Temporal and Spatial Variation of Sea Level in the East China Sea during 1993-2015

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Abstract. Based on AVISO satellite altimetry data, the seasonal and spatial patterns of the sea surface height anomaly (SSHA) during 1993-2015 in the East China Sea (ECS) were determined. The SSHA variations related to thermo-steric effects were evaluated. Significant seasonal variations of the SSHA in the ECS were observed. The SSHA was lower in winter and spring and higher in summer and autumn. The peak values of the SSHA lagged behind those of sea temperature by one month. The regional distribution of the SSHA was obvious in different seasons because of sea depth and dynamic ocean processes. The annual mean growth rate of the SSH in the ECS during 1992-2015 was 2.82 mm.y\(^{-1}\).

1. Introduction
Due to global warming, sea levels continue to rise. According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [1], the growth rate of global SSH during 1993-2010 was 2.8-3.6 mm.y\(^{-1}\), which is significantly higher than the average growth rate (1.5-1.9 mm.y\(^{-1}\)) during 1901-2010. This indicates that the global sea level rise has accelerated in the past two decades. Furthermore, the sea level along China’s coast is rapidly rising. According to the 2015 Chinese Sea Level Bulletin, the growth rate of SSH in the East China Sea (ECS) during 1980-2015 was 3.0 mm.y\(^{-1}\). The fourth highest sea level in the past three decades was recorded in 2015 [2]. Due to the rise in sea levels, marine catastrophic events such as storm surges, coastal erosion, and seawater intrusion, are more likely to occur thereby threatening economic development and human living environment in the coastal areas. Studying sea level variations and the main forcing mechanisms and forecasting the sea level trend can help prevent marine catastrophic events effectively. Therefore, research on sea level variations can contribute significantly to disaster assessment.

There is an obvious seasonal and spatial variability of the SSH in the ECS. Zhan et al.,[3] used satellite altimetry data to analyze the variation of the seasonal sea level cycle in the ECS. The results indicate that the annual signals were dominant for the sea level variation during 1992-2007. Additionally, the semi-annual signals were more obvious in the South China Sea, while high frequency signals were more obvious in the Yellow Sea (YS) and East Sea (ES). The factors that contribute to sea level variation are [4]: variations of the seawater quality, such as ice melting, precipitation, evaporation, runoff, and other seawater exchange processes, and variations of the seawater density due to temperature or salinity variation, which can be referred to as steric effect. Guo et al., [5] reported that the seasonal variation and spatial distribution of SSH in the ECS were related to...
changes in seawater volume and thermo-steric effects, which are due to monsoon and seawater temperature changes respectively.

Based on satellite altimetry data, this study analyzes the spatial and seasonal variations of SSHA in the ECS.

2. Data description

2.1. Data sources
In this study, satellite altimetry data obtained from Maps of Absolute Dynamic Topography (MADT) datasets and tide gauge data from along the coast of China and over the adjacent shelf seas were used. MADT datasets are produced by Archiving, Validation and International of Satellites Oceanographic (AVISO) based on TOPEX/Poseidon, Jason 1, ERS-1, and ERS-2 data. The altimetry data covered a period of 23 years (1993 to 2015), and consisted of maps produced daily on a 1/4° × 1/4° Mercator grid. The research area is located at 23°-41° N, 117°-130° E.

2.2. Data validation and comparison
Data from two tide gauge stations, with the same location, were compared with the AVISO satellite altimetry data of the SSH in the Bohai Sea and the East Sea. Based on the calculated monthly data anomalies for 2013 to 2015 (Figure 1), we can deduce that the seasonal variation of tide gauge data is obvious in Dalian; the sea level was low during winter (December, January, and February) and high during summer (July, August, and September). The satellite altimetry data showed the same seasonal variation pattern as the tide gauge data. However, the tide gauge data had larger annual variations than satellite altimetry data. The variations of SSH recorded by Kamen tide gauge station are complicated. Although the SSH showed annual variations, it was higher in September, October, and November and lower in January, February, and March. In summary, the satellite altimetry data corresponds well with the data from tide gauge stations. Therefore, the satellite altimetry data can be used for a reliable analysis of the seasonal and spatial variations of SSH in the East China Sea.

Fig. 1 Comparisons of the monthly mean SSH data obtained from the tide gauge stations (blue line) and AVISO (black line) for (a) Dalian and (b) Kanmen during 2013-2015
3. Results

3.1. Seasonal variations of SSHA

The monthly average SSHA in the ECS during 1993-2015 was calculated to obtain the monthly distribution of climate status. Figure 1 shows the seasonal variation of SSHA in the East China Sea during 1993-2015.

The seasonal variation of the sea level in the Bohai Sea (BS) was spatially consistent. From December to March, the SSHA was less than -10 cm in most regions of the BS. With increased solar radiation intensity, the seawater expanded and the sea level rose significantly in June. In August, the positive anomalies of SSHA exceeded 10 cm and the highest sea level was recorded. In the coastal areas of the Yellow Sea (YS), the seasonal sea level variation was consistent with that of the BS. The sea level was low during winter and spring and high during summer and autumn. The SYS lagged behind the NYS by one month during the same period. Influenced by the cold water mass of the YS, a low sea level center appeared in the central area of the SYS in September.

