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Freshening of the upper ocean in the South China Sea since the early 1990s

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ABSTRACT

Ocean salinity is often used as a dynamical tracer for investigating the Kuroshio intrusion into the South China Sea (SCS). In this study, we found that the upper-ocean water in the SCS had a freshening trend since the early 1990s. Salinity in the upper 100 m of the SCS (S_{SCS}) decreased by ~0.24 psu in the period 1993–2012, yielding a negative trend of −0.012 psu yr^{-1}. The maximum freshening occurred in the surface layer west of the Luzon Strait, and freshening gradually lessened from northeast to southwest and with depth, indicating the important influence of the Kuroshio intrusion. Quantitative analysis of salinity budget from the surface to 100 m depth in the SCS suggests that the weakened Kuroshio intrusion is the leading factor controlling the S_{SCS} freshening, while the increased air-sea freshwater flux plays a minor role. Based on GODAS (Global Ocean Data Assimilation System) model output, the Luzon Strait transport (LST) in the upper 100 m decreased in a negative trend of −0.12 Sv yr^{-1} (1 Sv=10^6 m^3 s^{-1}) from 1993 to 2012, corresponding to a freshening trend of the S_{SCS} at a rate of −0.011 psu yr^{-1}. Both the LST and S_{SCS} changes are closely related to the Pacific Decadal Oscillation (PDO). Our findings demonstrate that the strength of the Kuroshio intrusion into the SCS weakened markedly since the PDO phase shifted in 1990s, which resulted in the pronounced freshening of the SCS water.

1. Introduction

Ocean salinity is one of the most fundamental parameters in physical oceanography, and it plays an important role in modulating ocean and climate variability (Katsura et al., 2013). Salinity is a key variable in computing the geostrophic circulation (*e.g.*, Suga et al., 2000; Qiu and Chen, 2012). Because of its better conservative property compared with temperature, salinity is often used as a dynamical tracer for circulation studies (*e.g.*, Chen and Huang, 1996; Yan et al., 2013; Nan et al., 2013). Salinity also has thermodynamic importance. The stratification of salinity can affect the mixed layer depth, and advection of salinity anomalies from subtropical regions can influence tropical climate changes (Lukas and Lindstrom, 1991; Lukas, 2001). Salinity also has climatologic importance. Any change in the hydrological cycle can be reflected in the ocean salinity field (Williams et al., 2007). Because of its importance, salinity changes have been reported on both global and regional scales. Durack and Wijffels (2010) noted that, at the global scale, salty regions get saltier and fresh regions get fresher from 1950 to 2008, which is consistent with an amplification of the global hydrological cycle. In the northwestern Pacific, Suga et al. (2000) found that salinity of the North Pacific Tropical Water increased remarkably associated with the mid-1970s regime shift. Lukas (2001) reported a pronounced freshening (−0.15 psu) of the upper ocean in the Pacific Subtropical Gyre from 1991 to 1997. Sugimoto et al. (2013) found that the Subtropical Mode Water in the north Pacific, characterized by low potential vorticity, freshened markedly in 2009 and 2010.

The South China Sea (SCS) is the largest semi-enclosed marginal sea in the north Pacific (Fig. 1). The general circulation pattern in the SCS is driven primarily by the East Asian monsoon and significantly influenced by the Kuroshio intrusion through the Luzon Strait (Qu, 2000; Qu et al., 2004; Wang et al., 2013). In past decades, much work has been done on the temperature changes, circulation, eddy activities, and Kuroshio intrusion *etc.* in the SCS (see Hu et al., 2000; Nan et al., 2014; and references therein). However, studies on salinity changes in the SCS are limited. Though Huang et al. (2015) investigated the response of salinity variation in the Taiwan Strait to the interannual variation of the Kuroshio intrusion using *in situ* measurements, the decadal variation and long-term trend of the salinity in the interior SCS

