas is controlled by monsoon-induced circulation. Bottom water inflow at depths of 1900-2700 m has been directly measured by a current meter (Liu and Liu, 1988), and inferred from the hydrographic data (Wyrki, 1961; Broecker *et al.*, 1986).

This paper reports the hydrographic and chemical properties of seawaters observed during two expeditions in the WPS and the SCS west of Luzon in 1990. The purpose of the study is to examine the differences in hydrography and chemistry between the two seas, and to explore the possible processes that could bring about the changes of the SCS waters which are derived mostly from the WPS waters. The results showed that the chemical characteristics of the subsurface water and the intermediate water were distinctive in the two seas. Even the "thermocline water", which is rather uniform in T-S over a large area in the WPS and the SCS (Masuzawa, 1972), were distinctive chemically. Such chemical distinction is potentially useful as a tool for tracing the water exchange, especially in the layer between 100 and 600m.

## 2. MATERIALS AND METHODS

Water sampling and CTD measurements were undertaken at two groups of hydrographic stations on board the Ocean Researcher I for this study (Figure 1). One group of 20 stations in the WPS was sampled during October 11-18, 1990. The other group in the SCS, consisting of 7 stations, was occupied during December 16-30, 1990.

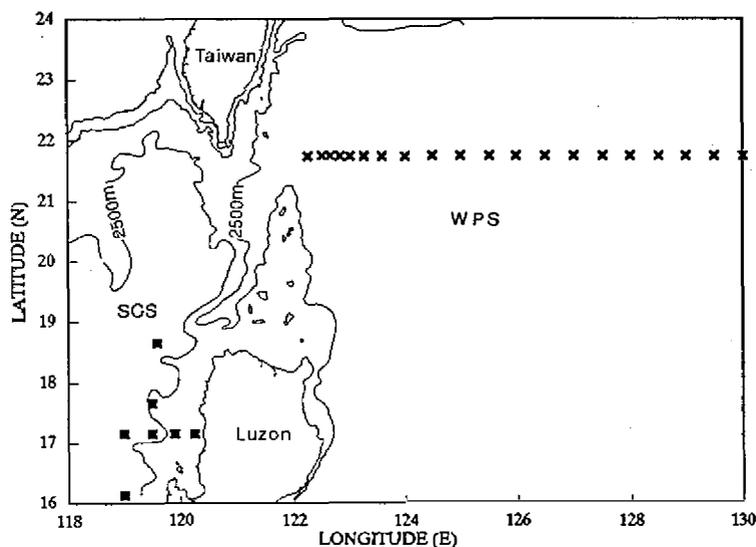


Fig. 1. Station locations. The zonal array of crosses in the WPS were stations occupied on October 11-18, 1990. The squares in the SCS were occupied on December 16-30, 1990.

The continuous temperature and salinity profiles and discrete water samples were obtained by a CTD-Rosette (Seabird Electronics Inc., Bellevue, WA, SBE-11) assembly fitted with eleven 2.5 liter Niskin bottles. Samples for analyses of dissolved oxygen and nutrients were collected from Niskin bottles of the Rosette assembly (General Oceanics Inc., Miami, FL, U.S.A.). Discrete salinity samples were also taken in order to check the accuracy of the salinity data from the CTD.

Dissolved oxygen and nutrient analyses were carried out on board. Oxygen was measured by the Winkler titration method (Carpenter, 1965). Nutrients were analyzed colorimetrically. Nitrate analysis was done with a self-made flow injection analyzer. A pair of micro-flow-cells (1 cm light path, 80  $\mu\text{L}$ ) were installed in a Shimadzu 160A double beam spectrophotometer. Sample and reagent flows were added at a proportion equivalent to 2.5:0.1:0.1:0.1 for sample, ammonium chloride, sulphanilamide and naphthyl-ethylenediamine, respectively (Strickland and Parsons, 1972; Pai *et al.*, 1990a). The salt gradient interference was reduced to less than 0.1  $\mu\text{M}$  using filtered surface water as carrier flow. The detection limit of 0.3  $\mu\text{M}$  was achieved. The precision of the on-board measurement was tested on a deep water sample, and the results of six replicates gave a mean concentration of  $36.5 \pm 0.3 \mu\text{M}$  (r.s.d.=0.9%). Phosphate was determined by the molybdenum blue method (Murphy and Riley, 1962; Pai *et al.*, 1990b). The salinity samples were analyzed with an Autosol salinometer (Model 8400A, Guildline Instr. Ltd., Ontario, Canada) against IAPSO standard seawater in a land-based laboratory immediately after the cruises. The possible salinity increase due to evaporation was estimated to be less than 0.005 psu (Fang *et al.*, 1990).

### 3. RESULTS

Although the WPS is the only important source of the open ocean water to the SCS, the hydrographic and the chemical properties of the SCS waters west of Luzon were quite different from those of the WPS. The profiles of potential temperature ( $\theta$ ),  $\sigma_\theta$ , salinity (S), dissolved oxygen, apparent oxygen utilization (AOU), nitrate ( $\text{NO}_3^-$ ) and phosphate ( $\text{PO}_4^{3-}$ ) are presented in Figures 2-4. In each figure, data of all SCS stations and an averaged profile of the WPS stations were plotted as a reference for the SCS stations. Averaging data of the WPS was for clarity. A comparison of profiles of the two seas illustrates the difference in vertical distribution of the hydrographic and chemical parameters. In addition to the depth profiles, property-property plots for all sampling stations of both seas were presented to indicate the variation of water characteristics.

