SEA LEVEL RISING TRENDS IN THE SOUTH CHINA SEA OVER 1993-2011

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ABSTRACT: Using 19 years of satellite altimeter data, the sea level rising rate over the South China Sea is analyzed. The results show that the basin-averaged sea level rising rate of the SCS is about 4.5 mm/year over the period of 1993-2011, which is much larger than the global sea level rising rate of 3.2 mm/year since 1993. The steric effect analysis based on Levitus' dataset shows that the total steric effect can only explain a half of the sea level rising rate in the SCS. Both of the rising rates of the satellite sea level and the steric sea level are geographically non-uniform. The water mass contributions to the sea level rising, including water transport through the straits and fresh water flux at the sea surface, are investigated as well to explain another half of sea level rising rate. However, due to the constraint of accuracy of transport rate from re-analysis dataset, the sea level rising budget is not closed in the current study.

Keywords: Sea level rising, South China Sea, satellite altimetry data, steric sea level.

INTRODUCTION

Sea level rising is receiving more and more attentions of global researchers as one of the catastrophic consequences of climate change. Globally, the available tide gauge measurements indicate that the global mean sea level has risen at a rate of 1.7-1.8mm/year during the last century (Church and White, 2011), while the satellite altimetry data indicate a higher rate of ~3.2mm/year since 1993 (Stammer, et al., 2013). Besides the accelerating rising of global mean sea level, studies also reveal that the sea level rising rate is geographically nonuniform. For example, the rates of sea level rising in Western Pacific have been faster by a factor up to 3-4 times the global mean rate in the past two decades. To better understand the global sea level rising and to provide more accurate information for coastal mitigation measures to natural hazards associated with sea level rising, it is of significant importance to quantify the regional sea level rising and to analyze its contributing factors.

The South China Sea (SCS) is the largest marginal sea in the tropics. It covers an area from the equator to 23ºN and from 99ºE to 121ºE, which connects to the Pacific Ocean in the east and the Indian Ocean in the west through several straits. The mean water depth of the bottom topography is ~1800m with a maximum depth more than 5400m. The temporal variations and spatial inhomogeneities of the interannual sea level oscillation and sea level rising have been studied by several researchers using satellite altimetry data or tidal gauge measurements (Rong, et. al. 2007, Cheng and Qi, 2007, Cheng and Qi, 2010). By using the TOPEX/Poseidon (T/P) altimeter data, Cheng and Qi (2007) found that the mean sea level over the SCS rose at a rate of 11.3mm/yr during 1993-2000 and fell at a rate of 11.8mm/yr during 2001-2005. They further pointed out that the steric sea level anomaly contributes significantly to the SLAs over the central SCS and the water mass anomaly dominates the SLA over the shallow waters (Cheng and Qi, 2010). Combining the altimeter data and tide gauge records, Rong, et al. (2007) revealed that the interannual variation of the SLAs in the SCS is closely related with El Niño and Southern Oscillation (ENSO). Most recently, Peng, et al. (2013) investigated the interannual sea level variations in the SCS over 1950-2009 by re-constructing the past sea level. Most of the previous studies focused on the interannual variation, while the sea level rising rate is only simply mentioned. This is partially due to the short period of satellite altimetry data available since 1993 by the time when those studies were conducted. So far there are nearly two decades (from January 1993 to the mid-2012) altimetry data available, which is, relatively speaking, much longer than the data used in the previous studies. These continuous satellite data combining with the other in-situ or re-analysis datasets provide an opportunity to quantify the sea level rising budget. Therefore, in this study, the 19-year satellite sea level data will be used to investigate the region-averaged sea level rising trend and the corresponding geographical distribution. The latest steric seal level data and water mass-related variables will also be explored in the analysis of sea level rising budget.

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The paper is organized as follows. Section 2 briefly describes the sources of data used in the study. Section 3 presents the rising rate of the sea level based on the satellite altimetry measurements. Different components contributing to the sea level rising are analyzed in section 4. At last, section 5 concludes the results and findings in the study.

