Interannual variability of sea surface height anomaly in the South China Sea

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Abstract. Spatial variability of Sea Surface Height Anomaly (herein after SSHA) in the South China Sea was investigated through the response of sea surface to interannual phenomenon. In this research, satellite altimetry data were used which covered periods from 1992 to 2015. Signal analysis was performed to separate dominant spectrum for each stations. From the analysis, it is found that the dominant feature for South China Sea is high period signal i.e annual and decadal signals. This research will focus the analysis only on interannual variability response of SSHA. During northeast monsoon, SSHA in South China Sea region is increased due to the accumulation of water mass over southern basin. Highest increase of SSHA occurs during strong La Niña, while the highest decrease of SSHA takes place during El Niño. The distribution of change in SSHA varies with strong influence of latitude and longitude to the response of upper layer. During El Niño, increasing SSHA was detected in several locations; likewise, during La Niña the decrease was also found.

1. Introduction

South China Sea (SCS) is a marginal sea that lies as an extension of western part of the Pacific Ocean (Figure 1). This semi-enclosed basin is also known as the “Mediterranean of Asia”. This semi-enclosed basin is the biggest in the South East Asia and has complex topography with a steep continental slope [1]. The topography is characterized with long continental shelf in the northern and southern part of SCS and deep basin with a maximum depth of around 5000 in its central eastern part [2]. SCS is connected directly with western part of the Pacific Ocean through the Luzon Strait and the Indonesian seas through the Karimata Strait.

Study on the SCS has getting a lot of attention. It is not only because it has a quite unique setting in term of location, but also is known to connect major ocean circulation, namely the Indonesian Through Flow (ITF) and extension of the western boundary current of the Pacific Ocean [3]. Along with technological advancements, altimetry satellites have become a widely used tool for assessing ocean parameters. Satellite observation is found to be useful to overcome the limitations to study the SCS. Based on previous studies, it was concluded that the most dominant variations of sea surface height (SSH) in the SCS are seasonal, inter-annual, and decadal variations. The SCS is right on the
axis of the two monsoon directions, namely the southwest and northeast monsoon seasons, so that the SSH in this region is strongly influenced by monsoons. The location of the South China Sea adjacent to the Pacific Ocean also causes these waters to be affected by global circulation effects such as ENSO and PDO. The results of the study by [4] showed a significant mesoscale variability in the northern border of the Luzon Strait with large temporal fluctuations. Through wavelet analysis on altimetry satellite and XBT data, it is known that the main driver of SSH variability in the northern South China Sea is the Kuroshio intrusion. In the North itself there are two significant variability bands, namely around the Luzon Strait and from 10°N [4].

![Figure 1. Map of the South China Sea (source: http://icgem.gfz-potsdam.de/ICGEM/).](image)

With the statistical method of root mean square (RMS) and empirical orthogonal function (EOF), [2] SSH variations in the SCS was examined. It is seen that the SCS has three dynamically active regions. The first area is located around the western basin of the Luzon Islands at 17°N, 188°E with a radius of around 150 km. The second area is at 15°N, 114°E, while the third area is located around the Vietnamese coast at 12.5°N, 110°E. Then, [5] conducted a study of SSH on its interannual and decadal variability. The results obtained showed that seasonal characteristics of SSH in the study area. There are negative anomalies along the southeast and north coasts, as well as positive values in the middle basin. If the influence of Rossby wave and Kuroshio intrusion is dominant in the northern and central parts of the basin, then the coastal and continental slope of SSH variability is dominated by wind stress.

T/P altimetry satellite data in the SCS from year of 1992 to 1995 was used and then EOF harmonic analysis was performed to determine the main component (principal component) of sea surface height anomalies (SSHA) [6]. It is known that wind stress curl is the main driver of circulation in the basin in the SCS except around the Luzon Strait. The influence of monsoon is also seen from the results of [1]. In general, seasonal variations from large-scale circulation (LSC) can be divided into four phases based on the season. In winter (November-February), the main feature seen is the double cyclonic circulation dominated by the northern sub-basin gyre. Spring (March and April) is a transitional period
where the northern part of the cyclone remains rotate anti-clockwise but the southern part of the gyre becomes anticyclonic. Other characteristics include decaying process of Kuroshio intrusion from the Luzon Strait. In the summer (May-July) the circulation in the SCS flows to the northeast. The direction of circulation has not changed throughout the fall (August-October), but the monsoon jet that moves off Vietnam's coast changes from anticyclonic to cyclone. [6] argued that a strong curl in winter caused the formation of cyclonic gyre, while in the summer dipole were caused by wind stress differences in the north and south. [2] also found the Kuroshio intrusion into the northeastern part of the SCS through the Luzon Strait from June to September. Based on altimetry satellite data with a span of five years, [2] obtain results that the SCS surface circulation correlates with the monsoon. [7] studied SSH based on steric sea level and response to wind stress using assimilation data from ORA – S3 ECMWF models and XBT observation data. After periodic signals are separated, it is known that SSH in the South China Sea (SSH-LSC) has its own annual cycle with a minimum value in February and maximum in August and an amplitude of 1.81 cm.

