NOTES

The barrier layer in the southern region of the South China Sea

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Abstract **By analysing the CTD data in the southern region of the South China Sea gathered during six cruises between 1989 and 1999, a barrier layer with seasonal variation just like what exists in the equatorial oceans is found in this region. It is the first discovery in such a marginal sea yet. It is strong in autumn and a little weak in summer and winter. The thicker the barrier layer, the higher the average temperature of the upper mixed layer. The region with the thicker barrier layer overlaps the region with the higher average temperature of the upper mixed layer, and accords with the thicker region of the warm pool in the South China Sea got from the Levitus data. The barrier layer in the southern region of the South China Sea has significant influence on the heat storage of the upper ocean there.**

Keywords: barrier layer, South China Sea, thermocline, pycnocline, mixed layer.

In the upper ocean or sea, there is generally a mixed layer, with nearly homogeneous water temperature and density produced by wind mixing. Below the mixed layer there is a layer where the water temperature and density vary repidly with depth, that is thermocline and pycnocline respectively. In general, though the depths of the tops of the thermocline and pycnocline nearly overlap each other, Lindstrom et al.[1] discovered that the depth of the top of the thermocline is much deeper than that of the pycnocline in the western equatorial Pacific Ocean during two cruises in 1987. Between the two depths density increases with depth while the temperature remains nearly homogeneous. The combination of the near-zero vertical temperature gradient and the significant gravitational stability makes downward heat transport from the ocean surface difficult. This poses a closure problem in the upper ocean for the heat budget if the net surface heat flux is not negligible (which is rare in the ocean). In 1989, Godfrey et al.[2] named the layer "barrier layer". As stated above, the barrier layer is specifically referred to a heat barrier layer.

Due to the significant effects of the barrier layer on the upper ocean heat budget and of the equatorial oceans on the globe climate variation, the phenomenon of the barrier layer was studied in all equatorial ocean regions, including its geographical distribution and its seasonal variation, the mechanisms of its formation and maintenance[3, 4], its evolution and effect on the heat flux[5] and its numerical models[6]. In the western equatorial Pacific Ocean, the existence of the barrier layer is intimately related to a high positive precipitation-evaporation balance. The barrier layer mostly enhances the formation and maintenance of the equatorial warm pool, raises the temperature of the surface layer and forces the heat transporting horizontally, so it might strengthen the ENSO phenomenon. As a consequence, it has attracted the attention of international cooperative research efforts such as TOGA, TOGA-COARE and TOGA-COARE-IOP.

So far, the studies on the barrier layer have been focused on the equatorial oceans and no work about the barrier layer in a marginal sea such as the South China Sea has been found in references. By analyzing the CTD data in the southern region of the South China Sea gathered during six cruises between 1989 and 1999, a barrier layer just like what exists in all equatorial oceans is found in this region. Its thickness clearly varied seasonally and was intimately related with the average temperature in the upper mixed layer. Fig. 1 gives an example of the curves of temperature (T)-depth, salinity (S)-depth and density (σ_t)-depth collected by a CTD cast in September 1994. The horizontal solid line and dashed line in the figure are the top depths of the thermocline and the pycnoline respectively, and the water layer between them is the barrier layer.

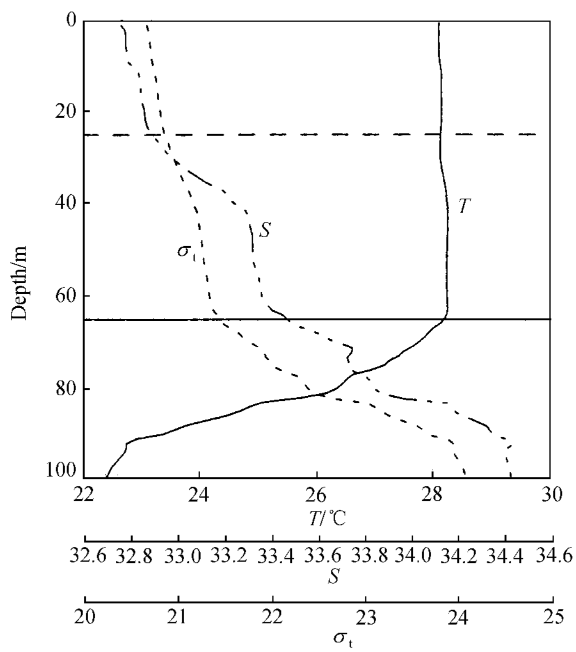

Fig. 1. Temperature (T), salinity (S) and density (σ_t) as functions of depth at one CTD cast of the September 1994 survey. The horizontal dashed line and solid line are the top depths of the pycnocline and rmocline respectively. The water layer between the two horizontal lines is the barrier layer.

