Chinese Science Bulletin **2006 Vol. 51 No. 4 472—479**

DOI: 10.1007/s11434-006-0472-2

Barrier layer in the northeastern South China Sea and its formation mechanism

PAN Aijun, WAN Xiaofang, XU Jindian,
GUO Xiaogang & LI Li

Environment and Dynamics Laboratory, Third Institute of Oceanography, State Oceanic Administration, Xiamen 361005, China
Correspondence should be addressed to Pan Aijun (email: aijunpan@tiosoa.cn)

Abstract Robust evidence for the barrier layer (BL) in the northeastern South China Sea (SCS) (16°—25°N, 112°—124°E) is presented. The occurrence rate of the BL peaks in the autumn (45.7%) and then the summer (31.1%) and the spring (23.3%), sequently. It is estimated that the annual occurrence rate of the BL reaches about 40.0% in the central northeastern SCS (18°—22°N, 112°—120°E) and the Luzon Strait. Stratification-formed (Rain-formed) mechanism is the major factor responsible for the occurrence of the BL in the northeastern SCS in the spring (the summer and autumn), respectively. The rainfall observation from TRMM provides reliable evidence for the latter.

Keywords: South China Sea, barrier layer, ocean stratification, rainfall, Luzon Strait.

A vertically uniform layer of temperature (isothermal layer), salinity (isohaline layer) and density (mixed layer) is usually formed in the upper ocean due to the wind stirring. Underneath is the layer with relatively strong vertical gradient as the thermocline, halocline and pycnocline. However, the depth of the isothermal layer (H_T) is not usually identical to the isohaline layer depth or the mixed layer depth (H_D)[1] (Fig. 1). Lindstorm *et al.*[2] first detected that the isothermal layer depth surpasses the mixed layer depth during two cruises conducted in the western Pacific warm pool, that is, between the base of the mixed layer and the upper boundary of the thermocline there is a layer with quasi-uniform temperature and strong vertical gradient

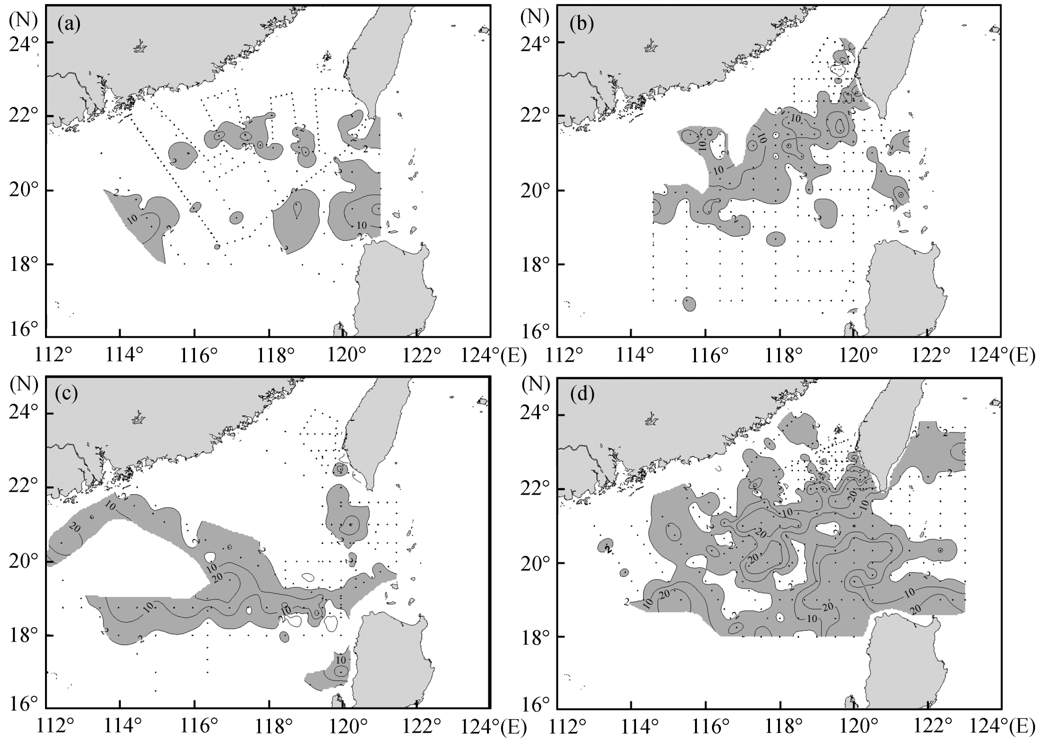

Fig. 1. Seasonal variation of the barrier layer and its thickness (unit: m) in the northeastern SCS. (a) March, 1992; (b) May, 1998; (c) June—July, 1998; (d) August—September, 1994.

of density, which is named the barrier layer (BL) by Godfrey *et al.*[3] The BL greatly inhibits the downward transport of the surface heat forcing, leading to the anomalous local warming of the upper ocean in some cases[4]. As a result, the anomalous atmospheric circulations and ocean-atmosphere interactions may be activated and possible climate variability could be induced.

