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Effect of the Yellow Sea warm current fronts on the westward shift of the Yellow Sea warm tongue in winter

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ABSTRACT

Based on long-term and high resolution NOAA/NASA AVHRR Pathfinder SST data and applying new indices, the present study gives a quantitative description of the pattern and interannual variation of the westward shift of the warm tongue (WSWT) relative to the bathymetric trough of the Yellow Sea (YS), which was only qualitatively mentioned in the previous works. The thermal fronts associated with the warm tongue are also accurately determined using a newly presented front-detection method. A new mechanism on the WSWT is presented according to the significant physical relations between the WSWT and fronts. The originally northward flowing YS warm current (YSWC) source water is prevented by the front on its northern side (YF-N), which resides in the east-west direction and across the entrance of the YS trough, from advancing further northward along the YS trough. Instead, the warm water is induced to flow westward along the front and connect with the northward flowing compensating flow in the interior YS, forming the entire westward shifted YS warm tongue. Observations confirm the above hypothesis by revealing the fact that when the northern front moves more southward or becomes stronger, the WSWT enhances. The other local dynamics, such as the wind in the YS and the YSWC itself, do not directly influence the WSWT; however, they do modulate it through determining the position and strength of the YF-N.

1. Introduction

The Yellow Sea (YS) warm current (YSWC), as one of main components of the YS circulation, is the only flow transporting warm and salt water toward the YS and Bohai Sea in winter (Le and Mao, 1990). In winter months this current is more often identified by a surface warm tongue penetrating the interior YS due to vertical homogeneity of temperature than the directly observed velocities which are much weaker than tidal currents. So, in the previous studies the warm tongue is often regarded as the indicator of the YSWC.

The warm tongue is one of the main thermal phenomenons in the YS in winter. Based on historic data (Le and Mao, 1990; Editorial Board for Marine Atlas, 1992; Tang et al., 2000, 2001) and satellite remote sensing data (Bao et al., 2002), the warm tongue was found to extend westward from west of Cheju Island till about 34°N, and then turn to northeastward before entering the North YS and the Bohai Sea with its main axis west of the deepest YS bathymetric trough, which is called the westward shift of the warm tongue (WSWT) (Fig. 1). This northeastward extending main tongue, along with a branch warm tongue separating from the main warm tongue between 34°N and 35°N and extending northwestward, composes a double warm tongue pattern (Wang and Liu, 2009). Though obvious interannual shifts in WSWT were noticed from limited observations (Tang et al., 2001), no objective method was applied to determine the accurate index of the WSWT, nor was detailed interannual variation described and analyzed from a viewpoint of long-term data. Furthermore, the mechanism why YSWC shits westward relative to the deepest YS trough is not clear. For example, Xie et al. (2002) suggested that possibly the causes were the westward Ekman drift caused by the northerly wind and advection from a northward flow on the western flank of the bathymetric trough and/or a southward flow near the Korean coast. Huang et al. (2005), however, argued that the barotropic transport driven by sea surface height (SSH) and the baroclinic transport driven by horizontal density gradients play the major roles in the shifting, while the Ekman wind drift plays a minor role. In this study, we present an alternative mechanism for the WSWT from the viewpoint of the effects of fronts and the frontal circulations.

The thermal fronts emerge where the warm YSWC water meets the cold water which is resulted from both the local cooling and the southward flowing cold coastal currents. Historic

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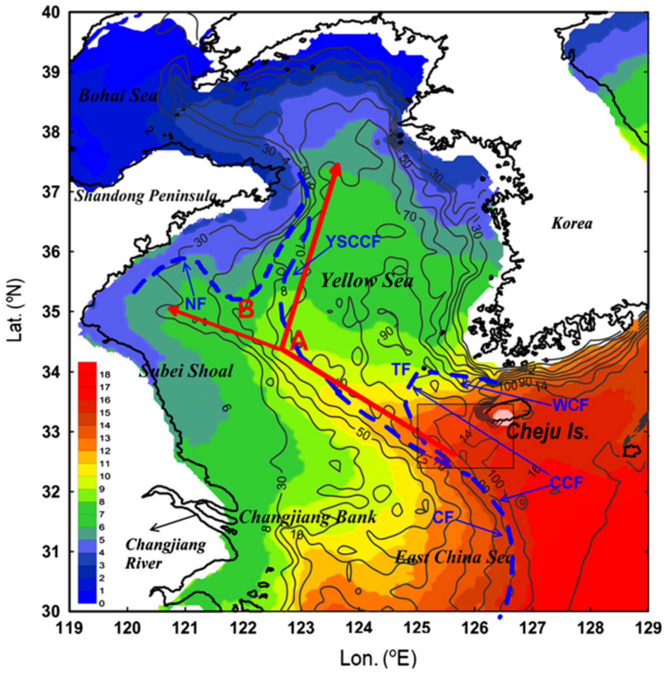

Fig. 1. The bottom topography (in m, contours) and the SST climatology of February (in °C, shaded) of the YS. The thick dashed blue lines present the sea (surface) thermal fronts revealed by the previous work, see text for details. The thick solid red lines indicate the axes of the main and branch warm tongues. Point A is the turning point of the main warm tongue axis from northwestward to northeastward, which represents the west most position of the main warm tongue axis. Point B represents the extent of the double-tongue pattern. The square roughly denotes the YSWC source region.

