La mer 34: 246–257, 1996
Société franco-japonaise d'océanographie, Tokyo

Some aspects on the circulation in the northern South China Sea

Joe WANG* and Ching-Sheng CHERN*

Abstract: The circulation pattern of the northern South China Sea (SCS) had long been a controversial topic for the regional oceanography. The results from recent multi-vessel surveys, over the northern and central SCS, show that the surface layer of the region to the northwest or west of north Luzon is mainly occupied by cyclonic flows during spring and summer ; this is quite discordant with our past knowledges on the circulation pattern of the northern SCS. Moreover, these cyclonic flows are composed principally of SCS water masses, and in summer they could extend further northwards to the areas from the west of the Luzon Strait to the southwest of Taiwan. However, the aforementioned areas are flowed principally by Kuroshio intrusion waters and associated with anti-cyclonic flows in winter. Details of the seasonal alternation of such flow fields could be inferred from the differences of the monthly mean sea levels between Kao-Hsiung and Port Irene and between Kao-Hsiung and San Jose ($\Delta\zeta_{KS}$). The former is dominated by annual variations, low in summer and high in winter. The latter is principally biannual, whose two peaks, occurring in March to May and in August to September respectively, correspond likely to the sequential occurrences of anti-cyclonic and cyclonic flows in the Luzon Strait. Transitions of flow patterns may occur respectively in June to July and in October to November when $\Delta\zeta_{KS}$ is low. These particular periods, corresponding closely to the timings of alternation or onset of the regional monsoon, imply the significance of wind stress on the evolution of current fields in the SCS.

1. Introduction

For years, current fields in the northern South China Sea (SCS) had darwn a number of attentions; WYRTKI (1961) compiled bimonthly surface current charts of the SCS and his study enlightened the monsoon-driven behavior of the main flow of the SCS; others, like the CSK works of CHU (1970, 1972) and NITANI (1970), also posteriorly hydrographic surveys of FAN (1982) and SHAW (1989) in the Luzon Strait and nearby areas, CHAN (1970), QIU, YANG and GUO (1984) and WANG and CHERN (1987*a*) in the northern and the central SCS, etc., had improved or extended WYRTKI's (1961) results of the northern SCS because over wihch his data base is rather sparse and crude from a modern viewpoint. Several obscurities were illuminated by these later surveys indeed, however, more controversies had been drawn by them too. For example, LI and WU (1989), based on NITANI's (1970) data, considered that the Kuroshio would form a loop current in the northeastern SCS, they also suggested that this is likely a typical pattern for summer. Their point of view, obviously, contravenes with what reported by CHU (1972) and FAN (1982), i.e., the southwesterly monsoon in summer drives the SCS surface waters flowing outward through the Luzon Strait to the Pacific. Moreover, Wang and CHERN (1987*a*) had reported that the northern SCS was occupied by anti-cyclonic flow systems during their spring survey, which they attributed to the intrusion of Kuroshio waters (WANG and CHERN, 1987*b*). Obviously, the anti-cyclonic pattern is absent in WYRTKI's (1961) current chart, so SHAW (1989) repelled it and he suggested the intrusion waters have to follow a cyclonic pathway. In our opinion, all of these controversies are simply the continuation of a longstanding question, i.e. the obscure behavior of

---

* Institute of Oceanography, National Taiwan University, Taipei, Taiwan, Republic of China

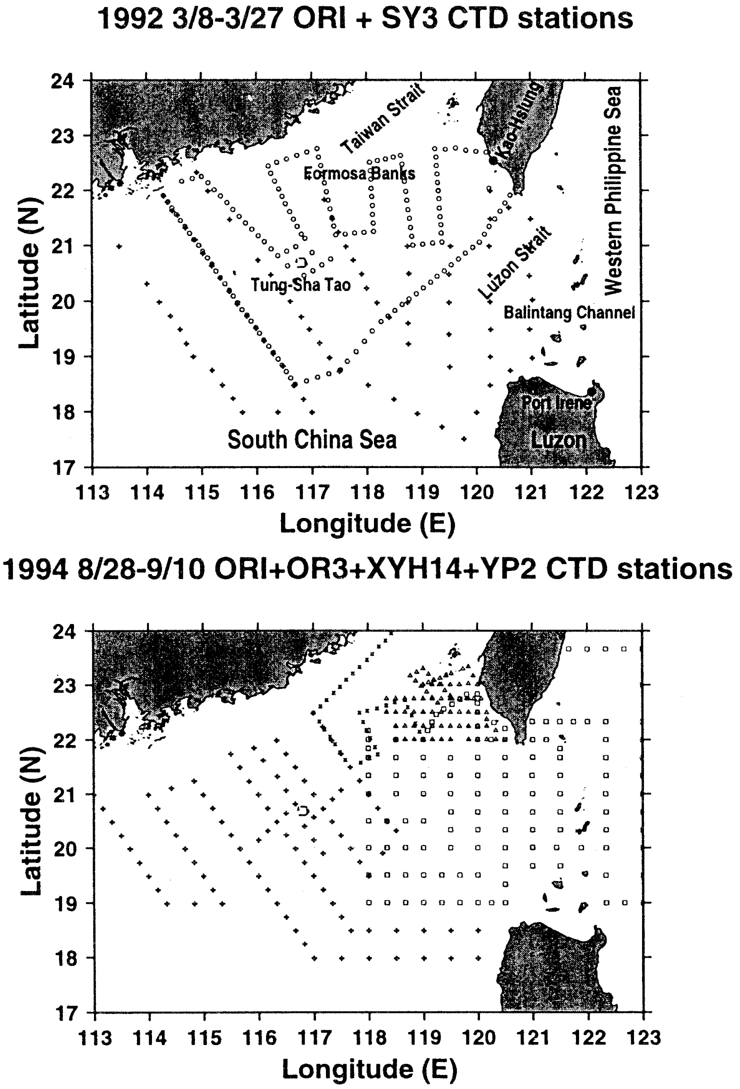

Fig. 1. Hydrographic stations of the joint SCS surverys ; (a) cruise 311, from March 8 to 27, 1992 ; where o signs denote (CTD) stations of ORI and + that of R/V SY3 (upper panel) ; (b) cruise 399, from August 28 to September 10, 1994 ; where □ CTD stations of ORI, △ OR3, × YP2, and + XYH14, respectively (lower panel).

the so-called SCS branch of Kuroshio (Wu, 1982). We are still lacking of enough observations in constructing a more comprehensive model capable of covering all of these disputes.