Former studies on the BL are mainly focused on the equatorial ocean[5−11]. Chu *et al.*[1] explored the BL in the regional sea (Sulu Sea and Celebes Sea). Domestic researches on the BL in China are mostly devoted to the southern SCS[4,12]. Recently, Du *et al.*[13] presented the climatological feature of the BL and its formation mechanism with emphasis in the southern SCS using Levitus94 dataset. However, the sparsely vertical sampling rate of the climatology data is unable to provide the convincible results. Study of the BL in the northern SCS is reported recently[14]. In the present study we tend to focus our attention on the BL in the northeastern SCS (16°—25°N, 112°—124E°) (including the Taiwan Strait), by presenting the seasonal feature, evaluating its seasonal occurrence rate and exploring its formation mechanism.

1 Data

Historical CTD data adopted in this paper are provided by the "Cooperative Investigation and Study on the Circulation in Northeastern South China Sea"[15,16] and the "South China Sea Monsoon Experiment (SCSMEX)"[17]. These data are grouped in March 8—27 of 1992 (246 CTD profiles), August 28 to September 10 of 1994 (339 CTD profiles), May 1—25 (283 CTD profiles) and June 9 to July 21 (193 CTD profiles) of 1998, respectively. The vertical sampling interval is 1 m. In addition, monthly surface fluxes from COADS and the high-resolution (0.25°×0.25°) rainfall data from TRMM[18] are used to explore the formation mechanism of the BL in the northeast SCS.

2 Criteria for determining the BL

Usually, there are two types of criteria to determine the isothermal layer depth (H_T) and mixed layer depth (H_D), in terms of difference or gradient[1]. The gradient criterion adopted by Chu *et al.*[1] is suitable for the determination of the thermocline or the pycnocline in the deep ocean. However, part of the research domain in this paper locates in the continental shelf where the water depth is less than 200 m. Thus, two types of gradient criteria are adopted for determining the isothermal layer depth and the mixed layer depth as follows:

Over shallow water area:

$$\partial T/\partial z = 0.2\ ℃\cdot \mathrm{m}^{-1},\ \ \partial \sigma_t/\partial z = 0.1\,\mathrm{kg}\cdot \mathrm{m}^{-4};$$

Over deep water area:

$$\partial T/\partial z = 0.05\ ℃\cdot \mathrm{m}^{-1},\ \ \partial \sigma_t/\partial z = 0.015\,\mathrm{kg}\cdot \mathrm{m}^{-4}.$$

Difference between the isothemal layer depth (H_T) and the mixed layer depth (H_D) is defined as the BL thickness (BLT); BLT $=H_T-H_D$. Meanwhile, two other thresholds for determining whether a BL occurs in a CTD station are further adopted, (1) Individual points with vertical gradient exceeding the criterion are precluded; (2) CTD stations with BLT$\leqslant$1 m are precluded.

3 Seasonal features of the BL and its annual occurrence rate

The northeastern SCS usually refers to the geological location confined by the Luzon Strait, the Taiwan Island, Guangdong Province and the 16ºN latitude. The 200 m isobaths emanating from the Taiwan Island extend southwestward along the shelf break zone. Region ensued by the Luzon Strait, the Taiwan Island and the 200 m isobaths is the deep ocean basin (>2000 m). Taiwan Bank is located at about (118ºE, 23ºN) with water depth less than 30 m, east of which is the Penghu Channel that is deeper than 100 m. The northeastern SCS is connected with the northwest Pacific and the East China Sea through the Luzon Strait and the Taiwan Strait, respectively. Monsoon prevails in the northeastern SCS, which results in the complicated upper ocean circulation.

3.1 Seasonal features

Fig. 1 shows the distribution of the CTD profiles (CTDs) and the seasonal feature of the BL. Among 246 CTDs in March 1992 there are 46 CTDs where BL occurs. The rate of the BL occurrence reaches 18.7% and most of the BL thickness is under 6 m. Discontinuous BL showing the "nubby" pattern with thickness between 2—6 m is detected in the shelf break zone along the 200 m isobaths. Moreover, strong BL (thicker than 10 m) is found in both the outer sea of Guangdong Province (18º—20ºN, 114º—115ºE) and the central Luzon Strait. The maximum value of the BL thickness (about 25 m) is located in the central Luzon Strait at about (19.5ºN, 121.0ºE) (Fig. 1(a)).