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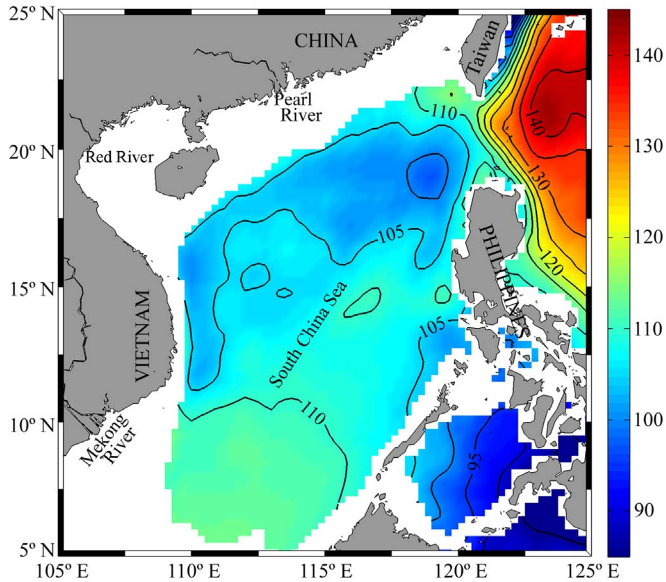

Fig. 1. Mean Absolute Dynamic Topography (ADT, units: cm) in the SCS derived from the 20-year satellite altimeter data from 1993 to 2012.

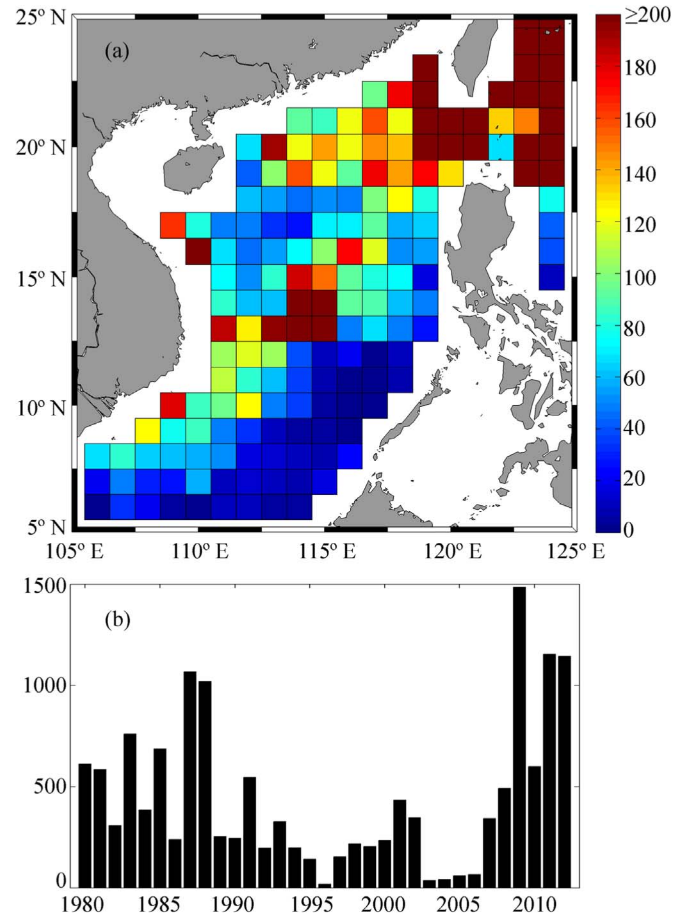

Fig. 2. Distribution of salinity profiles (a) binned in 1°×1°cells and yearly numbers (b) in the SCS (< 121°E) derived from WOD13.