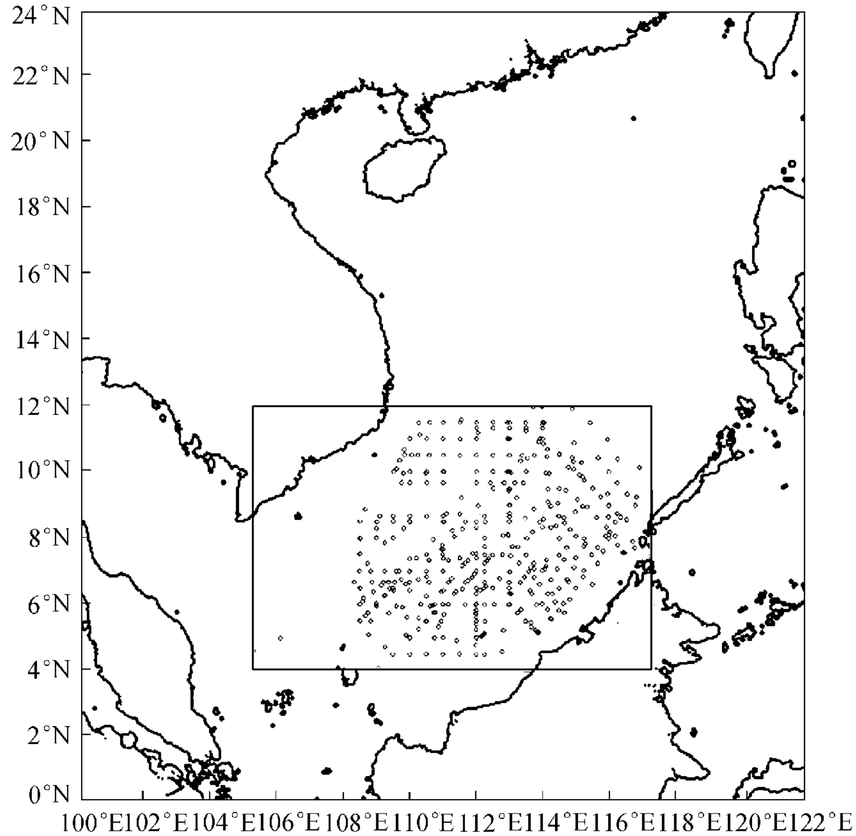

Fig. 2. A map of the South China Sea showing the locations of CTD casts during the six surveys between 1989 and 1999.

1 Data and methods

The CTD data in the southern region of the South China Sea used here were collected during six oceanographic surveys between 1989 and 1999. The locations of the CTD casts in all surveys are shown in fig. 2. The surveys were performed respectively in December 1989, May—June 1990, December 1993, September 1994, November 1997 and July 1999. The data were processed according to [7,8], and got the fine data with 10000 Pa interval before the analyses of physical oceanography. And then the following three methods were used to identify the depths of the tops of the thermocline and pycnocline. The water layer between the two calculated depths was referred to the barrier layer.

Method 1. Following [9], the thermocline is defined as the water layer where the temperature gradient exceeds $0.05℃ \cdot m^{-1}$ and the pycnocline as that where the density gradient exceeds $0.015\ m^{-1}$. Occasionally these threshold gradients are exceeded at single data points or over a very small depth range. These cases are not considered to represent the thermocline or pycnocline and are discarded.

Method 2. This method replicates the procedure used by [3]: The top depth of the thermocline is defined as the depth where the temperature drops to 0.5°C below the observed sea surface temperature (SST), while the density of the top depth of pycnocline is calculated with the sea surface salinity (SSS) and the temperature on the top depth of the thermocline there.

Method 3. The top depth of the thermocline is determined by method 1. The top depth of the pycnocline is determined by method 2.

2 Results

The results from the three methods above are quite similar in most cases, especially on the average values. But at some locations the top depth of the thermocline derived from method 2 was greatly deeper than that from method 1, while the opposite was true for the top depth of the pycnocline. So the thickness of the barrier layer was significantly thicker than that from method 1 there. The reason is that method 2 depends strongly on observed SST and SSS, which are both lowered by local rain. It then brought great errors to the analyzed results on the thermocline and pycnocline. Therefore, the results got from method 1 are used in the present analyses.