Here, we aim to examine the influence of ENSO in the SCS by using the EOF method, energy spectrum, correlation and coherence analysis. We divided the SCS into several geographical regions to understand its spatial-temporal influence of ENSO in the regions.

2. Methods and Data

Signal analysis with the filtering process consists of various types, one of which is a low pass filter. Low pass filter is a data filtering process where a frequency lower than the cut-off frequency is passed, while a signal with a higher frequency is ignored. The general formulation of filters [8] is:

\[ y_n = \sum_{k=-M}^{M} h_k x_{n-k} + \sum_{j=-1}^{L} g_j y_{n-j} \]  

(1)

where \( x_n, y_n \) are time series variables and \( h_k, g_j \) are the weighting functions.

To analyze inter-annual data, Hovmöller diagram analysis is used. Hovmöller diagrams are commonly used in long period data to interpret signals such as in ENSO and MJO. The Hovmöller diagram is very helpful in visualizing large amounts of data. The Hovmöller diagram can display patterns or movements of a parameter, such as rainfall and water mass, using time scales and latitude or longitude on both different graph axes [9]. In addition, one method used to detect the strongest signal in SSH variability is the EOF method that has been applied for the case in Makassar Strait, Indonesia [10].

The data used is monthly SSHA data from a combined altimetry satellite program obtained from the AVISO website (http://www.aviso.altimetry.fr/en/home.html). Monthly SSHA data has a period of 22 years, starting from January 1993 to August 2015. Data has been processed in grid form with a spatial resolution of 1/4 ° by 1/4 ° and has high accuracy for research purposes. In addition to the AVISO website (Archiving, Validation and Interpretation of Satellite Oceanographic Data), the same data is also available on the NOAA (National Oceanic and Atmospheric Administration) site. The data can be accessed at the address http://coastwatch.pfeg.noaa.gov/erddap/gridddap/erdTAsshmday.html and through the Copernicus Marine Environment Monitoring Service website (http://marine.copernicus.eu/).

The study location is the area of the South China Sea at 30°N - 0° and 100° - 120°E. The study area is divided into 7 (seven) geographical regions as shown in Fig. 2. Area A located in passage of water from Pacific Ocean enters into South China Sea through Luzon Strait, while Area G is the place where water mass come out from the strait.
3. Result