#### 3.1 Hydrography

Figure 2 shows the profiles of  $\theta$ ,  $\sigma_\theta$ , and S. The surface temperatures of the SCS waters were comparable to those of the WPS, whereas the salinities of the surface water in the SCS were much lower than those of the WPS by up to 1 psu (Figure 2). The low surface salinity of the SCS is attributed to the basin-wide precipitation and river runoff from southeastern China and the Indochina Peninsula (Wyrski, 1961).

The profiles showed that the mixed layer of the SCS was quite thin. The thickness, varying from 15 to 30 m, was thinner than that observed in the WPS (60 m). The thinness of the mixed layer in the SCS was caused by the very low salinity in the surface layer, which was underlain by a sharp salinity increase. A moderate salinity maximum of about 34.60 psu existed around 50-150 m below the surface. The salinity maximum in the SCS was nearly at the same depth as that in the WPS, but the salinity value was lower by about 0.3 psu.

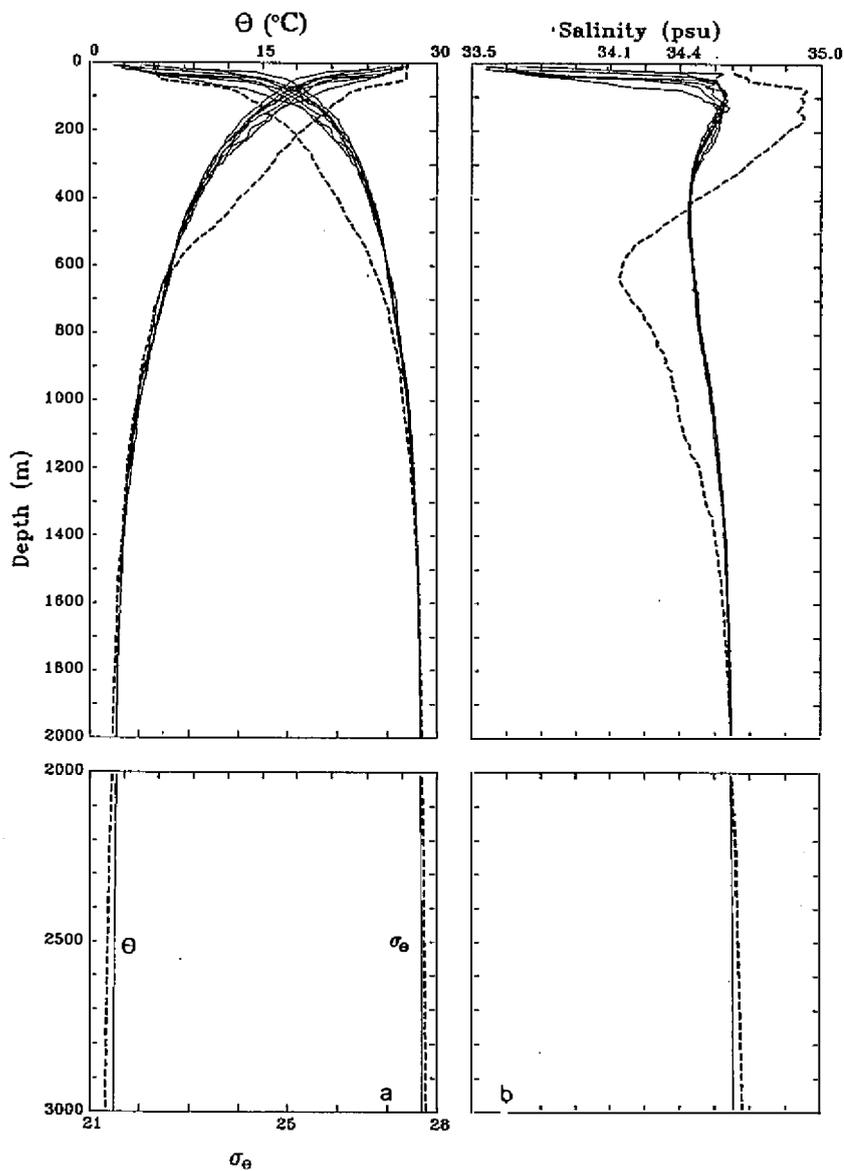


Fig. 2. Vertical profiles of (a) potential temperature,  $\theta$ , and  $\sigma_\theta$  (b) salinity. Solid curves represent the data of SCS stations. The dashed curve represents the averaged profile of all stations in the WPS.

In the subsurface layer, i.e., from the bottom of the mixed layer to 600 m, the temperature in the SCS was considerably lower than that of the WPS. The difference was almost as great as 5°C. Consequently, the isopycnals were lifted upward for about 200 m from the WPS to the SCS. The permanent thermocline in the SCS, centered at the temperature of 15°C, was

also shallower by about 200 m. Below the depth of 600 m, the temperature profiles from the two seas almost merged but the SCS water was slightly warmer than the WPS. The potential temperature gradient at a depth below 2000 m in the WPS ( $-0.6\text{ }^{\circ}\text{C}/\text{km}$ ) was about twice that in the SCS ( $-0.3\text{ }^{\circ}\text{C}/\text{km}$ ).

Below the surface layer, the salinity variation of the SCS was rather small relative to that of the WPS. There was only a 0.2 psu change (34.4–34.6 psu) for the SCS, as opposed to 0.95 psu (34.15–35.10 psu) for the WPS. The salinity profiles of the SCS showed a minimum at the depth of about 400 m which was 200 m shallower than that in the WPS. The minimum value (34.45 psu) was higher than that of the WPS by 0.3 psu. Unlike the potential temperature profiles, the salinity profiles of the two seas did not merge at depths below 600 m but did so below 1900 m. Below 2000 m, the salinity remained fairly constant in the SCS while it continued to increase in the WPS.

