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On steric and mass-induced contributions to the annual sea-level variations in the South China Sea

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ABSTRACT

The steric sea level (SLA_{steric}), water-mass change (SLA_{mass}) and their contributions to the sea level anomaly (SLA) in the South China Sea (SCS) are studied by using altimetry data, Ishii data and GRACE data. Annual harmonic results and correlation analysis indicate that the SLA_{steric} has a significant contribution to the SLA over deep basin and that its phase leads SLA 1–3 months in different parts of the SCS, whereas the SLA_{mass} explains the SLA to a great extent over shallow water areas. The area-averaged SLA in the western SCS has an amplitude of ~7.6 cm and a phase of ~360°, which is ~3.8 cm higher and peaks ~108° later than SLA_{steric}. The SLA_{mass} has an amplitude of ~6.3 cm and a phase of ~337°. The simultaneous correlation coefficient between SLA and SLA_{mass} is 0.78, which indicates that mass variation dominates the sea-level variation in the western SCS. Unlike the western SCS, the area-averaged SLA in the central SCS peaks at 254° with a smaller amplitude of ~3.3 cm, which is ~1.8 cm lower and peaks ~15 days later than corresponding SLA_{steric}. The simultaneous correlation coefficient between SLA and SLA_{steric} is 0.81; therefore, the contribution of steric variation to the sea-level variation is dominant in the central SCS.

1. Introduction

The South China Sea (SCS) is the largest marginal sea in the northwestern Pacific Ocean, which connects with the Java and Sulu seas in the south through a number of shallow passages, with the Pacific Ocean in the north through the deep Luzon Strait and with the East China Sea through the shallow Taiwan Strait. Its bottom topography features a mean depth of 1800 m and a maximum depth of more than 5400 m, covering a region from the equator to 23°N and from 99°E to 121°E (Fig. 1). In the early days, due to limited measurement record length, most studies on the sea level of the SCS mainly focused on annual variations (Shaw et al., 1999; Ho et al., 2000; Liu et al., 2001a,b; Li et al., 2003). Using TOPEX/Poseidon (T/P) altimeter data, scientists have revealed significant annual variations of sea level in the SCS in their research. Low sea level is over the entire deep basin during winter, with two centers, one off Luzon and the other off the Sunda Shelf, in response to the northeasterly monsoon. With the southwesterly monsoon dominating in summer, sea level is high off Luzon and the Sunda Shelf, while a low region off Vietnam separates the two highs (Shaw et al., 1999; Ho et al., 2000). Liu et al. (2001b) argued that the sea surface height anomaly over most of the SCS is forced primarily locally within the SCS, firstly by surface dynamic forcing and secondarily by surface heat-flux forcing.

As the length of altimetric time series increases, new studies are focusing on inter-annual and long-term variations of sea level in the SCS (e.g., Li et al., 2002; Fang et al. 2006; Cheng and Qi, 2007; Rong et al. 2007). Results from Li et al. (2002) indicated that the mean sea level over the SCS increased at a rate of about 10.0 mm/yr from 1993 to 1999 according to the T/P data. Fang et al. (2006) indicated that the sea level in the SCS between 1993 and 2003 rose at 6.7 ± 2.7 cm/decade and found that the sea level in the SCS was somewhat correlated with El Niño and Southern Oscillation (ENSO) on the interdecadal time scale. Cheng and Qi (2007) found that the mean sea level over the SCS rose at a rate of 11.3 mm/yr during 1993–2000 and fell at a rate of 11.8 mm/yr during 2001–2005. The authors also pointed out that the thermal change in the upper layer of the SCS has a significant contribution to sea level variations.

There are two major components of sea-level variability. One is the steric component (Church et al., 2001; Cazenave and Nerem, 2004; Carton et al., 2005), due to changes in the sea water temperature and salinity at all depths. The other component is related to water-mass change as a result of either ocean mass redistribution or water-mass flux (Church et al., 2001; Cazenave and Nerem, 2004; Carton et al., 2005; Chambers, 2006a). Satellite altimetry measures the combined effect of the steric and mass variations. Objective analysis data and ocean data assimilation, however, allow the steric sea-level change to be examined alone (Fukumori, 2002; Carton et al., 2005; Levitus et al., 2005; Ishii et al., 2006). For example, the Ishii subsurface temperature data makes it possible to calculate upper-ocean thermosteric sea level

