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The impact of monsoon winds and mesoscale eddies on thermohaline structures and circulation patterns in the northern South China Sea

Ruixiang Zhao[a], Xiao-Hua Zhu[a,c,*], Xinyu Guo[b]

[a] State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China

[b] Center for Marine Environmental Study, Ehime University, 2-5 Bunkyo-cho, Matsuyama 790-8577, Japan

[c] Ocean College, Zhejiang University, Zhoushan 316021, China

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ABSTRACT

We deployed 5 pressure-recording inverted echo sounders (PIES) along a section in the northern South China Sea (NSCS), and estimated well the distributions of temperature, salinity and velocity across the section. Applying the empirical orthogonal function (EOF) method, we found that variability of the estimates is dominated by two modes: one named the seasonal mode affecting strongly on the hydrographic distribution with explained variability of temperature/salinity by 62.9/72.2%; the other named the eddy mode, corresponding to the arrival of mesoscale eddies, affecting strongly on the circulation pattern with explained variability of velocity by 63.2%. Temporal variation of the seasonal mode is highly correlated with the monsoon winds southeast of Vietnam, suggesting a nonlocal forcing mechanism. Case studies looking at the structures and evolutions of three captured eddies, whose impacts were well quantified by the eddy mode. The monsoon (eddies) significantly affects temperature, salinity and velocity shallower than 635 m (860 m), 160 m (150 m) and 1055 m (920 m), respectively. The monsoon (eddies) can induce maximum temperature, salinity and velocity anomalies up to −1.6 to 2.1 °C (−2.5 to 2.2 °C), −0.11 to 0.14 psu (−0.13 to 0.27 psu) and −0.31 to 0.46 m/s (−0.40 to 0.38 m/s), respectively. Mean volume transport (VT) across the section is 1.0 Sv (1 Sv=1 × 10^6 m^3 s^{-1}, positive to the northeast). Seasonal VT (with eddy impacts removed) is −4.6 Sv, 11.4 Sv, −5.1 Sv and −4.1 Sv for spring, summer, autumn and winter, respectively.

1. Introduction

The South China Sea (SCS), located west of the northwest Pacific Ocean, is one of the world's largest marginal seas. It is semienclosed by the China mainland to the north, Philippine Islands to the east, Indonesia Islands to the south and the Indo-China Peninsula to the west. It is connected to the Pacific Ocean mainly through the Luzon Strait with maximum sill depth of about 2400 m. It contains a broad continental shelf shallower than 100 m situated in the northern South China Sea (NSCS), south of the China mainland. The SCS features a unique circulation pattern and distinctive seawater properties, and abounds with mesoscale eddies, which have been extensively studied with in situ hydrographic measurements (Wang et al., 2008; Chen et al., 2010; Hu et al., 2011, 2012), satellite observations (Hwang and Chen, 2000; Wang et al., 2003; Yuan et al., 2007; Nan et al., 2011) and numerical simulations (Wu and Chiang, 2007; Xiu et al., 2010).

The circulation of the SCS has strong seasonal variability and it is generally accepted that the circulation in the upper layer is primarily driven by the East Asian monsoon (Qu, 2000; Hu et al., 2000; Su, 2004; Liu et al., 2008). The basinwide winds are northeasterly in winter and southwesterly in summer, and the transition periods are from April to May and September to October, respectively (Wang et al., 2004). The pioneering work of Wyrtki (1961) gives a schematic map of the SCS surface circulation for boreal winter and boreal summer. In winter, a cyclonic gyre exists basinwide in the SCS; in summer, a weak cyclonic gyre remains in the northern SCS and an anticyclonic gyre exists in the southern SCS. Based on historical hydrographic data from the SCS, Xu et al. (1982) computed the dynamic height distribution and confirmed the above seasonal circulation patterns. They further pointed out that these circulation patterns can extend down deeper than 500 m. Liu et al. (2001) suggested that the seasonal circulation of the deep SCS basin is forced by the basinwide wind stress curl, reaching a quasi-steady upper ocean baroclinic Sverdrup balance. However, long term mooring observations carried out by Zhu et al. (2015) suggested that

* Corresponding author at: State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China.

E-mail address: xhzhu@sio.org.cn (X.-H. Zhu).

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the NSCS circulation does not exactly follow Sverdrup balance, and in summer the mean flow is northeastward rather than southwestward as in winter. Their volume transport time series is quite consistent with the one derived from HYCOM model output (Bleck, 2002). Zhu et al. (2015) attribute this discrepancy to the weak and complicated summer circulation there. So, it is likely that the hydrographic data collected by former researchers like Wyrtki (1961) and Xu et al. (1982) were not sufficient to provide adequate spatial and temporal coverage, resulting in the inferred NSCS circulation being vulnerable to mesoscale eddy activity. The impacts of monsoon winds and eddies were rarely separated quantitatively and assessed. So what is the pattern of the monsoon forced climatological circulation? How is the seasonal circulation driven? How much impact can monsoon winds and mesoscale eddies exert on the hydrography and circulations in the NSCS? What is their relative importance? We will address these issues in this paper.

