Seasonal and semi-annual variability of sea surface height in Makassar Strait

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Abstract. Seasonal and semi-annual variability of sea surface height anomaly (SSHA) of Makassar Strait for 21 years in 1993-2013 is investigated using monthly product from several altimetry satellite observations. The time series data were obtained from AVISO and analyzed using spatial diagram and S-Transform. Results show that the monthly variation of mean SSHA increase from north to south part of the strait. The SSHA was dominantly for the 9-14 months that influenced by monsoonal system. During Northwest Monsoon the SSHA increases around 3 to 9 cm with the maximum in February in the southern part of the strait. The semi-annual variation was also detected for the 5-7 months signal period and commonly occurs during transitional monsoon in April/May and November/December. This phenomenon related with Kelvin wave propagation from Lombok Strait to Makassar Strait.

1. Introduction
Sea surface height is generated by the astronomical and also non-astronomical forces. It has periodical modulation based on the astronomical interact forces for example moon-earth, moon-sun etc. There are also several non-astronomical phenomenons that can influence the sea surface height, such as: monsoon, ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation). Sea surface can change its height as a response of the forces that work in an entire water. The significant height can be analyzed from the Sea Surface Height Anomalies (SSHA). In this paper we will focus the research on non-astronomical tides for the seasonal and semi-annual period using the satellite altimetry data. The region is affected by monsoonal and semi-annual circulation. The advantage using the altimetry data that the whole region of the strait can be provided data. Makassar Strait is chosen as the research area because it is an interesting area where the main pathways of Indonesian Througflow (ITF) from Pacific Water enter into the Indonesian regions and flow to Indian Ocean. This strait brings 80% water from Pacific Ocean into the Indonesia regions. Beside its interesting feature from view of ocean dynamics, this area also has important roles on marine transporation, fishereies and trading routes.

2. Data and methods
The data using in this research was obtained from monthly Sea Surface Height Anomaly (SSHA) was produced from Data Unification and Altimeter Combination System (DUACS). The data was collected from several satellites for example Topex/Poseidon (T/P), Jason 1, Jason 2 ERA 1 and 2, GFO, Envisat, and Geosat. The length of data was 21 years from January 1993 till December 2013.
The data was constructed in grid form with spatial resolution $1/3^\circ \times 1/3^\circ$ in long time series data that homogen, well calibrated and accurate. The research area can be seen in Fig. 1. We choose three points as representative from the north, central and south region of Makassar Strait. These three points lay at the altimetry track.

**Figure 1.** Map of Makassar Strait with X, Y and Z location. (Map source: Google Earth, 2015)

The SSHA was analyzed with statistical and signal analysis approaches. We used the monthly and annual mean SSHA. The signal processes covered the low pass filter (lpf) and high pass filter (hpf), and S-Transform. The cut off period of seasonal variability is 9-14 months, while for the semiannual variability is between 5-7 months. The S-Transform calculated based on Gaussian Window (Wang, 2010) and can be defined as follow:

$$S(\tau, f) = \int_{-\infty}^{\infty} h(t) g(\tau - t) e^{-j2\pi ft} dt$$

(1)

where $h(t)$ is function of time series of observed SSHA and $g(t)$ is window function that can be defined as follow:

$$g(t) = \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}}$$

(2)

where,

- $\tau$: time of spectral localization
- $f$: Fourier frequency
- $t$: time series

The S-Transform can analyze the compatibility of data signals with Gaussian Window. The results that can be obtained from S-Transform is 2-dimensional power spectrum that shows the frequency or period signals from time series data.
3. Results

3.1. Seasonal Variability

Monthly mean variation of SSHA data for 21 years (January 1993 till December 2013) was used to analyze the seasonal variability of SSHA along the Makassar Strait. In Fig. 2, we can analyze the monthly mean variation of SSHA. The Y-axis refers to monthly mean SSHA during 21 years SSHA, while X-axis refers to station locations in Makassar Strait based on Fig. 1.

*Figure 2. Monthly mean variation of SSHA shown in Hovmöller diagram. The data from January 1993 until December 2013.*

During Northwest Monsoon (NW Monsoon) that happened in December till February, mean monthly sea level in Makassar Strait increase around 3-9 cm. The sea level increased from north to southern part of the Strait. The maximum height is found in Z point at the end of February. In contrary, during the Southeast Monsoon that occurred June until August, the sea level height decrease -1 to -8 cm. The sea level decreased from north to southern part of the Strait. The minimum height is found in Z point at the end of July.