By contrast, the occurrence rate of the BL increases greatly in May—July 1998. Among 283 (193) CTDs in May (June—July) there are 79 (60)CTDs where the BL occurs. The rate of the BL occurrence reaches 27.9% (31.1%), respectively (Fig. 1(b), (c)). Most of the BL in May 1998 is found in the shelf break zone, extending southwestward no more than 19ºN. The BL thickness enhances relative to March and part of it exceeds 10 m. Maximum BL thickness (27 m) occurs near the Penghu Channel (21.6ºN, 119.7ºE). Besides, the BL above 2 m is also detected in the central Luzon Strait. With regard to May, BL in June—July is mainly located in the belt zone extending from the northern Luzon Island to the Pearl River Estuary. The BL is thicker than 10 m, part of which surpasses 20 m. Maximum BL of 34 m occurs near the Pearl River Estuary, about (20.5ºN, 112.5ºE).

Among the 339 CTDs from August 28 to September 10 of year 1994 there are altogether 155 CTDs where the BL occurs. Compared with the BL in March—July, the rate of occurrence reaches about 45.7% and most of the BL is thicker than 15 m (Fig. 1(d)). The BL occurs in almost the whole northeastern SCS basin and shows a multi-high-centre pattern (BLT>25 m), which may be related to the mesoscale eddy activities as "eddy shedding" from the Kuroshio [19]. The CTDs with maximum BL of 60 m is located in the central Luzon Strait (20.3ºN, 120.5ºE).

In the present paper, March—May is defined as the spring, June—August as the summer, and so on the analogy of this. CTD observations from August 28 to September 10 of year 1994 are considered to be the autumn. Scatter diagrams of H_T and H_D (Fig. 2) show that the rate of BL occurrence increases gradually from the spring to the autumn. Meanwhile, the BL thickness also enhances with the seasonal trend.

3.2 Annual occurrence rate

The northeastern SCS is uniformly classified as 2°×2° grids within each grid detecting the total CTDs and those CTDs with the BL occurrence; thus the annual occurrence rate of the BL is quantified. It is

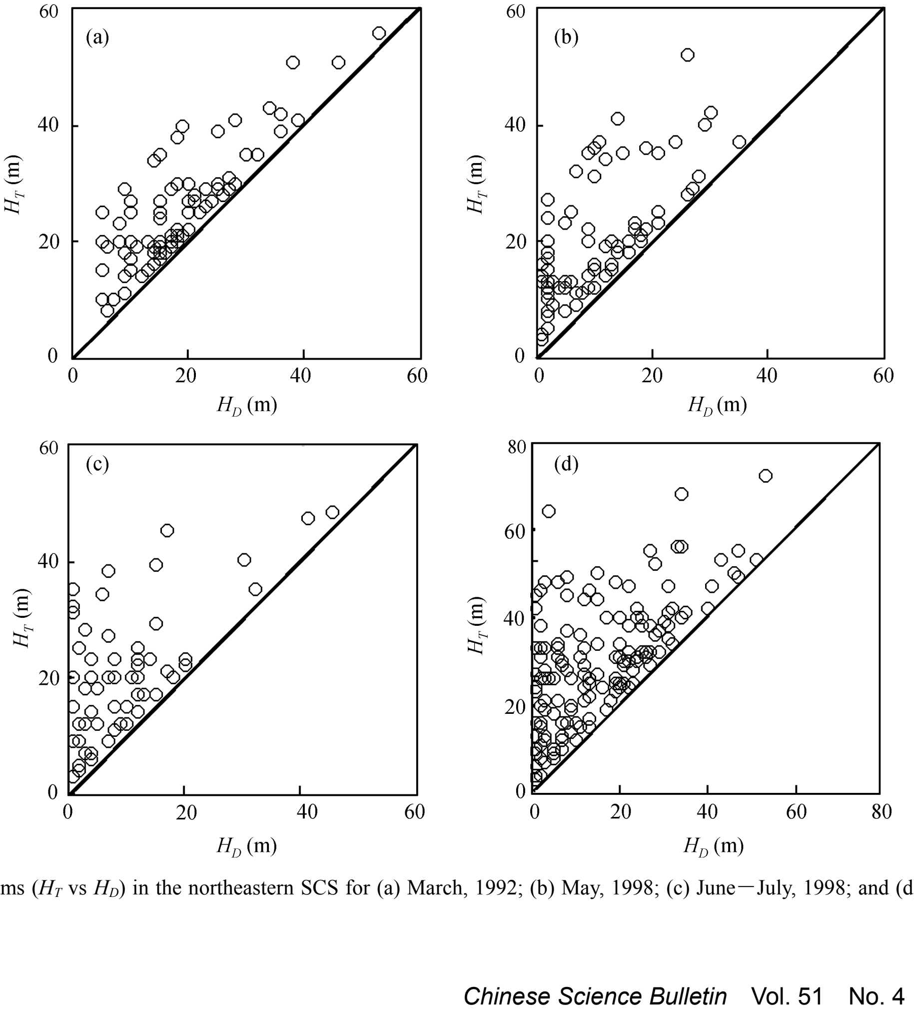

Fig. 2. Scatter diagrams (H_T vs H_D) in the northeastern SCS for (a) March, 1992; (b) May, 1998; (c) June—July, 1998; and (d) August—September, 1994.

defined as: $\text{AOR\_BL}=\frac{\text{CTDs}_{\text{BL}}}{\text{CTDs}_{\text{totoal}}}$. The AOR_BL south of the Taiwan Strait is about 19%. Significant AOR_BL of 40.0% is found in the central northeastern SCS (18º—22ºN, 112º—120ºE) and the Luzon Strait. The BL occurs also frequently on both eastern and western sides of the Taiwan Island (61.1%), the region east of the Taiwan Island (22°—24ºN, 122°—124ºE) (33.3%) and the region northeast of the Luzon Island (18°—20°N, 122°—124ºE) (80.0%), respectively (Fig. 3).