Recently, two larger-scale, multi-vessel surveys had been conducted in the northern and central SCS. The first was performed jointly by R/V Ocean Researcher I (ORI, managed by Institute of Oceanography, National Taiwan University) and by R/V Shi-Yan 3 (SY3, by South China Sea Institute of Oceanology, Academia Sinica, SCSIOAS) from March 8 to 27, 1992 (Fig. 1a); the second, by four ships, i.e. ORI, R/V Ocean Researcher 3 (OR3, by National Sun Yat-Sen University), R/V Xian-Yang-Hong 14 (XYH14, by State Oceanic Administration) and R/V Yeng-Ping 2 (YP2, by Fujian Institute of Oceanography), was carried out from August 28 to September 10, 1994 (Fig. 1b). One of the purposes of these surveys is to present

Table 1. CTD data used.

Cruise #	Duration	Survey area	Note
283	1991 5/23-5/28	LS, NE SCS	ORI only
311	1992 3/ 8-3/27	LS, N SCS	With SY3
391	1994 6/14-6/20	LS, E Taiwan	ORI only
399	1994 8/28-9/10	LS, NE SCS	With OR3, XYH14, YP2
415	1995 4/ 4-4/13	LS, E Taiwan	ORI only

synoptic views of the distributions of water masses and current fields in the northern SCS under different seasons, which may fill in some of blanks in our past studies. In terms of this data base, we may identify several active flow-systems which are dynamically significant to the circulation pattern of the northern SCS. The evolution of such systems, however, could be inferred from the time series of Monthly Mean Sea Levels (MMSLs) of nearby tide stations. These, probably enlightening some of the aforementioned obscurities, are reported in the following sections.

2. Data base

Two kinds of data are used for the inspection on the seasonal behavior of large scale current fields of the northern SCS. The first is CTD data collected by ORI solely or by ORI and other research vessels[1] jointly, from which the spatial distribution of water masses and dynamic-height anomalies, thereby large scale motions, could be inferred. For later rerference, informations of cruise number (of ORI only), duration and coverage of cruises are briefed in Table 1, where the abbreviation LS denotes the Luzon Strait, N northern, S southern, E eastern and NE northeastern, respectively. The second is the MMSL data of three tide stations, i.e. San Jose, Port Irene and Kao-Hsiung (Fig. 1a; from January 1989 to December 1993)[2], from which the time series of the differences of MMSLs between any two of them, i.e. $\Delta\zeta(t)$, where t denotes time, is obtained readily. By geostrophy, $\Delta\zeta(t)$ is associated with the volume fluxes through the section between two stations, it is therefore an useful clue for reconstructing the temporal behavior of flow fields from few spatial snapshots by CTD surveys.

3. Spatial distribution of water masses

The SCS is a semi-enclosed ocean basin, whose exchanges of mass and salt with the western Philippine Sea are mainly by virtue of the flows in the Luzon Strait. WYRTKI (1961) had reported the seasonal behavior of the conveyance of high salinity North Subtropical Lower Water (LW) and less saline North Pacific Intermediate Water (IW) into the SCS. During the northeasterly monsoon, LW and waters above it flow into the SCS while IW flushes out in lower layers. However, it is in the reverse order during the southwesterly monsoon. The Kuroshio, being the major current system in the western Philippine Sea, is the principal conveyer for these waters. A massive part of sub-surface waters in the main stream of the Kuroshio belongs to the more saline LW, whose salinity maximum, S_{max}, is about 34.9psu (or higher) to the east of Luzon, while the salinity minimum, S_{min}, of IW is about 34.20−34.30psu in the same region. In the SCS, however, usually $S_{max}\sim$34.60psu and $S_{min}\sim$34.40psu (NITANI, 1970). It is these differences making S_{max} and S_{min} to be handy indexes for discriminating waters circulated in the SCS from that immigrated with the Kuroshio stream (CHU, 1972).

For the sake of later illustrations, spatial distributions of S_{max} in spring (ORI-311) and summer (ORI-399) are shown in Figs. 2 and 3,

---

[1] For the purpose of cross checking the quality of CTD data collected by different vessels, several common stations had been arranged during cruises; comparisons of T-S curves of common stations show no great deviations between each other (XU and SU, 1993 ; HU, 1995).

[2] The former two were retrieved via the anonymous ftp from the archives of British Oceanographic Data Centre (BODC), and the third one is provided by the Central Weather Bureau of the Republic of China (CWB). The location of San Jose (121°5′E, 12°20′N) is out of the range of Fig. 1a, so is not shown.