3.1. Mean standard deviation of SSHA

The distribution of SSHA in the study area can be generally analyzed from the standard deviation (STD) (Figure 3). STD values in the middle of SCS is between 2 cm to 4 cm indicating deviations from the mean. The sea level of the central and southern basins tends to be lower than the northern basin and the area around the Philippine archipelago. The offshore areas of Vietnam and the Gulf of Thailand have a standard deviation of about 5 cm to 6 cm, while higher values are found in the eastern part of the Luzon Strait. A high SSHA surface of 7 to 8 cm is visible in west of the Luzon Islands, and the standard deviation value of SSH is smaller to the east until it reaches 3 cm in the middle of the basin. Off the coast of the southern Hainan Islands, SSHA were also found to be high with an elementary grade of 6 to 7 cm. This value is similar to the SSHA standard deviation in the west and north of the Luzon Islands. The area around the Luzon Strait has high variability [4,6] and meso-scale variability in the northern part of Hainan Island and Luzon Islands can be caused by cyclonic gyre circulation.
3.2. Climatology of SSHA
Figure 4 showed the monthly spatial variation of sea surface height (SSHA) in the SCS. In winter (December - February) the sea surface conditions in the SCS are divided into two, namely the SSHA which is lower in the northern basin around the Luzon Strait and SSHA which is high in the southern basin around the Gulf of Thailand. The SCS circulation in winter is characterized by these characteristics, where SSHA in the middle basin is lower than the surrounding waters [1]. In this season, there is a northeast monsoon that carries cold air masses from the Asian continent to the waters of the South China Sea. Circulation on the surface is affected by different directions of monsoon. There is a flow from offshore Vietnam to the southern basin and in the middle part cyclonic circulation patterns are formed [11]. Due to the northeast monsoon, there was an accumulation of water mass in the Gulf of Thailand and the coasts of Kalimantan and Vietnam. In November, two different centers of SSHA were seen in the middle basin, which were around 13° and 15° N. Kuroshio intrusion is seen along the coast of Taiwan, while SSHA showed positive values on the Chinese coast in December. Apart from the Luzon Strait, Kuroshio intrusion was also seen through the Mindoro Strait in January and February. According to [11], Kuroshio intrusion was related to the northeast monsoon where the wind blowing southwest caused Ekman transport, so Kuroshio turned westwards through the Luzon Strait. The difference in SSHA height between point A and B is not so large in December, but when entering January there is a difference of 5 cm. There is a big difference in this month where the G point is about 10 cm higher than points A and B. The low SSHA center around the Luzon Strait begins to disappear in March and April, while the sea level is high, around 5 cm in February and March on the coast of Vietnam, it experienced a decline to its normal height. Entering May, the high SSHA value in southeastern Vietnam extends to the northwest of the Philippines, while the low surface sea level around the Taiwan Strait extends to the Beibu Gulf and the Gulf of Thailand.
SSHA patterns in summer are characterized by dipole structures where the northern and southern basins are higher than in the middle basin. There are several anticyclonic gyre in the western part of the islands of Luzon and Hainan. These results are consistent with previous studies from [1]. Summer is the period of the southwest monsoon, that is, the east coast winds from the northeast in the southern hemisphere move to the equator and become the southwest monsoon along the South China Sea. The southwest monsoon carries a lot of moisture and also changes the circulation pattern in the South China Sea to the southwest. It is seen that from June to August the sea level in the northern basin of the South China Sea is higher than the middle and south basin. Surface anticyclonic circulation is seen in June where there are three structures of maximum sea level from the middle basin that moves towards the north. Sea level at regions E and F this month is about 5 cm. In the summer, sea level at region A is relatively higher than other points. The structure is split into two with a height of about 15 cm in the western part of the Luzon Strait and the southern basin. In September the value of SSHA on the coast of China and the northern coast of Vietnam increased by about 10 cm. Then, in October the increase in SSHA in these waters increased to around 20 cm. In October, the winter circulation on the
surface has begun to appear where the middle basin is surrounded by several SSHA altitude centers around latitude 5° and 10° N. Almost all points have a uniform surface height, which is about 5 cm. Exceptions occur at regions E and F located in the middle basin.

The maximum height of the surface of the SCS occurs during winter. The coastal areas of Vietnam and China have SSHA values of 20 cm from June to August, but during the summer can be reduced by 15 cm. Although in the summer there is an expansion of the water mass, the accumulation of water masses due to the monsoon is more dominant in determining the surface height of the SCS.

3.3. Spectrum energy analysis
In order to know the dominant signals at the research location, an energy spectrum signal or Fast Fourier Transform is performed. It is seen that the phenomenon that has a large influence on the area studied is a phenomenon with higher period such as annual and decadal periods. Almost all regions show that the annual period signals are stronger than the ten-year signals. However, exceptions occur in regions B and D where decadal signals are more dominant than annual signals. In addition to the annual, inter-year signals also have a high energy spectrum (not shown in manuscript).

ENSO is part of global phenomenon. [12] emphasized that the eastern equatorial Pacific (ENSO index) is important in order to understand climate variability patterns more deeply. There are several differences in views between the driving forces that are more dominant in SSH variability in the SCS. [13] argue that the long-term variability in the SCS is more influential than PDO, while [14] and [12] argue that PDO is more dominant than ENSO. The following is the correlation between SSHA and ENSO.

![Figure 5. Correlation between SSHA and ENSO.](image)

3.4. Wavelet coherence analysis on SSHA
Wavelet coherence is used to observe correlations on frequency and time intervals at once [15]. Ocean Nino Index (ONI) and SSHA of the SCS showed significant coherence in the inter-year period. The vector of coherence indicates the phase difference between ONI and SSHA at each time and period, with the right arrow referring to one phase, the left arrow is the anti phase, ONI which precedes the SSHA with the arrow 90° up and vice versa with a 180° arrow. Curved areas with gray gradations indicate "cone of influence". The following will be compared to the influence of SSHA on ENSO in each region.
From the results of the main component analysis, different correlation values were found between SSHA and ENSO in each region. Both correlation values always have the same sign in each mode, both positive and negative. For example, the first mode component of region A is positively correlated with ENSO, while in region D is negative. In addition, correlation values in some regions also have similarities. In the G region, the first mode variance is 93.2%, but the correlation value of the PC1 component with ENSO has a difference of 0.05. Coherence analysis is needed to understand the role of ENSO in modulating variability in the SCS.