4 Formation mechanism of the BL in the SCS

Chu *et al.*[1] put forward two mechanisms responsible for the BL: the rain-formed mechanism and the stratification-formed mechanism. His theory is of vertically one-dimensional and precludes the possible contribution from the horizontal advection. In the present paper, similar diagnostics on the formation mechanism of the BL in the northeastern SCS is conducted using the ocean surface flux data (net heat flux, wind stress and net freshwater flux (P—E)) from COADS and the high-resolution rainfall data from TRMM.

The surface wind stress, net heat flux and net freshwater flux (P—E) in the northeastern SCS have significant seasonal variability (Fig. 4). The magnitude of the wind stress ranges from 0.20 $\text{N}\cdot\text{m}^{-2}$ in November to 0.02 $\text{N}\cdot\text{m}^{-2}$ in May. The wind stress is weak during the summertime (April—September) and strong during the wintertime (October—March). The net heat flux varies from –197.7 $\text{W}\cdot\text{m}^{-2}$ in December to 99.6 $\text{W}\cdot\text{m}^{-2}$ in May. The net freshwater flux (P—E) has similar seasonal variations to that of the net heat flux with precipitation over evaporation in May—September and ranges from 0.51 $\text{mm}\cdot(3\text{h})^{-1}$ in August to –0.55 $\text{mm}\cdot(3\text{h})^{-1}$ in January.

In March the northeastern SCS is under the influence of relatively strong winds (0.10 $\text{N}\cdot\text{m}^{-2}$), weak surface cooling (–13.0 $\text{W}\cdot\text{m}^{-2}$), and negative net freshwater flux with evaporation over precipitation (–0.31 $\text{mm}\cdot(3\text{h})^{-1}$) (Fig. 4). The whole basin is controlled by the strong northeast monsoon. Heat losses at the ocean surface strengthen northward, which is confined in the northern part of the northeastern SCS[20]. In addition, the net freshwater flux weakens gradually from the shelf break zone to the deep ocean, being unfavorable for the BL formation (Fig. 5). Generally, both great heat losses and strong wind stress favor the “entrainment” regime, which suggest the stratification-formed mechanism for the occurrence of a BL.

Similar atmospheric forcings as the weak surface wind stress (0.02—0.03 $\text{N}\cdot\text{m}^{-2}$), strong surface warming (99.6—94.2 $\text{W}\cdot\text{m}^{-2}$) and the positive net freshwater flux (0.10—0.34 $\text{mm}\cdot(3\text{h})^{-1}$) (Fig. 4) are experienced in May-July. Though the strong net freshwater

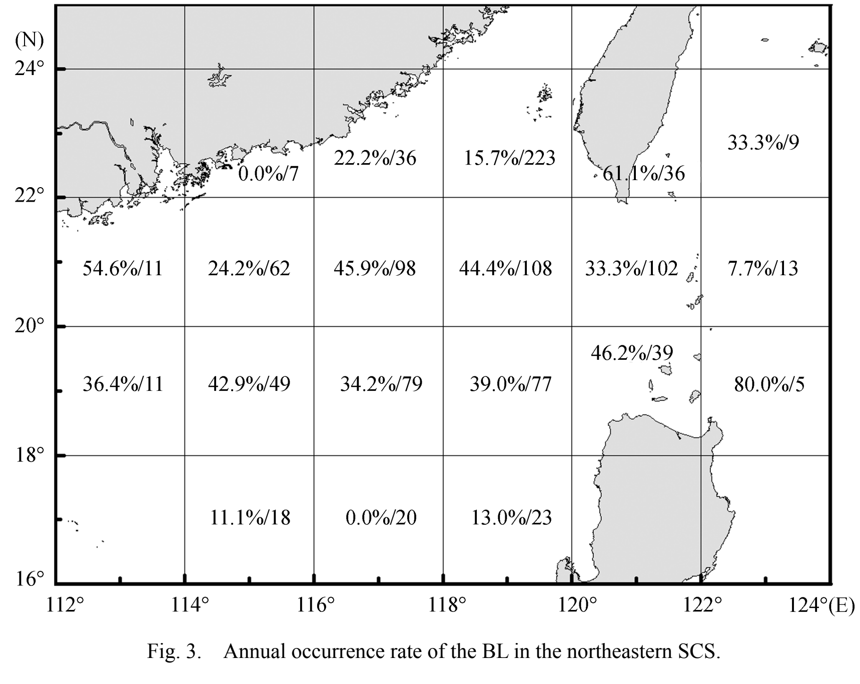

Fig. 3. Annual occurrence rate of the BL in the northeastern SCS.