DATA SOURCES

Satellite Data

A merged and gridded Delayed Time Updated (DT-Upd) product of Maps of Sea Level Anomalies (MSLA) is used in the study. The DT-Upd MSLA products are produced by AVISO based on TOPEX/Poseidon, Jason 1, Jason 2, Envisat and ERS-1, 2 data (see SSALTO/DUACS User Handbook). This product has been corrected by usual geophysical errors such as solid earth, ocean and pole tides, wet and dry troposphere, ionosphere and inverted barometric effects. The monthly sea level anomaly data on a 1/3º x 1/3º Mercater grid are obtained from AVISO website. In this study, the altimeter data over the period of January 1993 to December 2011 are used to compute the regional average and the spatial distribution of the sea level rising rate.

Steric Sea Level Anomaly

Steric sea level (thermosteric, halosteric, total) are provided by Levitus et al. (2012). They estimated the change of ocean heat content and the thermosteric component of sea level change of the 0–700 and 0–2000 m layers of the World Ocean for 1955–2010 based on the updated data from World Ocean Database 2009 [Boyer et al., 2009] plus additional data processed through the end of 2010. Yearly gridded thermosteric sea level anomaly data over 0-700m layers are provided on 1º x 1º grid from 1955 to 2011. Due to the constraint of salinity data and deep ocean data, the yearly holasteric component and the total steric data as well as thermosteric component over 0-2000m layers are only available for 2005-2011. However, their running pentadal (5-year) dataset are available from 1955-59 to 2008-12. Thus the yearly gridded pentadal data of steric sea level anomalies are used in current study.

Fresh Water Input and Water Mass Transport through Straits

The fresh water input over the SCS is mainly the net flux between precipitation and evaporation. The precipitation data are from the Version 2.2 (V2.2) of the GPCP (Global Precipitation Climatology Project) monthly product. The time span of GPCP V2.2 product is currently January 1979 through the delayed present. The evaporation data are from the WHOI OAFlux project (http://oaflux.whoi.edu) The OAFlux project provides near-real time 1-degree global analysis for the variables including evaporation from January 1958 onward. For both of the precipitation and evaporation data, the data over the period of 1993-2011 are used in the current analysis to keep consistent with the MSLA data. The mass transport values are estimated based on the meridional and zonal velocities from Simple Ocean Data Assimilation (SODA) global reanalysis dataset. This datasets are provided on a 0.5º x 0.5º grid with 40 layers from 5m to 5347m, with a time span of 1958-2010 (version 2.2.4). Thus, the period of the transport estimates is from 1993 to 2010.

LINEAR TRENDS AND GEOGRAPHICAL DISTRIBUTION OF SEA LEVEL OVER THE SCS

Fig.1. shows that the region-averaged sea level in the SCS is rising at a rate of ~4.5mm/year over the past two decades. Considering the global mean sea level rising rate of ~3.2mm/year since 1993 (Stammer, et al., 2013), the sea level of SCS is rising at a faster rate. Because SCS locates at the west end of the western Pacific and it is largely influenced by the western Pacific through the transport (Qu, et al., 2004), the larger sea level rising rate of the SCS is consistent with the rate in the western Pacific which is much larger than the global mean rate as well (Meyssignac and Cazenave, 2012). Besides the linear trend of sea level rising, Fig.1 also shows that the sea level over the SCS has clear seasonal and interannual oscillations. The most significant seasonal variation is mainly driven by the monsoon system (Chen, et al. 2012, Liu, et al., 2008). The interannual variation is highly correlated with El Nino Southern Oscillation Index (ENSO Index), such as Nino3.4. The correlation coefficient between the region-averaged interannual SLA with Nino3.4 can be as high as 0.67 with the ENSO leading SCS SLA by about 5 months (figure is not shown).