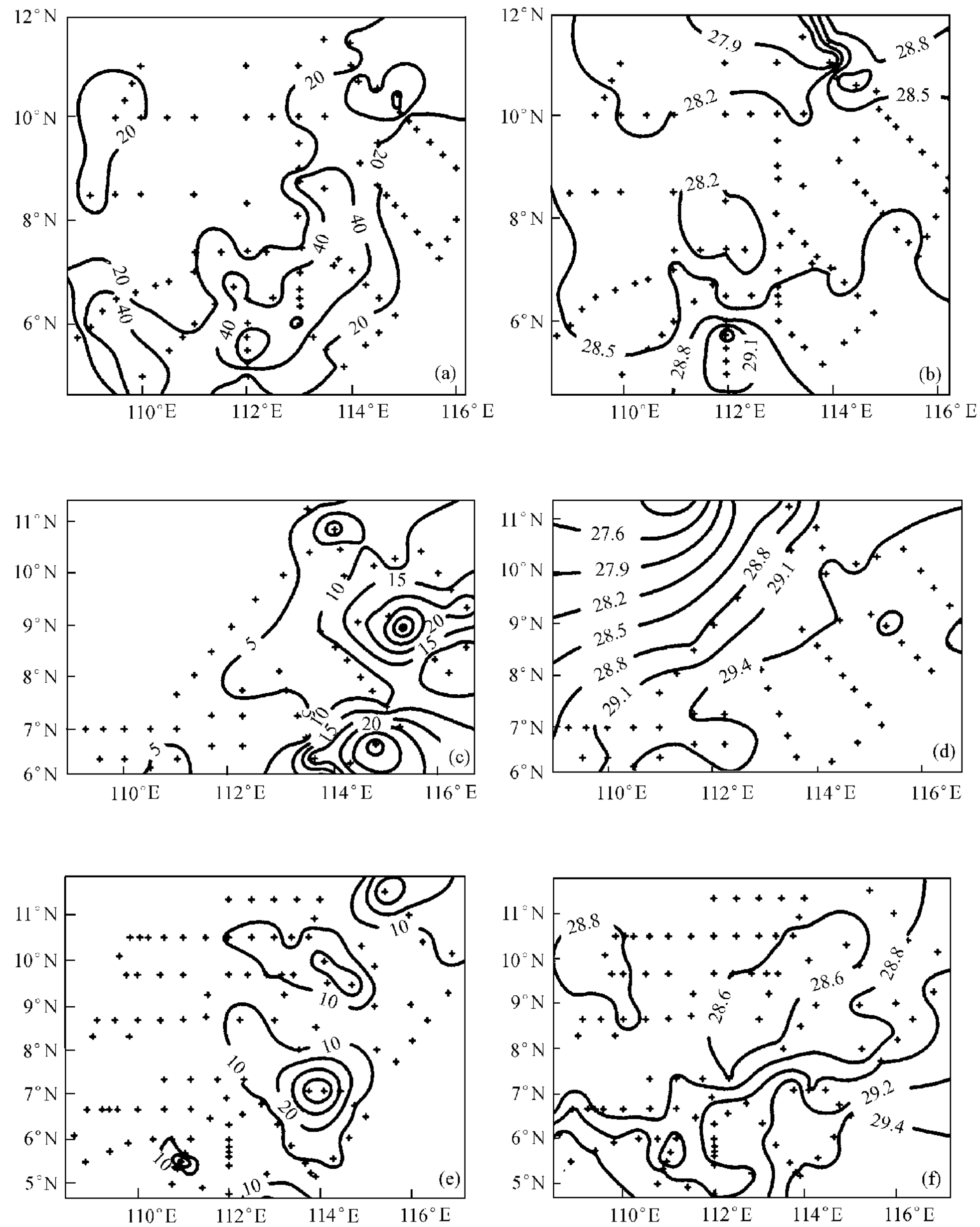

Fig. 3. The comparisons of the geographic distribution between the thickness of the barrier layer and the average temperature of the upper mixed layer. Crosses show the positions of the CTD casts. (a), (c) and (e) are the thickness (m) of the barrier layer (m) during the September 1994, the November 1997 and the July 1999 surveys respectively. (b), (d) and (f) are the average temperature (℃) of the upper mixed layer during the September 1994, November 1997 and July 1999 surveys respectively.

Though the three methods produce somewhat different results, the results all showed the existence of the barrier layer in the southern region of the South China Sea. According to the analyzed results of the six surveys, the barrier layer was much thicker in the region surrounding the line from (116°E, 12°N) to (112°E, 4.5°N) near the Palawan Trough in the southern region of the South China Sea and the southwestern corner (about the west from 110°E and the south from 6°N) linking with it, and out of this region there was much weak or even no barrier layer (fig. 3). For example, in fig. 3(a) the thickness in the thicker barrier layer region mentioned above was mostly larger than 30 m, even up to 50 m or above, while it was less than 30 m outside the region. Similar results were got from the surveys of November 1997 and July 1999 (fig. 3(b), (c)).