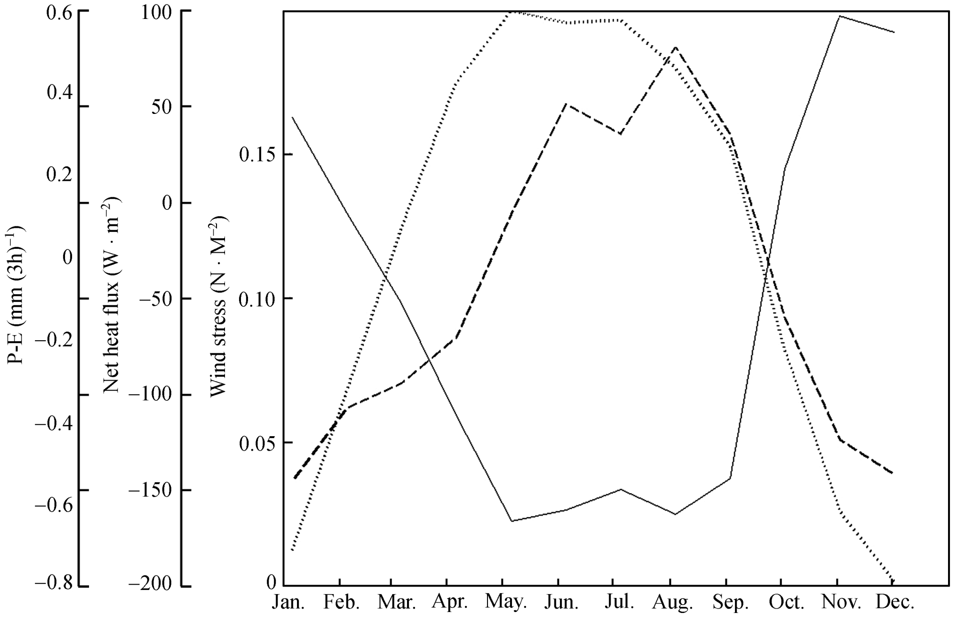

Fig. 4. Seasonal variation of the region-averaged wind stress (solid line, unit: N · m^{-2}), net heat flux (dotted line, unit: W · m^{-2}) and the net freshwater flux (P—E) (dash line, unit: mm · (3h)$^{-1}$) for the northeastern SCS (17°—24°N, 114°—122°E) and data from COADS.

flux (Fig. 5) favors the formation of salinity stratification and then the occurrence of the BL, the strong surface warming and weak winds both cause a shallow isothermal layer that greatly counteracts the contribution from the net freshwater flux. All these conditions are against the growth of the BL during May—July. With regard to May, the northeastern SCS in June-July is under nearly the same surface heat and wind forcing. The only difference is the net freshwater flux, which greatly surpasses that in May (>0.24 mm · (3h)$^{-1}$) and is more favorable for the formation of the BL (Fig. 1). Considering the low spatial resolution of the monthly COADS dataset cannot provide strong evidence for the regional feature of the BL distribution, and concurrent high-resolution rainfall data from TRMM are further adopted. Comparing Fig. 1(b) and (c) with Fig. 6(a) and (b), it is easy to find that the strong rainfall corresponds the local strong BL, which again verifies the rain-formed mechanism for the BL.

In August—September the northeastern SCS is under the influence of weak surface wind stress (0.03 N · m^{-2}), weak surface warming (49.5 W · m^{-2}) and strong freshwater flux (0.41 mm · (3h)$^{-1}$) (Fig. 4). Compared with June-July, the surface freshwater flux increases by 0.07 mm · (3h)$^{-1}$ while the heat gain decreases by 44.7 W · m^{-2}. These conditions favor the occurrence of the BL as the rain-formed mechanism. In short, rain-formed mechanism (in the summer and the autumn) and stratification-formed mechanism (in the spring) are two main mechanisms responsible for the occurrence of the BL in the northeastern SCS.