Fig. 2 shows the geographical distribution of the sea level rising trend. Generally, the whole SCS is experiencing a sea level rising with different rates. The deep basin shows larger rising rates than the shallow shelf. The spatial pattern of rising trend is different with the one reported by Rong, et al.(2007). One major reason may be that satellite data used in their study are only for about one decade (1993-2004). Due to the different behavior of interannual variations at different locations in the SCS, the pattern of rising rate may be largely changed. However, both the current result and Rong et al.'s indicate that positive sea level trend are in most of the basin and the rising trend is not homogeneous.

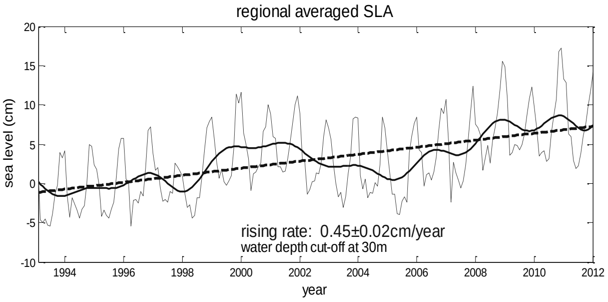

Fig. 1 Region-averaged sea level variations and rising trend over the SCS from 1993-2011. The red line indicates the seasonal variation after 3-month moving average is applied on the original regional mean. Solid blue line is the interannual curve after the seasonal signal is filtered out. The dashed line is the linear trend over the study period.

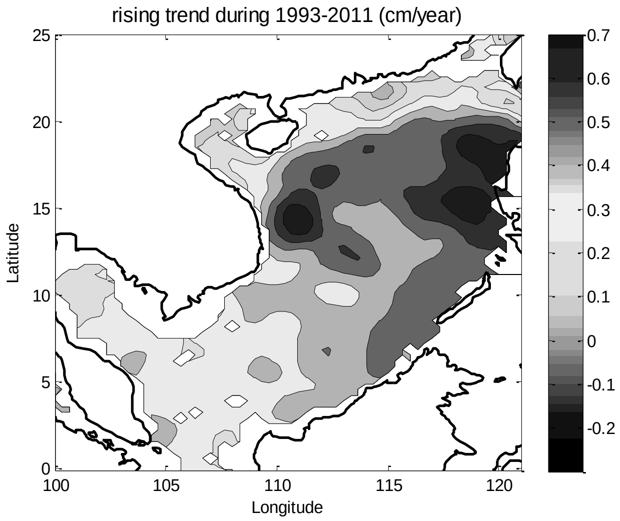

Fig. 2 Geographical distribution of the linear sea level rising rate over the SCS.

CAUSES OF SEA LEVEL RISING

The main causes of the sea level rising are the thermal expansion (steric rise) and the input of water mass (eustatic rise). The former is due to the change of sea water density resulting from the change of temperature and salinity, while the later is, in the case of the SCS, due to the difference of precipitation and evaporation and the water transports (inflow and outflow) through several straits connecting the SCS and the surrounding oceans and seas, including Luzon Strait, Taiwan Strait, Karimata Strait and Mindoro Strait.

Steric Sea Level Rising over SCS

Fig.3 shows the geographical distribution of the total steric sea level rising rate using the pendatal data from 1991-95 to 2007-11. It is shown that the steric sea level rising rates are also spatially non-uniform. The steric sea level rising mainly occurs in the northern and southern SCS. In the middle zone (about 8N-12N), the steric effect induces sea level falling, instead of rising. Further, the rising rate in the northern SCS is larger than the southern SCS.

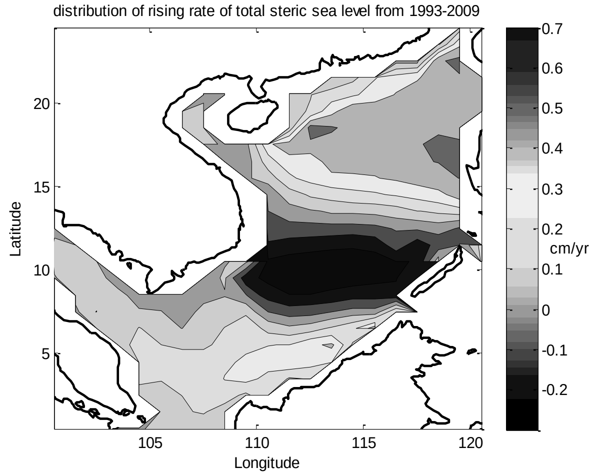

Fig. 3 Geographic distribution of the linear rising trend of total steric sea level over the SCS for 1993-2009.