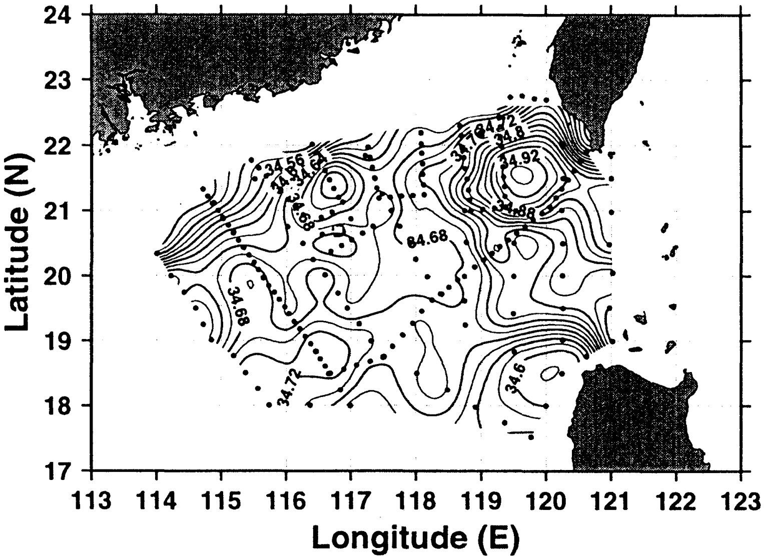

Fig. 2. The distribution of Smax (in psu) during ORI 311 from March 8 to 27, 1992.

respec-tively. A common feature, i.e. the tongue-like pattern of isohalines in the Luzon Strait, is clear in these figures. If the isohaline which is the closest to the Kuroshio front is chosen as the outer boundary of the intrusion water[3], then we may infer that waters immigrated directly with the Kuroshio could reach to 118.7° E in spring of 1992 but merely to 119.8° E in summer of 1994. Along the rim of these tongues (in the SCS side) are circulating waters whose salinity is in between waters in the Kuroshio and that in the central SCS. Moreover, the orientation of isohalines in the Luzon Strait south of 21° N is worth noticing too; they are nearly meridional in summer, but mainly latitudinal during spring. This feature, associated closely with the variation of the path of the Kuroshio stream, is discussed next.

4. Spatial distribution of current fields

Horizontal distributions of dynamic height anomaly, ΔD, (in *dynamic meter*) in spring and summer on 20 db (relative to 800 db), likely representing geostrophic streamlines in the surface layer, are shown in Figs. 4 and 5 respectively. The distribution of ΔD on 150 or 200 db (likely corresponding to the layer of S_{max} in the SCS) is quite analogous to the surface one in either season, so for the sake of brevity it is not shown. Apparently, there are several common as well as contrary features between both seasons, a brief of them is reported hereinafter.

The most striking feature is perhaps the cyclonic flows in the central to northern SCS (Figs. 4 and 5). The region south or southeast of Tung-Sha Tao (Pratas Islands) and west of northern Luzon, over which ΔD is always lower than its surroundings, no matter in spring or summer. This implies the region is occupied by a nearly-persistent cyclonic system. Though the feature is absent in WYRTKI's (1961) flow chart of summer, but consistent with that reported by SCSIOAS (1985). On the other hand, the flow pattern northeast of this region varies greatly with seasons. During the spring cruise a consistently-northwestward flow[4] emerged (Fig. 4) while in summer a pair of cyclonic[5] and anti-cyclonic eddies were found (Fig. 5); these, especially the summer case, are not in accordance with WYRTKI's (1961) charts.

---

[3] Such as the Smax 34.8 psu and 34.9 psu for the cruise of ORI-311 and ORI-399, respectively, cf. Figs. 2 to 5.

[4] It could extend vertically from the surface down to deeper layers, say more than 600 db.

[5] The cyclonic flow in the northern SCS possesses a cold-cored structure, whose circulation sense could extend vertically to a much deeper layer, say more than 1500 db (Wang 1986).

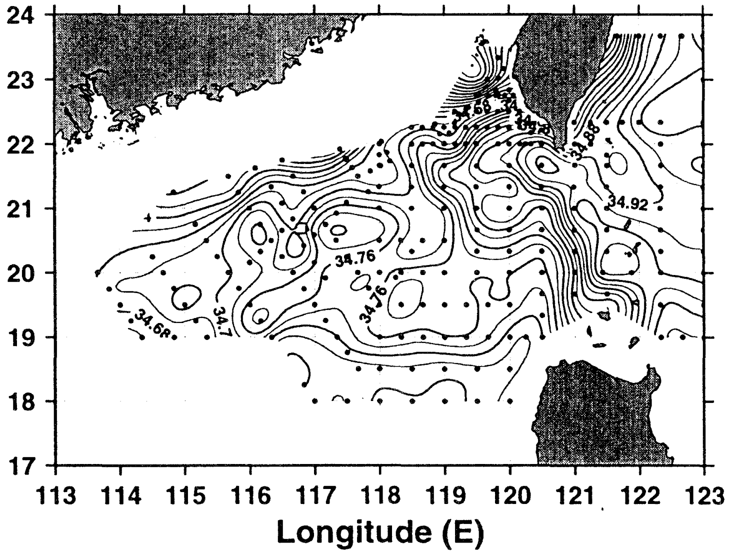

Fig. 3. The distribution of S_{max} (in psu) during ORI 399, from August 28 to September 10, 1994.

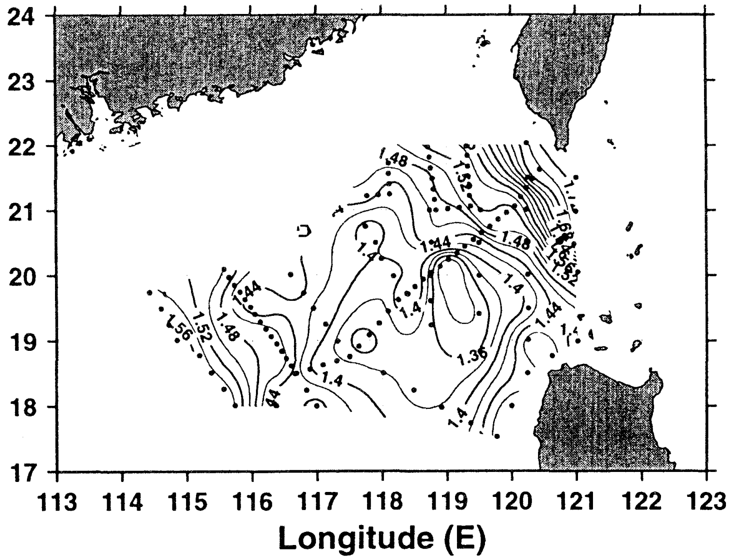

Fig. 4. The distribution of ΔD (in dyn.m) of 20 db with relative to 800 db, during ORI 311, from March 8 to 27, 1992.

