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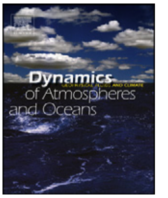

Barrier layer in the South China Sea during summer 2000

Lili Zeng[a], Yan Du[a,b,*], Shang-Ping Xie[b], Dongxiao Wang[a]

[a] *Key Laboratory of Tropical Marine Environmental Dynamics, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, PR China*

[b] *International Pacific Research Center and Department of Meteorology, SOEST, University of Hawaii, Honolulu, HI, United States*

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ABSTRACT

Using temperature–salinity profiles obtained from a cruise in summer 2000, the structure and formation of the barrier layer (BL) in the South China Sea (SCS) are investigated. Fresh water flux, ocean circulation, and wind stirring are important for BL formation, depending on regions. In the eastern SCS, Philippine mountains induce heavy rainfall, resulting in a fresh water cap at the surface and the formation of a thick wide spread BL. In the northwestern basin on the lee of the Annam Cordillera range, by contrast, a rain shadow reduces fresh water flux, which along with wind-induced upwelling, prevents the BL forming. Southeast of Vietnam, a thick BL forms as the Mekong River plume is advected by the northeastward western boundary current and its offshore extension. In the southeastern basin, the surface water is mixed deeply under the strong southwesterly monsoon, unfavorable for the BL formation despite heavy rainfall. In the Luzon Strait, the east/southeastward surface Ekman drift carries fresh SCS surface water, riding on the intruding Kuroshio meander that carries well-mixed, warm and saline water. The vertical overlapping of these two water masses gives rise to a thick BL.

1. Introduction

Ocean stratification with a surface isothermal layer (IL) deeper than the mixed layer (ML) is recognized as early as 1936 on Meteor cruises (Defant, 1961). The salinity-stratified IL between the ML and

* Corresponding author at: Key Laboratory of Tropical Marine Environmental Dynamics, South China Sea Institute of Oceanology, Chinese Academy of Science, 164 West Xingang Road, Guangzhou 510301, PR China. Tel.: +86 20 89023180; fax: +86 20 84451672.

E-mail address: duyan@scsio.ac.cn (Y. Du).

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the top of the thermocline is referred as a barrier layer (BL) as it acts as a barrier to turbulent entrainment of cold thermocline water into the ML (Godfrey and Lindstrom, 1989; Lukas and Lindstrom, 1991). In the equatorial Pacific between 10°N and 25°N, surface freshwater fluxes and strong wind bursts are main mechanisms for modulating the BL formation (Ando and McPhaden, 1997). In the subtropical North Pacific, the subduction of high saline water is responsible for the BL formation in winter (Sato et al., 2004). In the tropical Atlantic, Silva et al. (2005) investigate the role of continental river flows in the formation of shallow pycnocline. Recently, many studies begin to investigate the BL in marginal seas. Chu et al. (2002) reveal the existence of the BL in Sulu and Celebes Seas. Shenoi et al. (2004) study the influence of remote forcing on the BL in the southeastern Arabian Sea. In the Bay of Bengal, surface circulation redistributes the low salinity waters and changes the distribution of BL during monsoon seasons (Vinayachandran et al., 2002; Thadathil et al., 2007).

The South China Sea (SCS) is a large tropical marginal sea under strong monsoon influence. The prevailing winds are southwesterly in summer and northeasterly in winter (Liu and Xie, 1999). The SCS connects the western Pacific and the eastern Indian Ocean via many straits. Among these straits, the Luzon Strait is of most importance, where the Kuroshio intrusion is regarded as one of the most important processes to the SCS ocean circulation (Qu, 2000; Qu et al., 2000, 2004, 2005, 2006; Gan et al., 2006; Wang et al., 2006a; Yu et al., 2008). The SCS basin is surrounded by mountains, many higher than 500 m, such as the Annam Cordillera range in western Vietnam and mountain ranges on the Philippine islands. Xie et al. (2006) reveal that Asian narrow mountain ranges anchor monsoon convection centers. As the southwest summer monsoon impinges on narrow mountains, moisture-laden air is forced to rise, causing intense convection on the windward side. Much of orographic precipitation falls over or flows through rivers into the ocean. Around the SCS, the Pearl River, Red River, and Mekong River are three largest (Fig. 1). Their volume transports show large seasonal variations. Take the Mekong River as an example; the river runoff during July–October accounts for about 70% of the annual discharge ($\sim 5.2 \times 10^{11}$ m^3, Dai and Trenberth, 2002), about 16% of the total rainfall in the SCS basin during the same time ($\sim 3.2 \times 10^{12}$ m^3). The SCS receives fresh water from both local rainfall and river discharge.

Several studies investigate the BL in the SCS. Using in situ observations, Wu et al. (2001) and Zhu and Qiu (2002) describe the spatial structure of BL in the southern SCS. Pan et al. (2006a,b) discuss the BL distribution over the northeastern and central SCS. Using a climatology derived from historical observations, Du (2002) and Du et al. (2004) study the seasonal cycle of ML and BL, and relate them to monsoonal winds and surface heat fluxes. With the summer monsoon onset in May, increased winds stir the upper ocean and a thick ML forms with uniform temperature and salinity. In the presence of strong rainfall from June to October, fresh water forms a shallow ML. The BL isolates the isohaline surface layer from the cool thermocline.

The paucity of in situ observations has limited the above studies to describing general features of the BL, and its formation mechanism over the SCS remains unclear. The present study investigates the spatial distribution of the BL and its formation mechanism in the summer SCS. We analyze cruise observations in summer 2000, a year that can be regarded as normal (Wang et al., 2006b) without a strong El Niño/Southern Oscillation (ENSO) event. Satellite measurements are used to study dynamical and thermodynamical processes important for the BL formation. We attempt to relate the formation of SCS BL to atmospheric processes such as surface winds and precipitation. The BL affects the heat exchange between the ML and thermocline, and thereby between the ocean and atmosphere, processes important for the maintenance of warm pool in the SCS (Chu and Chang, 1997).

The paper is organized in the following manner. Section 2 describes briefly the data and analysis method. Section 3 presents the background atmospheric and ocean conditions in summer 2000. Section 4 describes the general characteristics of the upper ocean stratification and the BL's horizontal distribution. Section 5 investigates sub-basin features of the BL distribution and its formation mechanism based on cruise transects. Section 6 is a summary and discussion.

2. Data and methods

The cruise took place from 2 August to 3 September 2000, a joint survey by the Second and Third Institutes of Oceanography of the State Oceanic Administration, and the South China Sea Institute of Oceanology under the support of the National Key Basic Research Development (so-called