The very slight changes of potential temperature and salinity in the SCS below 2000 m were consistent with the notion that the sill depth of the Luzon Strait is about 1900 m (Broecker et al., 1986). The properties of the bottom water of the SCS were very similar to those of the water at the sill depth in the WPS, suggesting that the basin water originated from the WPS.

### 3.2 Chemical conditions

The oxygen profile of the SCS showed a remarkable drop from  $210\text{ }\mu\text{M}$  in the mixed layer to  $130\text{ }\mu\text{M}$  at the depth of 50 m, just below the seasonal thermocline (Figure 3). Below the surface layer, dissolved oxygen decreased more gradually to a broad minimum of about  $80\text{ }\mu\text{M}$  at depth about 600 m, and then increased with depth towards the bottom of the basin. Such vertical variation was entirely different from that of the WPS, where the oxygen profile showed only a small decrease in the top 500 m, a minimum of about  $70\text{ }\mu\text{M}$  at 1000 m, and a more pronounced increase towards the bottom below the minimum. In other words, the dissolved oxygen of the SCS water was lower than that of the WPS water at the same depth, except in the surface water and the intermediate water between 800 and 1400 m. Below the top 100 m, the magnitude of change in the SCS was only  $50\text{ }\mu\text{M}$ ; that was considerably smaller than that in the WPS ( $130\text{ M}$ ). The profile of AOU proved to be almost the mirror image of the oxygen profile, but there was no maximum in the AOU profile of SCS corresponding to the oxygen minimum. The lack of AOU maximum is worth discussion. AOU is defined as

$$AOU = [O_2]_{satd} - [O_2]_{obs}$$

where  $[O_2]_{satd}$  and  $[O_2]_{obs}$  represent the saturated and observed oxygen concentrations in seawater. The oxygen minimum of the SCS was considerably shallower than that of the WPS and had relatively high temperature. The temperature decreased by about  $4\text{ }^{\circ}\text{C}$  below the oxygen minimum. Because the increase of oxygen concentration with depth below the oxygen minimum was very modest, the increase of oxygen solubility with depth due to temperature decrease offset the oxygen increase and resulted in an almost constant AOU below 600 m.

As expected, the nutrient profiles (Figure 4) mimicked the AOU profile (Figure 3b). The surface mixed layer was almost devoid of nutrients in both the SCS and the WPS. Below the seasonal thermocline, nitrate concentration increased rapidly in both seas. A nitrate maximum (ca.  $42\text{ }\mu\text{M}$ ) existed at a water depth of around 1000 m in the WPS, corresponding to the minimum of the dissolved oxygen, but was not found in the SCS. Below the nitrate maximum, the nitrate concentration decreased slightly with depth to about  $37.5\text{ }\mu\text{M}$  at 3000 m in the WPS. These features were consistent with previous observations

in the WPS south of Okinawa Island (Scripps Institution of Oceanography, 1978; Yamamoto and Horikoshi, 1979).

Below the seasonal thermocline and above 600 m in the SCS, the nutrient concentrations were considerably higher than those in the WPS (Figure 4). The maximum differences in nutrient concentration between waters at the same depth of the two seas reached  $20 \mu\text{M}$  and  $1.2 \mu\text{M}$  for nitrate and phosphate, respectively. Unlike the nutrient profiles in the WPS, those in the SCS showed no maximum at 1000 m, but reached almost constant levels of  $38 \mu\text{M}$  for nitrate and  $2.7 \mu\text{M}$  for phosphate at depths greater than 1500 m.