5 Conclusions

Temperature and salinity profile data, monthly flux data from COADS and rainfall data from TRMM are adopted to present the seasonal features of the BL and to document its formation mechanism in the northeastern SCS (16°—25°N, 112°—124°E). In the autumn (August 28—September 10 of 1994) the occurrence rate of the BL reaches as high as 45.7% and most of the BL is thicker than 15 m. The BL exhibits a spatial pattern of multi-high-center (BLT>25 m), which may be induced by the eddy activities as "eddy shedding[19]" from the Kuroshio. In summer (June—July 1998) the BL occurrence rate is 31.1% and is mainly located in the belt zone extending from the northern Luzon Island to the Pearl River Estuary with part of the BLT exceeding 20 m. Least occurrence rate (23.3%) of the BL is found in the spring (March 1992 and May 1998). In the early spring (March 1992) except for the central Luzon Strait and the western side of the Dongsha Archipelago, the BL in most of the research regions is no more than 6 m. In the later spring (May 1998) the BL is mainly

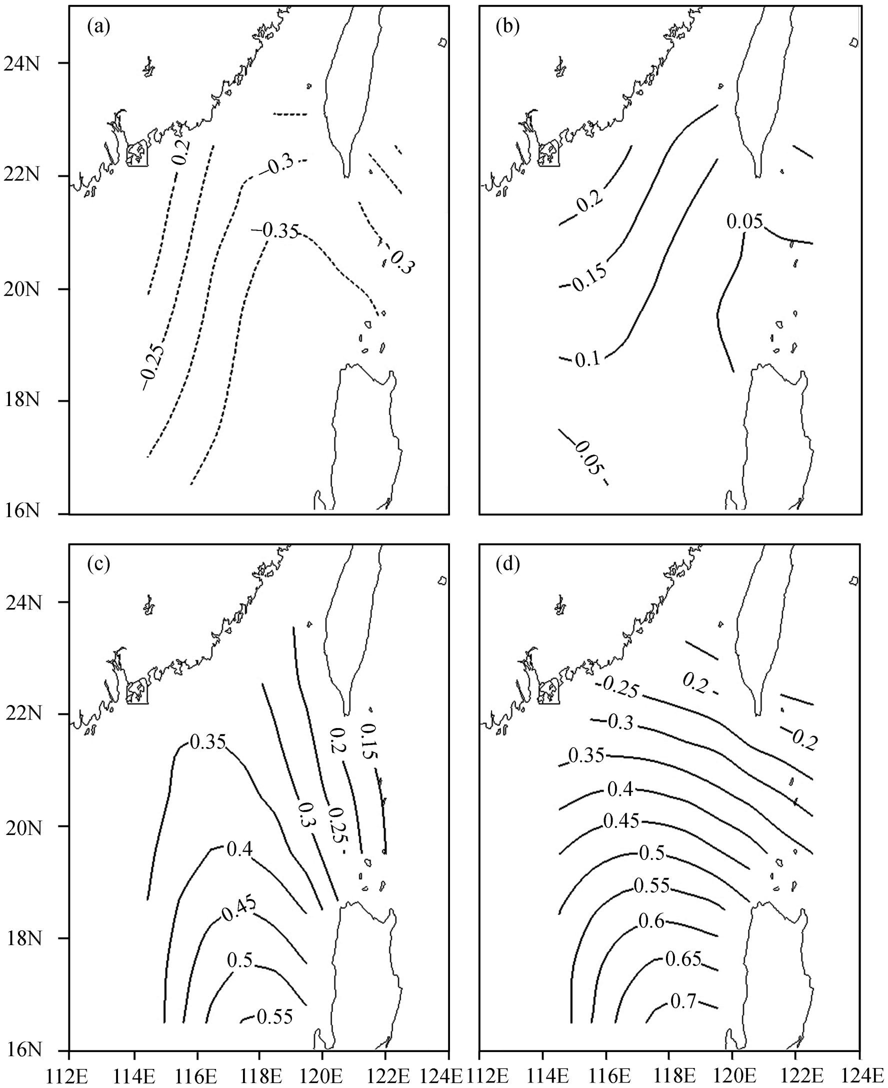

Fig. 5. The net freshwater flux of March (a), May (b), June—July (c) and August—September (d) for the northeastern SCS (unit: mm·(3h)$^{-1}$), and data from COADS.

located in the shelf break zone and extends southwestward by no more than 19ºN.

High AOR_BL of 40.0% is detected in the Luzon Strait and the central northeastern SCS (18º—22ºN, 112º—120ºE). Besides, the BL occurs also frequently on both eastern and western sides of the Taiwan Island (61.1%), the region east of the Taiwan Island (22º—24ºN, 122º—124ºE) (33.3%) and the region northeast of the Luzon Island (18º—20ºN, 122º—124ºE) (80.0%), respectively. Stratification-formed (rain-formed) mechanism is the main factor responsible for the occurrence of the BL in the spring (the summer and autumn) in the northeastern SCS, respectively, and TRMM observations provide reliable evidence for the rain-formed mechanism.