The influence of the monsoon against sea surface height at southern part of Makassar Strait is strong and become weak towards the north. Figure 3 show the time series of sea surface height anomaly along Makassar Strait. The maximum changes at southern part of the strait (gray line) with elevation ranges about -8 cm (Southeast Monsoon) till 9 cm (Northwest Monsoon). Whereas the maximum change of sea surface height anomaly at northern part of the strait (red line) is about -4 cm (Southeast Monsoon) till 3 cm (Northwest Monsoon). SSHA data which was used in Figure 3 has been filtered by low pass filter with cut-off period of 9 months and high pass filter with cut-off period 14 month. It means that the data shown in Figure 3 represent only signal with a seasonal period between 9 and 14 months.
3.2 Semi-annual Variability

Figure 4 shows a Hovmöller diagram of sea surface height anomaly for 21 years along the Makassar Strait that has been filtered by low pass filter with 5 months period cut off and high pass filter with 7 months cut off and known as the semiannual variability.
Rao et al. (2009) used sea surface height anomaly data to investigate semiannual variability of Kelvin wave. There were twice different phase in one year which consist of upwelling Kelvin (January – March and August – September) and downwelling Kelvin (April – June and October – December) in the Equatorial Indian Ocean. Kelvin wave propagates along the southern coasts of Sumatra, Jawa, and Bali entering Lombok Strait before moving northward along the western coast of Makassar Strait and reaching the Sulawesi Sea (Sprintall, et al (2010)). Figure 4 show Kelvin wave signals along the Makassar Strait. Generally, positive signal (red colour) show downwelling Kelvin which happened around April/May and November/December. Syamsudin (2004) used altimeter data show the frequent occurrence of Indian Ocean Kelvin wave either in April/May and November/December during f 1993 – 2001 (except 1994) along the southern coast of Sumatra, Jawa, and Bali. It proves that semiannual variability of Kelvin wave propagates along southern coast of Jawa entering Lombok Strait moving northward along Makassar Strait. In the Northern part of the Makassar Strait (Point-X) Kelvin waves raised sea level height about 1.2 cm and 1.7 cm in the southern part of Makassar Strait (Point-Z) The Kelvin wave which propagates in April/May is only triggered by western wind that blows in the Equatorial Indian Ocean (Iskandar et al., 2005). It’s caused Southeast monsoon wind weaken positive signal of Kelvin wave. Whereas another phase of Kelvin wave (November/December) is triggered by Northwest monsoon wind cause buildup of water mass that strengthen positive signal of Kelvin wave (Figure 4).

Figure 5a and 5b show signals that are generated from SSHA data at the southern part of Makassar Strait. There is a significant difference between before and after filtering process. The most dominant signal at the southern part of the strait (point-Z) is seasonal signal (9 – 14 months period with frequency of 0.11 – 0.07). Before filtering process the semiannual signal 5 – 7 months period with frequency of 0.15 – 0.2 can not be detected clearly, but the semiannual signal can be clearly seen after filtering process.

![Figure 5. S-Transform diagram of SSHA at southern part of the strait (point-Z), before (a) and after (b) filtering process](image)
Figure 6 shows Kelvin wave signal at the north (point-X) and central (point-Y) regions of Makassar Strait. Figures 5 and 6 show that Kelvin wave quite strengthen at the central region of the strait, then weaken toward Sulawesi sea. The further research is needed to describe the phenomena of Strengthen Kelvin wave signal at the central region of Makassar Strait.

Syamsudin (2004) investigated the semi-annual variability of Kelvin wave either in April/May or November/December during 1993 – 2001 (except 1994) along the southern coast of Sumatra, Java, and Bali. It is shown in the Figures 5 and 6 that Kelvin wave signal is weaken in 1994. Atsari (2013) described that Kelvin wave signal in 1994 is weakened by El Nino and Dipole Mode positive phenomenon. Figure 7 shows the difference phase at each observation point. The SSHA in X point is higher than in Y and Z points and forms a slope between X and Z. This slope indicated the direction of Kelvin wave. From Figure 7 it clear that Kelvin wave propagate towards the Northern part.
Kelvin wave velocity can be calculated based on the slope condition (Figure 7). We can calculate the Kelvin wave velocity using this simple formula as follow:

\[ v = \frac{\text{distance between point } x - z}{\text{time of propagation}} \]  

At the midterm of 2010, the velocity of Kelvin wave propagates along Makassar Strait is 0.164 m/s. The result is smaller than the Kelvin wave velocity at the southern coast of Jawa i.e 1.8 – 2.4 m/s (Syamsudin and Kaneko, 2014), but higher than at Sulawesi Sea i.e 0.12 – 0.14 m/s (Syamsudin, 2014). It means that the Kelvin wave which propagate from south part of Java entering the Lombok Strait decrease significantly toward Makassar.

4. **Conclusions**

Based on the study, the seasonal variability of sea surface height with cut off 9 – 14 months in the Makassar Strait caused by the monsoon. During Northwest Monsoon (NW Monsoon), mean monthly sea level height in Makassar Strait increase with range 3-9 cm. The sea level increased from north to southern part of the Strait. The maximum height is found in Southern part of the Strait at the end of February. In contrary, during the Southeast Monsoon (SE Monsoon) that occurred in June until August, the sea level height decrease -1 to -8cm. The sea level decreased from north to southern part of the Strait with minimum height is found in Southern part of the strait at the end of July. The weak signal of semi-annual variability appears around April/May and November/December along the Makassar Strait caused by Kelvin wave propagation. The signal can be weakened by El Nino and Dipole Mode (+) phenomenon. Downwelling Kelvin wave raised sea level height along Makassar Strait about 1.2 – 1.7 cm. Then at the midterm of 2010, the velocity of Kelvin wave propagation along the Makassar Strait is about 0.164 m/s
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