Spatial-temporal analysis of sea level changes in China seas and neighboring oceans by merged altimeter data

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Abstract. The knowledge of sea level changes is critical important for social, economic and scientific development in coastal areas. Satellite altimeter makes it possible to observe long term and large scale dynamic changes in the ocean, contiguous shelf seas and coastal zone. In this paper, 1993-2015 altimeter data of Topex/Poseidon and its follow-on missions is used to get a time serious of continuous and homogeneous sea level anomaly gridding product. The sea level rising rate is 0.39 cm/yr in China Seas and the neighboring oceans, 0.37 cm/yr in the Bo and Yellow Sea, 0.29 cm/yr in the East China Sea and 0.40 cm/yr in the South China Sea. The mean sea level and its rising rate are spatial-temporal non-homogeneous. The mean sea level shows opposite characteristics in coastal seas versus open oceans. The Bo and Yellow Sea has the most significant seasonal variability. The results are consistent with in situ data observation by the Nation Ocean Agency of China. The coefficient of variability model is introduced to describe the spatial-temporal variability. Results show that the variability in coastal seas is stronger than that in open oceans, especially the seas off the entrance area of the river, indicating that the validation of altimeter data is less reasonable in these seas.

1. Instruction

As a result of global warming and glacial melting, global sea levels have an obviously rising trend[1]. The rising of sea levels would lead to more flooding. It's a disaster to human long-term development, especially for the coastal areas [2, 3]. Knowledge of rate and acceleration of sea level changes is critical important for a variety of social, economic and scientific development. And it is also important for planning the response of coastal and island population to rising sea levels [4].

During past hundreds of years, the tide gauges were used to study sea level changing [5], while it has some uncertain problems in analysis. The references of different places are not the same, so corrections must be applied individually [6, 7]. And it's difficult to get a full map of sea level changes worldwide because most tide gauges are at coastal places, not open seas [8, 9].

People began to use radar altimeter on satellite to monitor the sea level in late 1960s. In the 1970s and 1980s, several satellites were sent and laid the foundations for a new generation of ocean satellites. Since the launch of Topex/Poseidon (T/P) in 1992, with precise orthography and location system, the accuracy of the satellite positioning began to enable monitoring of sea surface height variations due to low-amplitude ocean dynamical processes. Besides of T/P, ERS-1/2, Envisat, Spot, Jason-1/2/3 and HY-2A were sent in the last 20 years [10]. Researchers began to study sea level changes in large scales with satellite altimeter data, which was difficult with tide gauges [11, 12]. National Center for Space Studies (CNES) of France calculated the mean sea surface level worldwide with a 19 year satellite dateset [13]. Pascuel et al [14] analyzed the ocean mesoscale variability with merged data from 4 satellites and compared the result from tide gauge, showing that satellite data had a better description. Stammer et al [15] studied the variability and spatial structure of world sea surface height with data from T/P. Some others studied the rising rate of sea level with a single or merged missions' data, showing that the global rising rate is around 0.32 cm/yr during last 20 years [16-18].

In China, half of the population and product are in the coastal area. According to the Bulletin of China Sea Level by the National Ocean Agency (NOA) of China, the coastal sea level rises at 0.3 cm/yr in last 35 years, which is higher than the global average [19]. Researches also find out that the sea level changes are spatially no-homogeneous and vary in different seasons [20-22]. Most people's researching focuses are on the South China Sea (5° N-23° N, 105° E-123° E) as it's a half-open ocean connecting with the Pacific Ocean and has a deep basin bordered by two broad shelf regions [22]. The sea level variability in the South China Sea is proved to have deep correlation with global climatology and oceanography [23]. Guo et al [24] studied sea level rising characteristics on all China seas and the neighboring oceans, the altimeter data was updated to 2012. Results show that the most significant period of sea changing over seas is 1 year, in addition to changing cycle of 9 year in the South China Sea.

In this paper, we continue updating the altimeter data to the latest year 2015, make several improvements in data editing and merging, analyze the seasonal signals and introduce a spatial-temporal analysis method to estimate the level of spatial-temporal variability. To get a homogeneous along track data, the latest mean sea surface model CLS2011 [13] is applied to each dataset instead of its default model. We merge the along track data from different missions before gridding in order to reduce the systematical errors between missions. A modified Shepard algorithm is used for mapping, which can solve the uneven distribution and slope of samples [25]. When analyzing spatial-temporal characteristics, a coefficient of variability (CV) model is applied to divide the China seas into several levels respecting the variability.