6 Discussion

If we draw a contour line sketchily following the AOR_BL of 40.0% in Fig. 3, a “tongue” of the BL occurrence zone extending westward from the Luzon Strait can be quantified. Intuitionally, it may be linked with the Kuroshio intrusion. Considering that (1) the upper 300 m Kuroshio is warmer and more saline than the water of SCS, (2) the net fresh water (Fig. 5) and the net heat flux[20] have no corresponding spatial pattern with that of the BL. Thus, It can be deduced that the geostrophic advection as Kuroshio may be another

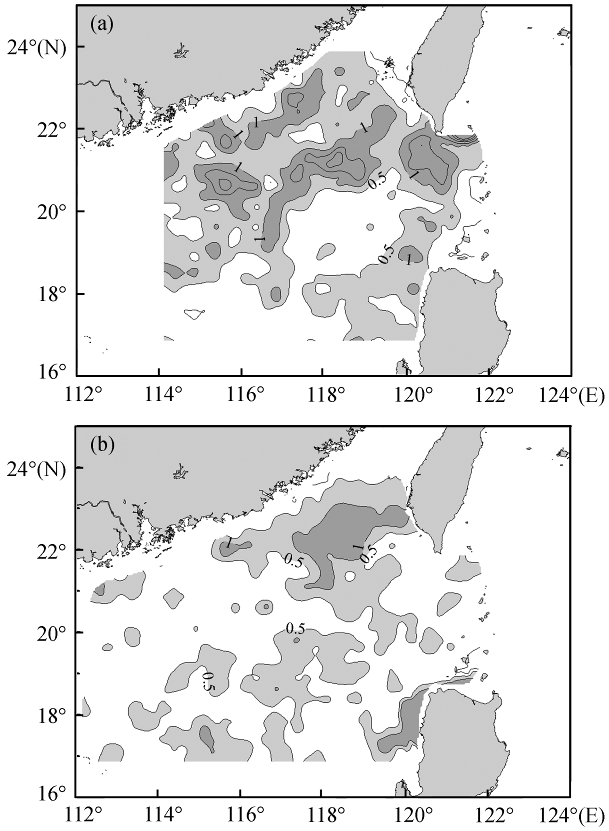

Fig. 6. Rainfall from TRMM (CI=0.5 mm·h^{-1}) for (a) May, 1998; (b) June—July, 1998; shaded areas are with rainfall larger than 0.5 mm·h^{-1}, and the dark shaded area with rainfall larger than 1.0 mm·h^{-1}.

possible formation mechanism. Because the rainfall is quite weak and the rain-mechanism fails to explain the occurrence of the BL in the spring, the Kuroshio intrusion should be responsible for the BL as the stratification-formed mechanism. Moreover, Kuroshio may intrude the SCS as the form of “eddy-shedding[19]”, which could be responsible for the multi-high-centre pattern of the BL in the autumn (August 28 to September 10 of year 1994). Further numerical simulations should be done for the exact contribution of Kuroshio on the BL in the northeastern SCS.

The western part of our research region is adjacent to the Pearl River Estuary; each year (especially in the summer and autumn) there is a large volume of fresh water joining the northeastern SCS. In the summer and autumn (especially the former) the upper ocean of the northeastern SCS is under the control of the southwest monsoon, which drives the southeast Ekman flow and the less saline water is carried to the deep sea. A shallow halocline (pycnocline) is thus formed due to the ocean advection. Spatial pattern of the BL in June—July of 1998 (Fig. 1(c)) is consistent with the above explanations and thus verifies that the ocean advection (Ekman advection here) should be another formation mechanism for the BL in the northeastern SCS. Of course, more evidence from data analysis and numerical simulations is needed for further document.

Moreover, the BL occurs in the shelf break zone southwest of the Taiwan Island in both May and August—September, while the BL occurrence zone in June—July (Fig. 1(c)) is only confined between 18º—20ºN and is inconsistent with the distribution of the main rainfall belt (Fig. 6(b)). This is caused by the data deficit for there is no CTDs in the shelf break zone in June—July (Fig. 1(c)) and thus, the corresponding BL cannot be detected.

Though a large amount of historical CTD data has been collected, covering almost the whole research region with relative high spatial sampling rate. For the data are only got in different seasons of 1992, 1994 and 1998, possible errors caused by the interannual variability cannot be precluded. We just hope to provide a relatively comprehensive view of the climatology feature of the BL in the northeastern SCS based on the data that could be collected at present. Here we still tend to owe the present conclusions to the “seasonal” timescale and hope to set up the foundation favorable for further study. Though it may contain some uncertainties, then how strong is the interannual variability? This issue still needs more observations and numerical studies.

From the definition of the BL, we know that the BL could enhance apparently the stability of the ocean stratification, which would effectively hinder the vertical heat transport and leads to a local warming of the upper ocean[4]. The local BL would also induce the local anomaly of the sea surface, which may activate the local anomalous atmospheric circulation. In the present paper, the threshold of the BL is defined with the criterion of BLT>1 m, which is quantified from the vertical sampling space of the CTDs. If we preclude the limit of the data, then it is truly important to clarify how strong the BL is. Though Wu *et al.*[4] verified the warming effect of the BL, quantification estimation is still needed to study the feedback of the BL on the upper ocean. This issue is related with the turbulence problem in the upper ocean and to elucidate it needs more moored observations and numerical simulations.