Since the steric sea level rising includes the effects of temperature (thermosteric effect) and salinity (halosteric effect). Their contributions to the steric sea level rising are separately estimated over the SCS. As shown in Fig. 4 and 5, the spatial distributions of thermosteric sea level rising rate and halosteric sea level rising rate are generally similar with the one of the total steric sea level. But the region having the largest rate of thermosteric sea level rising is next to the Luzon Strait, while for the halosteric sea level, the region shifts westward for the northern SCS. Additionally, the halosteric sea level in the southern SCS presents larger rising rate than the thermosteric component in the same region. In terms of magnitude, Fig. 4 and 5 show that both the thermosteric and halosteric components are important for the sea level rising. This is different with the global mean sea level rising, in which the salinity effect is normally ignored (Willis, et al, 2010). The estimate of region-averaged rising rate of steric sea level also confirms that the temperature and salinity almost equally contribute to the steric sea level rising of the SCS.

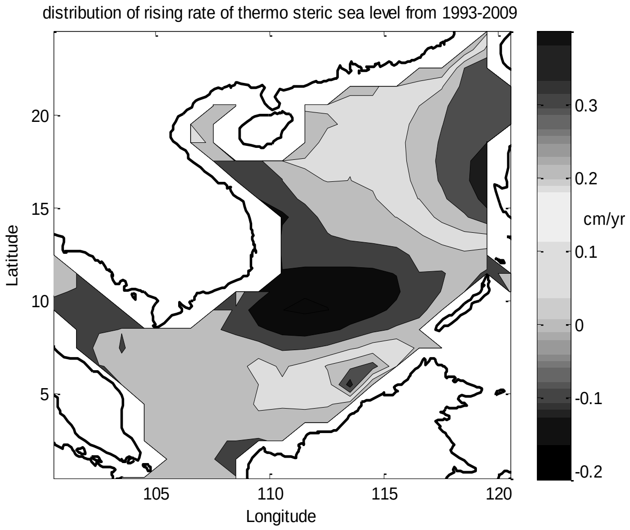

Fig. 4 Geographic distribution of the linear rising trend of thermosteric sea level over the SCS for 1993-2009

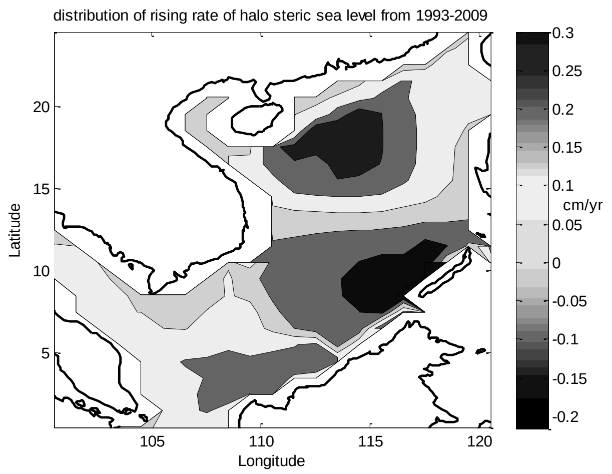

Fig. 5 Geographic distribution of the linear rising trend of halosteric sea level over the SCS for 1993-2009

