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Long-term changes of South China Sea surface temperatures in winter and summer

Young-Gyu Park [a,b,*], Ara Choi [a]

[a] Ocean Circulation and Climate Research Center, Physical Oceanography Division, Korea Institute of Ocean Science and Technology, Ansan, Republic of Korea
[b] Department of Integrated Ocean Sciences, Korea University of Science and Technology, Daejeon, Republic of Korea

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ABSTRACT

Utilizing available atmospheric and oceanographic reanalysis data sets, the long-term trend in South China Sea (SCS) sea surface temperature (SST) between 1950 and 2008 and the governing processes are investigated. Both winter and summer SST increased by comparable amounts, but the warming patterns and the governing processes were different. Strong warming in winter occurred in a deep central area, and during summer in the southern region. In winter the net heat flux into the sea increased, contributing to the warming. The spatial pattern of the heat flux, however, was different from that of the warming. Heat flux increased over the coastal area where warming was weaker, but decreased over the deeper area where warming was stronger. The northeasterly monsoon wind weakened lowering the shoreward Ekman transport and the sea surface height gradient. The cyclonic gyre which transports cold northern water to the south weakened, thereby warming the ocean. The effect was manifested more strongly along the southward western boundary current inducing warming in the deep central part. In summer however, the net surface heat flux decreased and could not contribute to the warming. Over the southern part of the SCS, the weakening of the southwesterly summer monsoon reduced southeastward Ekman transport, which is parallel to the mean SST gradient. Southeastward cold advection due to Ekman transport was reduced, thereby warming the surface near the southeastern boundary of the SCS. Upwelling southeast of Vietnam was also weakened, raising the SST east of Vietnam contributing to the southern summer warming secondarily. The weakening of the winds in each season was the ultimate cause of the warming, but the responses of the ocean that lead to the warming were different in winter and summer.

1. Introduction

The South China Sea (SCS) has area about 3.5 x 10^6 km^2 and is the largest marginal sea off the coast of east Asia (Fig. 1). To the north it is connected with the East China Sea through the shallow Taiwan Strait less than 100 m deep, and to the North Pacific through the Luzon Strait, deeper than 2000 m. To the south it is connected with the Sulu Sea through the shallow Mindoro strait of about 200 m depth, and the Java Sea through the Karimata strait shallower than 50 m. The deep basin, where the maximum depth is about 5000 m, is located in the northern central part.

The SCS is under the influence of the East Asian Monsoon and shows strong seasonal variability as reported in earlier studies, for example Wyrtki (1961), Chu et al. (1997), Liu et al. (2001), Chu et al., (1999), Ho et al. (2000). Basically, during the northeasterly winter monsoon period, cyclonic circulation occurs, while during the southwesterly summer monsoon period, anticyclonic circulation occurs (Fig. 2). In Asian marginal seas such as the East/Japan Sea (Yeh et al., 2010) and Yellow Sea (Yeh and Kim, 2010; Xie et al., 2002) where monsoonal effects are strong, warming trends due to the weakening of the winter monsoon have been reported. The SCS is no exception: Fang et al. (2006) reported that between 1993 and 2003 sea surface height (SSH) and sea surface temperature (SST) showed strong increasing linear trends, but, as they pointed out, the time span of the data was not long enough to infer long-term trends.

Zhang et al. (2010) reported that the SCS has become warmer due to global warming since 1990, and the warming trend is greater during winter. They further argued that the warming in winter is mainly due to ocean advection and damped by the surface heat flux, except in the southern part of the SCS. In summer both surface heat flux and oceanic advection contribute to the warming. They, however, did not present a clear explanation for the cause of the oceanic advection. In addition their analysis was for the waters along the entire coast of East and Southeast Asia,

* Corresponding author at: Ocean Circulation and Climate Research Center, Physical Oceanography Division, Korea Institute of Ocean Science and Technology, Ansan, Republic of Korea.
E-mail address: ypark@kiost.ac.kr (Y.-G. Park).