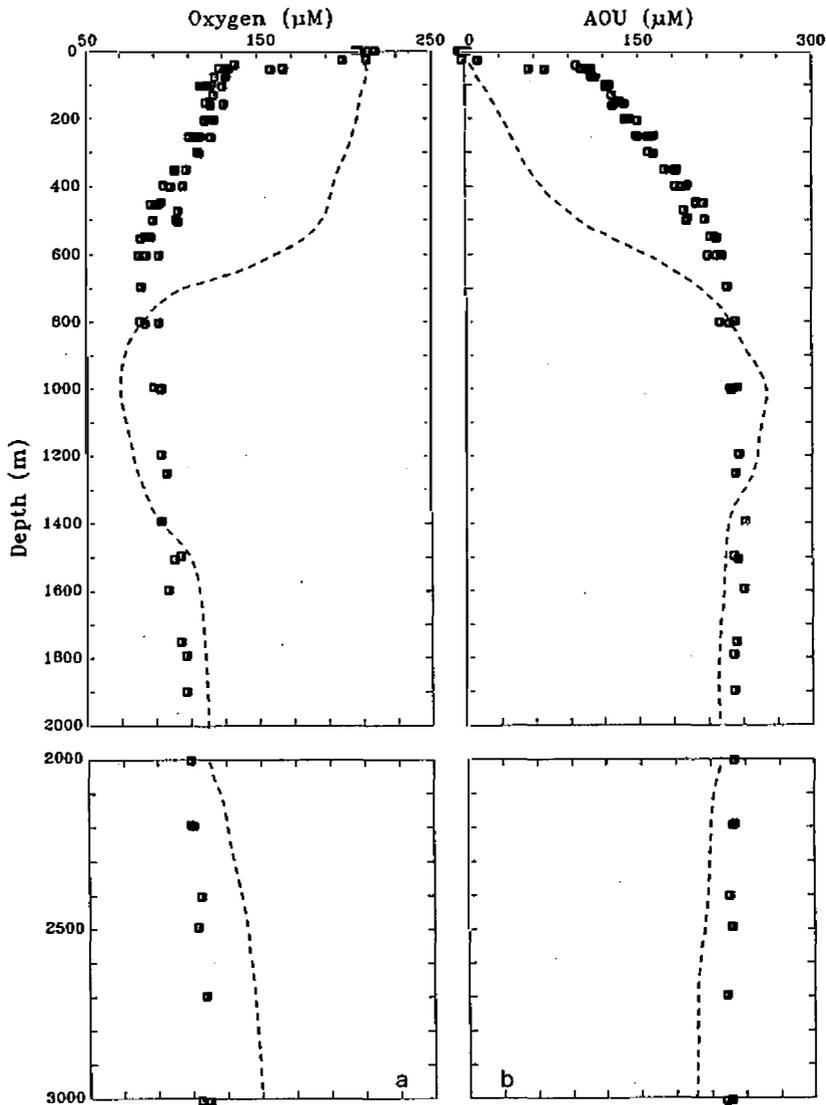


Fig. 3. Vertical profiles of (a) dissolved oxygen and (b) AOU. The squares represent the SCS stations. The dotted line were the averaged profiles of the WPS.

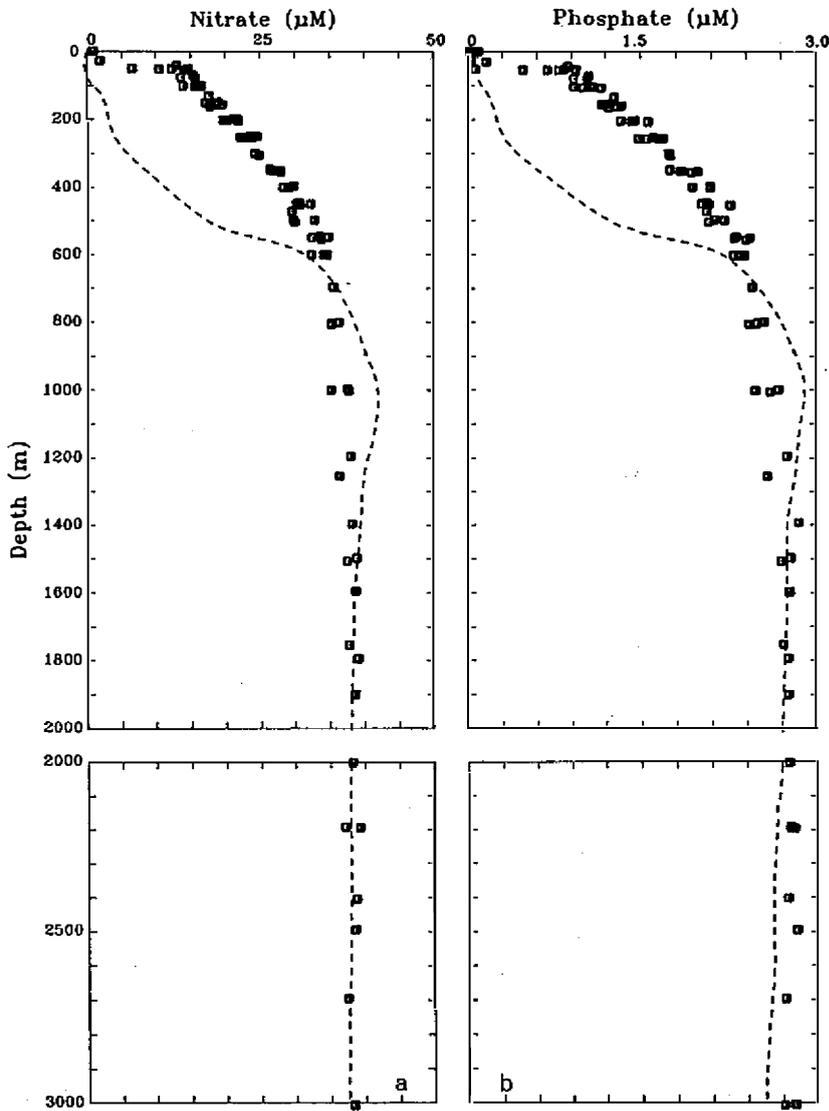


Fig. 4. The same as Fig. 3, except for (a) nitrate and (b) phosphate.

### 3.3 $\theta$ -S and $\theta$ -nutrient relationships

The  $\theta$ -S relationships of the WPS and the SCS all showed the characteristic inverse S-shape (Figure 5). In the WPS, salinity maxima of 34.90-35.10 psu corresponded to a  $\theta$  of 21-24°C, which represent the core of the saline North Pacific Subtropical Water at depths of 75-150 m (Nitani, 1972). For water between 4 and 8°C, the  $\theta$ -S curves demonstrated salinity minima of 34.15-34.20 psu, which represent the North Pacific Intermediate water at depths of 600-650 m (Nitani, 1972). In between the salinity maxima and the salinity minima, all the T-S curves converged in the region of 11-17°C and 34.30-34.70 psu.

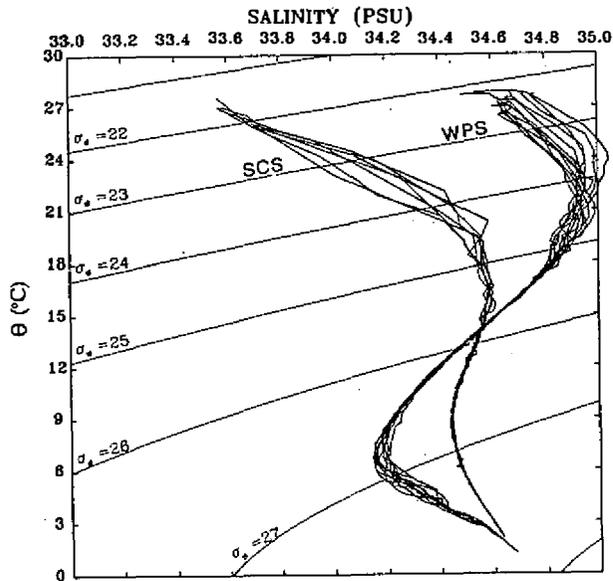


Fig. 5 . Potential temperature ( $\theta$ )-salinity relationships for the two groups: WPS and SCS.