In addition to the features in the SCS, the flows east of the Luzon Strait are worth special noticing too. The summer survey shows streamlines converging along the 121°E meridian (Fig. 5). The convergence zone, whose position well matches with that of the salinity front (Fig. 3), thus marks the main stream of the Kuroshio in the Luzon Strait. Obviously, this is a branch of the northward currents flowing along the east coast of Luzon, i.e. the Kuroshio in its beginning region (NITANI, 1970). After passing the Balintang Channel north of Luzon the branch enters into the Luzon Strait, in which it interacts with the SCS flows. Are cyclonic eddies west of the Kuroshio branch (Fig. 5) the products of the interaction process, or of whatever, deserve for our studies. Additionally, another important feature has been

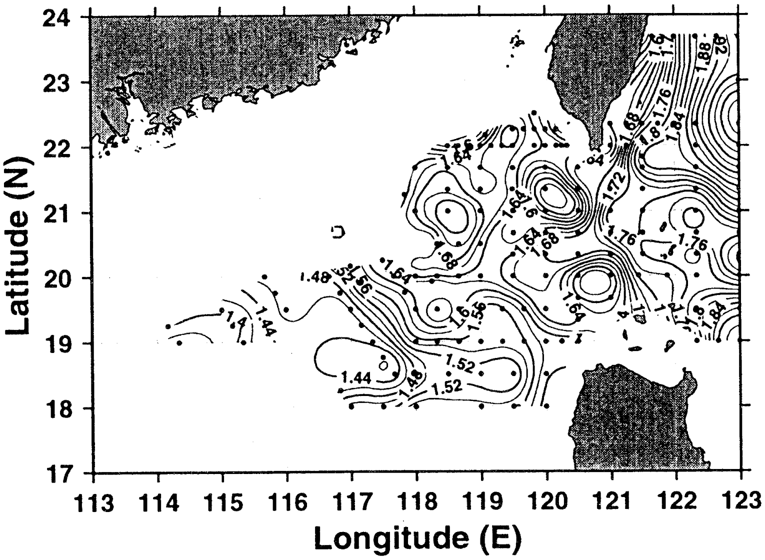

Fig. 5. The distribution of ΔD (in dyn.m) of 20 db with relative to 800 db, during ORI 399, from August 28 to September 10, 1994.

revealed by the summer survey too, i.e., the region east of 122° E and north of 21°N in which appears the second convergence zone of streamlines (Fig. 5). Vertical sections of geostrophic currents along several latitudinal transects east of Taiwan show that the current field frequently possesses a multiple core structure. This particular feature, had been noticed by CHU (1970), is likely caused by the confluence of different branches of the Kuroshio and outflows from the SCS, as suggested in Fig. 5.

The way how the flow pattern shown in Fig. 4 evolves into that in Fig. 5 is an interesting topic for the SCS regional oceanography. Hydrographic data collected from ORI cruises 283, 391 and 415 (Table 1) may illuminate some of ambiguities on the inter-seasonal transition process. Figs. 6 to 8 present the spatial distributions of ΔD on 20 db[6] as well as S_{max} in the northeastern SCS in April, May and June, respectively; from which an acute reader may notice the retrocession sequence of the high salinity Kuroshio intrusion waters from the SCS to the Pacific since March (*cf.* Figs. 2, 6, 7a, 8a and 3). The evolution of the pattern of ΔD shows that the Kuroshio intrusion waters, which are associated with the northwestwards flows on the upper-right portion of Fig. 4, may be disintegrated into two parts. The eastern one is a loop-like current pattern which recedes and returns to the Pacific side of the Luzon Strait since spring (Figs. 6 and 7), the other may stay at the region east of Tung-Sha Tao and south of the Formosa Banks (Fig. 5). Meanwhile, cyclonic eddies penetrate into the middle area from the south (Figs. 5 and 7).

5. Implications of sea surface slope

The differences of MMSLs between two opposite stations across a stream, $\Delta\zeta$, had lond been used for the inference of volume transports of currents in between (e. g., CHU 1976, among others). There are two tide stations in or near the Luzon Strait, i.e. Kao-Hsiung and Port Irene, their data are appropriate for our discussions. Additionally, the MMSLs at San Jose, likely representing the variation of the sea-level along the eastern coast of the central SCS, are cited too. Fig. 9 shows the time series of $\Delta\zeta$ between Kao-Hsiung and San Jose (Kao-Hsiung minus San Jose, $\Delta\zeta_{KS}$), and that between Kao-Hsiung and Port Irene ($\Delta\zeta_{KP}$). However, for unknown reasons, the MMSLs of 1991 summer are unusually higher at Kao-

---

[6] The depth of reference level used in Figs. 6 to 8 is dependent on the maximum depth of CTD casts, which was not unified during these cruises.