2. Data and method

Among previous and current missions, Jason-1 (2001-2013) and Jason-2 (2008-now) are the follow-on missions to Topex/Poseidon (1992-2006), as a cooperation between NASA and CNES. These missions have the same reference ellipsoid orbit parameters [26-28]. So they are chosen to map the sea level in focus seas to get a continuous and homogeneous result. The Geophysical Data Record (GDR) of the missions are processed to monthly gridded map with following steps:

2.1. Quality control and geophysical corrections

For each parameter in the Geophysical Data Record (GDR) file, it has a flag indicating whether the data is reliable. The bad data is a result of instrument conditions or processing error. The bad data must be removed from the dataset first. And editing criteria is a further way to improve the quality. For a homogeneous standard and result, the latest mean sea surface height model CLS2011 [13] is applied to all GDR data. Geophysical corrections are applied individually to get the sea level anomaly (SLA).

2.2. Along track gradient and crosscover adjustment

In theory, the repeating pass of different cycles should be in the same ground track. Because of various factors such as the earth gravity field model and the solar radiation, the satellite ground track is usually drift by ±1 km. The problem is solved by interpolating samples to a given orbit [27]. Also, SLA at the crosscover point of different passes should be the same while the difference is a result of systematical bias between two passes. An optimal adjustment model is designed to analyze and make adjustments to different month-mean passes to minimal the difference at crosscover point [16].

2.3. Data merging
There is a period of time that T/P and Jason-1, Jason-1 and Jason-2 are on board together. The validation and calibration between two missions were finished during the period [29]. There is a significant systematical bias between two missions. At China seas, different researchers give a bias around -8.6cm between T/P and Jason-1[30], and around 10cm between Jason-1 and Jason-2 [30]. In this paper, we compare the month by month data, and get a bias of -13.27 cm between T/P and Jason-1, and 10.45 cm between Jason-1 and Jason-2. The absolute bias in this paper is bigger than earlier research is a result of changing the mean sea level model. The default model of T/P is based on limited data while CLS2011 is derived from multiple-satellites as long as 19 years. CLS2011 is also the follow-on version of CLS2001, which is the default model of Jason-1.

2.4. Gridding
The along track scatter data is spatial interpolated regular maps to show the continuously spatial variance. As the satellite track points's distribution is uneven in longitude and latitude, it must be considered to balance the weight of different directions. Some scholars give a proper weight to different points before interpolation, while a modified Shepard method take the weight problem and slope of the area in account[30]. Modified Shepard method is improved from inverse-distance algorithm and makes several improvements to consider the uneven distributions of samples, remove samples with too-short distance and add a proper weight on specific direction if samples are on the slope.

3. Result and discussion

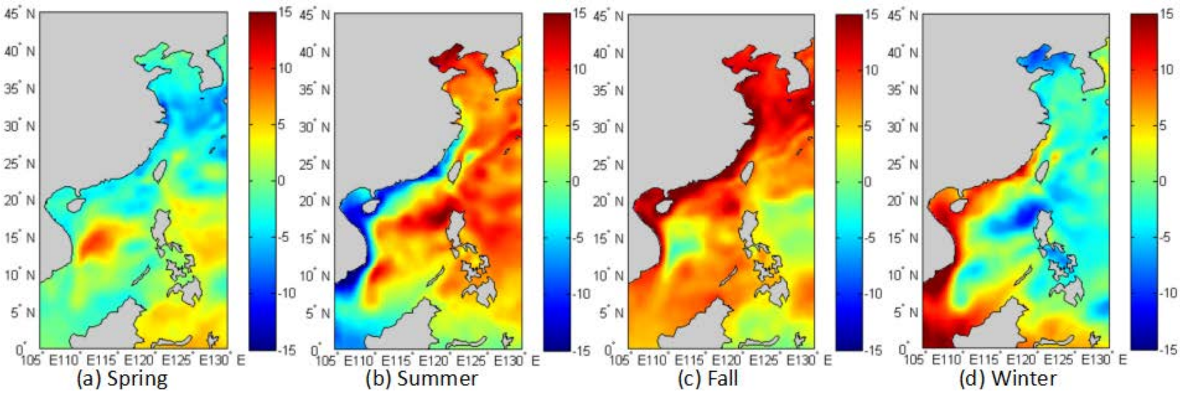

Figure 1. 1993 to 2015 season mean of SLA (cm). The season mean is a simple averaging of month mean.