Water Mass Contribution

The region-averaged total steric sea level rising rate is only about ~2.2mm/year, which only explains a half the satellite sea level rising over the same period (~4.5 mm/year). According to the sea level budget equation, the other half is supposed to be explained by the water mass contribution. Assuming the mean fresh water input, water mass transports through straits and the mean sea level in the SCS are internally balanced in a much longer term, we examined the anomaly of (P-E), and the anomaly of transport rate through the straits based on the available gridded dataset. As shown in Fig 6 and 7, although both the (P-E) and transports show similar interannual variations as the SCS SLA, which is highly correlated with ENSO, the rising/falling rates cannot close the sea level budget. While the net contribution of (P-E) can induce a sea level rising at a rate of ~6.7mm/year, the contribution of mass transport is far beyond the rate of falling expected to close the sea level budge. In fact, given a surface area of the SCS of 3.5 x 10^{12} m^2, a sea level rising/falling rate of 1mm/year in the SCS corresponds to about 0.0001Sv/year transport change (Cheng and Qi, 2007), which is out of the accuracy of the current model estimate. Therefore, SODA dataset may not be a good source for the estimate of mass transports into the SCS in the analysis of sea level budget.

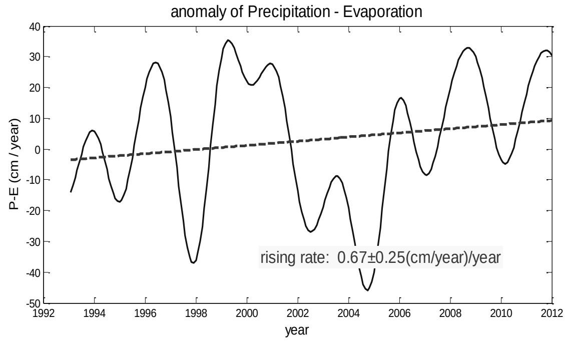

Fig. 6 Anomaly of region-averaged net fresh water flux at the sea surface over the SCS

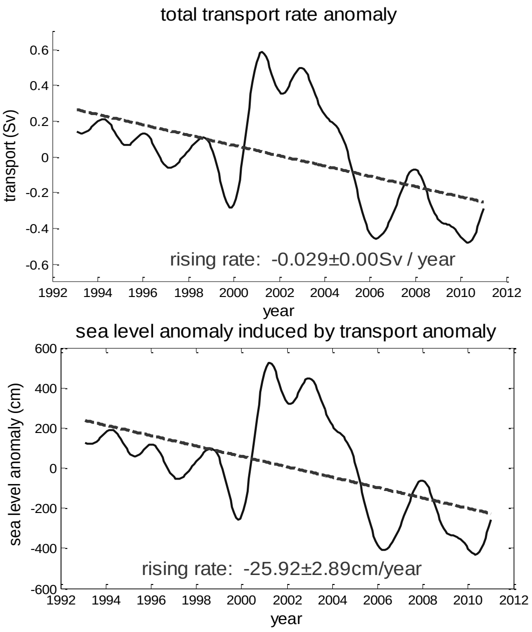

Fig. 7 Anomaly of total transport rate and its corresponding sea level changes of the SCS

CONCLUSIONS

In this study, 19 years of satellite altimeter data are used to analyze the sea level rising rate over the South China Sea. The results show that the basin-averaged sea level rising rate of the SCS is about 4.5 mm/year over the period of 1993-2011, which is much larger than the global sea level rising rate of 3.2 mm/year since 1993. The region-averaged sea level presents a clear interannual variation with a high correlation with ENSO phenomena. The steric effect analysis based on Levitus' dataset shows that the total steric effect can only explain a half of the sea level rising rate in the SCS. Both of the rising rates of the satellite sea level and the steric sea level are geographically non-uniform. The water mass contributions to the sea level change, including water transport through the straits and fresh water flux at the sea surface, present similar interannual variation as the sea level change. However, due to the constraint of accuracy of transport rate from re-analysis dataset, the sea level rising budget is not closed in the current study.

Since the launch of GRACE (Gravity Recovery and Climate Experiment) mission since 2002, there is a much more accurate method to estimate the water mass contribution to the sea level change. Therefore, the GRACE data will be used to close the sea level rising budget in the near future study.

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