and satellite remote sensing data revealed a narrow front expanding southeastward along the edge of shoals off Chinese coast from central South YS to northern East China Sea (ECS) which is called YS coastal current front by Ning et al. (1998) ("YSCCF" in Fig. 1). The narrow front is found to extend further southwestward along the southern edge of Changjiang Bank as a circle-like front (He et al., 1995; Hickox et al., 2000) ("CF" in Fig. 1). Meanwhile, a zonal front was found west of Cheju Island with in situ observations (Tang et al., 2001) and verified with satellite remote sensing images (He et al., 1995; Hickox et al., 2000) ("WCF" in Fig. 1). On the other hand, both numerical simulation and observation also suggested that the zonal front connects with the circle-like front at their west tips, forming into a frontal system "Cheju-Yangtze (Changjiang) River Front" (Park and Chu, 2006) ("CCF" in Fig. 1) or a tongue shaped front (Lie et al., 2000, 2009) ("TF" in Fig. 1). Additionally, Wang and Liu (2009) found that south of the Shandong Peninsula, there is a seaward curving frontal zone roughly between 5 and 6 °C isotherms between the cold coastal water and the warm double tongues which is named the N-shape front ("NF" in Fig. 1 and hereafter). Note we do not give the fronts in the eastern YS where is far away from the YS warm tongues.

Though the fronts are generated (partially) by the warm tongue, the former limits the domain of the latter through constraining the YSWC: a close relation is found in the intraseasonal variation and evolution between the frontal system and the temperature pattern in winter (Liu and Wang, 2009). Moreover, Lie and coauthors (Lie, 1985; Lie et al., 2000, 2001, 2009), based on in situ and remote sensing observations, found that the zonal front west of Cheju Island is pretty stable in blocking the YSWC from flowing into the YS interior through the deepest part of the YS trough; however, the western part of the frontal system is easily broken down to let the YSWC water in. Lie's work well revealed the effects of the fronts on the temperature pattern which is modulated by the YSWC (Ma et al., 2006) in the YS. However, detailed characteristics of the front and their variations from a long-term view are not yet established; and the accurate relation between the fronts and the warm tongue, especially the WSWT, remains unclear. This paper, applying long-term, wide coverage and high temporal-spatial resolution satellite sea surface temperature (SST) data, will focus on the distributional patterns and interannual variations of the fronts and the warm tongue in the South YS in winter and their relations. The effect of the fronts on the WSWT is particularly investigated.

2. Data and methods

The Version 4.1 of Advanced Very High Resolution Radiation (AVHRR) Pathfinder monthly SST data (Vazquez, et al., 1998), covering the period from January 1985 through December 2002 with 9 km resolution (varying slightly with latitude), is applied in the present study to determine the thermal pattern and SST fronts. The monthly mean SSH and the merged sea level anomaly (MSLA) data from October 1992 through August 2002 with 1/3° resolution, which is a production of Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) (Ducet et al., 2000), is used to evaluate the effects of the YSWC heat and mass transports in its source region on the WSWT and the fronts. It is worthy noted that though the SSH and MSLA data do not have sufficient accuracy in the western and northern parts of YS due to poor correction of tidal effect, they are as good in the concerned YSWC source region as in the open seas (see Morimoto, 2009). The original SSH and MSLA data were interpolated into the grids of the SST data; sea surface geostrophic velocities and anomalies are calculated correspondingly (see Section 5).

The position and strength of SST fronts are determined based on SST gradient. First, temperature gradient magnitude (GM), across-front direction (D_{across}) and along-front direction (D_{along}) are calculated with Eqs. (1) and (2),

$$GM=\sqrt{(\partial T/\partial x)^2+(\partial T/\partial y)^2} \quad (1)$$

$$D_{\mathrm{across}}=\tan^{-1}\left[(\partial T/\partial y)/(\partial T/\partial x)\right] \quad (2.1)$$

$$D_{\mathrm{along}}=D_{\mathrm{across}}+\pi/2 \quad (2.2)$$

where T, x and y refer to SST, the east and north directions, respectively, after the SST noise is removed with a 2-dimensional Gaussian filter. Compromising between the primary effect of the centered points and the subsidiary effect of the neighbor points, the Sobel operator is selected for calculating the gradient. Points of magnitude more than 0.025 °C/km are defined as frontal points. Second, frontal zones and frontal lines are determined. Using the gradient amplitudes and along-front directions, arrows can be plotted in the frontal area. According to Eq. (2), temperature on the right side of each arrow vector is higher than that on the left. Frontal arrow clusters in certain areas compose a frontal zone (Fig. 2a). Furthermore, the method proposed by Canny (1986) on determining edges is applied to pick up the point of maximum gradient from adjacent frontal points with the same across-front direction; and we define these points with maximum gradients as the central frontal points. Central frontal points within the same frontal zone, if plotted by arrows too, connect to each other and form the central frontal line (Fig. 2b). Following the procedure above, positions, strengths, lengths and widths of frontal zones and central frontal lines are accurately determined.