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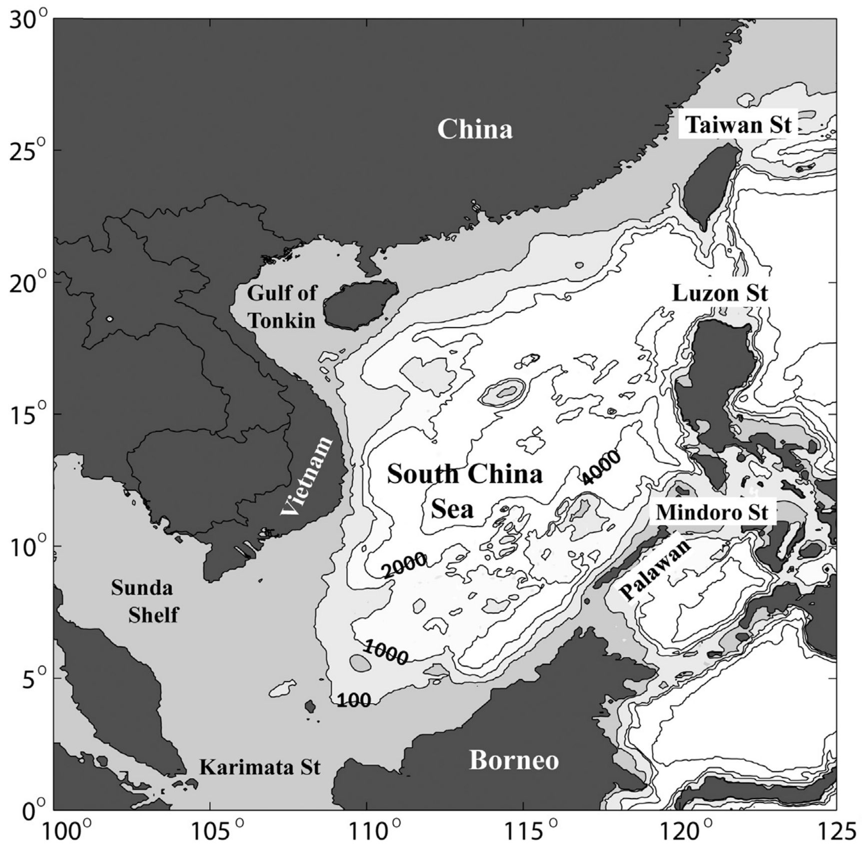

Fig. 1. Map of the study area.

and detailed processes for the SCS were not fully discussed.

Bao and Ren (2014) conducted an in-depth analysis of the long-term change in SST in the SCS, and other areas along the Chinese coast, since 1870. They reported that the SCS showed robust warming signals that were closely related to the monsoon through a comparison between a monsoon index and the mean temperature east of Vietnam where a cold water tongue is located. They suggested that the summer monsoon weakened, thus reducing the upwelling east of Vietnam and warming the area. The upwelling is a localized phenomenon due to the southwesterly wind along the coast (Chen et al., 2012; Pohlmann, 1987), so scrutiny of the local wind is necessary. More importantly, as we will display later, another part of the SCS showed stronger warming, but this phenomenon was not investigated. In winter the weakening monsoon was also correlated with warming, but how the change in monsoon induced the warming was not explained. Although Zhang et al. (2010) suggested an important role for oceanic advection, this effect was not investigated.

In this paper we investigate changes in the sea surface temperature of the SCS since the 1950s, together with their causes, using available oceanic and atmospheric reanalysis data as in Zhang et al. (2010), Bao and Ren (2014). The warming pattern we present here is similar to those reported by previous studies, because we are using a similar data set. Our study differs from the previous ones in being more focused on the processes governing the warming. In addition we are focused on the SCS, and show that even within the SCS different oceanic processes are acting in different seasons and areas.

The plan of this paper is as follows. In the next section we give an account of the data set we utilized. We then describe changes in the sea surface temperature for the past 50 years along with the governing processes. Finally we summarize our results and conclude.

2. Data

To assess changes in SST over the SCS, we utilized monthly reconstructed SST data from the Hadley Centre (Hadley Centre Sea Ice and Sea Surface Temperature data set; HadISST) between 1950 and 2008 (Rayner et al., 2003). The data set has $1^\circ \times 1^\circ$ spatial resolution and is reconstructed using a two-stage reduced-space optimal interpolation procedure, followed by superposition of quality-improved gridded observations onto the reconstructions to restore local detail. In addition, we analyzed surface wind and heat flux data from NOAA-CIRESS 20th C Reanalysis, version 2 (20CRv2), containing synoptic observation-based estimates of global tropospheric variability spanning the period from 1871 to 2010 at 6-hourly temporal and $2^\circ \times 2^\circ$ spatial resolutions (Compo et al., 2011). It is a comprehensive global atmospheric circulation data set, assimilating only surface pressure and using monthly Hadley Centre SST and sea ice distributions (HadISST1.1) as boundary conditions.

Ocean current and sea surface temperature data from the Simple Ocean Data Assimilation V.2.2.4 (SODA, Carton and Giese, 2008) are also utilized. The assimilation is calculated using a general circulation model based on the Parallel Ocean Model (POP) (Smith et al., 1992), which has average resolution 0.25° meridionally, and 0.4° zonally and 40 vertical levels with spacing varying from 10 m near the surface to 250 m near the bottom (5375 m). To compute mixing, the ocean model uses a vertical K-profile parameterization (KPP), while lateral sub-gridscale processes are modeled using biharmonic mixing (Carton and Giese, 2008). The ocean circulation model is forced using 20CRv2 atmospheric data. SODA 2.2.4 output data are remapped onto a horizontal 0.5°x0.5° grid (75.25°S- 89.25°N, 0.25°E–0.25°W). This oceanic reanalysis data set is available for the period between 1950 and 2008. The HadISST is analyzed only during this period, for consistency. Bao and Ren (2014) analyzed the entire HadISST.

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