The  $\theta$ -S curves of the SCS intersect those of the WPS at  $\theta=14.0^{\circ}\text{C}$  and  $S=34.55$  psu, which represents the extensively existing thermocline water (Masuzawa, 1972). Above and below the thermocline water, respectively, the salinity maxima and minima were less pronounced than those of the WPS. The salinity maxima of the SCS were at a greater density level (around  $\sigma_{\theta}=25.3$ ) than those of the WPS ( $\sigma_{\theta}=23.5$ - $24.5$ ).

The  $\theta$ -nitrate relationship (Figure 6a) of the SCS showed a monotonous increase of nitrate concentration with decreasing temperature, whereas that of the WPS showed a prominent maximum for temperatures between  $3$ - $4^{\circ}\text{C}$ , and a nitrate free region for temperatures above  $22^{\circ}\text{C}$ . The former trend intersects with the latter at both extremes of the temperature range and at about  $6^{\circ}\text{C}$ . Between  $7$  and  $24^{\circ}\text{C}$ , the SCS water was more enriched in nitrate than the WPS, but the situation was reversed between  $3$  and  $6^{\circ}\text{C}$ . Similar relationships in  $\theta$ -phosphate and  $\theta$ -AOU were also observed (Figure 7a,b).

There were two obvious breaks in the  $\theta$ -nitrate relationship (Figure 6a) of the SCS at temperatures of  $15$  and  $5^{\circ}\text{C}$ , respectively. Between the two breaks the  $\theta$ -nitrate relationship was well represented by a linear regression line. Outside this temperature range, the slope of the  $\theta$ -nitrate relationship became less negative. The plot of nitrate vs.  $\sigma_{\theta}$  also shows the change of the slope quite clearly, especially at  $\sigma_{\theta}=25.5$ , corresponding to  $15^{\circ}\text{C}$ . (Figure 6b). Similar trend were also shown by the  $\theta$ -phosphate and  $\theta$ -AOU plots (Figure 7).

#### 4. DISCUSSION

The seven stations in the SCS west of Luzon showed fairly uniform water properties. It is suggested that these waters were free from the immediate influences of water intrusion from the WPS or river runoff and terrigenous materials from southeastern China and the

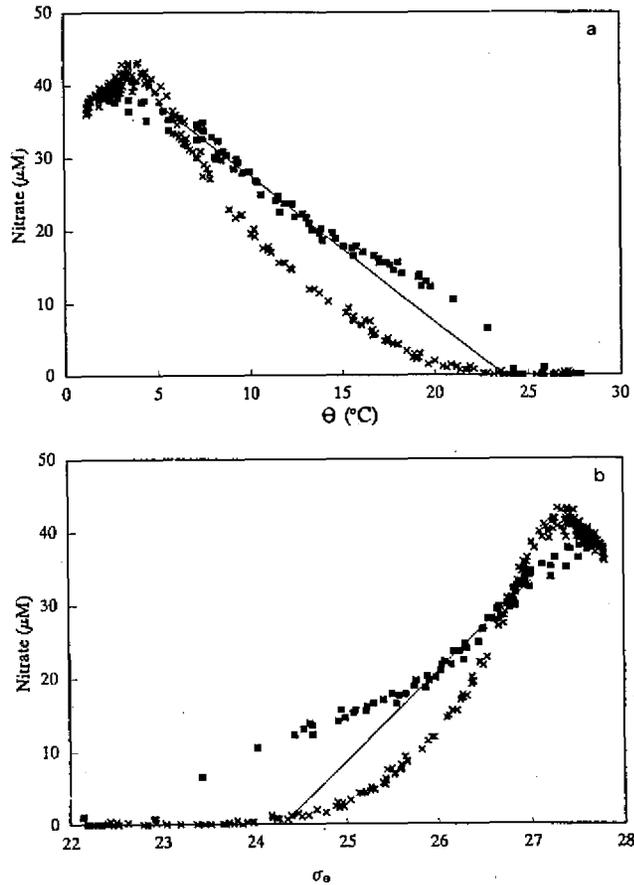


Fig. 6. Potential temperature ( $\theta$ )-nitrate and  $\sigma_{\theta}$ -nitrate relationships. The squares represent the data of SCS stations. The crosses were the data of WPS stations. The solid line represent the linear regression for the SCS data between 5 and 15°C.

Indochina Peninsula. Figure 8 shows the comparison of our results with the mean temperature, salinity and oxygen profiles in the central SCS area of 15-20°N and 115-120°E (Levitus, 1982). Most of our data were within the  $\pm 1$  s.d. range of the historical data. Our temperature and oxygen data of the upper 150-300 m were on the lower extreme of the ranges of the historical data. Such deviation probably reflected the seasonal or local variation. Therefore, our data are in good agreement with the historical data. Except for the surface layer, our data are a reasonable approximation for the central SCS.