have not been reported. Hsin (2015) related the multi-decadal change of salinity in the northern SCS to the multi-decadal changes of Kuroshio intrusion in the Luzon Strait. Nan et al. (2013) revealed that the Kuroshio intrusion into the SCS had a weakening trend from 1990s to 2000s, which resulted in a freshening in the northeastern SCS. However, the area and depth influenced by the weakened Kuroshio intrusion are not clear. On the other hand, using gridded Argo data, Yan et al. (2013) noted a sustained freshening of subsurface water in the Kuroshio east of the Luzon Strait during the period 2003–2011. Based on long-term repeated observations, Nan et al. (2015) demonstrated that both the surface and subsurface salinity in the northwest Pacific Subtropical Gyre including the Kuroshio had a freshening trend during the period 1987–2012. The effects of the long-term Kuroshio freshening on the salinity changes in the SCS remain to be quantified. Zeng et al. (2014) found that the upper-ocean salinity in the northern SCS decreased markedly (~0.4 psu) in 2012 because of abundant local freshwater flux and reduction of the Kuroshio intrusion. They also noted that the river discharge associated with abnormal precipitation played a leading role in the salinity near the Mekong River mouth. Wu et al. (2010) revealed a distinct increase in rainfall over southern China since the early 1990s, but the influences of interannual to decadal changes of the river discharge and freshwater flux on the salinity changes in the SCS remains unclear.

The present study has three objectives: 1) to investigate the long-term changes of salinity in the SCS based on reanalysis data, 2) to clarify what controls the salinity variability (*e.g.,* river discharge, air-sea freshwater flux, and Kuroshio intrusion), and 3) to quantify the influence of the Kuroshio intrusion variation on the salinity changes in the SCS. The rest of the paper is organized as follows. Section 2 describes the data and methodology. Section 3 presents the results on the long-term salinity changes in the SCS. Section 4 discusses the possible driving factors in the salinity changes. Finally, Section 5 summarizes the main findings.

2. Data and methodology

2.1. Observational data

To investigate the salinity changes in the SCS, we use yearly, objectively-analyzed subsurface temperature and salinity compiled by Ishii and Kimoto, 2009. The analysis is based on the World Ocean Database 2013 (WOD13), Global Temperature-Salinity Profile Program (GTSPP), the global temperature-salinity in the tropical Pacific from the IRD (L'Institut de recherche pour le development, France), the Centennial *in situ* Observation Based Estimates (COBE) sea surface temperature, and the Argo profiling buoy data since the early 2000s (Moon et al., 2013; Chen and Tung, 2014). The temperature-salinity profiles without quality check have been deleted. This global 1°×1° dataset at 24 levels in the upper 1500 m, called Ishii data in this study, is freely available at http://rda.ucar.edu/datasets/ds285.3. The dataset covers the period from 1945 to 2012, and the data from 1980 to 2012 are used in this study. To check the reliability of the gridded dataset, the number of salinity profiles and their distributions are plotted in Fig. 2 based on WOD13 (http://www.nodc.noaa.gov/OC5/WOD13/). There are a total of 14,594 verified salinity profiles (5912, 2249, and 6433 in the 1980s, 1990s, and 2000s, respectively) in the SCS (Fig. 2a). The profile numbers are larger than 200 in most years except for 1994–1996 and 2003–2006 (Fig. 2b). There is a temporal-spatial mismatch of yearly salinity profiles, which may cause interpolation error for Ishii data. For example, Fig. 2a shows that salinity profiles in the southeastern SCS are sparse. The reanalysis dataset has been widely used in several earlier studies (*e.g.*, Carton and Santorelli, 2008; Moon et al., 2013; Chen and Tung, 2014; Hsin, 2015).

Following Nan et al. (2013), surface geostrophic velocity was calculated from satellite altimeter data produced by the French Archiving, Validation, and Interpolation of Satellite Oceanographic (AVISO) as follows:

$$\mathbf{u_g} = (u_g, v_g) = \frac{g}{f}\left(-\frac{\partial \eta}{\partial y}, \frac{\partial \eta}{\partial x}\right), \tag{1}$$

where u_g (v_g) is zonal (meridional) component of geostrophic flow, g is gravitational acceleration, η is the Absolute Dynamic Topography