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Formation of spring warm water southwest of the Philippine Islands: Winter monsoon wake effects

Qinyu Liu*, Chengxue Sun, Xia Jiang

Physical Oceanography Laboratory, Ocean–Atmosphere Interaction and Climate Laboratory, Ocean University of China, Qingdao 266100, China

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ABSTRACT

From satellite observations and the reanalysis data, the late spring formation of warm water with temperature higher than 30 °C to the southwest of the Philippine Islands (8–18°N, 115–120°E) is investigated. Our analysis suggests that the blockage of the winter monsoon by the Philippine Islands results in this "Luzon warm water" (LWW) to the southwest of the Luzon Island and the "Vietnam cold tongue" (VCT) to the southeast of the Vietnam coast during winter and early spring in the South China Sea (SCS). The VCT is formed by the southward cold advection by the western boundary current and surface heat loss in the SCS. During the winter monsoon, the LWW first forms due to weak winds southwest of the Philippine Islands and the countering effect of warm Ekman advection against cold geostrophic advection. In spring its temperature exceeds 30 °C (LWW30), helped by strong solar radiation and the winter monsoon wake effect lee of the Philippine Islands. With the winter monsoon weakening, LWW30 extends southwestward in late spring but disappears quickly after the summer monsoon onset. Reduced latent heat flux in the winter monsoon wake is the dominant factor for the spring fast warming southwest of the Philippine Islands.

Both VCT and LWW persist from winter to early spring as the Philippine Islands block the winter monsoon. Their interannual variations are correlated with the variation of the LWW30 since the blockage of the winter monsoon by the Philippine Islands modifies surface latent heat flux and ocean advection from winter to early spring. These results strongly suggest that the LWW30 is a result of land–sea–winter monsoon interaction.

* Corresponding author at: Songling Road 238#, College of Physical Oceanography and Marine Environment, Ocean University of China, Qingdao 266100, China. Tel.: +86 532 66782556; fax: +86 532 66782556.
E-mail address: liuqy@ouc.edu.cn (Q. Liu).

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1. Introduction

The South China Sea (SCS) is an important source of water vapor during the summer monsoon in East Asia. In the South China Sea, spring (April to May) is the transition period from winter to summer monsoon. Yan (1997) indicated that the warm water of the SCS extends northwards rapidly in April and May, which provides sufficient heat and water vapor for the onset of the summer monsoon in the SCS. From observations, Chu et al. (1997) studied the warm pool (SST higher than 28 °C) in the central and eastern parts of the SCS during spring, which was called the SCS warm pool. They concluded that it is caused by the increase of solar radiation and the convergence of upper layer flow by the negative wind stress curl, under the control of the subtropical high.

Analysis of the SCS warm pool has since been an active area of research (e.g. Yang and Liu, 1998 among others). From the spatial structure and seasonal variation of the warm water, Jia et al. (2000) and Liu et al. (2002) showed that the local surface heating was the dominant cause of the rapid increase in the warm water thickness. Analysis of heat balance (Yang et al., 1999; Wang et al., 2006) demonstrated the importance of net surface heat flux in forming the spring warm water. Significant cooling ensued after the onset of the southwest monsoon as ocean circulation overcame the warming effect of the surface heat flux (Wang and Wang, 2006). Qu (2001) studied the relationship among SST, surface heat flux, wind stress, mixed layer depth, and entrainment rate during the boreal spring in the SCS. His analysis also emphasized that, despite the dominance of net surface heat flux in the annual SST cycle, oceanic dynamical processes cannot be neglected. These results are consistent with earlier numerical experiment results (Liu et al., 1997) that sea surface wind interacts with the upper ocean circulation and is important for the SST distribution in the SCS.

Further studies have since focused on specific spatial features of the SST. High-resolution satellite data (Xie et al., 2003; Liu et al., 2004) revealed the existence of cold filaments in the summer and cold tongues in winter caused by ocean current advection. Liu et al. (2004) first proposed to divide the winter SCS into two regions along the southwest diagonal: Ekman upwelling in the southeastern basin, and downwelling in the northwestern basin, respectively. In particular, the Ekman upwelling, which occupies most of the deep SCS (depth >200 m), drives a basin-scale cyclonic gyre in the SCS. In boreal winter south of Vietnam, the cold advection along the western boundary forms a conspicuous gap in the Indo-Pacific warm pool, which was also referred to as the "Vietnam cold tongue" (VCT) (SST < 26 °C). The SST is much higher east of the VCT region, especially southwest of the Philippine Island. We refer to the warmer water southwest of the Philippine Island (8–18°N, 115–120°E) as the "Luzon warm water" (LWW).

Chu and Chang (1997) first discovered the existence of the warm water with temperature higher than 30 °C west of the Philippine Islands in 1996 spring. Similar phenomenon was found in 1998 (Li, 1999) before the summer monsoon onset. The warm SST usually exists in the SCS before the monsoon onset, and plays an important role in the summer monsoon onset (Wu and Wang, 2001; Ding et al., 2004). High-resolution satellite data confirmed the presence of the warm water with temperature higher than 30 °C west of the Philippine Islands in 1998–2005, the emergence and rapid extension of the warm water appears to affect local convection and summer monsoon onset (Jiang et al., 2006).

Interannual variations in SCS are related to the ENSO, a large-scale mode of climate variability. In summer interannual SST variance has a local maximum over the climatologically cold filament, with variance much greater than the variance in the adjacent Indian and western Pacific Oceans. The cold filament variability displays significant lagged correlation with SST in the eastern equatorial Pacific and Indian Oceans (Xie et al., 2003). In winter, the interannual variability of the VCT is associated with changes in the winter monsoon al wind curl, the latter closely related to the El Nino and Southern Oscillation in the Tropical Pacific (Liu et al., 2004). Short wave radiation and latent heat flux anomalies are the major contributors to the first peak of the SCS SST anomalies in February (Wang et al., 2006).

In comparison, there was relatively little research on interannual variability of the warm water in late spring. In order to understand the interannual variation of warm water with temperature higher than 30 °C southwest of the Philippine Islands (8–18°N, 115–120°E) (LWW30), Table 1 summarized the correlation coefficients between SST in May and the local surface net heat flux (winter