Table 1 Some characteristics of the barrier layer during the six surveys

Survey	Total number of CTD casts	No. of CTD casts with BL	Mean thickness of BL/m	Maximum thickness of BL/m	Location of thickest barrier layer/BL
December 1989	40	31	7.1	48	(115.90° E, 8.08° N)
From May to June 1990	36	21	4.1	28	(115.96° E, 9.34° N)
December 1993	76	58	5.2	29	(113.50° E, 5.50° N)
September 1994	111	100	22.9	66	(113.01° E, 6.01° N)
November 1997	66	58	8.5	38	(114.79° E, 6.69° N)
July 1999	109	89	8.3	49	(114.09° E, 7.08° N)

The barrier layer was the most strongly developed in autumn (September 1994). Its maximum thickness was up to 66 m and average thickness was up to 22.9 m. But it was a little weak in other seasons (see also table 1 and fig. 3(a),(c),(e)). However, most of the CTD casts in December 1989, December 1993 and from May to June 1990 were out of the thicker barrier layer region mentioned above. It may be one of the reasons why the average thickness of their barrier layers was thinner during these surveys.

It should particularly be pointed out that the average temperature of the upper mixed layer was higher in the region where the barrier layer was thicker. The thickest thicknesses of all the six surveys were reached in the thicker warm water region of the warm pool in the South China Sea (SCSWP)[10] (table 1). Fig. 3 shows the comparisons of the geographic distribution between the thickness of the barrier layer and the average temperature of the upper mixed layer of the surveys in September 1994, November 1997 and July 1999 respectively. It can be seen that in the thicker barrier layer regions the average temperatures of the upper mixed layer were close to or above 28.5℃, 29.4℃ and 28.8℃ respectively (fig. 3(b),(d), (f)). Therefore, the regions with the thicker barrier layer and with the higher average temperatures of the upper mixed layer overlapped, and accorded with the region of the thicker SCSWP got from the Levitus data[10].

3 Discussion

As stated previously, the barrier layer with clear seasonal variation exists in the southern region of the South China Sea, and a corresponding relationship exists clearly between the thickness of the barrier layer and the average temperature of the upper mixed layer. Then two questions will be arise: What are the mechanisms of its formation and maintenance? And which effects does it have on the upper ocean heat budget in the regions? For them, a simple discussion was given here by analyzing the data available and further studies must be done later.

The studies on the barrier layer in the equatorial Pacific Ocean showed that local heavy rainfall is the important mechanism to produce and maintain the barrier layer in the western Pacific Ocean[3, 4]. But there is no such observed evidence in the southern region of the South China Sea, where local heavy rainfall is unable to accumulate so much fresh water to produce a substantial barrier layer. To discover the mechanisms, further studies are needed. It is supposed that the strong monsoon wind mixing, local currents and sea surface heat flux could be the main factors for its formation and maintenance.

The analyses of the seasonal and annual variation of the barrier layer in the southern region of the South China Sea are unfortunately limited by lack of the data. But the results here suggest that the barrier layer in the southern region of the South China Sea has clear seasonal variation, namely it is strong in autumn and a little weak in summer and winter.

The corresponding relationship between the thickness of the barrier layer and the average temperature of the upper mixed layer may indicate that local heat storage increases in the mixed layer while a barrier layer exists. The fact that the regions with a thicker barrier layer in fig. 3, the regions with higher average temperature of the upper mixed layer, and the thicker regions of the SCSWP[10] overlap each other makes the above conclusion more reliable. It has long been observed that the summer SST in the deeper region in the southern region of the South China Sea is often higher than that in the shallower region around its perimeter. This is contrary to the more common situation that the water in the shallow region is warmer than that in the deep sea in summer. Therefore, the existence of a barrier layer may be the reason why the observed higher SSTs in the deeper part of the southern region of the South China Sea in summer are formed. In view of the fact that enhancing heat storage in the mixed layer depends on the barrier layer characteristics, therefore it can be concluded that the barrier layer in the southern region of the South China Sea has significant influence on the heat storage of the upper ocean there. Further work is required to investigate the time-space scale of the barrier layer in the southern region of the South China Sea before drawing definite conclusions about its importance to the heat budget of the South China Sea.

Acknowledgements We thank Prof. Gan Zijun for his valuable suggestions to the manuscript. This work was supported by the National Key Science Project (Grant No. 97-926-05-02) and the National Natural Science Foundation of China (Grant No. 49976002) and the Research Foundation for the Doctoral Program of Higher Education of China (Grant No. 98042306)

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(Received January 11, 2001)