The hydrographic and chemical conditions of the 20 stations in the WPS were compared to previous observations in the wider area of the WPS (Scripps Institution of Oceanography, 1978). The comparison indicated that our observations were consistent with previous results, and our stations were representative for the water adjacent to the Luzon Strait, the entrance of the SCS. Similar hydrographic conditions were used by Shaw (1991) to represent the

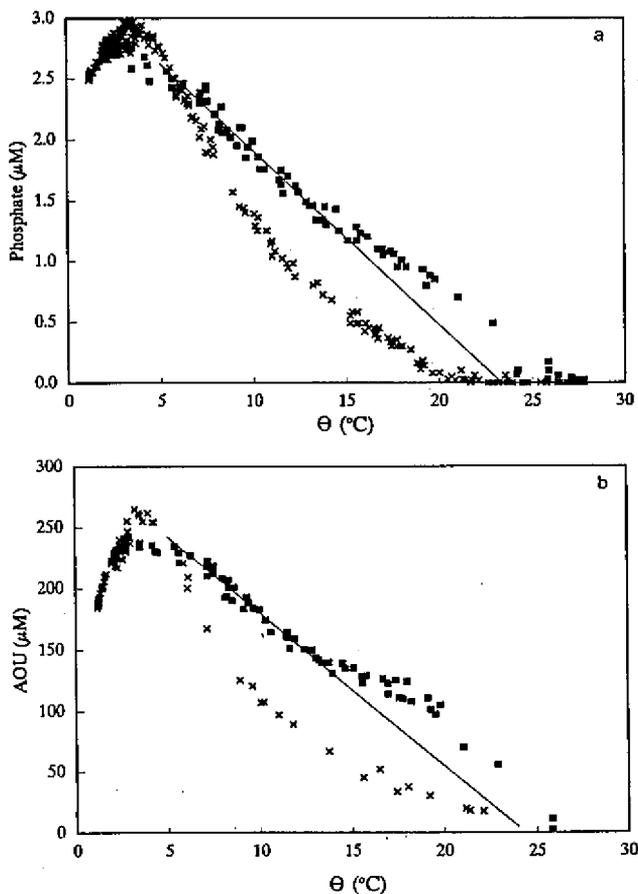


Fig. 7. Potential temperature ( $\theta$ )-phosphate and potential temperature ( $\theta$ )-AOU relationships. The squares were the data of SCS stations. The crosses were the data of WPS stations. The solid line represent the linear regression for the SCS data between 5 and 15°C.

intrusion water from the WPS to the SCS.

For the convenience of discussion, the water column is divided into four layers: the surface water (0-100 m), the subsurface water (100-600 m), the intermediate water (600-1500 m), and the deep water (>2000 m). The lower boundary of the surface layer corresponds to the mean depth of the salinity maximum (Figure 2b). The bottom of the subsurface layer corresponds to the salinity minimum of the WPS (Figure 2b). This boundary also marks the temperature crossover, below which the temperature of the SCS was higher than that of the WPS. The lower boundary of the intermediate water corresponds to the lower crossover in the oxygen profiles (Figure 3a). The water characteristics are controlled by the origin of water, and physical and biological processes undergoing in the water body. Therefore, these factors are discussed below.

One of the major sources of water entering the SCS is the deep water from the WPS

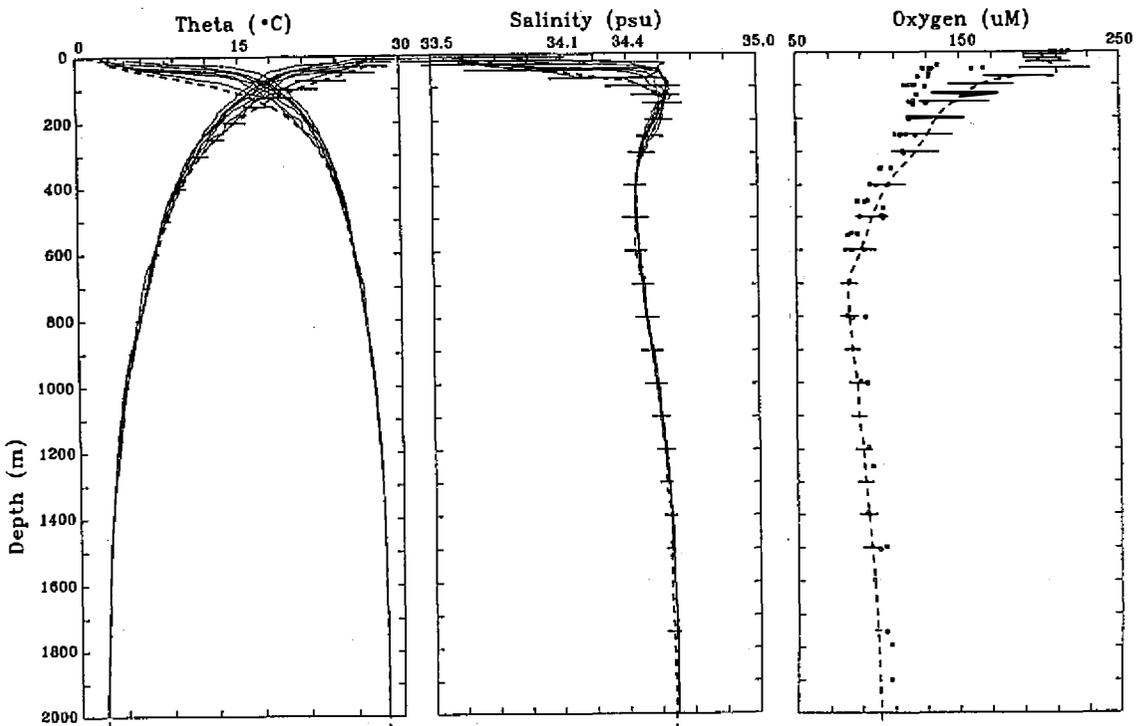


Fig. 8. Comparisons of vertical profiles of (a) potential temperature, (b) salinity and (c) dissolved oxygen between our observations in the SCS and the mean data from the area of 15-20°N and 115-120°E compiled by Levitus (1982). Solid curves and symbols represent our data. The dashed curves and the horizontal bars represent, respectively, the mean and the 1s.d. range of all data available in the NODC.