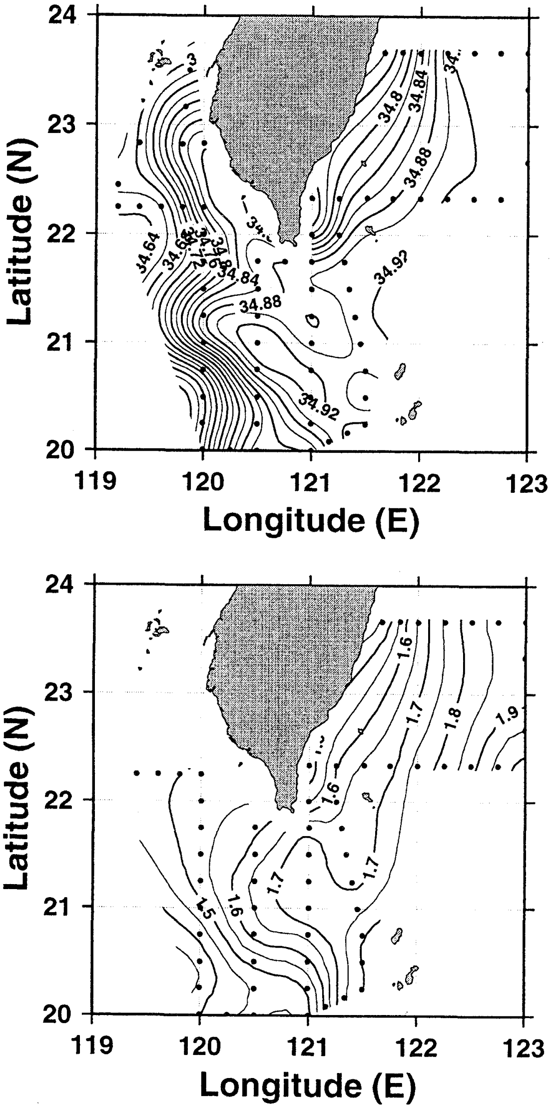

Fig. 6. The distribution of (a) Smax (in psu, upper panel), (b) ΔD (in dyn.m, lower panel) of 20 db with relative to 600 db, during ORI 415, from April 4 to 13, 1995.

Hsiung and lower at San Jose than other years, also there were many missing data in Port Irene during 1991, so discussions are restricted on the 1992 and 1993 time series only.

Several factors, e. g. the variation of atmospheric pressure, the bench mark of tide stations, longshore wind stress and the large scale currrents, etc., are influential to the magnitude of MMSL (Chu, 1976). In the Luzon Strait area, however, the barometric effect may provide a minor contribution to $\Delta\zeta$. On the other hand, the uncertainty of the bench mark of tide stations can induce only a constant offset which is irrelevant to the annual variation of $\Delta\zeta$. Therefore, what we present in Fig. 9 are caused mainly by the joint effects of geostrophy and wind stress. The time series of $\Delta\zeta_{KP}$ reveals a regular annual cycle; it is high from October to February and low from May to September and the annual range is about 25∼30cm[7] (Fig. 9). However, $\Delta\zeta_{KS}$ possesses an entirely different structure; it is biannual with both peaks occur in March to May and in August to September and with contiguous troughs in June to July and in October to November, respectively. The annual range of $\Delta\zeta_{KS}$ is relatively small and its magnitude merely about 15 cm (Fig. 9). The annual variation of $\Delta\zeta_{KP}$ is consistent with our previous knowledges, i.e., water flows are outward from the SCS to the Pacific during summer and reverse in winter (Wyrtki, 1961; Chu, 1972 : Fan, 1982), but $\Delta\zeta_{KS}$ is rather curious because of its biannual behavior really beyond our intuition.

To conceive the causation of the biannual cycle, we have to inspect the original time series carefully. The MMSLs of San Jose in 1992 and 1993 are, on the average, lower than those of the other two stations in August and/or September, but higher in October and/or November, respectively. However, the highest MMSL shifts to Kao-Hsiung in March to May, and to Port Irene in June and July. What effects cause this variation ? Beforehand any speculations, perhaps we could use the method of empirical orthogonal decomposition for exploring modal structures embedded in the time series; for details one should refer to Kundu, Allen and Smith (1975). Table 2 gives the eigenvalue λ_n, the explained variance $\lambda_n/\Sigma\lambda_n$(in percentage of total variance) and the three components of the eigenfunction $\phi_n(x_n)$ resolved, where the subscript n denotes mode number, $n=1, 3$, $\phi_n(x_i)$ the normalized eigenfunction of mode n and x_i three different tide stations, i.e., x_1 represents Kao-Hsiung, x_2 San Jose and x_3 Port Irene, respectively. The time series of amplitudes of three empirical modes, $E_n(t)$, acquired from the decompositon is shown in Fig. 10. By definition,

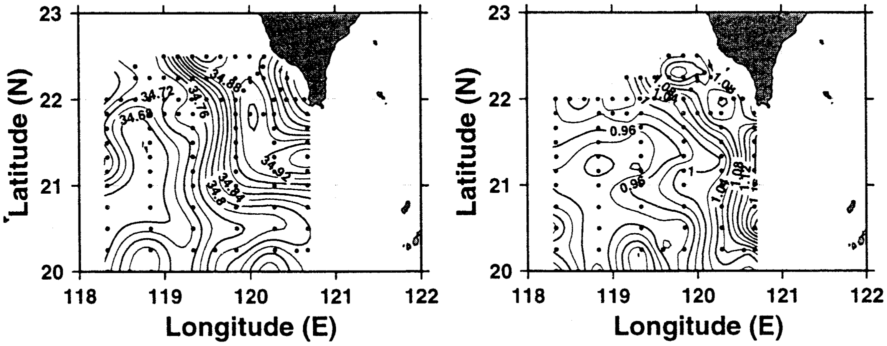

Fig. 7. The distribution of (a) S_{max} (in psu, left panel), (b) ΔD (in dyn.m, right panel) of 20 db with relative to 400 db, during ORI 283, from May 23 to 28, 1991.

we have

$$\zeta_{xi}(t) = \Sigma^3_{n=1} E_n(t)\phi_n(x_i) \text{ and}$$
$$E_n(t) = \Sigma^3_{i=1} \zeta_{x_i}(t)\phi_n(x_i),$$

where $\zeta_{xi}(t)$ denotes the MMSLs of the tide station x_i (KUNDU *et al.*, 1975).

