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Spatial and temporal variability of sea surface temperature and warming trends in the Yellow Sea

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ABSTRACT

The spatial and temporal variability of sea surface temperatures (SST) in the Yellow Sea was investigated using satellite data and *in-situ* measurements over 29 years from 1981 to 2009. We found that the first empirical orthogonal function (EOF) mode of SST variability, which accounts for 47.59% of the total SST variance, exhibited a warming signal during the study period. We examined the relationships between the dominant EOF mode, long-term trends of SST changes and *in-situ* temperatures, and bathymetry. As a result, the shallow regions demonstrated more significant increasing rates than the deep area in the Yellow Sea. Vertical stratification of the water column revealed long-term changes, which led to differential surface warming. The warming rates decayed *monotonically* with depth. The spatial features of long-term SST warming trends were most remarkable near the Yangtze River, due to the effect of river discharge. Abrupt changes in the time-varying amplitude of the first EOF mode in winter could be explained by Arctic Oscillation.

1. Introduction

The Yellow Sea is a marginal sea located in the northwest Pacific Ocean, surrounded by the Korean Peninsula and mainland China. It is quite shallow with an average depth of only 44 meters and a maximum depth of about 152 meters (Fig. 1b). In the central region, a relatively deep bathymetry of less than 60 m was elongated in the north-south direction, as shown in the 60-meter contour of water depth in Fig. 1b. The study area also includes the Bohai Sea and a small area of the northern East China Sea.

Since the Yellow Sea and the Bohai Sea are shallow and located at the eastern end of the largest continent in the world, they can quickly respond to atmospheric climate change and in turn lead to local climate variability as a result of the air-sea feedback process. Cold and warm current systems (Fig. 1a), water masses, as well as hydrographical, year-to-year and interdecadal variabilities of the Yellow Sea have been studied extensively based on *in situ* measurements and numerical model experiments (Chu et al., 2005; Ichikawa and Beardsley, 2002; Lie and Cho, 2002; Park et al., 2011; Xie et al., 2002; Yanagi and Takahashi, 1993). Seasonal and non-seasonal variabilities of the thermohaline structure have been investigated by taking into account the link between surface fluxes across the air-ocean interface and the formation of water mass features in the Yellow Sea (Chu et al., 2005; Hirose et al., 1999; Ishii and Kondo, 1987; Kim and Kimura, 1999; Kim et al., 1994). The bathymetry of the Yellow Sea was known to play an important role in the vertical mixing process at SST frontal regions (Huang et al., 2010). The majority of the Yellow Sea is composed of a shallow area with a wide continental shelf, which suggests that its water column will be readily affected by seasonal variations in atmospheric conditions such as heating, cooling, and wind stress (Chu et al., 1997).

Sea Surface Temperature (SST) is one of the most important oceanic and atmospheric variables which has been widely used in a variety of research to develop an understanding of ocean dynamics, as well as physical and biogeochemical processes in the upper ocean. The importance of SST variability in the Yellow/Bohai Sea has been addressed by numerous satellite-based studies throughout past decades using SST databases from the National Oceanic and Atmospheric Administration / Advanced Very High Resolution Radiometer (NOAA/AVHRR) data, Moderate Resolution Imaging Spectroradiometer (MODIS) data, and numerical model results based on data from institutions such as the Hadley Center, the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR), and the European Centre for Medium-Range Weather Forecasts (ECMWF) (e.g., Lin et al., 2005; Shi and Wang, 2012; Tseng et al., 2000; Wei et al., 2010; Yeh and Kim, 2010).

The Yellow/Bohai Sea is a small marginal sea in the north-west Pacific, however, its physical properties, water mass, and circulation are both spatially and temporally complicated (Chu et al., 2005). It has been

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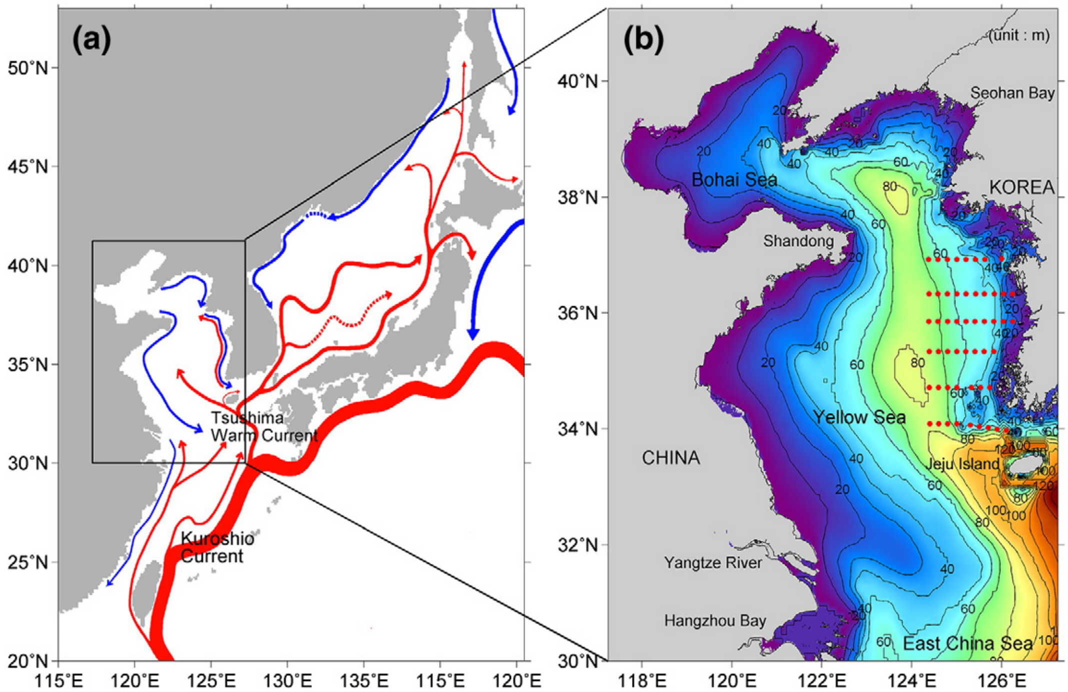