at the sill depth (1900 m) of the SCS. The influx of water can be estimated in several ways. Wang (1986) assumed a steady state model of balancing the downward heat flux with upward advection of the colder deep water which presumably originates from the WPS. He estimated the vertical velocity at 1500 m to be 19 m/yr under the assumption of an eddy diffusivity of 10 cm<sup>2</sup>/sec (Wang, 1986). His estimate is about three times the mean upwelling velocity in the open ocean (Broecker and Peng, 1982). The influx of the deep water from the WPS was calculated to be 0.42 Sv from the area ( $7 \times 10^{11} \text{m}^2$ ) of the SCS at 1500 m. Direct observation of the inflow at depth ranges of 2000-2700 m in the Luzon Strait (Bashi Channel) yielded an estimate of 1.2 Sv (Liu and Liu, 1988). The residence time of the basin water was estimated to be 40-115 years from the volume ( $1.5 \times 10^{15} \text{m}^3$ ) of the basin water (i.e., the deep water below the sill depth of 1900 m) and the previously estimated influxes.

Broecker *et al.* (1986) reported the present day  $\Delta^{14}\text{C}/\text{C}$  value,  $-205 \sim -204\text{‰}$ , for water below 1340 m in the SCS, and  $-206 \sim -196\text{‰}$ , for water below 1360 m in the WPS. They concluded that the very small difference in  $\Delta^{14}\text{C}/\text{C}$  value between the SCS and the

WPS indicates rapid water exchange between the two basins. Therefore, the rather short residence time of the SCS basin water calculated above is reasonable. Based on dynamic considerations, Wyrski (1961) suggested that the monsoon-induced circulation controls the water exchange in the intermediate water and above. During the northeast monsoon, the upper layer of about 200 m enters the SCS and the water between 400 and 900 m flows out of the SCS. During the southwest monsoon, the situation is reversed. Because the NE monsoon is stronger and lasts longer, the inflow should be dominant in the surface and subsurface waters, while the outflow is dominant in the intermediate water.

The salinity maximum and minimum observed in the SCS west of Luzon support the notion of intrusion above 400 m. The salinity minimum in the SCS was found at about the same density level (around  $\sigma_\theta=26.75$ ) as that of the WPS, suggesting the low salinity waters of the two seas might be related through isopycnal mixing. In fact, Shaw (1989) found intrusion water along the isopycnal of 26.75 in the SCS southwest of Taiwan in spring. Such water may spread farther into the interior of the SCS and cause the salinity minimum. On the other hand, the salinity maximum was found at a density level ( $\sigma_\theta=25.3$ ) different from that of the WPS ( $\sigma_\theta=23.5\sim24.5$ ). Shaw (1991) demonstrated that the WPS water between the depths of 150-250 m ( $S=34.7\text{-}34.9$  psu) intrudes into the SCS horizontally in fall and winter. The high salinity water can be found as far as 800 km from the Luzon Strait, following the passage of a cyclonic flow. It is possible that such horizontal intrusion brought high salinity water into the SCS and caused the salinity maximum in the subsurface water.

The oxygen and nutrient distribution observed in the intermediate water of the SCS supports the notion that outflow is more important in the intermediate water. The oxygen minimum in the SCS was observed at a depth (around 600 m) much shallower than that (around 1000 m) of the WPS. The nutrient profiles in the SCS showed no maxima and the nutrient concentrations in the intermediate water of the SCS were mostly lower than those of the WPS. If the water with minimum oxygen and maximum nutrients from the WPS enters the SCS, the chemical characteristics should be maintained by continual oxygen consumption unless the productivity in the overlying water was so low that the chemical signals were totally wiped out by vertical diffusion. However, the enrichment of nutrients in the subsurface water indicated that the downward flux of biogenic material is quite important. It is unlikely that oxygen consumption was especially low in the intermediate. The most likely reason for lack of nutrient maximum which exists ubiquitously in the WPS is that the inflow of the WPS water at the intermediate depth is insignificant, and, therefore, outflow could be more important.

There were three salient features revealed in the chemical hydrography in the SCS that are not readily explained by the aforementioned water circulation, i.e., the inflow of the deep water and the water exchange in the upper layers. First, below the thin surface layer, the SCS water had much more uniform properties, especially salinity, than the WPS water; secondly, as a corollary of the first, the subsurface water (100~600 m) had considerably lower temperature and oxygen and higher nutrient than that of the WPS (Figures 2~4); and thirdly, the SCS water with  $T>6^\circ\text{C}$  showed strong enrichment in nutrients relative to the WPS water of the same temperature (Figures 6 and 7).

The uniformity in salinity below the surface layer may be attributed to diapycnal mixing but the raised isopycnals and chemical isopleths can not be attained by vertical mixing. That the salinity maximum (about 34.6 psu) of the SCS was considerably lower than that of the WPS water could result from its mixing with the overlying low salinity water (Wyrski, 1961). The relatively high value of the salinity minimum in the SCS could also result from vertical mixing because the salinity surplus from 400 to 1500 m in the SCS, as compared to the WPS, may be averaged out by the salinity deficit in the overlying water (Figure 2). However, such

processes are highly improbable because an extensive vertical mixing over a range of 1500 m is involved. In addition, there is no corresponding change of temperature resulting from such mixing. The cooling in the upper 600 m of the SCS with respect to the WPS was so pronounced that the slight warming in the water column below 600 m can not compensate for such change. There are also no known sources of cold water near the study area that could produce the observed cooling by horizontal transport.