Obviously, both of modes 1 and 2 are dominated by the annual cycle, only mode 3 is principally biannual (Fig. 10). By simple manipulation on the above equations, we have

$$\Delta\zeta_{KS} = \sum_{n=1}^{3} E_n(t)(\phi_n(x_1) - \phi_n(x_2));$$

from Table 2, $(\phi_n(x_1)) - \phi_n(x_2))$ is 0.13, -0.12 and 1.40 for modes 1, 2 and 3, respectively. Though the energy density of mode 1, i.e. λ_1, is about 9 and 37 times to that of mode 2 (λ_2) and mode 3 (λ_3), after taking square root this proportion (of E_n) becomes 1 : 0.33 : 0.16. So their contribution to $\Delta\zeta_{KS}$ is 1 : -0.31 : 1.57 for modes 1, 2 and 3, respectively, which confirms that $\Delta\lambda_{KS}$ is mainly induced by modes 3 and 1 fluctuations. Similarly, $\Delta\lambda_{KS}$ is caused principally by modes 2 and 1. Comparing the flow patterns presented in the last section with the time series plot of E_3 in Fig. 10, we may suggest that the hump of E_3 in March, 1992 is due to the fact that Kao-Hsiung was located on the right-hand side of the northwestward Kuroshio intrusion currents, thereby surface elevation of Kao-Hsiung is relatively higher (Fig. 4). The other hump, occurred in August or September, however, was likely due to the geostrophy of

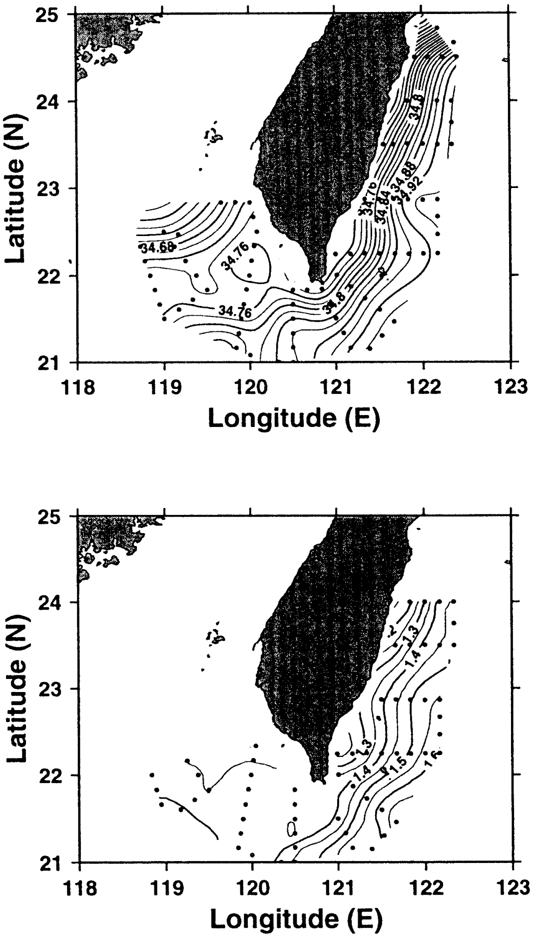

Fig. 8. The distribution of (a) S_{max} (in psu, upper panel) (b) ΔD (in dyn. m, lower panel) of 20 db with relative to 600 db, during ORI 391, from June 14 to 20, 1994.

---

[7] The magnitude exceeds WYRTKI's (1961) result a lot.

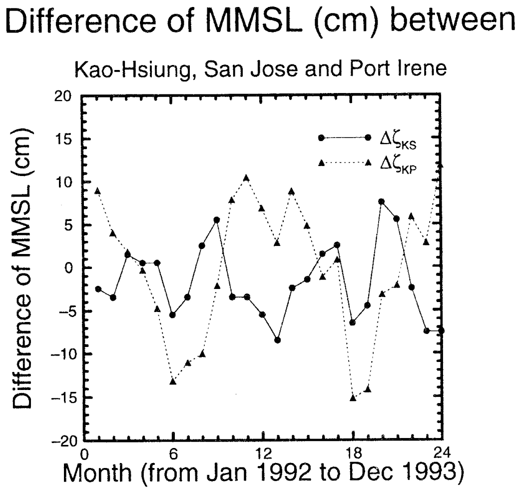

Fig. 9. Tge time series plot of $\Delta\zeta_{KS}(t)$ and $\Delta\zeta_{KP}(t)$, from January 1992 to December 1993.

the northward currents along the southwest coast of Taiwan as well as the southeastward flows from the central SCS into the Sulu Sea (WYRTKI, 1961); both may induce a similar effect on $\Delta\zeta_{KS}$ (Fig. 5).

In addition to the peaks of $E_3(t)$, the troughs, appeared in June and in October, November or January respectively, are worth noticing too. The prior one is likely associated with the entirely eastward movement of waters from the SCS to the Pacific, either by the retrocession of the Kuroshio intrusion waters in the northern Luzon Strait[8] or by the northward extension of the above-mentioned cyclonic-flow system from the central SCS to the southern Luzon Strait (Figs. 6 to 8), the latter is likely associated with the cessation of winter monsoon and the later inception and augmentation of summer monsoon. The posterior one may correspond to the net outward flows from the SCS to the Pacific through the northern reach of the Luzon Strait, which is in compensation with the intrusion of Kuroshio waters on its south. Recent observations of CHUANG (personal communication) from a moored current meter[9] may partially support the latter speculation. Another interesting point is that the timing of the occurrence of these troughs matches quite well with the onset of southwesterly or northeasterly monsoon respectively. This can not attribute simply to coincidences but might imply the significance of the monsoon driven effects on the SCS circulations.

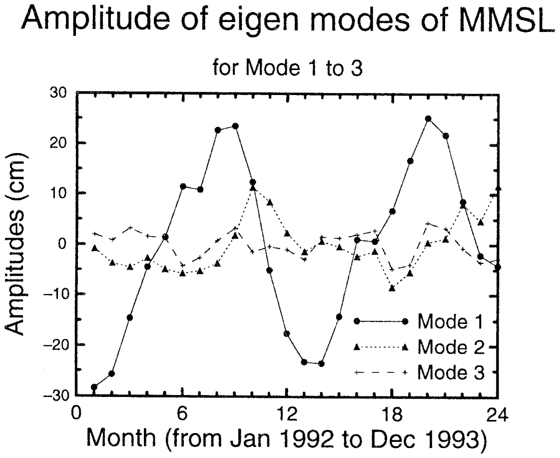

Fig. 10. The time series plot of $E_n(t)$ for all three eigen modes resolved, from January 1992 to December 1993.