The seasonal variation pattern of SSHA in the offshore areas was different from that in the coastal areas of the ES (East sea). In the offshore areas of the ES, the sea level fell in winter and began to rise in spring. Meanwhile, SSHA in the ES exceeded 10 cm in August except for the regions between the Yangtze Estuary and the Taiwan and the path of the Kuroshio current. The seasonal sea level variation in the coastal areas of the ES and the Taiwan Strait are consistent. The sea level was low from April to August, while high sea levels appeared between October and December. The SSHA in a region of northeastern Taiwan was around the zero contour all round year, indicating a weak seasonal signal in this region.

To forecast the seasonal variation of SSHA in the ECS more accurately, we applied the average spatial variation during 1993-2015 to the gridded monthly SSHA data. From the abovementioned analysis, we know that the seasonal sea level variations over the coastal areas of the ECS are consistent. The BS and YS are located at 37° N-41° N, 117° E-126° E, the SYS at 32° N-37° N, 117° E-126° E, the offshore areas of the ES at 25° N-32° N, 122° E-126° E, and the Taiwan Strait and coastal areas of the ES at 23° N-32° N, 117° E-122° E.

In this study, the trend of the time series was first removed. Figure 2 shows the time series of the sea level height anomaly from 1993 to 2015 in different sea areas of the ECS. Furthermore, the annual fits were superimposed. Both the amplitude and the phase of sea level anomalies in the different sea areas are different. Least-squares fitting methods [6] were applied to the data; an annual amplitude of 10.6 cm was obtained for the ECS. The lowest and highest sea levels were recorded in March and September respectively. However, the lowest and highest ocean temperatures were recorded in February and August respectively. Since the heat capacity of seawater is three-folds higher than that of the atmosphere, both seawater cooling and warming showed a one-month lag. Correspondingly, the seasonal sea level variation lagged behind atmospheric conditions in the ECS by one month. However, SSHA distributions in the BS, YS, and ES were affected by seasonal temperature changes, sea depth, and dynamic ocean processes.

Due to the shallow depth of the water and the agitation of water by wind stress, the seawater temperature was uniform from the surface to the bottom in the BS and YS. Therefore, the highest and lowest sea levels in the BS and YS were recorded in August and February respectively. The seasonal sea level variation in the Taiwan Strait and coastal areas of the ES was affected by the seasonal variations in the Taiwan Warm Current. Therefore, the highest and the lowest sea levels were recorded in November and May respectively. The amplitude of annual seal level variation in the coastal areas was larger than that in offshore areas. The amplitudes of annual sea level variation in the BS and YS and the Taiwan Strait and coastal areas of the ES were 12.0 and 11.6 cm respectively. Additionally, the amplitudes of annual sea level variations in the YS and offshore areas of the ES were 9.9 and 9.0 cm respectively.

In summary, the sea level of the ECS showed seasonal variations and a significant spatial distribution.
Fig. 2 Seasonal distributions of the SSH in the study areas

Fig. 3 Time series of SSH in the ECS during 1993-2015

(BS: Bohai sea and North Yellow Sea; SYS: South Yellow Sea; ES: Offshore areas of the East Sea; TWS: Taiwan Strait and coastal areas of the East Sea; ECS: East China Sea)
3.2. Analysis of the SSHA trend

Figure 4 shows that there is a clear upward trend in the sea level of the East China Sea. By removing the annual cycle and half-year periodic signals from the SSHA data and performing 30- and 60-day low-pass filtering [7], the data were linearly fitted by applying least-squares fitting methods (Figure 4). During the study period (23 years), the annual mean sea level in the ECS showed a significant linear rise trend with a growth rate of 2.82 mm.y\(^{-1}\). According to the AVISO statistical data, the global sea level growth rate was 3.21 mm.y\(^{-1}\) during the same period [8]. The upward trend of the SSH in the East China Sea was slightly less than that of the global SSH.

![Figure 4](image_url)

**Fig. 4** Time series of the SSHA rise trend in the ECS during 1993-2015

4. Conclusion

Based on the AVISO satellite altimetry data, the temporal and spatial variations of sea surface height anomaly (SSHA) in the ECS during 1993-2015 were analyzed.

The SSH of the ECS had a significant seasonal variation. The SSH was lower during winter and spring and higher during summer and autumn. The peak values of SSH lagged behind that of the sea temperatures by one month. Overall, the SSH was lower in the northern part and higher in the southern part of the ECS. The SSH showed obvious regional distributions in different seasons because of sea depth and dynamic ocean processes. The annual mean growth rate of the SSH in the ECS during 1992-2015 was 2.82 mm.y\(^{-1}\).

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