Fig. 1. (a) Schematic current maps in the seas around Korea, where the red (blue) arrows represent the warm (cold) currents and the yellow box shows the study area (Park et al., 2013), and (b) bathymetry of the study area, where the red dots represent the Korea Ocean Data Center (KODC) stations. The blue (red) arrow along the South Korean coast represents the currents in winter (summer).

nearly impossible to examine the spatial variations of SST warming signals at coastal regions due to the low spatial resolution of the data sets. The warming signal of the Yellow Sea was reported by Yeh and Kim (2010) based on an EOF analysis. They examined long-term trends over several decades from 1950 to 2008 using the HadISST (Hadley Centre sea ice and sea surface temperature) database with a low spatial resolution of 1 × 1 degree (Rayner et al., 2003) and focused on a basin-wide scale rather than on detailed spatial patterns of recent warming signals as suggested in this study. Previous research using low-resolution data and high-resolution NOAA/AVHRR data did not focus attention on the detailed spatial patterns of SST variabilities either.

The objectives of this study are (1) to investigate the spatial patterns of dominant temporal SST variability by applying harmonic analysis and empirical orthogonal function (EOF) decomposition, (2) to compare the pattern of warming signal with long-term trends from SST and *in-situ* measurements, and discuss a potential cause of the spatial pattern of warming rates, (3) to understand the link between the spatial patterns of the SST variations and bathymetry, and (4) to examine the relationship between abrupt interannual SST variations of and Arctic Oscillation (AO) index variations.

2. Data and methods

2.1. Sea surface temperature and AO index

To examine the spatial and temporal variability of SST in the Yellow Sea, the Bohai Sea, and a northern part of the East China Sea, we have utilized a monthly SST database (4 km × 4 km) from NOAA/National Oceanographic Data Center (NODC) covering NOAA/AVHRR data from 1981 to 2009 (http://data.nodc.noaa.gov/pathfinder/). Sea surface temperature anomalies (SSTAs) at a spatial grid were obtained by subtracting the average of SST for that particular month over the entire 29-year record. The anomaly data was then used to analyze EOF modes and long-term trends.

In addition to NOAA SST database, we used data from a sub-domain of the northwest Pacific dataset of Next Generation Sea Surface Temperature (NGSST) (13–63°N, 116–166°E), which was a combination of infrared SSTs (~1.1 km) and microwave SSTs (25 km) with a high-spatial resolution (0.05°) (Sakaida et al., 2009). Since it is a daily product, we anticipate that it can be used to confirm the results of harmonic components of monthly NOAA SSTs, particularly in terms of phase. Through detailed subjective scrutiny of NGSST images, we selected NGSST data spanning an eight-year period (23 July 2002 – 22 July 2010) for comparison with NOAA SST analyses. Ice-covered pixels were already masked from the datasets of both NOAA SST and NGSST through a series of procedures based on visible, infrared, and microwave observations (Casey et al., 2010; Sakaida et al., 2009). To understand the spatial distinction of SST warming, we estimated the SST trends by linear regression and tested its statistical significance with a 95% confidence interval (e.g., Kendall, 1975).

The Arctic Oscillation (AO) index is determined by the atmospheric pressure difference between the Siberian high and Aleutian low. AO phase is positive (negative) when the difference is small (large). A negative (positive) AO index produces a strengthened (weakened) Siberian high and then induces a very low (high) surface air temperature over eastern China (Gong et al., 2001; Isobe and Beardsley). The AO index provided by the Climate Prediction Center (CPC) of NOAA NCEP (National Centers for Environmental Prediction) was used to understand the high interannual SST variability in winter.

2.2. In-situ temperature and vertical stability

In order to investigate long-term trends of sea water temperatures and seasonal changes in vertical stability in the Yellow Sea west of Korea, we used temperature and salinity measurements from CTD (Conductivity, Temperature, Depth) data of the Korea Oceanographic Data Center (KODC) which were observed on a bimonthly basis at specific stations (34–37°N, 124.3–126.5°E) from 1981 to 2009. Vertical