Table 2. Empirical eigenfunctions for MMSLs of Kao-Hsiung, San Jose and Port Irene.

Items	Mode 1	Mode 2	Mode 3
λ_n(cm^2)	263.3	28.4	7.1
$\lambda_n/\Sigma\lambda_n$	88.1%	9.5%	2.4%
$\phi_n(x_1)$	0.50	0.50	0.71
$\phi_n(x_2)$	0.37	0.62	-0.69
$\phi_n(x_3)$	0.79	-0.61	-0.12

6. Discussion and summary

Foregoing investigations reveal quite a complicated flow pattern occurred in the northern SCS, which is in general not in accordance with our previous knowledges. Nevertheless, from them we have identified several dynamically-active systems, i.e., firstly, the system with cyclonic flows in the central SCS, which is a common feature for both the spring and summer surveys; secondly, the Luzon Strait branch of Kuroshio and its intrusion motions; and thirdly, the anti-cyclonic gyre south of Formosa Banks as well as its neighbors, the cyclonic eddies west of the Luzon Strait, found during the summer cruise. The synoptic-scale variation of the northern SCS is basically governed by these systems.

The cyclonic-circulation system is likely a permanent feature of the central SCS. The report of SCSIOAS (1985) had documented the finding of a seemingly persistent structure, i.e., a cold eddy appears at southwest of Tung-Sha Tao almost all the year round. Based on Fig. 5, we may suggest that the foregoing two are actually the same thing. However, not all observations support this view point; e.g., in the central SCS, though a cyclonic gyre does present in WYRTKI's (1961) current chart of winter but the position deviates a lot, also it is absent in other seasons[10]. LIU and SU (1992) had suggested a nonlinear adevection mechanism, i.e., the cyclonic system colud be induced by the fluxes of positive vorticity from the west flank of the Kuroshio through the Luzon Strait to the central SCS. However, during summer the thermocline in the northeastern SCS is usually much steeper and shallower than that in the Kuroshio (cf. NITANI, 1970). These might imply upwelling motions are more energetic in the SCS basin. Could the cyclonic syetem be simply a manifestation of the latter activity ? This is an interesting topic deserving for further studies.

The behavior of the Luzon Strait branch of Kuroshio (Fig. 5) is of significance to the interaction of the South China and western Philippine Seas. Extended southward from the southern tip of Taiwan is the Heng-Chun Ridge, a steeply-raised submarine topography. Geostrophic currents calculated, along meridional transects across the Luzon Strait[11], show the segment in between 20.5 and 21°N is seemingly a major pathway for surface waters flushing into or out of the SCS, where the latter latitude is just near the southernmost sill of the foregoing ridge. This suggests the importance of flow-topography interaction on the dynamics of the SCS. With a favorable flow direction, the Kuroshio branch may interact with the ridge; inevitably, this will induce many interesting features, e.g., branching of inflows in front of the ridge (cf. WHITEHEAD 1985) and also its influences on the downstream.

The anti-cyclonic eddy south of Formosa Banks and its counterparts, the cyclonic ones west of the Luzon Strait (Fig. 5), are unknown features that have never been well-documented in literatures hitherto. WANG (1986) had reported the lower layer structure of the cold eddy southwest of Taiwan, whose cyclonic motions could extend from the surface down to 1500 db and even below. However, the connections between this eddy and the cyclonic flows in the central SCS were unknown during that time. Now, from Fig. 5, clearly the former is likely an extension of the latter, but how and why the latter evolves into a series of eddies remains to be studied.

The circulation of the SCS is governed principally by the alternative exertion of northeasterly and southwesterly monsoons as well as the influence from the Kuroshio east of the Luzon Strait; the latter is also a major provider of salt, mass, heat and vorticity to the SCS. This nature has been illuminated by a number of numerical experiments (e. g. SHAW and CHAO 1994; CHAO, SHAW and WU 1996, among others). So, intuitively, we may suggest that the evolution of above-mentioned dynamically-active systems is driven by these factors too. However, the flow pattern in the northern SCS, as emerged from our observations, is far more complicated than that had ever been derived from numerical models. This might be attributed to the coarse resolution or the false usage of open boundary conditions, especially across the Luzon Strait, in the numerical calculation. Recently, a scientific plan on the monitoring of currents in the Luzon Strait has been shaped and granted in Taiwan; which anticipates to install several arrays of current-meters and to make repeated CTD surveys, in and across the Luzon Strait, in the following two years. Only through these efforts can details of the foregoing processes be clarified.

In summary, in terms of field hydrographic

---

[8] Perhaps in the form of a loop current, as suggested by LI and WU (1989).

[9] Which shows persistently eastward to southeastward flows occurred from late October of 1994 to February of 1995, where the location of the current matter is in the northern Luzon Strait (CHUANG, 1995).

[10] Neither found in numerical model results derived from climatological data, e.g. SHAW and CHAO (1994).