From the month mean product, we calculate the season (Spring: Mar to May, Summer: Jun to Aug, Fall: Sep to Nov, Winter: Dec to Feb) mean from 1993 to 2015. From Figure 1, the sea level in coastal seas has a opposite characteristics to that in open oceans, especially in Fall. In Spring and Summer, the mean sea level in coastal seas is lower than that in open oceans while in Fall and Winter, the sea level in coastal seas is higher than that in opens oceans. Compared with in situ data in coastal Guangxi and Xisha, which is in the middle of the South China Sea, from NOA'S Bulletin of China Sea Level[19] in past 4 years, sea levels at coastal Guangxi are higher than the reference in 3 years, while those at Xisha are lower than the reference. In general, sea levels in Winter and Spring are 5 to 10 cm lower than those in Summer and Fall in the same year, the result is consistent with in situ observations [19].

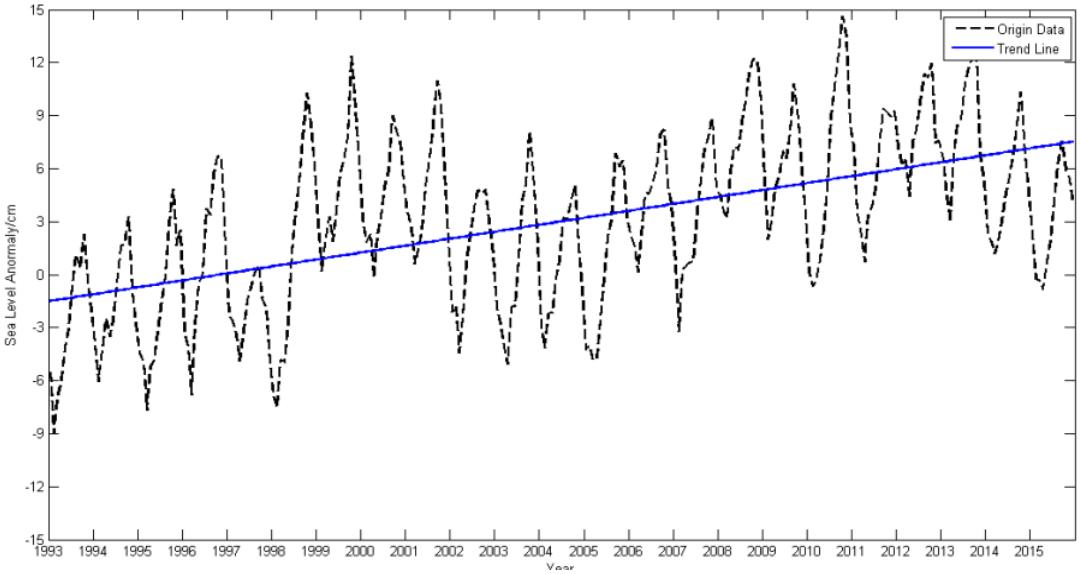

Figure 2. The sea level rising rate in China seas and neighboring oceans. The trend line is $y = 0.39x - 785.65$.The model is significant different from zero at 95% confident. Statistical calculations are based on the student's t-test and the degrees of freedom are estimated by considering the autocorrelation of data [24, 31]

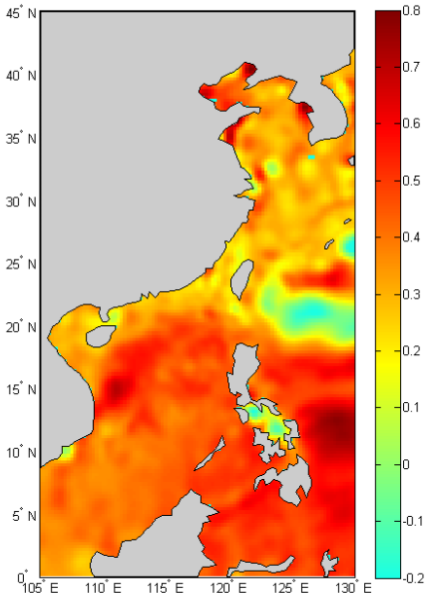

Figure 3. Spatial distributions of 1993-2015 rising rate (cm/yr). Each rising rate is calculated from the 23-year time series data. 99% rate falls into the domain [-0.2 0.8].

