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Interannual variation of the southern limit in the Yellow Sea Bottom Cold Water and its causes

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ABSTRACT

The Yellow Sea Bottom Cold Water (YSBCW) occupies a wide region below the Yellow Sea (YS) thermocline in summer. The southern limit of the YSBCW shows pronounced interannual variability. A regional ocean model with realistic forcing was used to identify the structure of the YSBCW and to investigate the causes of its interannual variability from 1981 to 2010. Sea surface temperature (SST) in winter is strongly correlated with the southern limit of the YSBCW in summer. The correlation coefficient between the August southern limit and the February SST is −0.884. This result suggests that cold SST is associated with the increased southern limit in the following summer. Linear regression suggests that the southern limit increases by about 55 km when the SST in February decreases by 1 °C. The southern limits are more extended to the south in August than in June in some years despite surface heating. The difference in southern limits between June and August is positively correlated with the summer southerly wind stress with a correlation coefficient of 0.529. The contribution of SST in winter on the southern limit of the YSBCW in summer is larger than the wind stress in summer. The SST in winter is mainly determined by the air temperature and wind speed in winter. The other factor affecting winter SST is the previous year's bottom water temperature. The winter SST is significantly correlated with the bottom water temperature in previous year. The southern limit of the YSBCW in the observed data in the limited area has relatively weak correlation with the winter SST and summer southerly wind stress possibly due to observation error and uncertainty of the reanalysis wind.

1. Introduction

The Yellow Sea (YS) is a shallow and semi-enclosed marginal sea located between Korea and China (Fig. 1). Adjoining rivers bring sediments rich in nutrients to the YS (Park et al., 2011). High primary productivity, abundant marine life, and dominating monsoon conditions demonstrate the importance of the YS for the marine ecosystem and geography (Teng et al., 2005). Shallow depths of less than 100 m and pronounced seasonal changes in the YS cause large variation of the water temperature.

Strong northerly wind drives deep convection in winter, resulting in vertically well-mixed waters from the surface to the bottom during winter (Fig. 2). This vertically homogeneous temperature structure can be observed until spring. On the contrary, increased solar radiation drives strong stratification in summer. Because this strong stratification prevents vertical mixing between the sea surface and the bottom in summer, cold water that forms in winter maintains its temperature beneath the stratified thermocline. This cold water occupies the central region of the YS at depths deeper than 50 m ($T < 10$ °C) (Youn et al., 1991; Zhang et al., 2008) and is known as the Yellow Sea Bottom Cold Water (YSBCW) (Guan, 1963; Hu and Wang, 2004; Hur et al., 1999; Kim and Kimura, 1999; Park et al., 2011; Zhang et al., 2008).

Previous researches have explored several aspects of this unique water mass, which includes studies of interannual and long-term changes in sea water temperature in the YS (Hu and Wang, 2004; Wei et al., 2010; Zhang et al., 2008). Winter air temperature may affect variability of the YSBCW temperature (Guan, 1963; Park et al., 2011). Park et al. (2011) reported that changes in atmosphere forcing are strongly correlated with variability of the YSBCW temperature. From the historical studies, the YSBCW temperature was affected by air temperature. This theory has been widely accepted.

The bottom temperature in the YS is higher in winter than in summer due to the intrusion of the Yellow Sea Warm Current (YSWC) in winter and southward flow of the YSBCW in summer (Xu et al., 2003).

The northward flow of the YSWC is driven by strong northerly wind in winter (Moon et al., 2009). The YSWC transports warm and saline water into the YS (Ma et al., 2006). The winter temperature may be affected by the intrusion of the YSWC (Wei et al., 2010).

Southward migration of the YSBCW in summer has been reported recently. Zhang et al. (2008) used short-term observed data to show that the cold bottom water moves from the north to the central area

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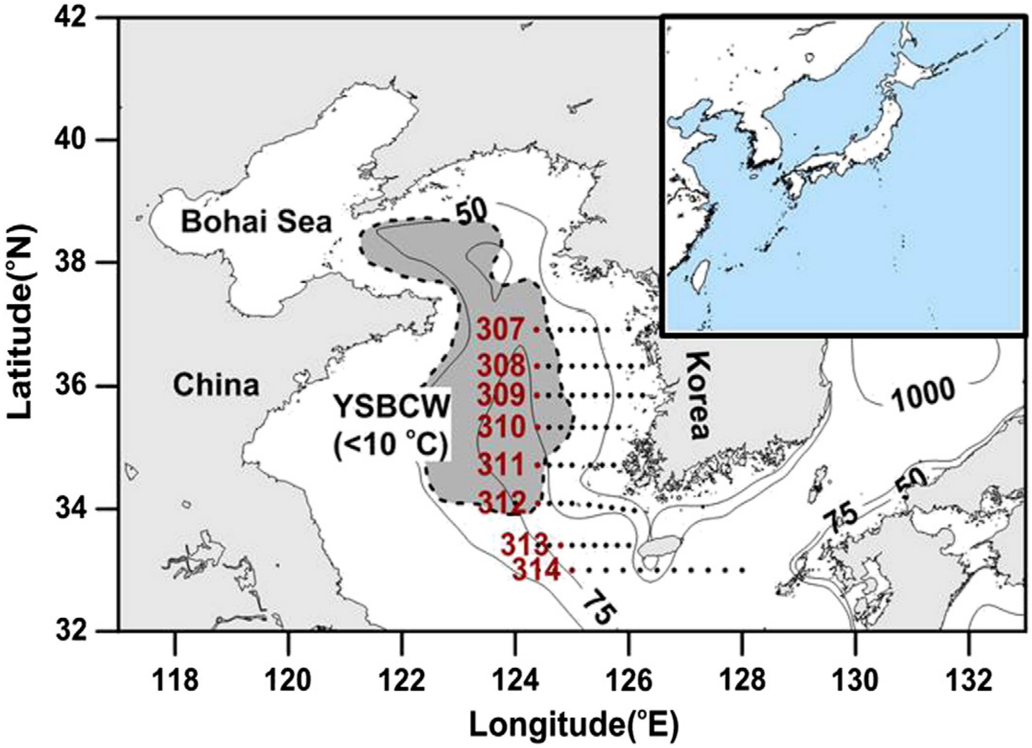