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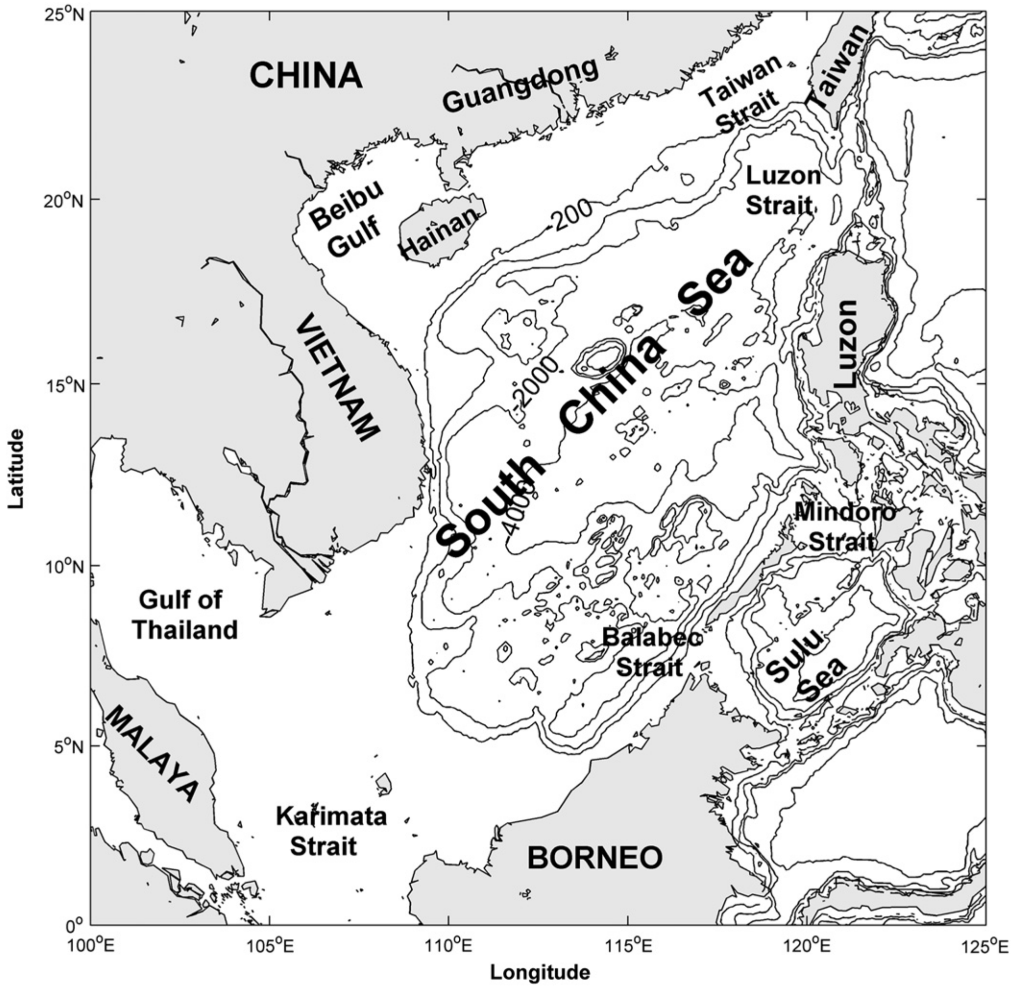

Fig. 1. Bathymetry of the South China Sea, with contours showing 200, 2000, and 4000 m only.

with satisfying accuracy (Ishii et al., 2006). This dataset has provided satisfactory results in estimating sea-level change due to heat-content change in the SCS (Cheng and Qi, 2007; Rong et al., 2007). The launch of the Gravity Recovery and Climate Experiment (GRACE) in 2002 provides an entirely new tool for monitoring water-mass change in the ocean (Nerem et al., 2004; Tapley et al., 2004; Wahr et al., 2004; Chambers, 2006b). Data from GRACE has been used to estimate the water-mass variations in various ocean regions, and has made good progress in studies of marginal seas, such as the Mediterranean (García et al., 2006).

Although previous studies have revealed seasonal to long-term variations of sea level in the SCS, the variations of steric sea level and water mass have been less studied as well as their contributions to total sea-level change by combining satellite data and objective analysis data of temperature and salinity (Shaw et al., 1999; Ho et al., 2000; Liu et al., 2001a,b; Li et al., 2003; Fang et al., 2006). In this paper, we examine the sea-level budget using altimetry data, Ishii data and water-mass data derived from GRACE. Since GRACE data only covers a limited time period, we will focus on the annual variation, which is dominant in all observations. This paper is organized as follows. In Section 2, the data and methods are introduced briefly. In Section 3, results and discussions are presented. Conclusions are given in Section 4.

2. Data and method

Sea level anomaly (*SLA*) data being used in this study is merged TOPEX/Poseidon, Jason and ERS-1/2, or the Envisat *SLA* data, distributed by CLS Space Oceanography Division (see http://www.aviso.oceanobs.com/). Various corrections, such as ionosphere delay, dry and wet tropospheric corrections, electromagnetic bias, solid Earth and ocean tides, ocean tide loading, pole tide, inverted barometer correction, sea state bias and instrumental corrections, have been applied to the altimeter measurements (Le Traon and Ogor, 1998; Le Traon et al., 1998; Dorandeu and Le Traon, 1999). The accuracy of the merged data is about 2–3 cm. In this study, weekly *SLA* data are first averaged to produce monthly mean data. To be consistent with other data used in this study, the altimetric data over 2003–2006 are used and mean between January 2003 and December 2006 is subtracted from the original data.

A monthly $1^\circ \times 1^\circ$ gridded temperature and salinity dataset are used to estimate thermosteric and halosteric sea level in the SCS (Ishii and Kimoto, 2009). Compared with the historical temperature analysis of Ishii et al. (2006), this version introduces depth bias correction for XBT and MBT data in order to remove positive temperature biases in these observations. The data span from 1945 to 2006, with depth from surface to 700 m. As for the altimetric data, only the 2003–2006 data are used and mean the between 2003 and 2006 is subtracted from the original data.

Satellite measurements of the Earth's gravity field are provided by GRACE, which are used to infer movement of water mass over the Earth surface (Wahr et al., 2004; Chambers, 2006a). In the present study, we use mapped grids available from GRACE Tellus project (http://grace.jpl.nasa.gov/data/mass/) that are based on the Level 2 coefficients from the Center for Space Research (CSR) at the University of Texas from August of 2002 through August of 2008 (Chambers,