To analyze the rising rate of sea level, least-square method is used to solve the linear model $y = ax + b$ to get the rising rate 0.39 cm/yr in China seas and the neighboring oceans. It is 0.08 cm/yr lower than Guo's [24] result 0.47 cm/yr, which is derived from the 1993-2012 altimeter data of the same missions. From Figure 2, we can find out that in the last three years (2013-2015), the sea level has a descending trend. If we chose the same period as Guo's research, the rising rate is 0.48 cm/yr. The 3-year descending trend and the 1999-2004 descending trend are also found in inter-decadal cycles of the SLA temporal variability [32].

The 0.39 cm/yr rising rate is higher than 0.30 cm/yr (from 1980 to 2015) given by NOA [19]. The Bulletin of China Sea Level' s focus area is coastal seas, and from Figure 3, coastal seas rising rates in the Southeast coastal seas are 0.1-0.2 cm/yr lower than those in the open oceans. Another reason is that the rising rate in last two decades are high than ever before [3, 19, 33]. Figure 3 also shows the spatial distributions of rising rate, it' s the highest in the South China Sea (5° N—23° N, 105° E—125° E) and lowest in the East China Sea (23° N—32° N, 117° E—130° E). In most cases, the rising rate in coastal seas are lower than those in open oceans.

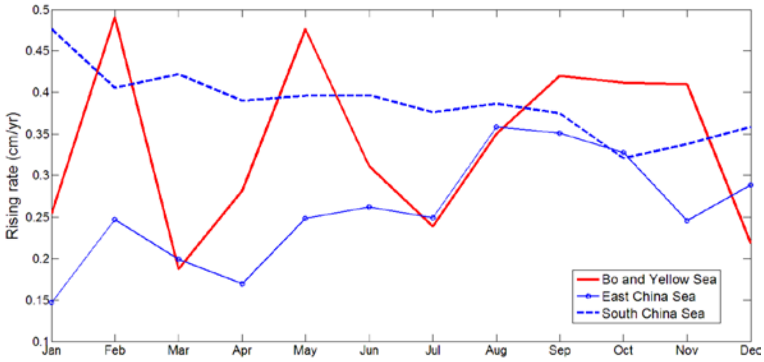

Figure 4. The rising rate of each month in different regions.

From Figure 4, we confirm the temporal variability in different regions, the rising rate in the South China Sea is the highest in 7 months in the year while in the East China Sea, it's the lowest in 7 months in the year. The variability in Bo and Yellow Sea (32° N—45° N, 115° E—127° E) is the most significant, the rising rate in February is 0.3 cm/yr higher than that in March.

To make a quantitative analysis on the spatial and temporal variability, given a 3×3 window around a pix in a map, the spatial variance is defined as follows:

$$CV_s = \frac{s_{window}}{\mu_{window}} \quad (1)$$

s_{window}, μ_{window} is the standard deviation and average value of data in the 3×3 window. The spatial-temporal coefficient of variance $CV_{s,t}$ is the time average of CV_s. In this paper, month mean SLA data is standardized to domain [0,1], and the results are given in Figure 5 and Figure 6.

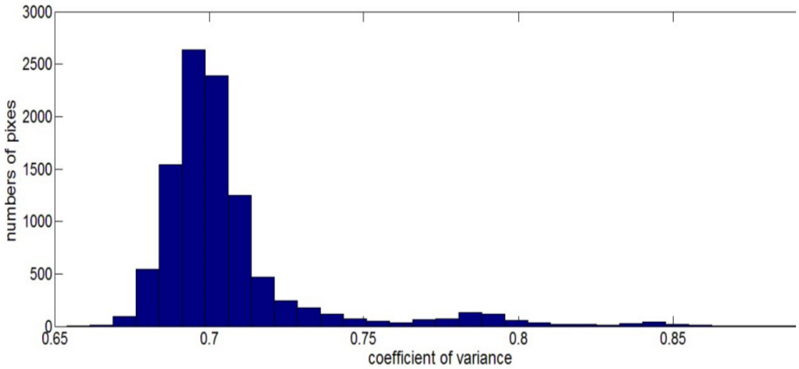

Figure 5. The distribution of CV in China seas and neighboring oceans. X-axis stands for the coefficient of variability and Y-axis stands for the number of pix with the specific CV. 99% of the CV falls into the domain [0.65 0.9]