Figure 6 shows wavelet coherence in the E region located in the waters of the Gulf of Thailand. The correlation between PC1 and ENSO in this region is 0.11. Because the first time series on wavelets was SSHA and the second time series was an index, then in 2002 to 2004 sea level was higher than normal. In 1995 and 1996, a strong correlation was found between ENSO and SSHA. In this time span, ENSO is in phase with SSHA variability. The conditions of the ENSO and SSHA phases were also found in 1995 to 2000, but with a smaller correlation value. For periods over 32 months indicated the interannual variability, changes in SSHA precede ENSO events.

![Wavelet Coherence: SSHA - ENSO (E Area)](image)

**Figure 6.** SSHA Wavelet coherence with ENSO in E area.

Wavelet coherence in region F is given in Figure 7. This region is located off the southeast coast of Vietnam. The correlation of PC1 with ENSO in this region is 0. Similar to region E, region E also has a positive correlation between SSHA and ENSO. However, significant correlations are in different bands.
4. Summary
Satellite altimetry data from 1992 to 2015 was used to conduct the study of spatial variability of South China Sea and to analyze sea surface height response to interannual phenomenon. In order to examine dominant spectrum on each stations, signal analysis was performed using several methods, such as empirical orthogonal function (EOF), power spectra and wavelet coherence. Based on previous results, it is found that South China Sea is a region heavily influenced by monsoon. During the northeast monsoon, Kuroshio intrusion is apparent along the coast of Taiwan. On the other hand, several anticyclonic gyres are found on the western part of Luzon and Hainan. Interannual phenomena show dominant features in almost every regions. Inter-year signals in general have higher energy spectrum than decadal signals, with the exception in B area and D area. ENSO and SSHA have significant correlations to each other, but the response of the upper layer to inter-year phenomenon differs on many areas. Wavelet analysis was utilized to see whether the correlations in each regions are coherence. Strong coherence between SSHA and ENSO occurred in 1995 and 1996, where ENSO was in phase with SSHA variability. For periods over 32 months, changes in SSHA precede the inter annual ENSO events. It is suggested that different phases of ENSO (warm and cold) imply a non-uniform response, as some geographical regions display higher SSHA during warm phase (El Niño) and lower SSHA during cold phase (La Niña) in South China Sea. The role of long term variability response such as decadal and inter decadal variability as shown in the results should be analyzed in more detail research.

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References
[1] Li L 2003 Annual variation of sea surface height, dynamic topography and circulation in the South China Sea-A TOPEX/Poseidon satellite altimetry study Science in China (Series D) Vol.46 No. 2
[2] Ho C R, Zheng Q, Soong Y S, Kuo N J and Hu J H 2000. Seasonal variability of sea surface height in the South China Sea observed with TOPEX/Poseidon altimeter data. Journal of Geophysical Research, Vol. 105 C6 (13), 981-13, 990
[3] Qu T, Yan Du, Gary M, Akio I and Dongxiao W Connecting the tropical Pacific with Indian Ocean through South China Sea Geophysical Research Letters, Vol. 32 L24609, doi:10.1029/2005GL024698, 2005
[4] Wang L et al Mesoscale variability in the South China Sea from the TOPEX/Poseidon altimetry data Deep-Sea Research Vol. I No. 47, 681-708, 1999
[5] Cheng X, Xie S P, Du Y, Wang J, Chen X and Wang J 2016 Interannual-to-decadal variability and trends of sea level in the South China Sea Clim Dyn 46 3113-3126
[6] Shaw P T, Chao S Y and Fu L. Sea surface height variations in the South China Sea from satellite altimetry. Oceanological Acta 22, 1-17, 1998
[7] Zhou J, Li P and Yu H 2012 Characteristics and mechanisms of sea surface height in the South China Sea Glob Planet Change 88-89 20-31
[8] Emery W J and Thomson R E 2001 Data Analysis Methods in Physical Oceanography (Elsevier)
[9] Liberto T D 2015 Hovmoller Diagram: A climate scientist’s best friend (Climate.gov)
[10] Radjawane I M and Azminuddin F 2016 Seasonal and semi-annual variability of sea surface height in Makassar Strait J. of Physics: Conference Series 739(1)
[11] Wang J and Chern C S 1987 Acta Oceanogr. Taiwan 18 104-113
[12] Pei Y, Zhang R H, Zhang X, Jiang L and Wei Y 2015 Variability of sea surface height in the South China Sea and its relationship to Pacific oscillations ACTA OCEANOL SIN 34 (12) 80–92
[13] Qiu B and Chen S M 2012 Multidecadal sea level and gyre circulation variability in the Northwestern Tropical Pacific Ocean J Phys Oceanogr. 42 193-206
[14] Wu C R 2013 Interannual modulation of the Pacific Decadal Oscillation (PDO) on the low-latitude western North Pacific Prog Oceanogr. 110 49-58
[15] Rong Z, Liu Y, Zhong H and Cheng Y 2007 Glob Planet Change 55 257-272