Fig. 1. Bathymetric map of the Yellow Sea (YS) and schematic diagrams of the Yellow Sea Bottom Cold Water (YSBCW; gray) determined on the basis of model results. Numbers represent observation lines routinely observed by the National Fisheries Research and Development Institute. The insert box shows model area.

of the YS during the summer, and Jacobs et al. (2000) used a numerical model to reveal that the southeasterly summer monsoon generates a southward flow of the bottom layer. The seasonal migration of the YSBCW has a large impact on primary products and marine habitats due to dramatic changes in water temperature of the southern YS (Wang et al., 2003).

Despite many previous studies, long-term variation of the southern limit of the YSBCW is still unclear, and its driving mechanisms are poorly understood. Therefore, the purpose of this study is to investigate the interannual variations of the southern limit of the YSBCW and its causes by using long-term numerical model results based on realistic data.

2. Data and numerical model

The Regional Ocean Modeling System (ROMS), which is a three-dimensional ocean circulation model, was used for this study. The model domain is from 18.5°N to 48.5°N and from 117.5°E to 154.5°E and includes the YS, the East China Sea, the Japan/East Sea, and the Northwestern Pacific (Fig. 1). The horizontal grid has a resolution of 0.1° with 20 vertical levels. The open boundary data of the model were provided from a regional northwest Pacific (NWP) model (Cho et al., 2009) nested within a global model known as Estimation of the Circulation and Climate of the Ocean (ECCO; www.ecco-group.org). The initial values for temperature, salinity, velocity, and sea surface height were obtained from the NWP model (Cho et al., 2009). The model was run from January 1981 to December 2010. The monthly mean values from the European Center for Medium-range Weather Forecasting (ECMWF) reanalysis data were used as the surface forcing data. Bulk-flux formulae (Fairall et al., 1996) were adapted. Tidal forcing with ten major tidal components was applied (Egbert and Erofeeva, 2002). Vertical mixing was calculated by using the Mellor–Yamada turbulence closure scheme (Mellor and Yamada, 1974). The horizontal viscosity coefficient was 300 m^2/s. Further details on the model have been reported by Cho et al. (2009, 2013).

Temperatures observed by the National Fisheries Research and Development Institute (NFRDI) during the last 30 years (1981–2010) were analyzed. Temperature data has been routinely observed bimonthly at the standard depths in the sea near the Korean Peninsula. Most offshore stations of each observed line corresponding to the deep trough in the YS were selected to study the variation of the southern limit of the YSBCW in August. These stations are shown as filled red circles in Fig. 1. In Fig. 1, the number at each station represents the line observed by NFRDI. We analyzed the temperature selected from model grid corresponding to the observation. From 34°N to 37°N and from 125°E to 127°E, spatially averaged SSTs were used to examine the correlation between the southern limit of the YSBCW and the winter SST.

To relate the YSBCW interannual variations with changes in atmospheric conditions, we used monthly mean air temperature and wind stress from the ECMWF reanalysis data obtained during the last 30 years, from 1981 to 2010. For winter air temperature, we averaged the December, January, and February air temperatures over a domain bounded by 33°N, 42°N, 117°E, and 127°E. Winter wind speed and summer wind stress were calculated by using the V (north–south) component wind speed spatially averaged from 30°N to 42°N and from 117°E to 127°E in December, January, and February and in June, July, and August, respectively.

To identify the previous year's oceanic conditions that affect YSBCW variability, the bottom temperature, i.e., the spatial mean temperature at a depth of 75 m in October was analyzed.

3. Result

3.1. Model validation

Numerical models can indicate the entire distribution of the YSBCW and effectively correlate its dynamical interactions with the causes (Jacobs et al., 2000). Monthly mean model temperature can effectively define the distribution of the YSBCW in summer, represented in Fig. 1