[11] For those cruises shown in Table 1, as well as others not cited.

surveys and the MMSLs of coastal tide stations, we may suggest that the flow pattern of the northeastern SCS is governed basically by aforementioned dynamical systems. The less variant one is likely the cyclonic system located at the northern central SCS basin to the northwest of north Luzon, in which is the center of the monsoon-driven cyclonic gyre in winter, but the stem of a series of cyclonic eddies in summer; the latter then separates the Kuroshio east of the Luzon Strait and the anticyclonic eddy south of Formosa Banks. After the onset of winter monsoon, the northern extension of the cyclonic system withdraws southwards, meanwhile the Luzon Strait branch of the Kuroshio penetrates into the northeastern SCS and the intruded waters, as well as circulating waters, may develop anticyclonic gyres or eddies in the northern SCS during winter and spring (WANG and CHERN, 1987a). As the cessation of winter monsoon in spring, the intruded Kuroshio waters retreat eastwards and northwards; some of them are flushed out through the Taiwan Strait by the northward currents along the west coast of Taiwan (the Kuroshio branch in the Taiwan Strait, WANG and CHERN, 1988), the remainder may form a loop-like flow pattern in the northeastern SCS. As time goes by, the aforementioned cyclonic system, stimulated further by the inception and augmentation of summer monsoon, extends northwards continuously. So, the anti-cyclonic gyre at the northern SCS breaks; one of it, the loop pattern, migrates to the Pacific side of the Luzon Strait gradually (Figs. 6-8), the rest, still in the form of anticyclonic motions but having a much reduced size, resides at the south of Formosa Banks in summer; the space left is then replaced by cyclonic eddies penetrated from the central SCS (Fig. 5). Obviously, the scenario is quite different from that presented by WYRTKI's (1961) flow chart; so far many aspects are preliminary and some of them still obscure, all of these deserve for further studies in the future.

Acknowledgments

This study is sponsored by the National Science Council, the Republic of China, Grants No. NSC83-0209-M-002A-017 and NSC84-2611-M-002 A-016OS. The MMSL data are provided by BODC (for San Jose and Port Irene) and CWB (for Kao-Hsiung), respectively.

References

CHAN K. -M. (1970): The seasonal variation of hydrological properties in the northern South China Sea. *In* The Kuroshio-A Symposium on the Japan Current, J. C. MARRY, (ed). East-West Center Press, Honolulu, 143–162.

CHAO S. -Y., P. -T. SHAW and WU S. Y. (1996): El Niño Modulation of the South China Sea. Deep Sea Res. (submitted.)

CHU T. -Y. (1970): Report on the variation of velocity and volume transport of the Kuroshio. *In* The Kuroshio - A Symposium on the Japan Current J. C. Marr, (ed). East-West Center Press, Honolulu, 163–174.

CHU T. -Y. (1972): A study on the water exchange between Pacific Ocean and the South China Sea. Acta Oceanogr. Taiwanica, **2**, 11–24.

CHU T. -Y. (1976): Study of the Kuroshio current between Taiwan and Ishigaki-jima. Acta Oceanogr. Taiwanica, **6**, 1–24.

FAN K. -L. (1982): A study of water mass in Taiwan Strait. Acta Oceanogr. Taiwanica, **13**, 140–153.

HU T. -K. (1995): On the distribution of water masses in the northern South China Sea during springtime. Master Thesis, Institute of Oceanography, National Taiwan University (in Chinese).

KUNDU P. K., J. S. ALLEN and R. L. SMITH (1975): Modal decomposition of the velocity field near the Oregon coast. J. Phys. Oceanogr. **5**, 683–704.

LI L. and B. -Y. WU (1989): A Kuroshio loop in South China Sea ? - on circulations of the northeastern South China Sea. Taiwan Strait **8**, 1, 89–95 (in Chinese with English abstract).

LIU X. -B. and SU J. -L. (1992): A reduced gravity model of the circulation in the South China Sea. Oceanologia et Limnologia Sinica, **23**, 2, 167–174 (in Chinese with English abstract).

NITANI H. (1970): Oceanographic conditions in the sea east of the Philippines and Luzon Strait in summers of 1965 and 1966. *In* The Kuroshio - A Symposium on the Japan Current, J. C. MARRY, (ed). East-West Center Press, Honolulu, 213–232.

QIU D. -Z., T. -H. YANG and Z. -X. GUO (1984): A westflowing current in the northern part of the South China Sea in summer. Tropic Oceanology, **3**, 4, 65–73 (in Chinese with English abstract).

SCSIOAS (1985): A research report on the general survey of the South China Sea (Ⅱ). Science Pub., Beijing (in Chinese).

SHAW P. -T. (1989): The intrusion of water masses into the sea southwest of Taiwan. J. Geophys. Res., **94**, 18213–18226.

Shaw P. -T. and S. -Y. Chao (1994): Surface circulation in the South China Sea. Deep Sea Res., **41**, 1663 1683.

Wang J. (1986): Observation of abyssal flows in the northern South China Sea. Acta Oceanogr. Taiwanica, **16**, 36–45.

Wang J. and C. -S. Chern (1987a): The warm-core eddy in the northern south China Sea. I. Preliminary observations on the warm-core eddy. Acta Oceanogr. Taiwanica, **18**, 92–103 (in Chinese with English abstract).

Wang J. and C. -S. Chern (1987b): The warm-core eddy in the northern south China Sea. II. A simple mechanism for the establishment and development of the warm-core eddy. (Acta Oceanogr. Taiwanica, **18**, 104–113 (in Chinese with English abstract).

Wang J. and C. -S. Chern (1988): On the Kuroshio branch in the Taiwan Strait during wintertime. Prog. Oceanogr., **21**, 469–491.

Whitehead J. A. (1985): The deflection of a baroclinic jet by a wall in a rotating fluid. J. Fluid Mech, **157**, 79–93.

Wu B. -Y. (1982): Some problems on circulation study in Taiwan Strait. Taiwan Strait, **1**, 1, 1–7 (in Chinese with English abstract).

Wyrtki K. (1961): Scientific Results of Marine Investigations of the South China Sea and the Gulf of Thailand 1959–1961-Physical Oceanography of the Southeast Asian Waters. Naga Report, Vol.2, pp. 195.

Xu J. -P. and J. -L. Su (1993): Water mass analysis on the Kuroshio water intruding into the South China Sea (abstract). Abstracts of the Taiwan Strait and nearby marginal seas oceanography workshop, August 12–16, Amoy, China.

Recieved January 4, 1996
Accepted May 31, 1996