Some other processes must be responsible for the temperature and salinity distribution in the SCS in addition to vertical mixing. One possible candidate is upward advection of the deep water which might raise the isotherms in the overlying water. Such advection may be related to the upwelling hypothesized by Wang (1986). It has been demonstrated by the vertical advection-diffusion model (e.g., Craig, 1969) that upward advection tends to bring the property of deep water to shallower water and, hence, makes the water properties more uniform. The advection might be superimposed upon the monsoon-induced circulation above the deep water. This also implies that the intermediate and the subsurface waters may contain a significant fraction of the upwelled water which was amended with nutrients during ascension. This extra source of nutrients may explain the enrichment of nutrients in the subsurface water with respect to the WPS water of the same temperature.

The historical data from the central SCS (Levitus, 1982) support our observations of the chemical characteristics of the SCS. Therefore, such a distinction in water characteristics can be used to trace the water exchange between the interior of the SCS and the WPS in the mixing zone near the Luzon Strait. As mentioned before, the water exchange between the WPS and the SCS is important in the subsurface layer and the intermediate layer, but the T-S relationships are not distinguishable within the layer of the thermocline water (centered at the  $\sigma_\theta$  level of 25.8). On the other hand, oxygen and nutrients were good indicators of such mixing in the subsurface layer, either along isopycnal surface or along horizontal surface. The nutrient concentrations differ significantly for the thermocline water at different localities. For instance, the mean difference of nitrate concentration at  $\sigma_\theta=25.8$  between the WPS and the NSCS was about  $8 \mu\text{M}$  (Figure 6b). Such a distinction could be used to discriminate waters of different origin, especially in the frontal region.

The processes that lead to the evolution of the SCS water are still poorly understood. For example, it is not clear how the inflow of the deep water exits the SCS. In other words, the upwelled deep water must turn into horizontal flow, but it is not known at what depth such divergence occurs. A more detailed examination of the hydrographic data is needed to explore the lateral variation of the salient features, which is related to the horizontal flow pattern in the SCS. A quantitative approach using numerical simulation is necessary to verify whether the hypothesized physical and biological processes could reproduce the observed hydrographic and chemical distributions. Finally, the dynamic mechanism that drives the circulation has to be addressed.

## 5. CONCLUSIONS

The chemical hydrography of the South China Sea west of Luzon and the West Philippine Sea showed that the water characteristics in these two seas were related but different in many aspects. A comparison with the historical data confirmed that our observations were representative for the central SCS and WPS waters near the entrance of the Luzon Strait. The deep water of the SCS was very uniform and resembled the WPS water at the sill depth of the Luzon Strait. The residence time of the deep water of the SCS was estimated to be 40-115 yrs based on previous estimates of influx from the WPS. The salinity maximum and minimum in the SCS were related to intrusion waters from the WPS. The lack of nutrient maxima

in the SCS was consistent with the notion that the outflow of the SCS water was mainly the intermediate water (Wyrtki, 1961). It is noteworthy that all hydrographic and chemical properties of the South China Sea were more uniform than those of the West Philippine Sea in the water column below the surface layer. The subsurface water of the SCS was much colder than that of the WPS, and more enriched in nutrients relative to the WPS water of the same temperature. These features may result from an upward advection possibly related to the rather rapid turnover of the deep water.

Although the temperature-salinity relationship is widely used to indicate the origin of water masses, it is not applicable for isopycnal mixing at the permanent thermocline level in this region due to the uniform T-S characteristics of the thermocline waters. Because apparent oxygen utilization and nutrients in the South China Sea were considerably higher than those of the West Philippine Sea in the subsurface layer which encompasses the permanent thermocline, the  $\theta$ -AOU or  $\theta$ -nutrients relationships were useful in discriminating these waters.

**Acknowledgments** This paper is contribution no. IESEP92-022 from the Institute of Earth Sciences, Academia Sinica (ROC). We acknowledge the cooperation of the crew and technical staff of the *R/V Ocean Researcher I* during our cruises. This paper was improved by the critical review of three anonymous referees. This study was supported by grants from the National Science Council of the Republic of China: 81-0209-M001-01 (KKL), 80-0209-M002a-20 (SCP), and 80-0209-M002a-13 (CTL), and also by the Academia Sinica.

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## 南海在呂宋西側之化學水文及其與 西菲律賓海之比較

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### 摘要

本文報導1990年12月在呂宋島西側之南海化學水文觀測結果，並與西菲律賓海相比較，以了解菲律賓海水進入南海後之變化情形及改變之原因。南海海水具有鹽度極大和極小值，以及南海深層水與西菲律賓海之相似性都顯示西菲律賓海水對南海之影響。然而，二海域1500公尺以上的水，有很明顯的差異。南海的次表層水(100-600m)較西菲律賓海同層的水來得冷，其所含之溶氧較同一溫度之西菲律賓海水來得少，而營養鹽來得多。然而，在中層水中(600-1500m)這種關係顛倒過來了。這些差異可以用來區分在二海域相接的界面區內，互相混合的水團。南海次表層水之所以較冷且富含營養鹽，而海水特性之所以變化較小，除了垂直混合之外，尚可歸因於海水向上的流動，這種湧升可能與南海的深層水相當快速的替換有關。