Although SCS mesoscale eddies have been observed and reported often, most of these observations have been either measurements of the ocean surface by satellite altimeter or infrared sensor, or derived from "snapshots" taken from hydrographic surveys. Satellite data have broad spans in space and time, but they can reveal little about hydrographic distributions and variability in the ocean interior. Hydrographic casts from research vessels can give snapshots of properties and structures of the mesoscale eddies captured, but it is difficult to use them to demonstrate the eddies' evolution processes; moreover, strictly speaking, theses casts are not simultaneous. Using mooring observations is a good way for overcoming some of these shortcomings, but due to costs and challenging operation conditions, mooring observations are quite rare in the SCS (Yuan et al., 2012; Zhang et al., 2013; Wang et al., 2015). Moreover, most mooring observations have not been lasted for a period over one year (needed to cover one annual cycle of the monsoon), and have not been capable of measuring the temperature, salinity and velocity distributions at the same time through the full water column. So one of the purposes of our paper is to fully demonstrate the hydrographic structures and evolutions of eddies passing through our observational region.

From October 2012 to July 2014, we deployed 5 pressure-recording inverted echo sounders (PIES) along satellite altimeter track 114 in the NSCS, and from the data obtained reliable estimates of temperature, salinity and velocity distributions across the deployment section. Applying the EOF (empirical orthogonal function) method to these estimates, we show that the first two modes can represent well- and even quantify the impacts of - the monsoon winds and mesoscale eddies. In this paper, we utilize these results to address our questions and study these impacts.

2. Data and methods

2.1. Data

From October 2012 to July 2014, we deployed 5 PIESs along the satellite altimeter (TOPEX/POSEIDON and Jason 1/2) track 114 in the NSCS. This section is situated at the gap between Hainan Island and the Xisha (Paracel) Islands, and is roughly perpendicular to the bathymetry contours of the continental shelf (Fig. 1). The PIES array is intended to capture the South China Sea western boundary current (Fang et al., 2012). Our PIESs were moored at the seafloor (water depth is 642 m, 1842 m, 2091 m 1348 m and 1030 m for stations P1, P2, P3, P4 and P5, respectively), measuring the round-trip acoustic travel time (τ) between the bottom and the sea surface at 10 min intervals. Almost simultaneously they also measure the near bottom pressure (P_{bot}). These records were windowed, detided (only for P_{bot}), despiked, and dedrifted (only for P_{bot}) following the procedure described by Kennelly et al. (2007). For the time scales of concern, the processed records were smoothed with a 30-day-moving-average and subsampled at an interval of 1 day. The 30-day-moving-average filter is adequate to retain the most of the signals from meso-scale eddies without introducing extra noise.

In order to evaluate the quality of the PIES estimates, we performed conductance–temperature-depth (CTD) casts at the PIES stations aboard Research Vessel Shiyan 3 during 15–16 December 2012, a period when the PIESs were deployed.

To construct the Gravest Empirical Mode (GEM) (see Section 2.2), we used 1355 profiles of temperature and salinity in the SCS obtained by historical CTD casts and Argo measurements. These CTD profiles were collected since the year 2000. The Argo datasets were from China Argo Real-time Data Center, downloaded from ftp://ftp.argo.org.cn/pub/ARGO/global/.

The 10 m wind dataset from ECMWF (European Center for Medium-Range Weather Forecasts) was used to study the monsoonal impact. The zonal and meridional component time series of the winds were smoothed with a 30-day-moving-average and subsampled at an interval of 1 day, consistent with the smoothing of the PIES data.

The along track SLA data of satellite altimeter Jason 2 and the gridded MSLA (Merged Sea Level Anomaly) products from AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic) during our observation period were used to identify eddies. The gridded MSLA product has been recently updated to have one day resolution in time, favoring our identification of eddy centers and trajectories.

2.2. Methods

The Gravest Empirical Mode (GEM) method is adopted to estimate temperature, salinity and specific volume anomaly profiles at the PIES sites during the deployment. The GEM method has been successfully applied to the study of the North Atlantic Current (Meinen, et al., 2000), Antarctic Circumpolar Current (Sun and Watts, 2001), Ryukyu Current (Zhu et al., 2003; Zhu et al., 2004; Zhu et al., 2008; Andres et al., 2008), Japan/East Sea (Mitchell et al., 2004; Park et al., 2005), the Kuroshio south of Japan (Book et al., 2002) and the Kuroshio Extension (Donohue et al., 2010), etc. In this study, we constructed the GEM for the SCS following Watts et al. (2001) rather than the multi-index GEM by Park et al. (2005). It is because the profiles in the SCS are very limited, especially for those with depth deeper than 1500 m and SST lower than 24 °C. Even though, our GEM performance (for further detail see Zhu et al., 2015) for temperature and salinity was comparable to that in previous studies, and the estimations were expected to be good. When the PIESs were making measurements, CTD casts were conducted at the PIES stations during 15–16 December 2012. The temperature and salinity profiles estimated from the PIES data using the GEM method turn out to be in good agreement with those obtained from the CTD casts (Fig. 2). The RMSD (root mean square difference) of full-depth temperature and salinity is 0.26 °C and 0.03 psu, respectively. Although the maximum difference of temperature (salinity) can exceed 2 °C (0.2 psu) in the surface and subsurface layers, this is of little importance to our study because these differences only appear in certain regions of limited water depth likely to be undergoing small scale processes, which do not concern us in this paper.

Shipboard ADCP current data, the bottom pressure record, and the estimated specific volume anomaly profiles are used together to estimate the velocity normal to the PIES section during our deployment, since no current meter was available to provide the reference velocity at depth for calculating the absolute geostrophic velocity. According to the agreement of velocity structures and volume transports from the PIES estimations, CTD derived geostrophic currents and ADCP measurements (Zhu et al., 2015; Fig. 5), we believe that the results were satisfactory. The procedure is presented in Zhu et al. (2015).

The empirical orthogonal function (EOF) method is utilized to investigate the spatial distribution and temporal variation related to