The coefficient describes the spatial-temporal variability of sea level changes in China seas and neighboring oceans. From Figure 5, the coefficient between 0.67 and 0.75 follows the normalized distribution while there is 5% extreme data higher than 0.75. From Figure 6, the coastal seas are the areas with the extremely high coefficient. It means the spatial-temporal variance in coastal sea is 0.05 higher than that in the open sea, especially at the entrance of the river. The Yangtze River, the Yellow River and the Pearl River are the three biggest rivers in China and the Mekong River is the biggest river in Southeast Asia. There are 8 sea gates in the entrance of Pearl River and 8 sea gates in the entrance of the Mekong River. So the seas off these areas show a significant high variability. The middle of the South China Sea is in the low variability level while most area of the Bo and Yellow Sea and the East China Sea are in the Medium level.

The map of CV can be applied to determine the position of offshore platform of altimeter absolute calibration. In absolute calibration of HY-2A radar altimeter, two positions in the Bo Sea and the South China Sea were chosen, whose seasonal signals of sea surface height were weak[3, 19, 33]. The method of determining the position could be more precise and reasonable with the CV model.

4. Conclusion

We process the GDR data to a merged month mean gridding product. The method has less systematical errors in theory and be consistent with others' results and in situ observation. From the season mean product, we find out that the sea level in China seas has significant difference among seasons. In general, the sea level in Summer and Fall is higher than that in Winter and Spring. Among all regions, the Bo and Yellow Sea has the most significant seasonal variability, the mean sea level in Summer is 15 cm higher than that in Winter. The rising rate from 1993-2015 altimeter data is 0.39 cm/yr, which is higher than the global average and NOA's observation but lower than the rate from 1993-2012 altimeter data because of the descending trend in last 3 years. The rising rate of the South China Sea is the highest in 7 months in the year while the rising rate of the East China Sea is the lowest in 7 months in the year. The temporal variance of the Bo and Yellow Sea is strictly stronger than the others. The result from altimeter data is consistent with the Bulletin of China Sea Level given by NOA. The CV model shows that the spatial-temporal variance in coastal seas is extremely higher than that in open oceans, especially the seas off the entrance area of rivers. The CV model can be applied to improve the method of determining the position in absolute calibration.

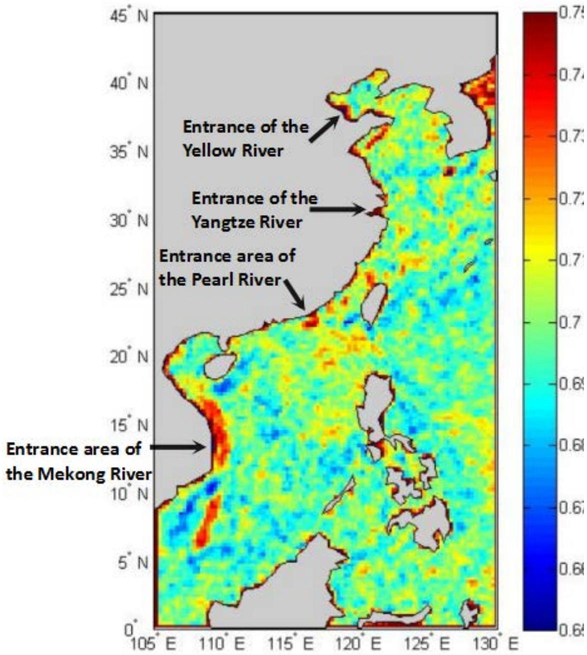

Figure 6. The coefficient of spatial-temporal variance of sea level changes. The CV lower than 0.7 is believed to be in the low level, CV between 0.70 and 0.75 in the medium level and that higher than 0.75 in the high level.

Acknowledgement

We are very grateful to AVISO for providing the data of T/P, Jason-1 and Jason-2. The Research is supported by the State High-Tech Development Plan of China (2014AA12330), the Public Benefit Technique Research and Social Development Key Program of the Science Technology Department of Zhejiang Province, China (2014A23002) and the Summer Internship Program for College Student 2016 of the State Ocean Administration of China.

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