Generally, robust evidence of the BL in the northeastern SCS is provided in the present paper. Further study is to focus on the formation and the maintenance mechanism of the BL and its feedback on the upper ocean thermal structure, which favors our deep understanding on the ocean mixing processes and air-sea interactions.

Acknowledgements This work was supported by the Key International Science and Technology Cooperation Projects, Ministry of Science and Technology of the People's Republic of China (Grant No. 2002CB714001), the National Natural Science Foundation of China (Grant No. 40231012) and the Natural Science Foundation of Fujian Province (Grant No. Z0515010).

References

1. Peter Chu, Qinyu Liu, Yinglai Jia *et al.*, Evidence of a barrier in the Sulu and Celebes Seas, Journal of Physical Oceanography, 2002, 32: 3299－3309.
2. Lindstorm, E., Lukas, R., Fine, R. *et al.*, The Western Equatorial Pacific Ocean circulation study, Nature, 1987, 330: 533－537.
3. Godfrey, J. S., Lindstorm, E., The heat budget of the equatorial western Pacific surface surface mixed layer, Journal of the Geophysical Research, 1989, 94(C6): 8007－8017.
4. Wu Wei, Tomczak, M., Fang Xinhua, Barrier Layer in the southern South China Sea, Chinese Science Bulletin, 2001, 46(7): 590－594.
5. Lukas, R., Lindstorm, E., The mixed layer of the western equatorial Pacific Ocean, Journal of Geophysical Research, 1991, 96: 3343－3357.
6. Sprintall, J., Tomczak, M., Evidence of the barrier layer in the surface layer of the tropics, Journal of Geophysical Research, 1992, 97 (C5): 7305－7316.
7. Feng, M., Hacker, P., Lukas, R., Upper ocean beat and salt balances in response to a westerly wind burst in the western equatorial Pacific during TOGA COARE, Journal of Geophysical Research, 1998, 105(C5): 10289－10311.
8. You, Y., Rain-formed barrier layer of the western equatorial Pacific Warm Pool: A case study, Journal of Geophysical Research, 1998, 103(C3): 5361－5378.
9. Vialand, J., Delecluse, P., An OGCM study for the TOGA decade, Part I: Role of salinity in the physics of the western Pacific fresh pool, Journal of Physical Oceanography, 1998, 28: 1071－1088.
10. Swenson, M. S., Hanson, D. V., Tropical Pacific Ocean mixed layer budget: The Pacific cold tongue, Journal of Physical Oceanography, 1999, 29: 69－81.
11. Kara, A. B., Rochford, P., Hurlburt, A. H. E., Mixed layer depth variability and barrier layer formation over the North Pacific Ocean, Journal of Geophysical Research, 2000, 105: 16783－16801.
12. Zhu Liangsheng, Qiu Zhang, Seasonal distribution and variation of barrier layer and its influence upon the vertical heat diffusion in the southern South China Sea, Acta Oceanologica Sinica, 2002, 24(s1): 171—178.
13. Du Yan, Wang Dongxiao, Shi Ping *et al*., Seasonal Variation of the Barrier Layer in the South China Sea and Its Relationship to the Sea Surface Flux, Chinese Journal of Atmospheric Sciences, 2004, 28(1): 101－111.
14. Jia Xujing, Liu Qinyu, Sun Jilin, A comparison between two Different Definitions of the Mixlayer and the Thermocline in the South China Sea, Transactions of Oceanology and Limnology, 2001, (1): 1－7.
15. Research Group of the Circulation in northeastern South China Sea, Study on the Circulation in Northeastern South China Sea, Oceanography in China (Vol. 6) (in Chinese), Beijing: China Ocean Press, 1996, 109.
16. Xu Jianping, Su Jilan, Hydrographic analysis on the intrusion of the Kuroshio into the South China Sea II. Observational Results during the Cruise from August to September in 1994, Tropic Oceanology, 1997, 16(2): 1－22.
17. Xu Jindian, Lili, Guo Xiaogang *et al.*, Multi-Eddy Features of South China Sea Circulation around onset of Summer Monsoon in 1998, Journal of Tropical Oceanography, 2001, (1): 44－51.
18. Wentz, F. J., Gentemann, C., Smith, D. *et al.*, Satellite measurements of sea surface temperature through clouds, Science, 2000, 288: 847－850.
19. Jia Yinglai, Liu Qinyu, Eddy Shedding from the Kuroshio Bend at Luzon Strait, Journal of Oceanography, 2004, 60 (6): 1063－1069.
20. Wang Dongxiao, Zhou Faxiu, Li Yongping, On the features in the annual cycle of SST and surface heat budget in the South China Sea, Acta Oceanologica Sinica, 1996, 15(1): 111－125.

(Received August 16, 2005; accepted October 19, 2005)